OBJECTIVE AND SUBJECTIVE INVESTIGATION OF THE APPLICATION OF 3D-PRINTED HYBRID ACOUSTIC MATERIALS IN LIVING LAB CONDITIONS

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Abstract

The combination of 3D printing and advanced parametric design tools has created new opportunities for complex geometries and functional integration. In this context, perceptual studies are essential to complement objective metrics and reveal the advantages of design solutions that make more effective use of complex surfaces. Therefore, this work investigates the application of 3D-printed hybrid acoustic materials (HAMs, which combine sound absorption and diffusion properties in a single office setting within a Living Lab. Both an objective and subjective investigation were performed to compare 6 configurations obtained by varying HAMs location at different heights and their geometric distributions, while preserving the same number of elements. The different settings have been characterized by monaural, binaural and spatial impulse responses measurements using two different types of sources, i.e. an omnidirectional dodecahedron and a Talkbox. The objective room acoustic parameters, Reverberation Time, Clarity and STI, have been estimated and the aspects related to the perceived speech clarity improvements have been investigated comparing the different configurations through a subjective ABX test. The results highlight the crucial role of design control variables and perceptual investigation in achieving optimized conditions.

Keywords: *additive manufacturing, hybrid acoustic materials sound scattering coefficient, 3D printing, acoustic characterization*

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1. Introduction

The increasing demand for sustainable, high-performance, and architecturally integrated acoustic solutions has stimulated significant interest in the application of additive manufacturing (AM) technologies to room acoustics [1]. Recent advances in AM have demonstrated its potential to produce acoustic metamaterials and architected surfaces capable of controlling sound absorption, diffusion, and scattering in ways that are difficult to achieve using conventional fabrication techniques [2]. Among the most promising developments in this field is the concept of Hybrid Acoustic Materials (HAMs), which aim to combine multiple acoustic functions within a single element. Traditional acoustic treatments are generally designed either to absorb sound energy or to diffuse reflected sound waves [3]. However, contemporary architectural spaces often require acoustic solutions that simultaneously control reverberation and improve sound spatial distribution [3]. Recent studies have highlighted the growing interest in hybrid absorptive-diffusive panels and customizable acoustic surfaces that merge sound absorption and diffusion functionalities into integrated systems [4]. Previous investigations by Tsiokou et al. [2] demonstrated the feasibility of producing highly customizable HAMs using additive manufacturing, focusing primarily on sound absorption performance and highlighting the challenges associated with their acoustic characterization. The work emphasized the importance of developing suitable measurement methodologies capable of capturing the acoustic behavior of geometrically complex and customizable materials.

Despite these advances, the subjective perception of diffusive surfaces remains largely unexplored, and only a limited number of studies have investigated the application of hybrid absorptive-diffusive materials in real environments. Living Labs (LLs) provide an opportunity to bridge the gap between controlled laboratory experiments and field studies by enabling investigations under realistic occupancy conditions [5]. However, their use in architectural acoustics remains limited. As highlighted by Pisello et al. [6], only a few studies have addressed acoustic performance in LLs, and even fewer have combined objective acoustic measurements with subjective perceptual assessments. This gap is particularly relevant for innovative solutions such as 3D-printed Hybrid Acoustic Materials (HAMs), whose effectiveness depends not only on measurable acoustic performance but also on occupant perception. Therefore, this paper aims to evaluate the acoustic performance of Hybrid Acoustic Materials (HAMs) in a Living Lab environment by combining objective acoustic measurements with subjective perceptual assessments.

2. Methods

The methodology considers the application of 3D-printed hybrid acoustic materials (HAMs), designed and developed by BioG3D (Greece), in a single office setting within the Living Lab (LL) of Politecnico di Torino (Italy). The HAMs (Figure 1) combine sound absorption and diffusion properties within the same panel and have been presented in detail in Tsiokou et al. [2]. Both objective acoustic measurements and subjective perceptual assessments were carried out to evaluate six HAM configurations, obtained by varying the panels' location, height, and spatial distribution across two room walls.

2.1 Living Lab and configurations

The chosen test environment is a Living Lab (LL) operating as a single-person office, with a floor area of approximately 10 m^2 floor area and a volume of 32.7 m^3 within a larger building, surrounded by similar rooms on two sides and a corridor on the opposite side of the façade. The Schroeder frequency of the room is 274 Hz, and the background noise level is below 18 dB(A). Six configurations have been obtained by varying HAMs location over two different walls of the room at different heights (80 cm and 160 cm) and by modifying their geometric distributions (12 columns and 5 rows, compact or with an alternating empty row), while preserving the same number of elements (Figure 2,a).

