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PSYCHOACOUSTIC EVALUATION OF A PILOT SYSTEM FOR SIMULATING DIVERSE ROOM ACOUSTICS FOR MUSICIANS

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ABSTRACT

This pilot project is part of a broader initiative to develop an immersive training environment for musicians, integrating virtual and augmented reality to facilitate adaptation to different room acoustic scenarios. A single-plane six-speaker auralization system was designed to simulate various room acoustics in a relatively dry practice room by convolving real-time music performance input with pre-recorded room impulse responses. Virtual environments varied in reverberation, with the system employing EQ calibration, delay synchronization, and ambisonic decoding for enhanced realism. The system is also capable of incorporating background sounds and/or disturbances. The system was evaluated in a psychoacoustic experiment involving six participants, who achieved 79.2% accuracy in recognizing four simulated environments. Realism ratings averaged 1.1 on a bipolar five-point scale (-2 to 2). Adding background sounds affected realism differently across scenarios. Interviews highlighted the system's potential to aid musicians in adapting their technique to different acoustics while noting challenges such as movement restrictions and microphone placement. The results validate the direction of the project, with future work focusing on refining the audio system and expanding the performance lab's capabilities.

Keywords: *Psychoacoustics, Room Auralization, Virtual and Augmented Audio Reality, Musical Performance*

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1. INTRODUCTION

Advancements in digital auralization and active acoustic technologies have led to diverse approaches for recreating and simulating acoustic environments. For instance, state-of-the-art laboratories such as Arup's SoundLab use spherical multi-channel speaker arrays and convolution techniques to let designers "hear" a space before it is built [1], while Empa's AuraLab in Dübendorf employs a hemispherical loudspeaker array to reproduce spatial acoustics with high precision [2]. At Virginia Tech, "The Cube"—featuring 140 channels—supports spatial audio research through versatile sound field reproduction [3], and the University of Sydney's "The Dome" utilizes a hemispherical array of 196 speakers to deliver high-resolution spatial audio [4]. Similarly, the Royal College of Music's Digital Innovation Lab offers a state-of-the-art recording and mixing suite equipped with Dolby Atmos 7.1.4 technology, enabling students to record, mix, master, and broadcast material in contemporary formats [5].

In the realm of physical room simulation, systems such as the "Experimental Theater" at UC San Diego leverage Meyer Sound's Constellation active acoustic system to dynamically tailor performance spaces [6]. Similar large-scale implementations can be found in educational settings at the "Maersk Tower Auditoriums" at the University of Copenhagen and the "KI-NEO Active Acoustic Halls" at the Karolinska Institute [7, 8]. Complementing these high-end approaches, projects like Icons of Sound have successfully demonstrated real-time auralization of historical spaces—most notably, the recreation of Hagia Sophia's acoustics [9].

While these sophisticated systems demonstrate real-time acoustic simulation in specialized venues, their benefits have yet to fully reach everyday practice spaces where musicians spend most of their time. Music students practice extensively—up to forty hours weekly—to refine performance skills, stage presence, fine motor control, and repertoire interpretation [10]. Yet, optimal practice locations remain scarce, forcing many to rehearse in small, acoustically inadequate rooms despite performing in large venues. This mismatch challenges musicians to adapt their playing to different acoustics, potentially affecting comfort and mastery. Research [11, 12] indicates musicians adjust aspects like tempo and vibrato in response to reverberation, suggesting that inconsistent practice acoustics may inadequately prepare students for performance anxiety and acoustic demands. Regular exposure to varied acoustic environments could mitigate these issues and enhance artistic growth [13].

