Localized Sound Zone with Directive Sound Source and Vibrotactile Shaker in Open Spaces

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Localized sound zone with directive sound source and vibrotactile shaker in open spaces

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ABSTRACT

Open spaces filled with multiple sound sources playing varied music can lead to discomfort, particularly for those with hearing disabilities, due to the blending of sounds into an indistinct cacophony. Unfortunately, creating localized sound zones presents a significant challenge with current audio systems, struggling to balance high-quality sound, minimal visual impact, reduced equipment, and affordability. This study focuses on improving the listener experience by creating a personal sound zone utilizing both a directional loudspeaker and a vibrotactile shaker and comparing it with other sound system designs. A comparative study evaluated sound quality and confinement, contrasting three commercially available audio solutions with a novel hybrid system named the 'Sound Shower'. The tested solutions included a High-Fidelity (HiFi) loudspeaker, a vertical parabolic speaker, and a sound laser speaker utilizing ultrasound technology alongside a vibrating platform. The Sound Shower uniquely integrates a parabolic speaker for mid-to-high frequencies with a shaker that delivers low frequencies through tactile vibrations. The results indicate that participants rated the parabolic speaker and the Sound Shower as more effective in creating independent sound zones, where competing music was less intrusive. Additionally, the Sound Shower's sound quality was comparable to that of the HiFi loudspeaker, with no significant difference observed, whereas the other solutions received lower ratings. This study suggests that the hybrid Sound Shower system can match conventional speakers' sound quality while maintaining a parabolic speaker's focused audio delivery characteristic.

1 Introduction

In indoor open spaces, such as exhibitions and fairs where there often are a lot of different sound sources, it is important to control individual sound zones to avoid a cacophony. With several solutions existing in the market to create personal sound zones and highly directive loudspeakers [1], there still do not exist systems that offer high sound quality while being highly directional and easy to install. This paper proposes and evaluates an innovative solution designed for broadband signals such as music. Existing solutions for creating personal sound zones either require an extensive amount of loudspeakers [2], relying on Digital Signal Processing (DSP) [3], or implementing highly directional parametric loudspeakers [4]. These solutions are limited by heavy use of equipment, complex cost-ineffective DSP, or suboptimal low frequency reproduction. This is challenging for public institutions e.g. museums that have small budgets.

Among the sound systems that were investigated for the specific purpose of addressing this need, the final selection is comprised of the following: A parabolic loudspeaker (renamed Dome), a Shaker, a parametric loudspeaker, and a HiFi loudspeaker. The Dome is a directional loudspeaker, marketed towards conferences especially, due to its balance of directionality and sound quality. The Shaker is specifically designed to transfer sounds to a tactile experience. The parametric loudspeaker is a high precision loudspeaker, that utilize ultrasound technology to deliver focused audio in settings like retail and museum environments. Headphones were considered but disregarded, as they limit and complicate communication between listeners, and they also raise a hygiene concern.

The proposed solution consists of a combination of a Dome and a wooden platform excited by a Shaker, to create vibrotactile stimuli that cover the low frequency range missing in the Dome. This combined setup was renamed 'Sound Shower', but was also referred to as DomeShaker. The idea with the hybrid solution is the visualization of being immersed in a local sound experience, as when taking a shower. The amalgamation of the aforementioned devices should lead to an immersive listening experience. Such a combination has not yet been studied to the best of the authors' knowledge. A setup consisting of a vibrotactile floor combined with conventional loudspeakers is the closest resembling system for multimodal reproduction of music [5]. A sound quality and a sound confinement test have been developed to investigate the effect of the proposed solution:

1. A HiFi loudspeaker is expected to outperform Dome, parametric, and Shaker systems in sound quality and frequency response due to its design, emphasizing HiFi audio reproduction;

2. A parabolic loudspeaker will more efficiently create an isolated sound zone than a traditional HiFi loudspeaker system;

3. A hybrid solution, with a parabolic speaker and a Shaker, will achieve better sound confinement than a HiFi loudspeaker with a similar level of sound quality.