2.1.1 Materials

The HAM panels (160 × 160 mm) were parametrically designed in Grasshopper (Rhinoceros 3D v7, Robert McNeel & Associates, WA, USA) to combine a gyroid-based open-cell porous core (5 mm pore size, 80% porosity) for sound absorption with a stepped Truchet-patterned surface for sound diffusion. The panels were fabricated using a dual-nozzle FFF Raise3D Pro2 Plus unit (Ø0.6 mm nozzle, 0.20 mm layer height, 40 mm/s printing speed, 60 °C bed temperature) (Raise3D, China) and colorFabb Light-Weight Polylactic Acid (LW-PLA) Natural (Ø1.75 mm) (colorFabb, The Netherlands). Two temperature-dependent profiles were developed to tune the material properties: 265 °C (Printing Profile A) to activate foaming and produce a lightweight porous gyroid core (20% infill), and 207 °C (Printing Profile B) to produce a dense diffusing surface layer (100% infill) (Figure 1). A total of 60 panels (requiring 1269 h 14 min of printing time, 21.1 kg of LW-PLA, and 296 kWh of energy) were fabricated. The set comprised 30 pairs of identical panels (i.e., A1–A1, A2–A2, B1–B1, etc.), following the classification in Tsiokou et al. [2].

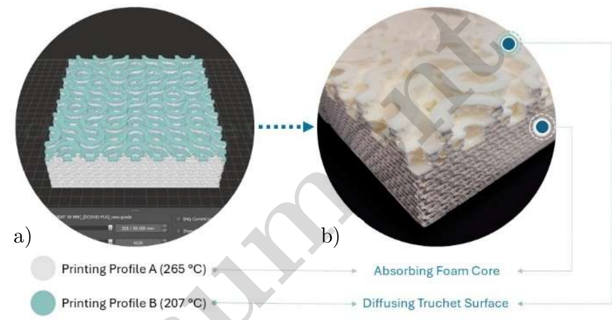

Figure 1. Fabrication of HAM panels (160 × 160 mm). a) Printing Profiles A and B preparation; b) corresponding Absorbing Foam Core and Diffusing Truchet Surface.

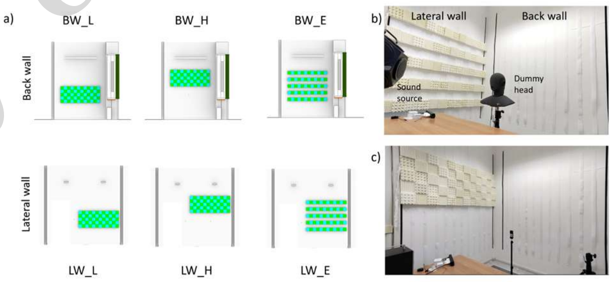

Figure 2. a) Schematic representation of the six HAM configurations installed on the lateral wall (LW) and back wall (BW) of the Living Lab. b) extended HAM during binaural measurements with a Dummy Head (LW_E); c) compact HAM in the higher position (LW_H).

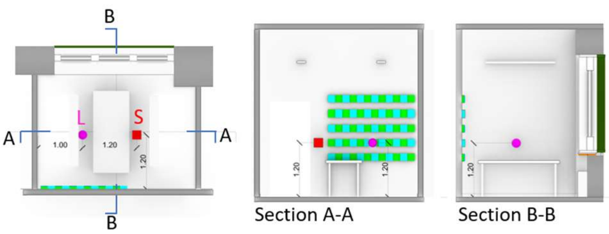

Figure 3. Measurement setup in the LL (floor plan and sections): pink = microphones, red = sources.

2.2 Objective acoustic measurements

The six different settings have been characterized by monaural (NTi XL2), binaural (Head Acoustics HMS II), and spatial impulse responses (Zylia ZM-1) measurements using two different types of sources, i.e. an omnidirectional dodecahedron (Bruel&Kjaer 4296) and a NTI Audio Talkbox (NTI Audio). The objective room acoustic parameters, including Reverberation Time (T_{30}), Clarity (C_{50}), and Speech Transmission Index (STI), were evaluated at the listener position (ear height: 1.2 m), corresponding to the head location of an occupant seated at the workstation. Figure 3 presents the floor plan, sections, and an axonometric view of the case study, showing the panel locations and the measurement setup.