While state-of-the-art acoustic simulation systems are impressive, their scale and complexity challenge the feasibility of creating a competitive solution. This project serves as a feasibility evaluation for the overarching Lucerne Interdisciplinary Network (IDN) project by developing a prototype system that integrates advanced simulation techniques into a compact, cost-effective solution for a specific dampened practice room. A baseline assessment of the room's acoustics led to the implementation of non-permanent modifications to reduce reverberation time. This prototype simulates multiple acoustic environments and background sound scenarios using convolution with existing impulse responses (IR). [1] By offering varied room auralizations and background noise profiles in a controlled setting, the system not only enhances musicians' education but also supports research into the effects of acoustic environments on posture and performance anxiety [14].

2. METHODS

2.1 Auralization

2.1.1 Hardware Setup

Room Modifications: The practice room featured permanent acoustic panels on the walls and ceiling, as well as thick curtains covering the window and door. Detailed acoustic measurements—including RT60 evaluations—were conducted to determine the optimal configuration of these treatments. Based on these measurements,

[1] Other IR generation methods were considered, but convolution with existing impulse responses (IR) was preferred for its efficiency and real-time suitability [14].

Figure 1: Photograph of the final six-speaker setup installed in the modified practice room.

the curtains were repositioned to achieve a lower reverberation time and minimize unwanted reflections. Additionally, a mobile acoustic panel was added to cover the pathway leading to the section of the wall that lacked permanent paneling, thereby reducing reflective energy and ensuring a more controlled environment for auralization.

Speaker Configuration: For the psychoacoustic experiment, a six-channel system was established using six Nexo PS10 loudspeakers arranged in a hexagonal formation. This configuration was driven by a Nexo NX-AMP 4x1 digital controller amplifier in combination with a dual channel Yamaha stereo power amplifier. Directional sound capture was provided by a Neumann KM185 microphone (see Fig. 1 and Fig. 2). The multi-channel arrangement enabled the creation of a spatialized sound field that closely approximated real-world performance spaces.

2.1.2 Integrated Signal Processing and System Overview

The digital audio workstation REAPER (v. 7.33) served as the central hub for processing and routing audio signals captured in the practice environment. In this setup, the microphone records both the musical performance and the ambient background noise naturally present in the room. Virtual background noises can be digitally added later in

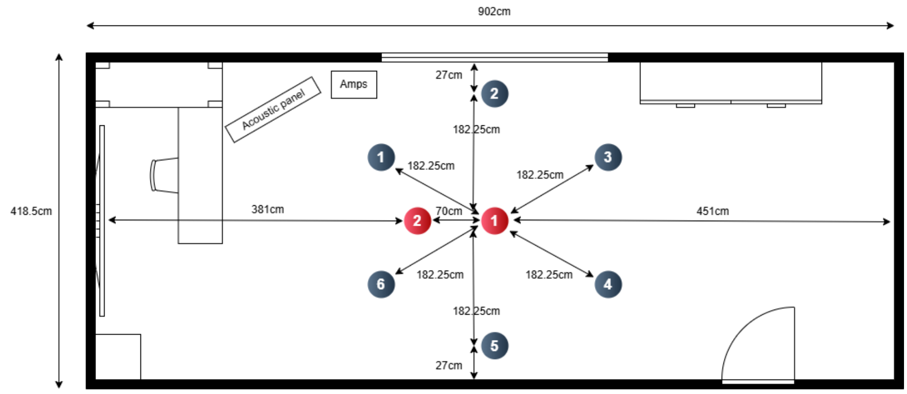

Figure 2: Six-speaker setup: Speakers are numbered in blue. The musician ("1") and microphone ("2") positions are marked in red. Measurements are from the objects' centers. Note: not to scale.

the signal chain to further enhance the auralization. Fig. 3 provides a visual overview of the signal flow, from the musician's instrument and any background sources to the loudspeakers and back to the microphone.

A. Frequency Conditioning and Convolution: Once the combined (physical) microphone signal is acquired, it is routed into REAPER, where it is first passed through a band-pass filter (65 Hz–20 kHz) to match the speakers' nominal frequency range. It is then convolved with selected room impulse responses (RIRs) sourced from the OpenAIR repository [15], which impart the desired acoustic characteristics. In parallel, any additional, digitally introduced background noise is blended into the signal to simulate specific environmental conditions.

