buildings

Article

Visualization of Acoustic Comfort in an Open-Plan, High-Performance Glass Building

Aldo A. Glean [1,*,†], Stanley D. Gatland II [2,†] and Ihab Elzeyadi [3,†]

[1] CertainTeed Corporation, Saint-Gobain Research North America, Northborough, MA 01532, USA
[2] Saint-Gobain North America, Malvern, PA 19355, USA; stanley.d.gatland@saint-gobain.com
[3] School of Architecture + Environment, University of Oregon, Eugene, OR 97403, USA; ihab@uoregon.edu
* Correspondence: aldo.glean@saint-gobain.com
† These authors contributed equally to this work.

Abstract: The aesthetic and functional appeal of high-performance, open-plan office buildings presents special challenges. Extensive use of glass at the building's perimeter to improve visual comfort and office communication can negatively impact acoustic comfort without proper design considerations. This study investigates the utility of a novel visualization approach to documenting the interactional impact of acoustical comfort on the health and well-being of occupants in an open-office environment. Room acoustic measurements of background noise and speech transmission index were conducted and distraction distances were calculated and visualized using a mapping technique. In addition, a comprehensive pre- and post-occupancy evaluation protocol was employed. The paper illustrates the reliability of the visualization approach to aid in the interpretation and comparison of various open-office acoustic solutions from a human-centric acoustic environment perspective.

Keywords: acoustic comfort; speech transmission index; speech intelligibility; open-plan office

Citation: Glean, A.A.; Gatland, S.D., II; Elzeyadi, I. Visualization of Acoustic Comfort in an Open-Plan, High-Performance Glass Building. *Buildings* **2022**, *12*, 338. https://doi.org/10.3390/buildings12030338

Academic Editors: Yue Wu, Zheming Liu and Zhe Kong

Received: 29 January 2022
Accepted: 27 February 2022
Published: 11 March 2022

1. Introduction

Architectural acoustics is an important consideration in the overall comfort of open-plan offices. Researchers [1–7] have made considerable effort to investigate the acoustics of open-office spaces and present potential solutions for improving their indoor environmental quality. Examples of these solutions are (1) configuring the floor plan to effectively balance and acoustically separate areas; (2) designing collaborative and transition spaces with sound-absorbing surfaces; (3) employing high-performance, noise-reducing interior partitions, and exterior facades; and (4) adding background noise control and enhancement measures for selective workstation. While these measures have proven to help achieve a comfortable indoor work environment, the lack of approaches to visualize their effectiveness have resulted in limitations of their applications in practice. This paper reports on the applicability of a novel visualization approach to aid in the interpretation and comparison of various open-office acoustic solutions from a human-centric acoustic environment perspective.

Poor acoustic indoor environments have been shown [8–11] to negatively impact the cognitive performance and well-being of occupants, thus negatively affecting their productivity. The presence of irrelevant speech from single and multi-talkers in an open-plan office, along with noise from printers, phones, and HVAC systems can lead to a reduction in the quality of the acoustic environment. However, in some cases, HVAC systems can improve the acoustic comfort in open-plan offices by providing sound masking. Yadav et al. [12,13] have studied the impact of both single and multi-talkers on sound pressure level and their effect on the cognitive and task performance of occupants in an open-office environment. Their studies [13] investigated the potential benefit of the "babble effect", acting as a sound-masking source, thus improving the acoustic comfort of the space, but its impact was found to be limited. Sound masking, which is the addition of background noise to reduce the impact of distracting sound sources, is one of the common solutions [14–16] for improving the acoustic comfort within open-plan offices. In some instances, multiple voices in open-plan offices can be a potential source of sound masking [17], thus improving the acoustic environment.

Acoustic comfort within an open-plan office can be characterized by the calculated distraction distance, which is based on sound transmission index (STI) measurements. This relates to speech intelligibility as a function of distance from the source. Haapakangas et al. [18] conducted an analysis of 21 open-plan offices using surveys and room acoustic measurements of distraction distance, spatial decay of speech, speech level at 4 m from the speaker, and background noise level. Their findings showed that the perception of noise was mainly related to background speech and that an increase in distraction distance predicted an increase in disturbance by noise. The other measured quantities were not significant standalone indicators of noise disturbances. Distraction distance is an important metric in characterizing acoustic comfort. Despite the apparent benefits of visualizing distraction distance as a tool to understand and compare the acoustic environment, there is a current gap in the literature of examples suggesting visualization procedures and techniques for practical application. This limitation impacts the comparative analysis of acoustical treatment evaluations and presents barriers to employing innovative acoustic treatments to open-plan office environments.