The expected outcome for hypothesis 1 is that among the included sound systems, the HiFi loudspeaker will be rated with a much better overall sound quality than other sound systems. In addition to that, it is also expected that the combined sound system, DomeShaker, will be rated as having a better sound quality than only the Shaker or Dome.

For hypothesis 2, the expected comfort level rating of the HiFi loudspeaker and the Shaker, when hearing two different songs simultaneously, will be rated more negatively compared to the other sound systems.

The expected outcome for hypothesis 3 is that for all the included sound systems, a traditional loudspeaker design will have a rating, where both songs are heard equally loud. Additionally, it is expected that the Shaker will have a significantly higher confinement rating than the Dome speaker alone, and also the DomeShaker - due to the parabolic speaker's directivity and because a cross-over filter is implemented.

2 Methods

A questionnaire was used to assess both the sound quality and the directionality of the sound systems. The sound quality test was done first to avoid a training effect after longer exposure to the audio systems and before possible listening fatigue occurred. The confinement test was done to investigate the efficiency of a system to create localized sound zones irrespective of their sound quality. Additionally, subjects would also determine the comfort level of listening to multiple sound zones to investigate any possible effect of tempo synchronization and musical key. Information about tempo and key was kept hidden. All participants were encouraged to share their experiences and comments after testing. None of the subjects were trained listeners.

2.1 Subjects

Twelve participants between the ages of 23 and 29 participated in the study. Of the 12 participants, 10 reported no history of hearing loss and were classified as having normal hearing listeners. One subject reported a bilateral hearing loss for which they used hearing aids, and the other subject reported frequent low frequency noise occuring in quiet conditions. All participants provided written consent before participating in the study. The Science-Ethics Committee approved the research protocol for the Capital Region of Denmark under reference number H-16036391.

2.2 Test Setup and Stimuli

Figure 1 shows the test setup in the room used for testing at the Technical University of Denmark (DTU).

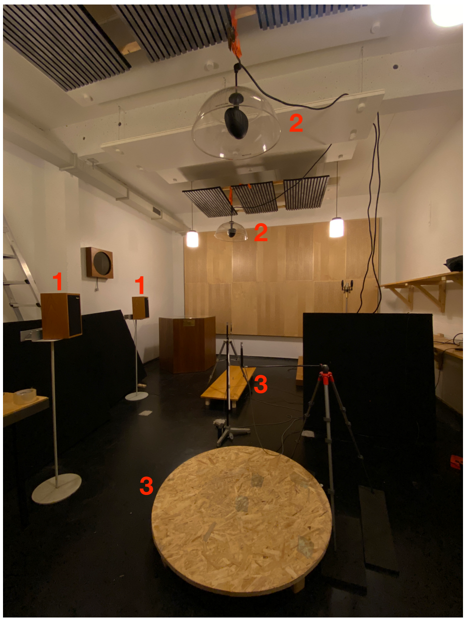

Fig. 1: Test setup showing three of the sound systems. (1) HiFi loudspeakers, (2) parabolic loudspeakers and (3) the platforms with attached transducers. Also seen in the figure are HBK microphones. Only one was used for calibration. The placement seen in the picture does not represent the actual placement for the tests.

A top view of the test setup is given in figure 2, to clarify the listening areas and sound system placement. The difference in platform shape was due to the availability of resources.

The test setup consisted of the following audio reproduction systems:

- Dome, SoundTube FP-6020 II loudspeaker;
- HiFi, Rogers LS3 / 5A loudspeaker;
- Parametric, HSS H450 parametric loudspeaker;
- Shaker, Clark Synthesis TST329 Gold Transducer;
- DomeShaker, A combination of the SoundTube FP-6020 II loudspeaker and the Clark Synthesis TST329 Gold Transducer.