B. Ambisonic Decoding and Channel Processing: Following convolution, the processed signal is organized into four B-format first-order Ambisonic channels. The channels are decoded into six separate outputs using the IEM AllRADecoder plugin [16] by entering the speaker positions as coordinates relative to the center for accurate spatial decoding. Each channel subsequently undergoes per-channel linearization via Cockos' ReaEQ [17] with filters calculated with Room EQ Wizard [18]. Due to hardware limitations, using a 4-channel and a 2-channel amplifier caused a 4 ms delay in speakers 1, 2, 5, and 6 relative to speakers 3 and 4. Thus, a 4 ms offset was applied to channels 3 and 4 (see Fig. 3).

C. Output Routing and Acoustic Feedback Paths: The final output comprises six individually equalized, time-aligned signals that are routed to their respective amplifiers and speakers via the audio interface. Once emitted, each speaker's output propagates independently through the room. Both the musician and the microphone receive acoustic signals from all speakers along their own physical paths—each characterized by a distinct RIR that reflects the propagation conditions (such as distance, reflections, and room geometry). Consequently, the musician experiences a spatially differentiated sound field, while the microphone captures the individual contributions of each speaker according to its specific acoustic environment.

2.2 Psychoacoustic Experiment

A psychoacoustic experiment evaluated how musicians perceive and interact with simulated acoustic environments. The experiment assessed participants' ability to distinguish different acoustic simulations, their perceived realism, and how additional background sounds influenced their perception of the simulation and their subjective judgment of their performance.

2.2.1 Experimental Design and Procedure

The experiment included preliminary instructions, training, three listening tests on room recognition, realism, and perception of background sound addition, concluding with an interview. Participants received information regarding the experiment's purpose and procedure. Then, they signed a consent form. For each block, participants were asked to play as they wished. In the training phase, participants briefly experienced three out of the four simulated environments without labels while performing. Next, in the room recognition task, participants completed nine simulated trials, with only the first eight analyzed. The order of the first eight rooms was randomized for each subject, and each room appeared at least