This study investigates the utility of novel visualization and a building performance evaluation technique to document the interactional impact of acoustical comfort on the health and well-being of occupants in an open-office environment. In this study room acoustic measurements were conducted from which the distraction distance was calculated. The employee experience was captured using a comprehensive Pre-Post Occupancy Evaluation (PPOE) protocol. This paper illustrates a visualization strategy to aid in the interpretation and comparison of various open-office acoustic solutions, which is also correlated to survey responses by occupants from a human-centric acoustic environment perspective.

2. Materials and Methods

2.1. Building Design-Acoustic Comfort

2.1.1. Traditional Building

A corporate headquarters was relocated from a traditional cellular private office complex (pre-move) to a LEED platinum-certified open-concept plan office (post-move) in 2015. The traditional late 1960's corporate campus consisted of four low-rise, multistory buildings having perimeter offices and centrally located cubicle workstations. Transparent glass and gypsum wall partitions separated the perimeter and central spaces. The building envelope consisted of a brick facade and large single-glazed fixed casement windows. Workstations were divided using 1524 mm tall fabric covered partitions. Space lighting was created using ballasted tube florescent lights integrated into the suspended acoustical ceiling. Numerous hard sound reflective surfaces were created in the open plan space by lighting fixtures, furniture, metal ceiling panels, gypsum and glass partitions. The traditional building exterior is presented in Figure 1a along with a typical workstation in Figure 1b.

(a) (b) (c) (d)

Figure 1. (**a**) Traditional building complex. (**b**) Typical workstation of traditional building. (**c**) LEED-certified platinum building. (**d**) Workstations in new LEED certified building.

2.1.2. LEED-Certified Platinum Building

The renovated four-story, all-glass-facade LEED platinum-certified building consisted of large, centrally located workstations with perimeter hallways and collaborative areas. Transparent glass and gypsum wall partitions separated the perimeter collaborative and central spaces. Individual workstations were separated by fabric-covered partitions with colored glazing extensions having varying heights of 1047 mm, 1448 mm, and 1625 mm. Slim profile LED luminaries with sharp cut-off angles were integrated into the suspended acoustical ceiling to provide additional space lighting. Hard reflective surfaces were limited to the perimeter of the large open-plan office space. An active sound masking system was implemented in all open-plan spaces to increase acoustic comfort at the 800 plus workstations. The LEED certified platinum building exterior is presented in Figure 1c along with a typical workstation in Figure 1d.

Table 1 provides a comparison of the traditional building complex and the new LEED-certified building, mainly from an acoustic surface characteristic perspective. The main differences highlighted are the office layouts, addition of collaborative areas, and perimeter hallways as opposed to perimeter offices. With this new open-office concept the addition of sound masking and ceiling tiles with higher absorption were critical to the acoustic comfort within the space.

Table 1. Comparison of acoustic comfort spatial and surface characteristics between office buildings.

Acoustic Comfort Spatial and Surface Characteristics		
	Traditional Office Building (Valley Forge, PA/Pre-move)	LEED-Certified Office Building (Malvern, PA/Post-move)
office plan	perimeter offices central workstations	open-concept office space central workstations perimeter hallways perimeter collaborative areas
perimeter wall	glass-NRC 0.04, gypsum board-NRC 0.06	glass-NRC 0.04
partition wall	glass-NRC 0.04, gypsum board-NRC 0.06	glass-NRC 0.04, gypsum board-NRC 0.06
floor	carpet-NRC 0.15	carpet-NRC 0.20
workstation partition	fabric-NRC 0.40	fabric-NRC 0.40
ceiling	mineral board tile-NRC 0.70	fiberglass tile-NRC 0.95

2.2. Measurement Procedure

The acoustic comfort experienced in an open-plan office can be assessed through the measurement of acoustic parameters such as spatial decay rate of speech, speech transmission index (STI), distraction distance, privacy distance and background noise levels. STI and background noise levels were measured to evaluate the indoor environmental quality (IEQ) of the LEED platinum-certified building described in Section 2.1.

