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Ruth Taylor Recital Hall Acoustic Improvements

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Final Project Report

Sound Dynamics Team

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ENGR 4382

Executive Summary

Dr. Joseph Kneer of the Trinity University Symphony Orchestra seeks to improve the acoustics of the Ruth Taylor Recital Hall on campus. The current dilemma can best be summarized as the louder "hot" zones in the percussion sections drown out the much quieter "dead" zones in the woodwind section. The Sound Dynamics Team was tasked with designing, building and testing a system that improves the acoustic balance of the stage that is visually appealing, easily stored and within budget. The following report covers the features of our complete design and the two subsystems that can be utilized by Dr. Kneer with a large degree of freedom. The initial purpose of each component was to take advantage of the different type of sound treatments available, such as amplification, dampening, and diffusing. This multivariate problem let to many challenges which eventually resulted in a change of focus in the design requirements, and how success was defined. Following the design overview is an evaluation of the final design through the scope of the project requirements and constraints, as well as the associated tests used in assessing the overall system's performance.

The project design was constrained by Dr. Kneer and the Engineering Department at Trinity. The design could not make any permanent changes to the physical structure of Ruth Taylor Recital Hall, could not be visually disruptive from the audience and needed to comply with all OSHA guidelines relevant to the designs chosen, all while staying within budget. The first constraint was achieved by ensuring each component was not only mobile, but also storable in the designated area backstage. The aesthetics of the hall were maintained by having the designs either minimally visible, as is the case of the acoustic mats, or painted a color pre-approved by Dr. Kneer, in the case of the acoustic walls. All OSHA guidelines were met through careful consideration in the design and fabrication phases of the project. The mats were made to be thick, dense and gripped on the bottom to allow for stability, durability and to eliminate risk of slippage. The acoustic walls were deemed in compliance with OSHA standards following the slipping and tipping tests administered. The budget was maintained through strategic planning, leaving the team almost $500 under budget.

While initially designed to maximize the effects of the intended sound treatment, complexity of the acoustic space and an inability to test with a full orchestra due to the coronavirus pandemic led the group to change its focus to instead provide Dr. Kneer with a system of tools to be used largely at his discretion. The testing for each component was still performed and documented in order to provide a general user's guide that informs the reader of the real-world effects of the components already built. The criterion for a successful positioning is if there is a change in 3 decibels from the baseline in the appropriate direction. That would mean a –3 dB change for the absorptive mats and a +3 dB change for the acoustic walls. The user guide satisfies the project requirements by mapping out the effects of positioning and angling of the walls with different instruments, noting which combinations led to a successful outcome in the user guide following this report.

Overall, the Sound Dynamics Team created successful prototype to treat the sound imbalances in Ruth Taylor Recital Hall. While the original project requirements had to be adjusted given the sheer complexity of the room acoustics and important COVID regulations, a foundational understanding of how the components interact with the space will allow Dr. Kneer to maximize the effectiveness of the components in a way that works best for his art and his students.

1. Introduction

Orchestras bring together different types of instruments to produce music that is greater than the sum of its parts, but this is difficult to achieve when an environment's acoustics interferes with the balance of the instruments. Dr. Kneer from the Trinity Symphony Orchestra is seeking a system of components that are capable of reducing "Hot and Dead" zones within the orchestra configuration shown below.