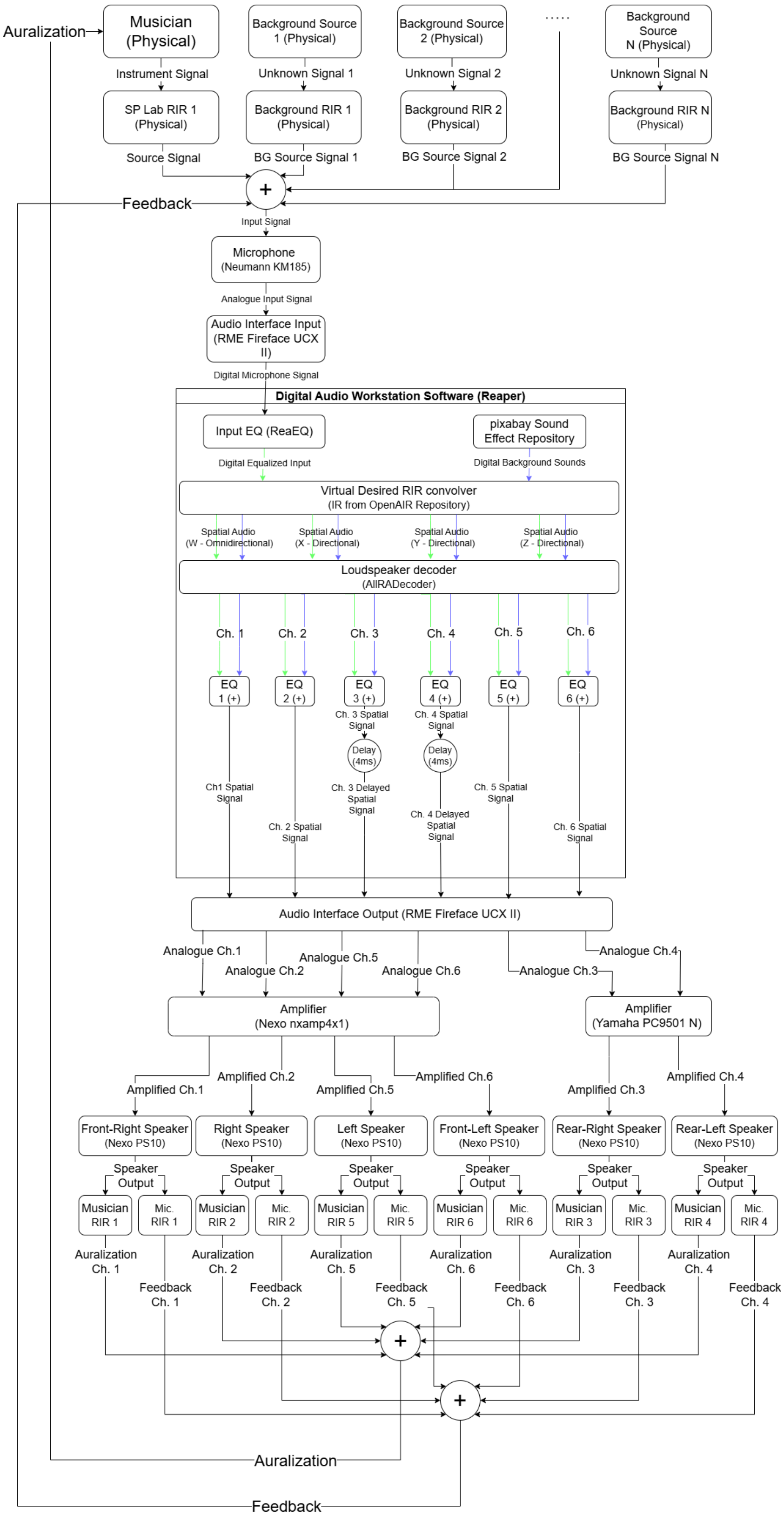

Figure 3: Signal flow block diagram.

twice. The ninth trial, a repeat of the first room, prevented subjects from identifying rooms through process of elimination. In the second listening test, participants rated the realism of the auralizations on a five-point scale (-2 to +2). In the third listening test, two environments were presented with and without added background sounds, evaluating the influence of additional auditory context on perceived realism. Lastly, a short open interview was conducted to capture experiential insights, practical issues, and suggestions not immediately evident from quantitative measures.

2.2.2 Participant Selection and Considerations

Participants (n=6; five HSLU Musik students, one hobbyist; one female) performed standing due to the fixed microphone height, restricting instrument selection. The group comprised saxophone (2), singers (2), horn, and baroque trumpet, enabling qualitative analysis of instrument-specific interactions with simulated acoustics.

3. RESULTS

3.1 Result of auralization setup

The evaluation of the auralization setup focused on the performance of the speaker array and the acoustic characteristics of the modified practice room.

3.1.1 Reverberation Time Measurements

Reverberation time (RT60) measurements were conducted in the practice room under various configurations. Two main scenarios were considered: scenario one included covering a metal shelf with one of the available curtains, while scenario two included draping the same curtain over a large exposed wall area. The averaged broadband RT60 values obtained were 0.382 s and 0.373 s respectively. Fig. 4 presents the detailed frequency-dependent RT60 values for both scenarios. Scenario two was selected due to its slightly lower reverberation time, indicating superior acoustic conditions for minimizing unwanted reflections and enhancing simulation clarity.