2.3 Listening test

The aspects related to the perceived speech clarity improvements have been investigated comparing the different configurations through a subjective ABX test. A reference spoken sentence from the validated Talkbox signals database (70dB at 1m) has been used as signal with duration of 8 s and recorded in the LL with different configurations. The study employed the ABX psychoacoustic methodology to assess whether listeners could perceive audible differences between pairs of binaural audio recordings [7]. In an ABX test, participants are presented with three audio samples, denoted as A, B, and X, where sample X is identical to either A or B. The task consists of identifying whether X corresponds to sample A or sample B. In the absence of a perceptible difference between A and B, responses are expected to be random, resulting in a correct identification rate of approximately 50%. For the present study, the listening tests were administered through a custom MATLAB-based graphical user interface developed in Italian, following the methodology described by Shtrepi et al. [8].

A group of 40 volunteers among professors, research assistants, and students aged between 21 to 62 years old with normal hearing ability participated in the test. All of them provided written consent for the anonymized use of their test results. A priori power analysis was performed in GPower 3.1.9.4 [9] using an Exact Binomial Test. The null hypothesis assumed a chance performance level of 50%, while the expected correct identification rate was 75%. With $\alpha = 0.05$ and power = 0.90, the required sample size was calculated to be N = 33. Considering a higher number of subjects, i.e. 40, the power increased to 0.94 ($\alpha = 0.04$).

The listening test sessions have been conducted in the anechoic room at Politecnico di Torino, which has a background noise of L_{Aeq} = 17.3 dB. During the duration of the tests, the room conditions, as well as the set-up, have been kept unvaried. The equipment consisted of one computer and the BPU Bundle of HEAD Acoustics for an aurally accurate playback. The playback unit and the included headphones, HD OP I.1 (open Sennheiser HD 560S), are already matched to each other at the factory by the model-specific standard equalization filter. The environment was made comfortable for the listeners and they were familiarized with the test procedure by an illustrated written and verbal explanation.

3. Results

3.1 Objective acoustic parameters

The application of the Hybrid Acoustic Materials (HAMs) produced measurable changes in the acoustic conditions of the Living Lab, although the magnitude of the variations depended on the panel location and geometric distribution. Figure 4 compares the values of Reverberation Time, Clarity and Speech Transmission Index (STI) for the six investigated configurations relative to the untreated condition (Empty). The analyzes was performed with AURORA 4.5 plug-in for Audacity 2.4.1.

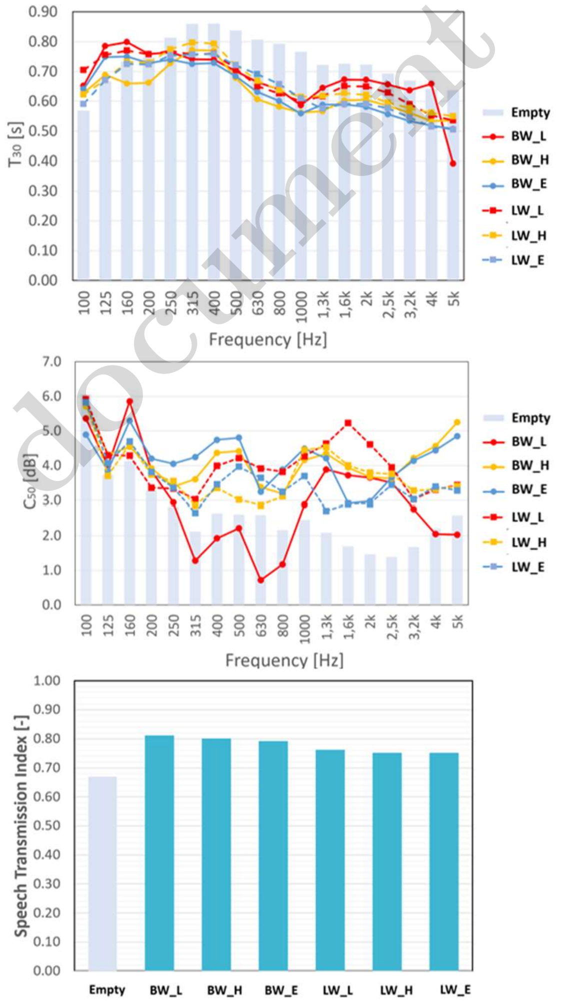

Figure 4. Reverberation time, clarity and STI for six configurations compared to the untreated condition (Empty).