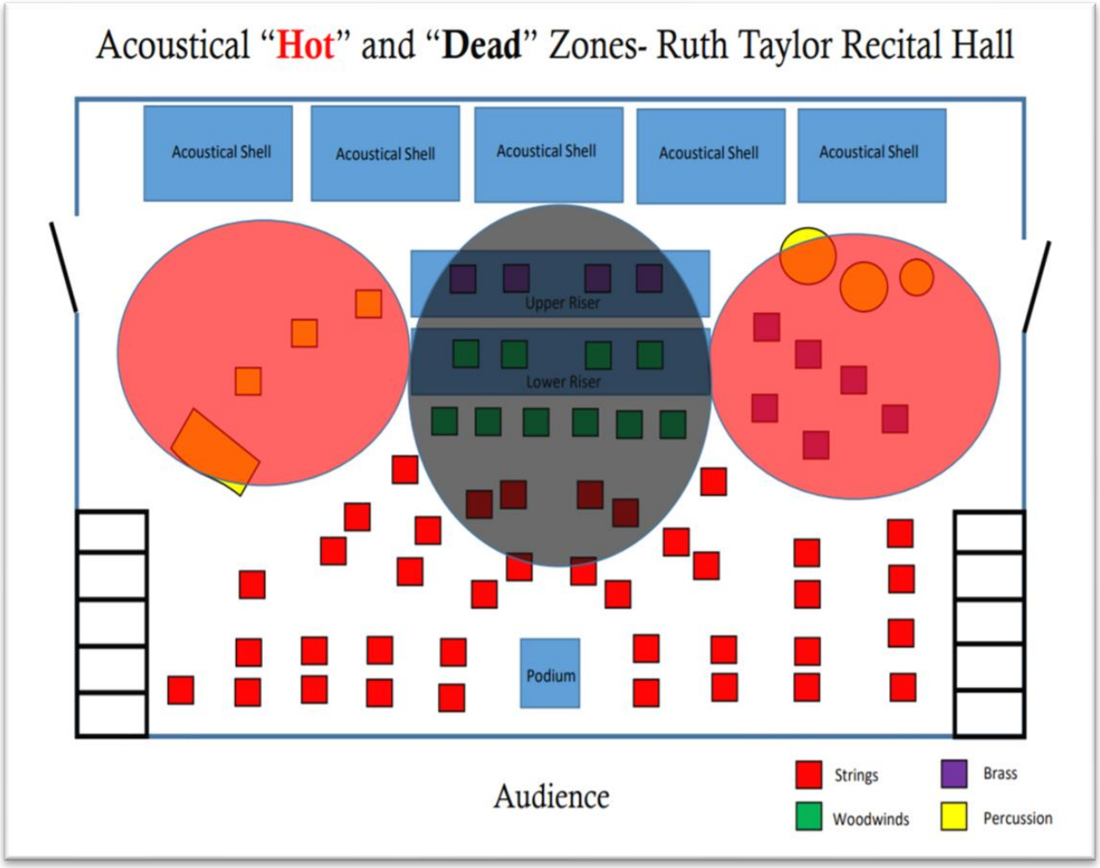

Figure 1. Acoustical "Hot" (Red) and "Dead" (Black) zones in Ruth Taylor Recital Hall

The objectives of the design are to build and test a system of components that reduce the acoustic imbalances of the hall and are easily stored in the available space backstage. The design cannot make any permanent changes to the structures of Ruth Taylor Recital Hall (RTRH). All design considerations must be in compliance with the list of OSHA safety requirements (see Appendix B).

The prototype devised by the team is a system of components that can be utilized with a large degree of freedom by Dr. Kneer. The acoustic walls are easily movable and storable due to their design (allowing them to lie flush with one another against the wall). The absorptive mats are not visually disruptive and can be rolled up and stored backstage as well. Both components were tested for acoustic effects on different instruments, as well as the OSHA standards of safety. Their performance and recommended use are outlined in a guide that is provided at the end of this report for the user's convenience and safety.

2. Overview of the Final Design

2.1 Guiding Research

During the first half of our project, the team focused on preliminary research to help narrow down our design parameters. Half of the group researched the recital hall's material properties, while the other members attempted to generate a rough computer simulation of the hall's acoustic properties.

2.1.1 Materials Research

The focus of the materials research was to understand the absorptivity values of materials both in Ruth Taylor Recital Hall, and those that could potentially be used in the acoustic components. One of the key findings in this stage of the project was the degree to which these values are frequency dependent, as shown in Table 1.

Table 1: Frequency dependency of typical project materials at key frequencies

	Material	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Audience	Empty Seats	0.49	0.66	0.8	0.88	0.82	0.7
	Filled seats	0.6	0.74	0.88	0.96	0.93	0.85
	Carpet	0.01	0.02	0.06	0.15	0.25	0.45
Structure	Brick Surfaces	0.03	0.03	0.03	0.04	0.05	0.07
	Back panel fabric	0.05	0.07	0.13	0.22	0.32	0.35
	Ceiling	0.73	0.99	0.99	0.89	0.52	0.31
Stage	Stage	0.15	0.11	0.1	0.07	0.06	0.07
	Walls on stage	0.15	0.11	0.1	0.07	0.06	0.07
Component	Curtains (light)	0.07	0.32	0.49	0.75	0.7	0.6
	Curtains (heavy)	0.17	0.35	0.53	0.75	0.7	0.6
	Shells	0.19	0.14	0.09	0.06	0.06	0.05
	Foam	0.11	0.3	0.91	1	0.98	1

2.1.2 Simulation

After our early brainstorming, the group sought to test the feasibility of our initial designs. To help preserve our budget and time, we elected to simulate these components before constructing physical prototypes. We only found one software package that was within budget, so we did not have alternative options in this respect. The simulations software used was I-Simpa, an open-source project focused on 3D acoustic modeling.

First, the group recorded spatial measurements for RTRH and used them to create a 3D model of the space in Fusion 360. This model could then be imported into I-SIMPA where a SPPS calculation (modeling sound waves as if they were energetic particles) was used to approximated the space's acoustic properties. The output from these simulations were sound-pressure-level (SPL, measured in decibels) heat maps such as the one presented in Figure 2.