3.1.2 Speaker Frequency Response and Equalization (EQ) Design

The frequency responses (FR) of individual loudspeakers were measured at the listener's position using Room EQ Wizard (REW). Fig. 5 displays the measured FR for speaker 1. These measurements reveal uneven frequency distributions across the spectrum, emphasizing the necessity for equalization (EQ) to achieve a balanced and accurate reproduction of the simulated environments. To correct the uneven frequency response, EQ filters were designed using REW to achieve a flat response up to 85 dB with a low-frequency cutoff at 65 Hz, reflecting the nominal frequency range of the Nexo PS10 speakers. Fig. 5 illustrates the EQ process for speaker 1, showing the original, target, and corrected frequency responses.

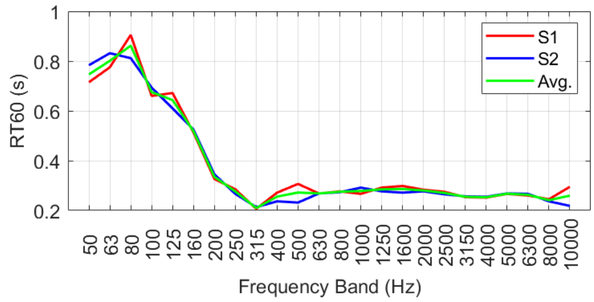

Figure 4: Results of RT60 measurements for scenarios one (covering metal shelf) and two (curtain over wall). Scenario two exhibited lower reverberation times across frequencies and was thus selected.

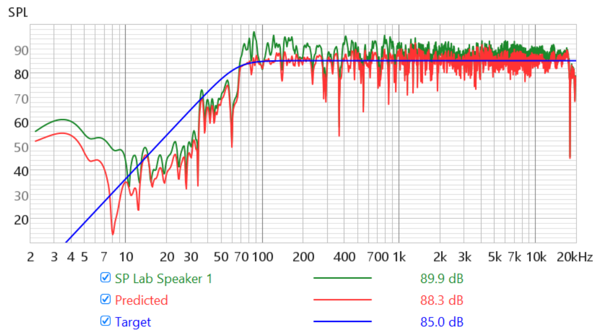

Figure 5: EQ filter design process of speaker 1. Green: FR of the speaker, Red: FR after the filter is applied, Blue: target FR

3.2 Results of Psychoacoustic Experiment

The psychoacoustic experiment yielded both quantitative and qualitative data regarding how musicians perceived the simulated acoustic environments. The following subsections summarize the main results.

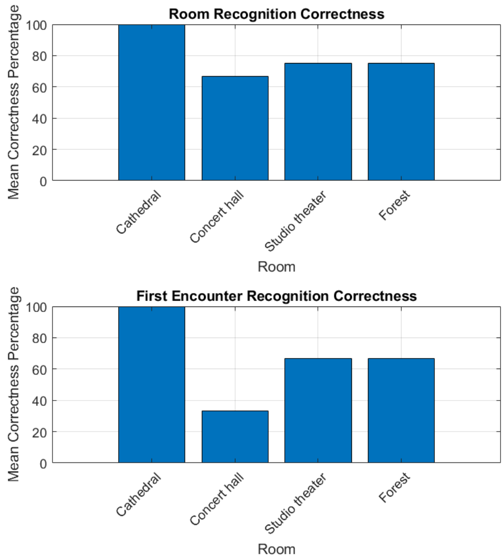

Figure 6: Top: Overall room recognition correctness (RRC); Bottom: First encounter correctness (FEC).

3.2.1 *Room Recognition Accuracy*

Participants were asked to identify each simulated acoustic environment based solely on its simulated reverberation response to their performance. Overall, the average room recognition accuracy was 79.17%. Recognition accuracy improved with repeated exposures, indicating a learning effect. Fig. 6 shows the overall room recognition correctness (RRC) alongside the first encounter correctness (FEC), that is, if a participant recognized the room correctly the first time they encountered it. In addition, the confusion matrix in Tab. 1 summarizes how frequently each simulated room was correctly or incorrectly identified. Furthermore, Fig. 7 illustrates the impact of trial order on recognition performance, demonstrating how recognition accuracy improved over successive trials.