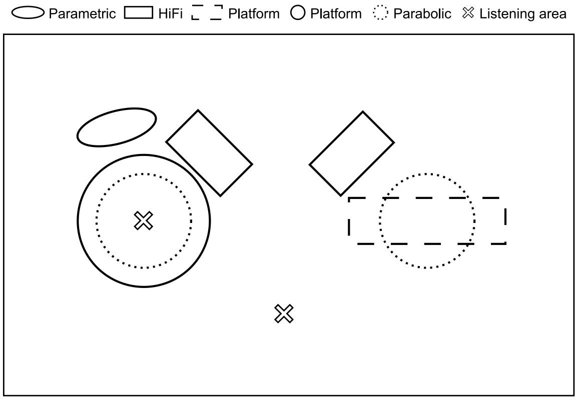

Fig. 2: Top view of the test setup portraying the relative positions of sound systems and listening areas. The marked listening areas refer to the position of the subject during the tests. The inside listening area corresponds to the marking on top of the circular platform. The sound quality test only used the inside listening area.

To ensure an equal listening level for all systems an HBK 1/2" Free Field microphone type 4291-L-001 was calibrated using an HBK Sound Calibrator. The target SPL in the listening position was 65 dB. The measurement microphone was positioned at the listening position, and the sound systems were adjusted to match the target using the recorded average RMS SPL of the stimuli. Filtering was only used for the DomeShaker combination to create a cross-over filter at 200 Hz.

As this solution was developed for the National Museum of Denmark's exhibition of the danish rock band D-A-D, two songs from the band were used for the sound quality test:

1. D-A-D, Nineteenhundredandyesterday (141 BPM);
2. D-A-D, Nothing Ever Changes (138 BPM).

These songs were synchronized to a BPM of 139.5, so that each song was adjusted equally in tempo. Additionally, the songs were fine-tuned using Flex Time in Logic Pro to account for the slight variations in tempo while the songs were recorded. Two additional songs, were used for the confinement test:

3. D-A-D, Reconstructdead (90 BPM);
4. D-A-D, Scare Yourself (123 BPM).

These two songs were not subjected to temporal editing. All stimuli were truncated to a 10 second length.

2.3 Procedure

The experiment was divided into two tests. During the first test, the participants were always positioned on the platform, under the dome. They were asked to evaluate the sound quality of different sound systems against a reference. The reference was the HiFi speaker, and the comparisons were made with the other four systems: Dome, Parametric, Shaker alone, and Sound Shower. A 10-second clip was first presented through the reference system, and then, one second later, the same clip was presented through one of the comparison systems, in random order.

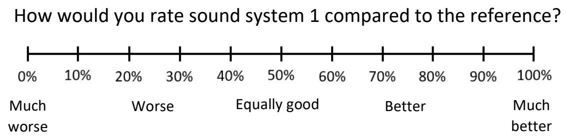

Fig. 3: Questionnaire rating of the sound quality test.

The subjects were asked to rate the sound quality of the comparison on a scale ranging from "Much Worse" to "Much Better," with the midpoint, 50 %, being "Equally Good" (see Figure 3). This process was then repeated for all four sound systems in random order.

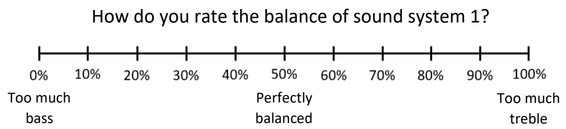

Fig. 4: Questionnaire rating of the bass/treble balance test.

To further investigate the discrepancy in sound qualities between each system and the HiFi reference speaker, the same procedure was repeated with a different question. The participants were asked to evaluate the quality of the comparison speaker on a scale from "Too Much Bass" to "Too Much Treble," with "Perfectly Balanced" as the midpoint (see Figure 4).

In the second test, the confinement test, the subjects were placed either in one listening area (on the platform under a dome, positioned inside) or between two listening areas. Two different songs were played in each listening area. They were asked to rate how much they could hear each song on a scale ranging from "I hear only song 1" to "I hear only song 2," with "I hear both songs equally loud" as the midpoint (see Figure 5). The sound level of each song was normalized, and they could have been played in synchrony (same tempo, synchronized, and in the same key) or asynchrony (different tempo and key).