Overall, the introduction of HAMs resulted in a reduction of the reverberation time on average from 0.8 s to 0.6 s at mid frequencies (250-3150 Hz), confirming the effectiveness of the absorptive component embedded within the panels. As shown in Tsiokou et al. [2], the single tiles present significant sound absorption coefficient (>0.5) in the frequency range 800-1000 Hz and above 2000 Hz with an extension at higher or lower frequencies depending on the tiles thickness (50 and 70 mm). However, because all configurations employed the same number of elements, the observed differences between configurations were mainly associated with the spatial arrangement and position of the panels rather than with changes in the overall amount of acoustic treatment. As a result, the room acoustic parameters exhibited only moderate variations among the tested cases.

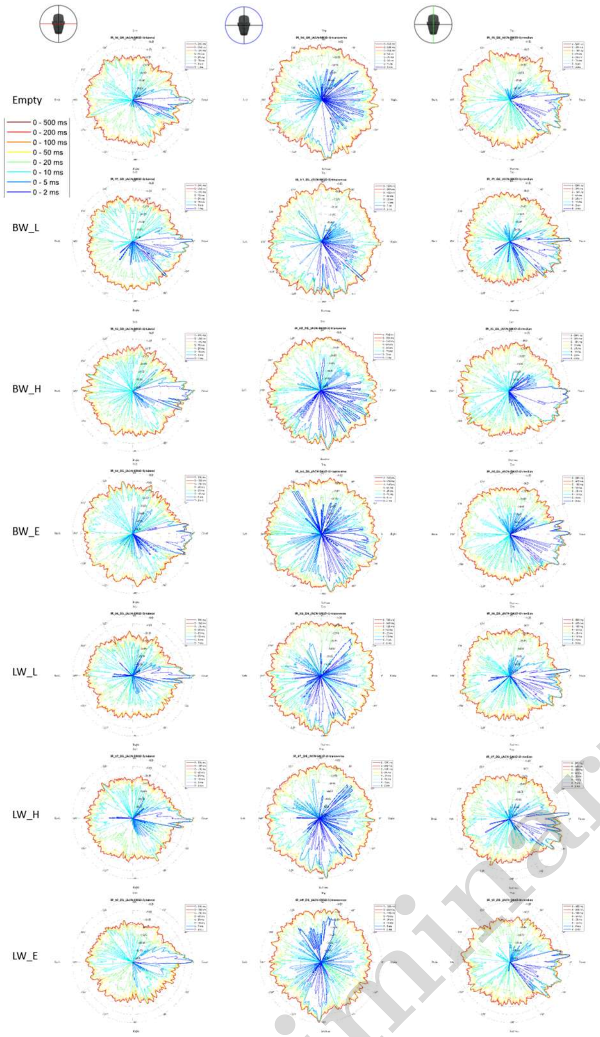

Figure 5. Spatial Impulse response rose decay plots for six configurations measured with a Zylia microphone array.

The improvements in speech-related metrics were more evident than those observed for reverberation time. Configuration BW_E characterized by a larger vertical extension of the treated surface achieved higher values of C50 indicating a more favorable balance between early and late arriving energy and enhanced speech transmission quality at the workstation position. The BW_L achieved the lowest C50 values decreasing at around 1 dB for the mid frequency range. This condition resulted worse than the untreated configuration. However, this effect was not observed for the corresponding configuration installed at a higher position on the back wall (BW_H), suggesting that panel height plays a significant role in the resulting acoustic performance. These findings indicate that the placement of the HAMs affects not only the absorption of sound energy but also the redistribution of reflections through their diffusive surface geometry. Speech Intelligibility improved with respect to the untreated condition (STI=0.67) and showed slightly higher values when considering the application on the back wall (0.79-0.81) rather than the lateral one (0.75-0.76), suggesting that the additional diffuse reflections may contribute to speech intelligibility while avoiding excessive attenuation of useful early reflections. This location was also studied and suggested as an improving strategy in the acoustic design of classrooms [10].

Additional insight is provided by the spatial impulse response analysis shown in Figure 5. The plots have been elaborated based on the analyses proposed in [11]. The rose-decay representations reveal the temporal and directional distribution of sound energy around the listener position. For all configurations, the direct sound is concentrated in the frontal direction (0°), corresponding to the location of the speech source. The subsequent reflections are distributed over a broad angular range, highlighting the contribution of room boundaries and workstation surfaces to the overall acoustic field.