3.2.2 *Realism Ratings*

After the recognition task, participants were asked: "On a scale of -2 to 2, to what degree of realism would you rate this acoustically?" This five-point scale included 0, with -2 representing "highly unrealistic" and 2 "highly realistic." The mean realism rating across all simulations was 1.08, indicating that the environments were generally perceived as somewhat realistic. Fig. 8 shows ratings per simulation, with the Forest the highest (approximately 1.33), with the Concert Hall the lowest (approximately 0.5).

Table 1: Confusion Matrix for Room Recognition.

	Correct Room			
Response	**Ca**	**CH**	**ST**	**F**
Cathedral (Ca)	12	4	0	0
Concert Hall (CH)	0	8	2	0
Studio Theater (ST)	0	0	9	3
Forest (F)	0	0	1	9

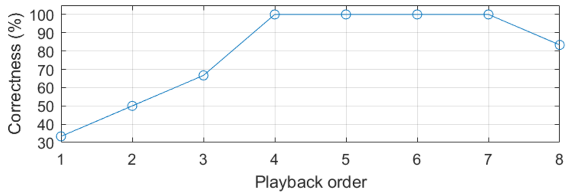

Figure 7: Room recognition correctness as a function of playback order. The vertical axis show relative correctness frequency in %.

3.2.3 *Impact of Background Sound*

In a subsequent block, participants answered the same realism question for two simulations with added background sounds (Fig. 9). Speech babble added to the Studio Theater reduced realism (0.83 to 0.16), whereas natural ambient sounds (birdsong, wind rustling leaves) added to the Forest increased realism (1.33 to 1.66), indicating background type critically affects perceived realism.

3.2.4 *Qualitative Feedback*

Following the quantitative tasks, a short interview was conducted to collect qualitative insights. Participants noted that the simulated environments showed potential for enhancing musical adaptability, particularly through exposure to diverse acoustical scenarios. While the spatialization and clarity of the simulations were generally

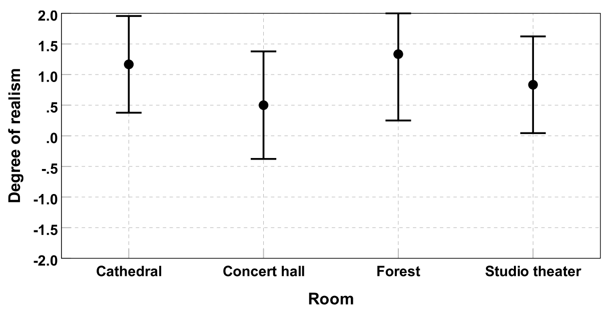

Figure 8: Mean room realism ratings and 95% confidence intervals. Note that the scale is from -2 to 2.

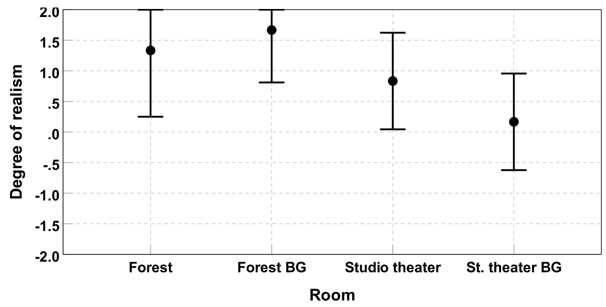

Figure 9: Mean room realism ratings and 95% confidence intervals with and without background sounds.

well-received, some participants expressed concerns regarding technical complexity and movement restrictions during performance, as well as the inflexible microphone placement.