The speech transmission index represents the transmission quality of speech with respect to intelligibility. Background noise levels represent the measured sound pressure level in absence of any occupants within the evaluated space. Both distraction and privacy distances are determined from the STI measurements and represent the distance from the speaker at which the STI falls below 0.50 and 0.20 respectively. ISO 3382-3 [19] provides a detailed description of these acoustic parameters along with the standardized measurement procedure which was used to acquire the data presented.

Speech is essentially the modulation of a band of noise. Measurements of speech transmission index (STI) were conducted using the STIPA (STI for Public Address Systems) method [20]. This method is an alternative to the full STI measurement, which uses a Gaussian noise signal as the carrier and is divided into seven-octave bands from 125–8000 kHz, where each band is modulated by fourteen modulation frequencies in one-third octave bands, from 0.63–12.5 Hz. This results in 98 combinations, which creates a time-consuming measurement. In the STIPA method a total of 12 modulation indices are measured from carrier frequencies in one-third octave bands ranging from 0.63 to 12.5 Hz. The modulation represents the combination of modulation and carrier frequencies used to mimic speech excitation. A Nor140 (Norsonic sound level meter) was used to measure the STI using the STIPA method at specific distances from the excitation source within the space. The sound level meter was also used to measure the background noise level at various workstations throughout the open office, in accordance with ISO 3382-3.

Workstations within the LEED-certified open office building were evaluated for the speech transmission index and background noise levels with and without sound masking. Ideally, the STI values will drop below 0.50 between 2 and 4 m. The background levels are expected to fall below a noise criteria (NC) level of 40 dB. Noise criteria are single numbers used to define goals for maximum allowable noise in a given space.

Measurements at various workstations allowed for a comprehensive acoustic comfort mapping of distraction distance from the STI. The maps can be used for quick visualization and spatial assessment of the expected acoustic comfort of the open-plan space with regard to distraction and privacy distances.

2.3. Post-Occupancy Evaluation Survey

The Space Performance Evaluation Questionnaire (SPEQ^{TM}) is an online occupant's survey with developed categories and scales representative of the most important issues identified by occupants to impact their comfort, satisfaction, performance, and health, as perceived and experienced in their work environments. The survey semantics and linguistics have been designed based on proven language constructs that represent layperson descriptions of their physical environment. SPEQ^{TM} was cross-tested and calibrated in field and lab settings. The survey was peer-reviewed by an expert panel of 20 professional building scientists, psychologists, space planners, architects, and physicians.

The data collected by the questionnaire evaluates 30 pre- and post-occupancy issues in 76 questions classified into seven main categories. All questions contained a skip-logic approach to skip irrelevant information based on the occupant's responses. This made the instrument more effective and reduced respondents' fatigue. The average response time of the questionnaire is 12 min, with a minimum of 8 and a maximum of 20 min. All answers were recorded on a five-point Likert scale, semantic-differential scale, a numerical open scale, or a categorized aggregated scale. The scales allowed for continuous data that was easily analyzed using simple and more complex statistical modeling and regressions. In addition, open-ended responses were encouraged for all questionnaire categories to allow occupants to voice their opinions without restrictions. The questionnaire contained a forced response to a consent form and pre-set reminders for missed question responses. Respondents were allowed to skip questions on the second attempt for most questions, with the ability to skip demographic questions to maintain the respondent's privacy. Neither compensation nor a fee was administered for a respondent to respond to the questionnaire. To facilitate statistical analysis, questionnaire responses were recorded into a numerical scale of one to five, such that five was "strongly agree", three was "neutral", and one was "strongly disagree". Subjective responses from SPEQ^{TM} questions were paired with objective acoustical measurements identified in Section 2.2 using timestamps for cross-tabulation analyses.

3. Results

The level of background noise in a space directly impacts speech intelligibility. Background noise level is governed by noise criteria (NC). For an open-office plan with forced-air distribution systems, the ASA S.12.2-2008 [21] recommended noise criteria (NC) curve limit is NC-40 or less. At NC-40 the corresponding sound pressure level range is 46 dB_A to 48 dB_A.