Although the general structure of the sound field remains similar across the six configurations, noticeable differences can be observed in the strength and directional distribution of the early reflections. Configurations with HAMs covering a larger wall area or positioned closer to the listener height appear to exhibit a more diffuse reflection pattern, characterized by a reduced concentration of energy along specific directions. Conversely, the more compact arrangements tend to preserve stronger and more directional reflection paths, particularly in the frontal and lateral sectors associated with the treated wall.

3.2 Subjective results

The subjective data gathered from the listening tests have been analyzed based on binomial distribution [12] in order to determine the statistical significance of the test results. The inverse cumulative probability is used to evaluate the minimum number of correct answers that are needed to indicate a perceptual difference. The inverse cumulative probability is given as a function of the trials (corresponding to the forty listeners), probability of correct answers (50%), and confidence level (95%). Therefore, the minimum number of correct answers necessary to indicate a significant difference between pairs at a 95% confidence level was found to be 26, i.e., correct answers should result equal or higher than 26 (Figure 6).

Figure 6 shows the correct answers for each comparison. The dashed horizontal line indicates the minimum number of correct answers necessary to detect a significant perceptual difference between configurations compared in one pair.

It is evident that all HAM configurations were perceived as significantly different from the untreated (Empty) condition, indicating that the introduction of the hybrid absorptive-diffusive surfaces produced audible changes in the acoustic environment. Among the comparisons between treated configurations, significant perceptual differences were observed between the low-height installations on the back and lateral walls (BW_L vs LW_L) and between the corresponding extended configurations (BW_E vs LW_E). In contrast, no significant differences were detected between the high-height configurations applied to the two walls (BW_H vs LW_H), nor between the low and high placements on the same wall (BW_L vs BW_H and LW_L vs LW_H).

The results further suggest that the effect of panel distribution depends on the installation wall. A significant perceptual difference was found between the compact and extended arrangements on the back wall (BW_L vs BW_E), indicating that increasing the treated surface extent on this wall produces an audible modification of the sound field. Conversely, the same comparison on the lateral wall (LW_L vs LW_E) did not yield statistically significant results, suggesting that listeners were less sensitive to variations in panel distribution when the treatment was located on the lateral wall. Overall, these findings highlight the importance of both panel location and geometric distribution in determining the perceptual impact of HAMs, while also indicating that some objectively different configurations may generate only subtle perceptual variations.

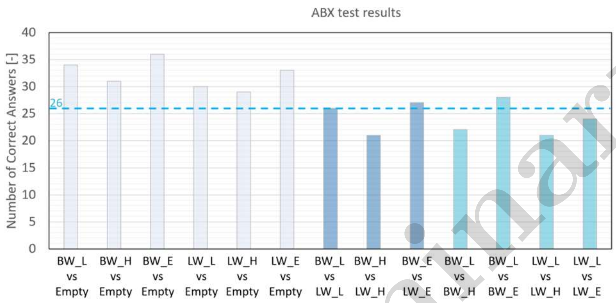

Figure 6. Subjective results. The dashed horizontal line indicates the minimum number of correct answers necessary to demonstrate a significant perceptual difference between configurations compared in one pair. x-axis indicates the pairs compared in each trial.

4. Conclusions

This study investigated the application of 3D-printed Hybrid Acoustic Materials (HAMs) in a Living Lab office environment through a combination of objective acoustic measurements and subjective listening tests. Six configurations were evaluated by varying the location, height, and spatial distribution of the HAM panels while maintaining a constant treated area.

The objective measurements demonstrated that the HAMs effectively modified the acoustic conditions of the room, producing reductions in reverberant energy and improvements in speech-related parameters, particularly clarity. Spatial impulse response analyses further revealed that the treatments primarily affected the directional distribution of early reflections, promoting a more diffuse sound field without substantially altering the overall reverberant characteristics of the room.

The subjective ABX tests confirmed that all HAM configurations were perceptibly different from the untreated condition, highlighting the audible impact of the hybrid absorptive-diffusive surfaces. Moreover, perceptual differences were found to depend on both panel location and distribution. In particular, configurations installed on the back wall produced more noticeable perceptual effects than equivalent arrangements on the lateral wall, suggesting that the interaction between treatment location and reflection paths plays a key role in the perceived acoustic response.