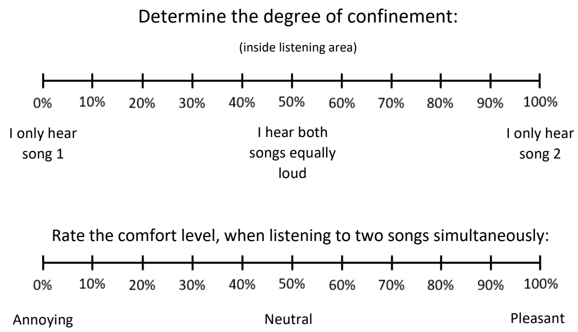

Fig. 5: Clippings of questionnaire rating scale of the confinement test.

Additionally, the subjects were asked to rate how comfortable they found listening to two songs simultaneously on a scale ranging from "Annoying" to "Pleasant."

The questionnaire ratings were evaluated for four songs, two positions, and four sound systems for a total of 32 repetitions. All participants responded in writing to printed questionnaires. The data was then transferred manually to an Excel sheet for analysis in MATLAB.

Presentation order was organized such that the same loudspeaker order was never presented across synchronized and unsynchronized songs or across subjects. To center the reference mean at zero, 50 was subtracted from all data points before statistical analysis. This means that for the sound quality test, any mean value below zero corresponds to a worse performance than the reference loudspeaker. For the confinement test, the zero mean represented a neutral rating. The rating scheme behind the bass/treble balance test was different, so any value that differed from zero was considered worse balanced than the reference.

3 Results

Statistical analysis was done of the data from both tests in the software JMP Pro. For the sound quality test, a one-tailed t-test (lower) was done and for the bass/treble balance test a two-tailed t-test was done.

For the confinement test, ANOVA tests were done for the confinement and comfort level ratings. The alpha (α) level was $\alpha = 0.01$ for t-tests to compensate for the amount of t-tests done. No significant effect size was found for synchronization conditions and the results are therefore not included in this section.

3.1 Sound Quality and Bass/Treble Balance

Figure 6 shows the mean rating result from the sound quality test. The parametric loudspeaker was rated as the worst performing loudspeaker. Interestingly, the Shaker and the Dome were rated more or less equally, but still quite below the zero mean that represents the reference loudspeaker.

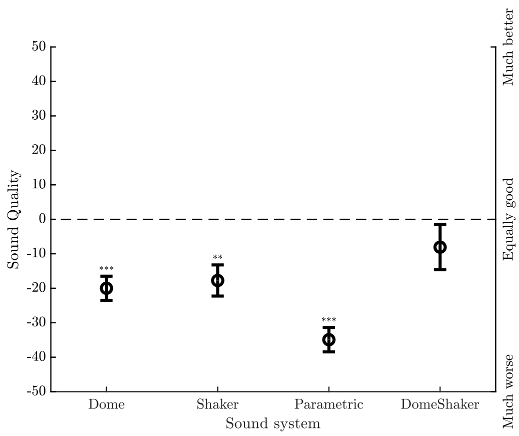

Fig. 6: Mean rating of the four different sound systems from the first part of the sound quality test. Values plotted represent mean $\pm$ standard error (*se*). Asterisks (*) indicate significance levels where, * = p<.05, ** = p<.01 and *** = p<.001.

The largest mean at -8.1 was seen for the DomeShaker system. Statistical analysis was carried out on the mean rating data from the sound quality questionnaire. The Dome, Shaker, and Parametric sound systems showed significant differences in t(11) = -5.71, p<.001, t(11) = -3.93, p=.001 and t(11)= -9.86, p<.001, respectively. However, no significant difference was found between the DomeShaker and the reference, t(11) = -1.23, p=.121.