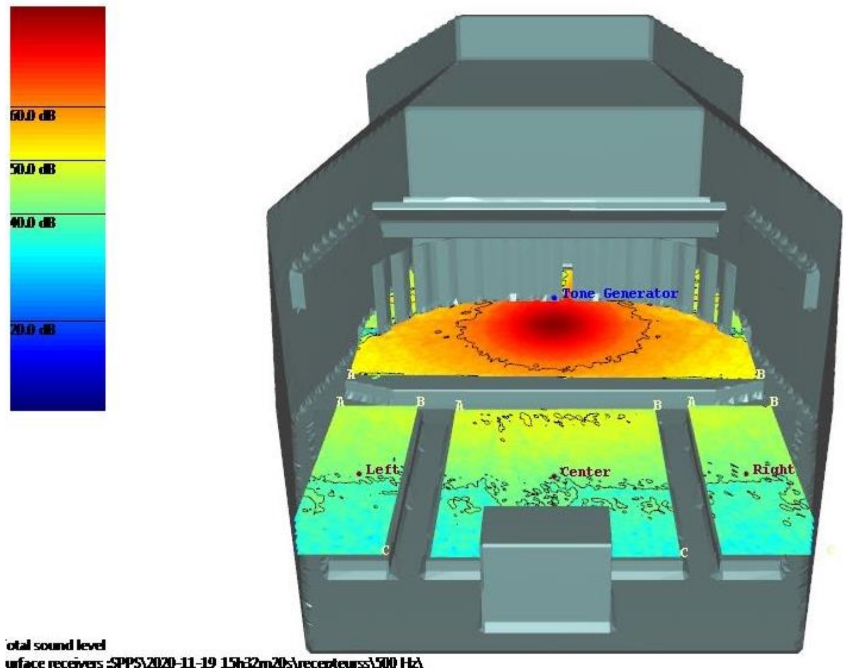

Figure 2: Simulation Verification for Ruth Taylor Recital Hall with no components

Since it was not feasible to collect all the relevant data for the hall during every test (humidity, certain material properties, measurements of inaccessible spaces, etc.) this first test was used in conjunction with our first round of real measurements in order to ensure the simulation was as close to reality as possible.

With the simulation calibrated, we then tested several basic designs to assess which would be most feasible. These component efficacy tests were conducted with simple representative components as well as with adjustments to the current position of the hall's acoustic shells.

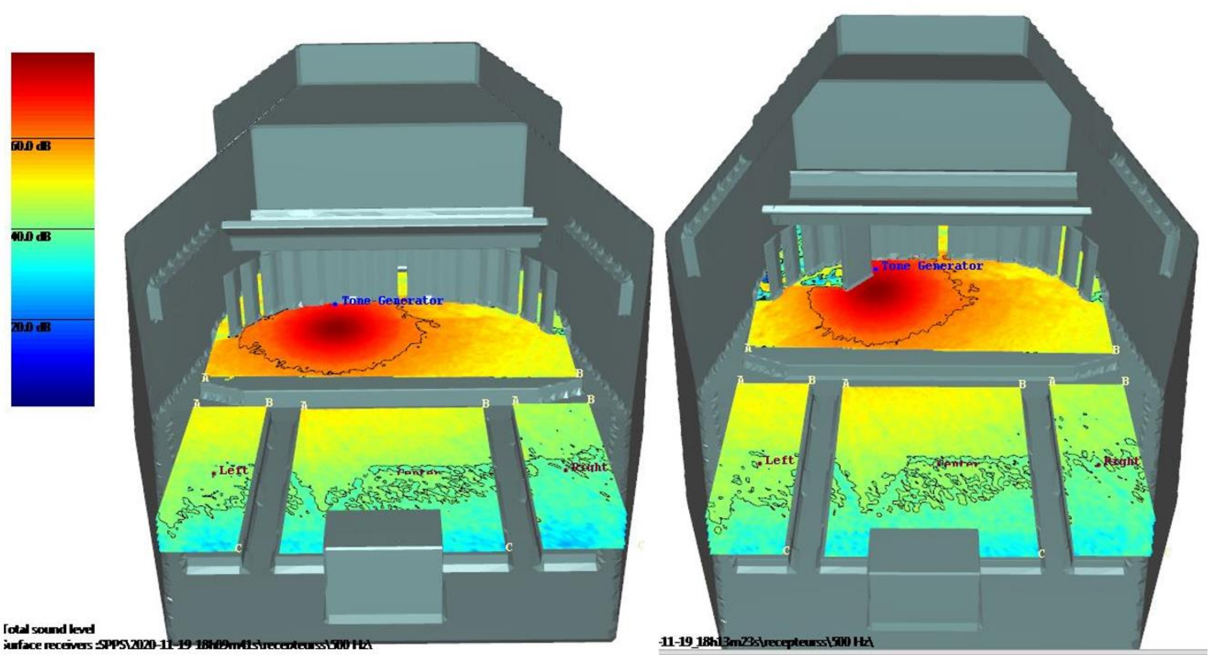

Figure 3: Comparison test of RTRH with no components (left) and with dampening wall (right)