Background noise levels were measured in the LEED building with and without the sound masking system turned on during occupied hours. The dots in Figure 2 indicate locations on the third floor at which the background levels were measured. The average sound pressure levels in the north wing with and without the sound masking system turned on were 46.6 dB_A and 41.1 dB_A, respectively. The sound masking system generated white noise in the space through an evenly distributed loudspeaker system located in the ceiling plenum. This increased the average background noise to the desired level to achieve good speech privacy between workstations. In Figure 2, the green dots indicate values that met the design criteria during occupied hours. Red dots indicate values that exceeded 48 dB_A due to conversations (red unfilled ovals highlight locations) occurring near the measurement location. However, this value was only exceeded with the noise contribution from the sound masking system.

Figure 2. Background noise survey north wing of LEED-certified building with sound masking on (**left**) and off (**right**). The green dots denote values that met the design criteria during occupied hours whereas the red dots denote values exceeding 48 dB_A. Design criteria were exceeded in some instances due to nearby conversation, denoted by the red, unfilled oval shapes.

Workstations were evaluated for spatial sound distribution of the STI to assess the distraction distance from the speaker at which the speech transmission index fell below 0.50. A comprehensive acoustic comfort mapping strategy was applied in order to fully characterize the space and provide visuals of spatial performance. STI measurements were conducted in the northeast wing of the building with and without the activation of the sound masking system. Additionally, the impact of speaker height (standing or seated) on distraction distance was assessed.

STI data is often presented in a table format or an X–Y graphical plot. Figure 3 (WS3154) shows the location, and STI as a function of distance from the speaker at different angles. This dataset illustrates the scenario of a speaker standing versus sitting with sound masking and captures the impact on the STI. The distraction distance target (STI 0.50-0.30 at 2–4 m) was met for the 90-degree orientation with the standing speaker, and for all orientations except the direct (0-degree orientation) and a single 45-degree orientation when the speaker was seated. Given the layout of the workstations relative to the location of the speaker the differences observed with the orientation of the listener to the speaker were expected.

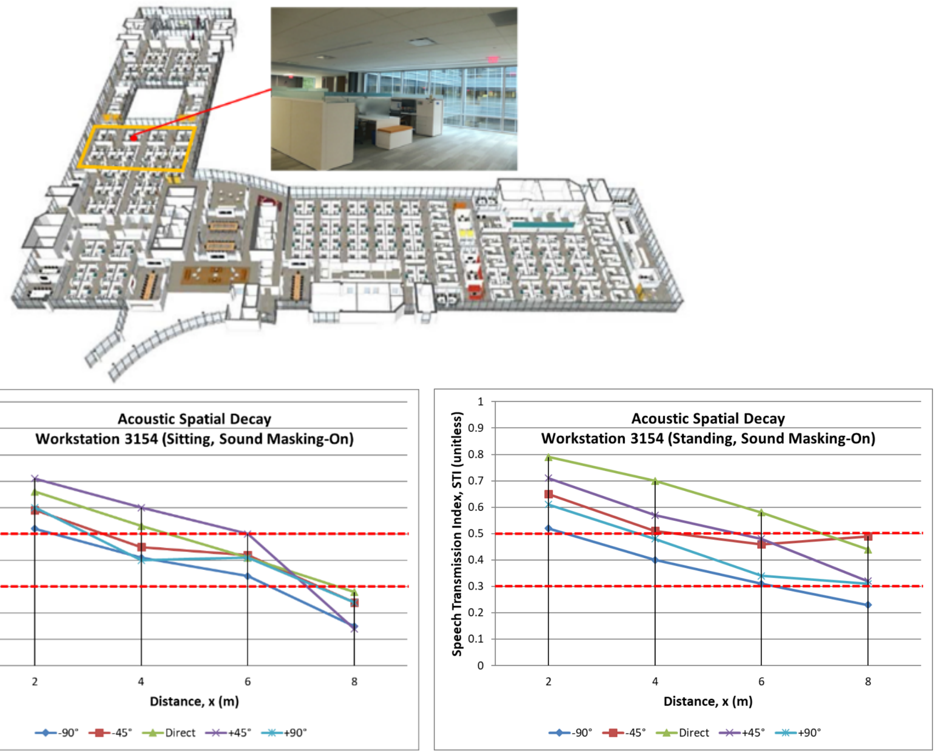

Figure 3. Office map depicting location on the third floor, north wing, at which measurements were conducted along with a snapshot of the interior space (**top**). Speech transmission index (STI) as a function of distance at different angles to a sitting speaker (**bottom left**) and a standing speaker (**bottom right**) with sound masking. The red dashed lines indicate a STI target value between 2–4 m.