Figure 7 depicts the mean rating result from the bass/treble balance test. A low rating of the parametric loudspeaker can also be observed. Like the parametric speaker, the Dome was also rated as having too much treble or, from another perspective, too little bass. The Dome and Parametric sound systems showed significant differences t(11) = 6.93, p<.001 and t(11) = 6.18, p<.001 respectively. The Shaker and DomeShaker showed no significant difference compared to the HiFi reference.

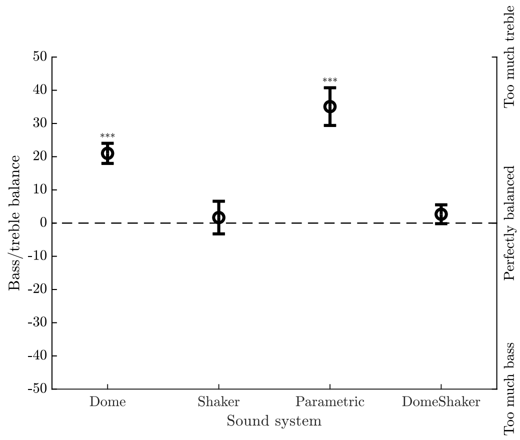

Fig. 7: Mean rating of the four different sound systems from the bass/treble balance test. Values plotted represent mean $\pm$ standard error (*se*). Asterisks (*) indicate significance levels where, * = p<.05, ** = p<.01 and *** = p<.001.

3.2 Confinement and Comfort Level

Figure 8 shows the mean confinement rating. The data were normalized so that the target song was designated as number 1 when inside a listening area. Therefore, a rating of -50 indicates that the listener could perceive only the target music (song 1). A rating of 0 indicates that the listener could perceive both songs equally well, and a rating of +50 indicates that the listener perceived the song from the opposite listening area. The result shows that both songs could be heard equally loud outside the listening area. However, inside the listening area, except for the Shaker, the target song was mostly perceived, with the best results achieved by the Dome and the DomeShaker.

The mean confinement rating data was analyzed using a standard least square regression model. Four sound systems (4) and two listening environments (2) were included as fixed factors, while the subjects and songs were included as a random factor, and the mean rating was chosen as the dependent variable. The analysis

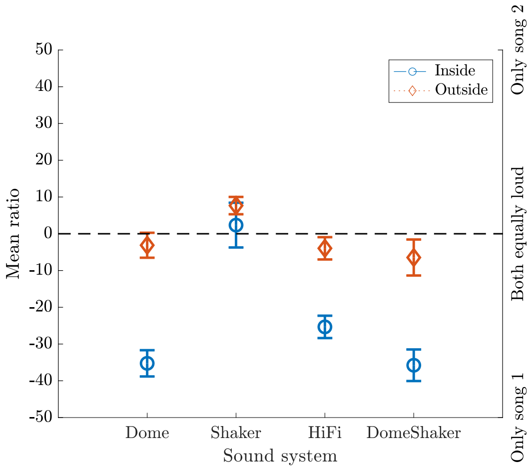

Fig. 8: Mean confinement rating of the four different sound systems from the confinement test, inside and outside the listening area. Negative values indicate song 1 to be louder and positive values indicate the opposite. Values plotted represent mean ± standard error (*se*).

showed statistically significant results for the sound systems with F(3) = 40.94, p<.001, the area with F(1) = 116.43, p<.001, the sound systems and area with F(3) = 21.67, p<.001. A post-hoc analysis was performed on the sound system within each listening area. The analysis showed that inside the listening area, the HiFi loudspeaker was significantly different from the Dome, Shaker and DomeShaker with t(59) = 3.08, p=.002, t(59) = -8.61, p<.001 and t(59) = -3.24, p=.001. The Shaker was also significantly different from the Dome and DomeShaker with t(59) = 11.69, p<.001 and t(59) = -11.85, p<.001. Outside the listening area, the Dome, HiFi loudspeaker and DomeShaker was found significantly different from the Shaker with t(59) = 3.35, p<.001, t(59) = -3.61, p<.001 and t(59) = -4.39, p<.001.