4. DISCUSSION

4.1 Discussion of results

The present study demonstrates that a DSP-based auralization system can effectively simulate distinct acoustic environments for musical practice. Both objective measures and psychoacoustic experiments indicate that the system delivers immersive spatial audio cues that musicians can perceptually distinguish. Overall, participants were able to recognize and rate the simulated environments with reasonable accuracy, and qualitative feedback confirmed the system's potential as a tool for both performance training and educational applications.

However, several issues emerged during testing. Although the system successfully reproduced distinct room acoustics, variations in recognition accuracy and realism ratings indicate that further optimization is needed. For example, the lower first encounter accuracy observed for the Concert Hall simulation appears to be a consequence of the training phase—since the Cathedral was not presented during training, participants often mistook the Concert Hall for the Cathedral when it was encountered first. In addition, the low realism rating for the Concert Hall may be attributed to the participants' extensive familiarity with real concert halls on campus, which allowed for more direct and critical comparisons that highlighted simulation inaccuracies.

Moreover, the addition of background sounds produced mixed results. Natural ambiance enhanced perceived realism in some cases, while speech noise degraded it in others. Notably, the current configuration employed a coherent mono playback over all six speakers, meaning that the same mono background signal—albeit convolved with the respective room impulse responses—was delivered through each loudspeaker. This approach likely limited the intended spatial differentiation of background audio and contributed to the adverse effects observed with speech noise. These findings imply that careful selection and spatial differentiation of background audio, as well as further optimization of training protocols, are critical for enhancing overall system performance.

4.2 Limitations and Further Research

While the results are promising, several limitations should be addressed in future research. The current psychoacoustic experiment involved a small, homogeneous sample (n=6); larger, more diverse participant groups would reduce large error bars and clarify instrument-specific interactions. Additionally, repertoire choices in this pilot study were unrestricted; future studies should systematically examine how acoustic simulations can be tailored to specific instruments, repertoires, and musical genres. Technical issues related to background audio spatialization suggest improved methods are needed to enhance spatial clarity and realism. Moreover, fixed microphone placement did not sufficiently account for varied instrument-specific sound projection; adaptive microphone positioning should therefore be explored. Lastly, additional acoustic treatment of the practice room would enhance the auralization.

Qualitative feedback underscored another critical aspect: realism should encompass not only acoustic authenticity but also the naturalness of musical performance itself. Participants noted restrictions, such as limited freedom of movement, affecting comfort and naturalness. Future research should investigate whether simulated acoustics remain natural and effective when musicians focus intensely on challenging repertoire or subtle sound articulations, essential for technical and psychological artistic development. Lastly, participants suggested that integrating visual or multisensory cues might further enhance immersion.

5. CONCLUSIONS

This project demonstrated the viability of a DSP-based auralization system for simulating diverse acoustic environments in a practice room. Through integrated hardware and real-time convolution techniques, distinct and immersive acoustic simulations were achieved, supporting musical practice and performance preparation.

The psychoacoustic experiment showed that musicians could generally distinguish and positively rate the realism of different simulated spaces. Recognition accuracy improved with repeated exposure, indicating a learning effect. Background sounds had a marked impact on perceived realism, with natural ambient audio enhancing and speech babble diminishing realism—highlighting the need for careful sound selection and improved spatialization methods.

Participant feedback emphasized not only acoustic realism but also the naturalness of the performance experience. Constraints such as fixed microphone placement and limited movement reduced comfort and immersion. While participants played freely chosen material, future work should assess how simulation effectiveness varies across instruments, repertoire, and musical genres—especially in scenarios demanding fine auditory feedback and expressive nuance.

Key technical limitations remain: the need for more accurate background spatialization, adaptive microphone placement, and improved room treatment. The system would also benefit from incorporating visual or multisensory cues to increase immersion.

In sum, this auralization system represents a promising step toward adaptable, high-fidelity practice environments. With further refinement and broader evaluation, it could become a valuable tool in both musical training and research into performance psychology and acoustic perception.

6. ACKNOWLEDGMENTS

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