Tables and line plots have been used extensively in the presentation of STI data. The plots are easy to interpret and present the data. However, this can at times be a challenge for architects, designers, owners, and developers, who are the solution decision-makers and would prefer the most user-friendly presentation of such data. A color-coded visualization of the STI acoustic comfort mapping can provide a quick and intuitive interpretation of the overall acoustic performance of the space. Overlaying the surface plot on a scaled drawing of the space can provide additional insights under various conditions.

To convey the space performance using the approach to STI acoustic comfort mapping, concentric semicircles were placed at 2-m intervals from the simulated speaker in a sitting position (Figure 4, left). The color map superimposed on the concentric circles convey the change in STI (Figure 4, right), and, by extension, speech intelligibility, at distances away from the speaker. Detailed scenarios are presented in Figure 5 which illustrate the STI measurements for standing and sitting with the sound masking system on and off. The plots, which can be interpreted relatively quickly, show the positive impact when the sound masking system is on and of the lower distraction distance (lower STI) in the seated versus standing positions.

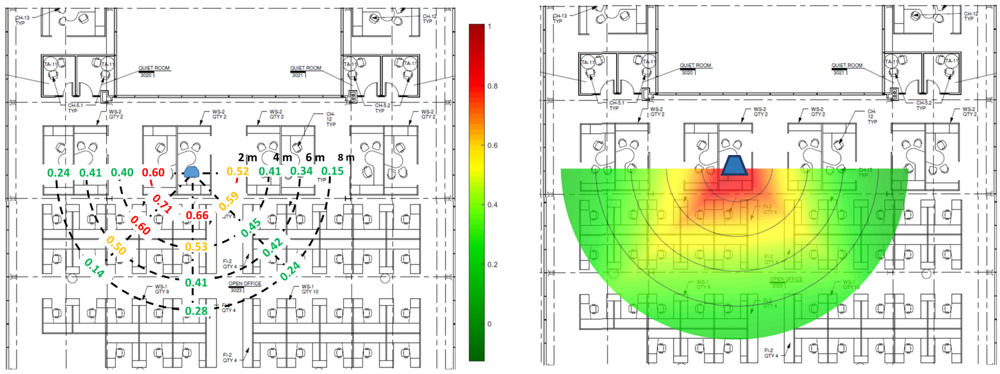

Figure 4. Acoustic comfort mapping with STI of north-facing workstation at the LEED building with the speaker in sitting position and sound masking on. (**Left**) Scaled drawing depicting STI measurements at various location and distances. (**Right**) Associated surface plot highlighting areas from good to bad STI rating.