The analysis found no significant difference between Dome and DomeShaker inside the listening area, or between Dome, HiFi and DomeShaker outside the listening area. No significant difference was found between the Shaker inside and outside the listening area. Between the Shaker inside, and the Dome and HiFi outside the listening area, there were no significant differences.

Figure 9 displays the mean comfort level rating from the directionality assessment test, with a focus on the effect of being inside and outside the listening area. The overall trend of the comfort level ratings in Figure 9 was that the Dome and the DomeShaker were rated higher than any other sound system both inside and outside the listening area. Regardless of the subject's position, the Shaker was rated almost equally bad in either conditions. In comparison, all of the other systems have a large difference in mean comfort level rating, between being inside and outside the listening area. As such, the results clearly showed the ability of the Dome and the DomeShaker to create a more comfortable listening environment no matter the synchronized condition or the position.

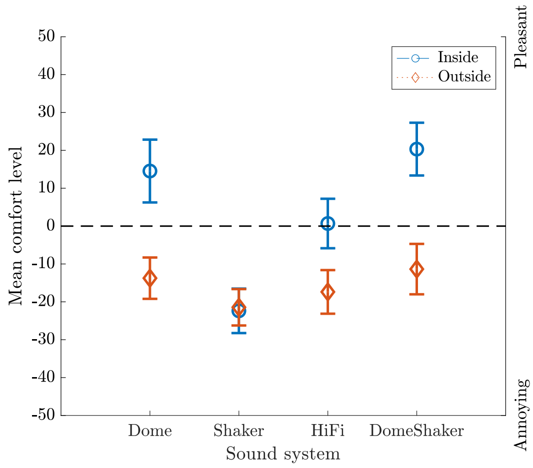

Fig. 9: Mean comfort level rating of the four different sound systems from the confinement test, inside and outside the listening area. Values plotted represent mean ± standard error (*se*).

The mean comfort level rating data was analyzed using a standard least square regression model, with the same conditions as for the confinement rating analysis. The analysis showed statistically significant results for the sound system with F(3) = 21.54, p<.001, the area with F(1) = 32.31, p<.001, the sound system and area with F(3) = 22.39, p<.001.

A post-hoc analysis was performed on the sound system within each listening area. The analysis showed that inside the listening area, the HiFi loudspeaker was significantly different from the Dome, Shaker and DomeShaker with t(55) = -3.32, p<.001, t(55) = 5.52, p<.001 and t(55) = 4.70, p<.001. The Shaker was also significantly different from the Dome and DomeShaker with t(55) = -8.83, p<.001 and t(55) = 10.22, p<.001. Outside the listening area, the DomeShaker was found significantly different from the Shaker with $t(55) = 2.41$, $p=.009$. The analysis found no significant difference between Dome and DomeShaker inside the listening area, between Dome, HiFi and DomeShaker outside the listening area or between Shaker and HiFi outside the listening area and Shaker inside the listening area.

4 Discussion

The study aimed to assess the effectiveness of a novel sound reproduction system, designed to match the sound quality of a HiFi speaker while efficiently creating a localized sound field, or "sound bubble." Our initial hypothesis states that this new system would maintain sound quality without the degradation observed in other commercial solutions. The results from our first test indicated a noticeable decline in sound quality for the Dome, parabolic speaker, and shaker compared to the reference speaker. However, while rated slightly lower than the reference, our hybrid solution did not show a statistically significant difference. Some participants expressed discomfort with the sensation of low-frequency vibrations through the platform, which may have influenced the lower average ratings for the DomeShaker in the sound quality part of the results (see Figure 6), preventing them from outperforming the reference loudspeaker.