Overall, the findings demonstrate that the acoustic performance of HAMs cannot be fully assessed through conventional objective parameters alone. Future research should incorporate additional spatial perception metrics, such as the Interaural Cross-Correlation Coefficient (IACC), Interaural Time Difference (ITD), and Interaural Level Difference (ILD), to provide a more comprehensive assessment of acoustic performance. The combined use of objective and subjective methods proved essential for identifying perceptually relevant differences between configurations and for supporting more informed design decisions. The study also highlights the value of Living Labs as realistic environments for evaluating innovative acoustic solutions and their impact on occupant perception.

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References

[1] F. Setaki, F. Tian, M. Turrin, M. Tenpierik, L. Nijs, A. Van Timmeren, 3D-printed sound absorbers: compact and customisable at broadband frequencies, Archit. Struct. Constr. 3 (2023) 205–215. https://doi.org/10.1007/s44150-023-00086-9.

[2] V. Tsiokou, L. Shtrepi, E. Badino, A. Astolfi, A. Karatza, Exploratory Acoustic Investigation of Customizable 3D-Printed Hybrid Acoustic Materials (HAMs) through Interlaboratory Impedance Tube Measurements, Acoustics 5 (2023) 653–675. https://doi.org/10.3390/acoustics5030040.

[3] T.J. Cox,, P. D'Antonio, Acoustic Absorbers and Diffusers: Theory, Design and Application, third ed., CRC Press, Boca Raton, 2017.

[4] B. Chojnacki, K. Schynol, K. Chojnacka, Application of Hybrid Absorptive–Diffusive Panels with Variable Acoustic Characteristics Based on Wooden Overlays Designed Using Third-Degree-of-Freedom Bezier Curves, Materials 17 (2024) 5421. https://doi.org/10.3390/ma17225421.

[5] R.J. Cureau, I. Pigliautile, A.L. Pisello, M. Bavaresco, C. Berger, G. Chinazzo, Zs. Deme Belafi, A. Ghahramani, A. Heydarian, D. Kastner, M. Kong, D. Licina, A. Luna-Navarro, A. Mahdavi, A. Nocente, M. Schweiker, M. Vellei, A. Wang, Bridging the gap from test rooms to field-tests for human indoor comfort studies: A critical review of the sustainability potential of living laboratories, Energy Research & Social Science 92 (2022) 102778. https://doi.org/10.1016/j.erss.2022.102778.

[6] A.L. Pisello, I. Pigliautile, M. Andargie, C. Berger, P.M. Bluyssen, S. Carlucci, G. Chinazzo, Z. Deme Belafi, B. Dong, M. Favero, A. Ghahramani, G. Havenith, A. Heydarian, D. Kastner, M. Kong, D. Licina, Y. Liu, A. Luna-Navarro, A. Mahdavi, A. Nocente, M. Schweiker, M. Touchie, M. Vellei, F. Vittori, A. Wagner, A. Wang, S. Wei, Test rooms to study human comfort in buildings: A review of controlled experiments and facilities, Renewable and Sustainable Energy Reviews 149 (2021) 111359. https://doi.org/10.1016/j.rser.2021.111359.

[7] J. Boley, M. Lester, Statistical Analysis of ABX Results Using Signal Detection Theory, 1 (2009).

[8] L. Shtrepi, S. Di Blasio, A. Astolfi, Listeners Sensitivity to Different Locations of Diffusive Surfaces in Performance Spaces: The Case of a Shoebox Concert Hall, Applied Sciences 10 (2020) 4370. https://doi.org/10.3390/app10124370.

[9] F. Faul, E. Erdfelder, A.-G. Lang, A. Buchner, G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences, Behavior Research Methods 39 (2007) 175–191. https://doi.org/10.3758/BF03193146.

[10] Y.-J. Choi, Effects of periodic type diffusers on classroom acoustics, Applied Acoustics 74 (2013) 694–707. https://doi.org/10.1016/j.apacoust.2012.11.010.

[11] J. Pätynen, S. Tervo, T. Lokki, Analysis of concert hall acoustics via visualizations of time-frequency and spatiotemporal responses, The Journal of the Acoustical Society of America 133 (2013) 842–857. https://doi.org/10.1121/1.4770260.

[12] D. Clark, High-resolution subjective testing using a double-blind comparator, Journal of the Audio Engineering Society 30 (1982) Paper 330-338.