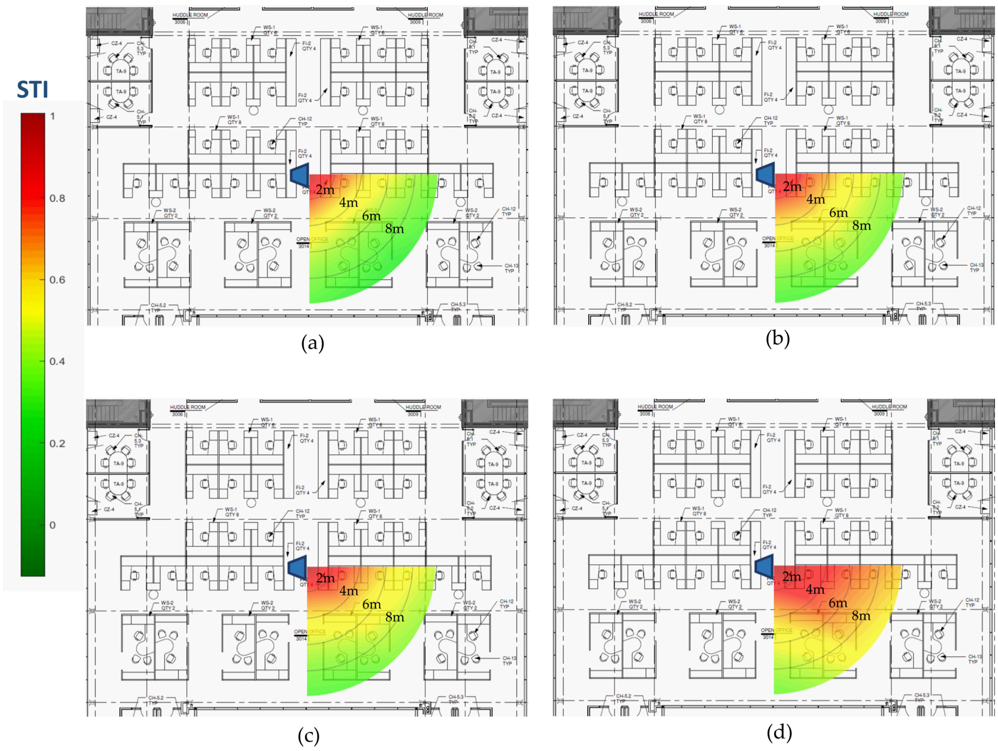

Figure 5. Acoustical comfort visualization through STI surface plots of measurements from the north wing workstation area on the third floor of the building. (**a**) Speaker in sitting position with sound masking on. (**b**) Speaker in sitting position with sound masking off. (**c**) Speaker in standing position with sound masking on. (**d**) Speaker in sitting position with sound masking off. The best- and worst-case scenarios for comfort shown in (**a**,**d**) respectively.

4. Discussion

4.1. Human-Centric Acoustic Comfort

The human-centric acoustic comfort model conceptualizes both the quality and quantity of the acoustical environment based on the occupant's perspective [22]. In this model, spatial and temporal impacts of comfort are evaluated physically and perceptually. To test the visualization approach proposed to acoustic comfort and its impacts on occupants' satisfaction, the SPEQ^{TM} survey was administered to the occupants of the traditional building prior to the move and one year after the move to the new LEED-certified building respectively. Focus groups were employed before the administration of the surveys to ensure that occupants were well habituated in the building and were even in their perception of both positive and negative attributes of the indoor environment. In addition, the after-move survey was administered one-year post-move to limit bias in perceptions between the new and old buildings.

Response to the survey was very high, with 42% of the 800 employees completing the survey prior to the move and 44% of the 800 plus employees completing the questionnaire one year after the move and relocation. Data tabulation and coding were performed on both the physical and human-response data sets. Physical measurements and survey responses were spatially tagged and statistically analyzed using the software Statistical Package for the Social Sciences (SPSS). This analysis ensured that spatial visualizations of physical acoustics metrics, such as STI, were correlated with occupants' perceptions of acoustical comfort and satisfaction responses to the SPEQ^{TM} questionnaire.

4.2. Occupants Perspective Analysis

To examine the correlation between acoustic comfort visualizations and occupants' perceptions, we calculated the mean difference in dissatisfaction and mean difference in satisfaction for the various aspects related to occupant perceptions of acoustical comfort (Table 2) in a traditional and a LEED-certified building. The reference in these calculations is the LEED building. For example, a negative sign (-) in dissatisfaction means a reduction in dissatisfaction responses for that item, hence more improvement. Similarly, a negative sign (-) in satisfaction means a reduction in satisfaction in this item, hence a lack of improvement and vice versa.

Table 2. Differences in perceived satisfaction of acoustic comfort attributes inside the LEED-certified building as compared with the traditional building.

Aspect	Mean Difference in Dissatisfaction (%)	Mean Difference in Satisfaction(%)	Total Perceived Difference (%)
overall acoustical satisfaction	−19.5	+22.7	42.2
noise from people talking in your area	−7.2	+12.0	19.2
noise from people talking in the hallway	−17.3	+16.9	34.2
noise from ventilation systems	−27.9	+31.2	59.1
noise from equipment	−25.3	+30.1	55.4
noise from lights	−10.6	+27.3	32.7
noise from outside the building	−10.4	+22.3	32.7

Employees responded to five different questions that collectively evaluated their acoustical comfort in the building pre- and post-occupancy between the traditional and LEED buildings. Across all questions, employees reported a higher level of acoustical comfort improvements of 42.2% in the LEED building as compared with the traditional building (Table 2). In addition, acoustical comfort improved across all parameters between 19% and 59%. The most improvement was the perceived reduction in noise of equipment and ventilation systems by 55.4% and 59.1%, respectively. Thanks to improvements in the building envelope and the provision of better daylighting and electric lighting systems, occupants reported an increased satisfaction of 37.9% for noise from lighting system and an increased satisfaction of 32.7% for outside building noise perception. The sound masking system and improvements in sound absorption material in the LEED building might be related to a perceived satisfaction with distractions of noise from people talking and walking in hallways despite being in an open-plan office. In general occupants perceived improvements in satisfaction of 19.2% for noise distractions due to talking and 34.2% improved satisfaction due to hallway noise as compared with the traditional building.