Listeners rated the DomeShaker as having a sound equalization not significantly different from the reference speaker (see Figure 7). As anticipated, both the parametric speaker and the Dome speaker were perceived as deficient in bass. These solutions, which primarily transmit mid to high frequencies, are suitable for signals where bass loss is acceptable, such as in speech. However, this becomes a notable issue for musical signals, especially in genres like rock music, where bass is crucial. Surprisingly, the Shaker alone was considered well-balanced, contrary to our expectation of it being perceived as lacking in high frequencies. This unexpected outcome might be attributed to the specific type of shaker used in our study. The Clark-Synthesis shaker, unlike most shakers that are designed solely for low frequencies, is engineered for broadband signals. This design might have enabled it to reproduce some higher-end sounds more effectively.

Our second hypothesis states that the Dome would be at least as effective as other commercial solutions in creating an isolated sound zone. The results of the experiments, as shown in Figures 8 and 9, evidently demonstrated that the Dome outperformed the Shaker and HiFi systems in terms of sound isolation within a designated listening area.

Our third hypothesis states that our new system will be as efficient or better as other commercial solutions in confining the sound while keeping a good sound quality. The results in Figures 8 and 9 clearly showed that our solution performed almost at peak levels, as the listeners positioned inside a designated listening area could hear mostly only the target sound. On the other hand using only Shakers to create different sound environments in an open space creates an uncomfortable situation, no matter where the listeners are positioned. The reason for this was most likely that the structures the Shakers were attached to, were materials that had much higher density than loudspeaker membranes, meaning the sound produced had a much longer decay [6]. This is thought to have polluted the listening environment more than normal loudspeakers would have. Another factor that might have contributed to the rating of the Shaker, is the fact that the platform the subject was standing on, had a mass loading element to it, compared to the other platform with no participant on it. The added mass would to some degree have attenuated high frequencies for the platform the subject was on, while the unloaded platform would not have had the same attenuation. This is thought to skew the rating away from the target song.

4.1 Limitations

To confirm the effectiveness of a sound reproduction system in creating a distinct listening area where one song is perceived as louder than another, it is crucial to start with two sounds that are perceived as equally loud. In our project, while we equalized both songs in terms of sound pressure level (SPL), this approach did not ensure consistent perceived loudness, especially given the dynamic fluctuations within the songs. A potential solution to address this issue is to develop the experiment using a programming environment like MATLAB, incorporating a loudness matching module. This module would enable participants to adjust the amplitude of the sound systems until they perceive them as equally loud before beginning the test. Not only would this create a more robust test design, it would also allow for easy data management and lower the risk of user error.

Furthermore, not including proper assessment of the test participants' hearing status is also a limitation of this study. With limited time for this study, a questionnaire assessment was decided to be used as an alternative to audiometry tests. Future work should assess participants' hearing status to better understand the results. Including a larger sample size would provide a better understanding of the proposed solution's impact and possibly reduce the variance seen in the data. Among the 12 participants in the study, two disclosed experiencing hearing difficulties. Nevertheless, upon reviewing their data, it was observed that their responses did not significantly deviate from the norm and thus did not qualify as outliers. Consequently, their input was retained and included in the calculation of the average results.

With two sound zones playing at the same time, some degree of masking is speculated to appear. Similarities were found by [7] in both the auditory and tactile perception. It was also found that in tactile perception, in the case of more than one stimuli being present, one could sometimes make the other appear more intense. Whether or not these traits are present when subjected to stimuli in both the auditory and tactile realm remains to be studied. While the presentation level was kept low (65 dB SPL) to minimize the effect of masking, it has not been possible for the authors to determine the amount of masking that might have occured during testing.

5 Conclusion

A novel approach to enhancing the listening experience in open spaces with multiple sources has been proposed, combining a Dome loudspeaker and a Shaker attached to a wooden platform. This method outperformed conventional loudspeakers in terms of comfort and sound isolation, offering a focused and immersive auditory experience for listeners. To further validate the effectiveness of this method and identify areas for improvement, the authors suggest refining the experimental test design. This could involve incorporating more comprehensive subjective and objective measures, such as questionnaires and acoustical analysis, to capture a broader range of listener perceptions and the acoustical characteristics of the listening environment.

5.1 Acknowledgments

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