This improvement in satisfaction from the survey findings correlates well with the observation and interpretation of Figures 4 and 5. Within the workstation the STI falls within the range of 0.8–1.0 due to the close proximity to the speaker, and as a result, speech is highly intelligible. However, when sitting and the sound masking is on as illustrated in Figure 4, STI values, on average fall under 0.50 in the 4–6 m range. In this range the speech intelligibility has a fair rating, and a fair to poor rating at distances greater than 6 m. This means that occupants will be less distracted due to office conversations at those distances. Figure 5 clearly illustrates the change in distraction distance between standing vs sitting and sound masking on or off. The perceived satisfaction is expected to decrease to a minimum when the sound masking is off and the occupant is standing as the STI, on average, remains above 0.60 at a rage of 2–8 m. In general, the survey indicated occupants were satisfied with STI ranges of 0.2–0.4 outside of their immediate workstation.

5. Conclusions

Architectural acoustic designs for open-plan office spaces aim at reducing transmission between workstations while creating acoustical privacy within the individual workstation. This approach, however, doesn't usually result in a pleasant or comfortable work environment due to average numerical values that do not reflect a human-centric acoustical experience for the occupants, according to their spatial locations. Through the use of sound-absorbing surfaces, high-performance, noise-reducing interior partitions, and sound-masking systems, a more spatial acoustical comfort approach is feasible. Predicting the success of this approach in the field can be challenging. The use of STI mapping and visualizations is a tool that can help predict and estimate occupants' perceptions prior to occupancy. The procedure outlined in this paper offers a design and spatial visualization tool to help designers and building owners predict and estimate acoustical performance in spaces from the occupants' perspective.

The results show strong correlations between improved acoustic qualities of the retrofitted, high-performance, LEED-certified building in spaces visualized within the STI standards, and overall acoustical satisfaction (Table 2). A comparative analysis of the occupants' attitudes and perceptions of the impact of the building on their comfort levels reveal a significant perceptual change to the impact of acoustical design on the employee overall satisfaction. A comprehensive design and employment of spatial visualization tools to predict and implement metrics of indoor environmental quality (IEQ) might result in improved comfort, satisfaction, and the perception of well-being for the occupants. It is the hope that further integration of building systems concerning IEQ measures and comfort visualizations can better predict acoustical performance in the early design stages and lead to better work environments that are more responsive to occupant's needs and comfort expectations.

Author Contributions: All authorshave equally contributed to this manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study procedures involving human subjects, Protocol Number: 04252016.035, was approved by the University of Oregon Institutional Review Board as per 45 CFR Part 46.110. Upon further review, it was determined that this study qualifies for exemption as per the Common Rule regulations of Title 45 CFR 46.101(b)(2) on 28 April 2018.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study as a requirement to proceed with taking the SPEQ questionnaire.

Data Availability Statement: Data for this study is stored in an institutional depository protected by the University of Oregon IRB Protocol Number 04252016.035. Access to the data is only granted to key personnel involved in the study and who successfully passed the CITI training module.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Yadav, M.; Cabrera, D.; Love, J.; Kim, J.; Holmes, J.; Caldwell, H.; de Dear, R. Reliability and repeatability of ISO 3382-3 metrics based on repeated acoustic measurements in open-plan officies. *Appl. Acoust.* **2019**, *150*, 138–146. [CrossRef]
2. Lou, H.; Ou, D. A comparative field study of indoor environmental quality in two types of open-plan offices: Open-plan administrative offices and open-plan research offices. *Build. Environ.* **2019**, *148*, 394–404. [CrossRef]
3. Mikulski, W. Acoustic conditions in open plan office—Application of technical measures in a typical room. *Med. Pr.* **2018**, *69*, 153–165. [CrossRef] [PubMed]
4. Jahncke, H.; Hongisto, V.; Virjonen, P. Cognitive performance during irrelevant speech: Effects of speech intelligibility and office-task characteristics. *Appl. Acoust.* **2013**, *74*, 307–316. [CrossRef]
5. Jensen, K.L.; Arens, E.; Zagreus, L. Acoustical quality in office workstations, as assessed by occupant survey. In Proceedings of the 10th International Conference on Indoor Air Quality and Climate, Beijing, China, 4–9 September 2005; Volume 3, pp. 93–101.
6. Noble, M.R. Green buildings: Implications for acousticians. *J. Acoust. Soc* **2005**, *117*, 2378–2378. [CrossRef]
7. Hodson, M.; Khaleghi, A.; Richter, M.; Razavi, Z. Design and evaluation of noise-isolation measures for the natural-ventilation openings in a 'green' building. *Noise Control Eng. J.* **2009**, *57*, 493–506. [CrossRef]
8. Ebissou, A.; Parizet, E.; Chevret, P. Use of the Speech Transmission Index for the assessment of sound annoyance in open-plan offices. *Appl. Acoust.* **2015**, *88*, 90–95. [CrossRef]
9. Ebissou, A.; Parizet, E.; Chevret, P. Effect of masking noise on cognitive performance and annoyance in open plan offices. *Appl. Acoust.* **2016**, *88*, 44–55.
10. Haapakangas, A.; Hongisto, V.; Hyönä, J,; Kokko, J.; Keränen, J. Effect of masking noise on cognitive performance and annoyance in open plan offices. *Appl. Acoust.* **2014**, *86*, 1–16. [CrossRef]
11. Kang, S.; Ou, D.; Mak, C.M. The impact of indoor environmental quality on work productivity in university open-plan research offices. *Build. Environ.* **2017**, *124*, 78–79. [CrossRef]
12. Yadav, M.; Cabrera, D. Two simultaneous talkers distract more than one in simulated multi-talker environments, regardless of overall sound levels typical of open-plan offices. *Appl. Acoust.* **2019**, *148*, 46–54. [CrossRef]
13. Yadav, M.; Kim, J.; Cabrera, D.; de Dear, R. Auditory distraction in open-plan office environments: The effect of multi-talker acoustics. *Appl. Acoust.* **2019**, *126*, 68–80. [CrossRef]
14. Renz, T.; Leistner, P.; Liebl, A. Effects of the location of sound masking loudspeakers on cognitive performance in open-plan offices: Local sound masking is as efficient as conventional sound masking. *Appl. Acoust.* **2018**, *139*, 24–33. [CrossRef]
15. Renz, T.; Leistner, P.; Liebl, A. The Effect of Spatial Separation of Sound Masking and Distracting Speech Sounds on Working Memory Performance and Annoyance. *Acta Acust. United Acust.* **2018**, *104*, 611–622. [CrossRef]
16. Haapakangas, A.; Kankkunen E.; Hongisto, V.; Virjonen, P.; Oliva, D.; Keskinen, E. Effects of Five Speech Masking Sounds on Performance and Acoustic Satisfaction. Implications for Open-Plan Offices. *Acta Acust. United Acust.* **2011**, *97*, 614–655. [CrossRef]
17. Keus van de Poll, M.; Carlsson, J.; Marsh, J.E.; Ljung, R.; Odelius, J.; Schlittmeier, S.J.; Sundin, G.; Sörqvist, P. Unmasking the effects of masking on performance: The potential of multiple-voice masking in the office environment. *J. Acoust. Soc* **2015**, *138*, 807–816. [CrossRef] [PubMed]
18. Haapakangas, A.; Hongisto, V.; Eerola, M.; Kuusisto, T. Distraction distance, and perceived disturbance by noise—An analysis of 21 open-plan offices. *J. Acoust. Soc* **2015**, *141*, 127–136. [CrossRef] [PubMed]
19. *ISO 3382-3*; Acoustics—Measurement of Room Acoustic Parameters—Part 3: Open Plan Offices. ISO: Genèva, Switzerland, 2012.
20. *Nor140 Sound Analyzer: Instruction Manual*; Norsonic: Lierskogen, Norway, 2021.
21. *ASA S12.2-2008*; American National Standard Criteria for Evaluating Room Noise. Acoustical Society of America: Melville, NY, USA, 2008.
22. Elzeyadi, I.M.K. Multi-Performance Spaces: Assessing the Impacts of an Innovative LEED™Platinum Educational Complex on the Triple Bottom Line. In *Adaptive Architecture: Changing Parameters and Practice*; Prieser W., Hardy A., Eds.; Taylor & Francis Group: Routledge, UK, 2017; pp. 34–43.