2.2 Selected Design

There were two major components in our design: the Reflective Walls and Absorptive Mats. The Reflective Walls are large plane-like structures; ideally used to redirect sound energy in the audience. The base of these walls was designed for flush, parallel storage within the hall's storage space. The tools required for construction consist of a drill (with bits), a standard Philips head screw driver, a sander, and an electric or hand saw. The base material for construction of the wall was standard plywood and 2x4s. The construction of these walls took place within the CSI makerspace. First, the frame of the walls was constructed after cutting the wood to desired dimensions and connected using wood screws of various, necessary lengths. The wheels of the walls were attached to the base legs of the walls that were then connected to the frame. The face of the walls was connected to the frame once the stable, standing upright on the wheels. Bolt, screw and fastener dimensions can be found in the Materials List (see Appendix B). At the end of construction, these components were painted a matte black in accordance with Dr. Kneer's aesthetic requests.

The Absorptive Mats are a horizontal plane of a thick rubber material that will be placed under instrument sections. The objective of this component is to transmit sound from the instruments above it, keeping that energy from bouncing off the floor of the stage and out into the audience. The source and order information of the Mats is included in the Materials List (see Appendix B)

3. Design Evaluation

This project had two main requirements: that the system of components should reduce the stage/space's acoustical imbalances, and that every component should be easily stored in the space allotted backstage. Of these two requirements, the first was much more involved in terms of testing, so the majority of this section will be devoted to the acoustic investigation/testing performed.

3.1 Reducing Acoustic Imbalances

The acoustic system must improve the acoustic properties of the performance space. This base requirement is fairly vague, and so, in the Project Proposal, it was specified with two criteria: concerning the stage and the audience. First, the acoustic system must remedy the areas on the *stage* that overly project or muffle the instruments situated there. Sounds played at the same volume in different areas of the stage should result in the same general decibel level at a fixed point within the audience. Second, the acoustic system must also even out the spread of the sound (to a standard volume measured via decibel meter(s) throughout the audience), which would help in removing various inconsistencies within the audience (where some seats hear louder sounds from certain orchestral sections than others).

<u>Associated Tests:</u>

A series of five tests were performed in order to evaluate this design criteria. However the first two tests, the Baseline and Pseudo-Component Tests, were only relevant *before* the final components were built. Since they did not investigate any of the final designs, their results are not included in this report.

The remaining tests—the Full Component, Baseline-Instrument, and Full Component-Instrument Tests—were all performed to investigate the effectiveness of the final designs and are discussed below. These final designs were the Reflective Walls, the Absorptive Mats, and the Absorptive Reef (which was eventually scrapped due to its ineffectiveness, though its results are briefly summarized below). Additionally, the Baseline-Instrument and Full

Component-Instrument tests are intrinsically tied to one another (one being a basis of comparison for the other) and will be discussed in the same subsection.

Test 3: Full Components (Tone Generator)

Test 3 was a series of tests taken with our designed and manufactured acoustic components, with a tone generator standing at three key stage placements and playing three key frequencies. The resulting sound intensity was then measured in three locations within the audience (see Figure 4). The main objective of this test was to determine the effectiveness of our generated components (in increasing/decreasing the volumes seen in the audience) with a single-frequency sound source.

This test was primarily used to determine general effects of each set of components, and to see if we needed to make any modifications to the components before moving on to testing with musicians (whose instruments would be markedly more complicated, tonally, than just a single sound frequency).

To carry out this test, a sound source was placed at various key positions on the stage, with a reflective or absorptive components (the Absorptive Mat, Reflective Wall, or Absorptive Reef) at appropriate positions next to the sources. At each position, we recorded nine sound intensity readings (once the decibel meters began to display a relatively stable decibel value): 250 Hz, 500 Hz and 1000 Hz recorded in the left, middle and right section of the audience. Figure 4 shows the positions of both the sound source, and the various components tested, as well as the positions within the audience where the volume measurements were taken. One important note is that these tests were performed with the stage cleared of all other components, so that we were investigating the effects of only one component at a time. However, we were not able to achieve this fully due to a large projector screen that we were not permitted to remove from the stage. Instead, we pushed this screen as far to one side as possible (see Figure 4) to reduce its effects on the acoustic results.

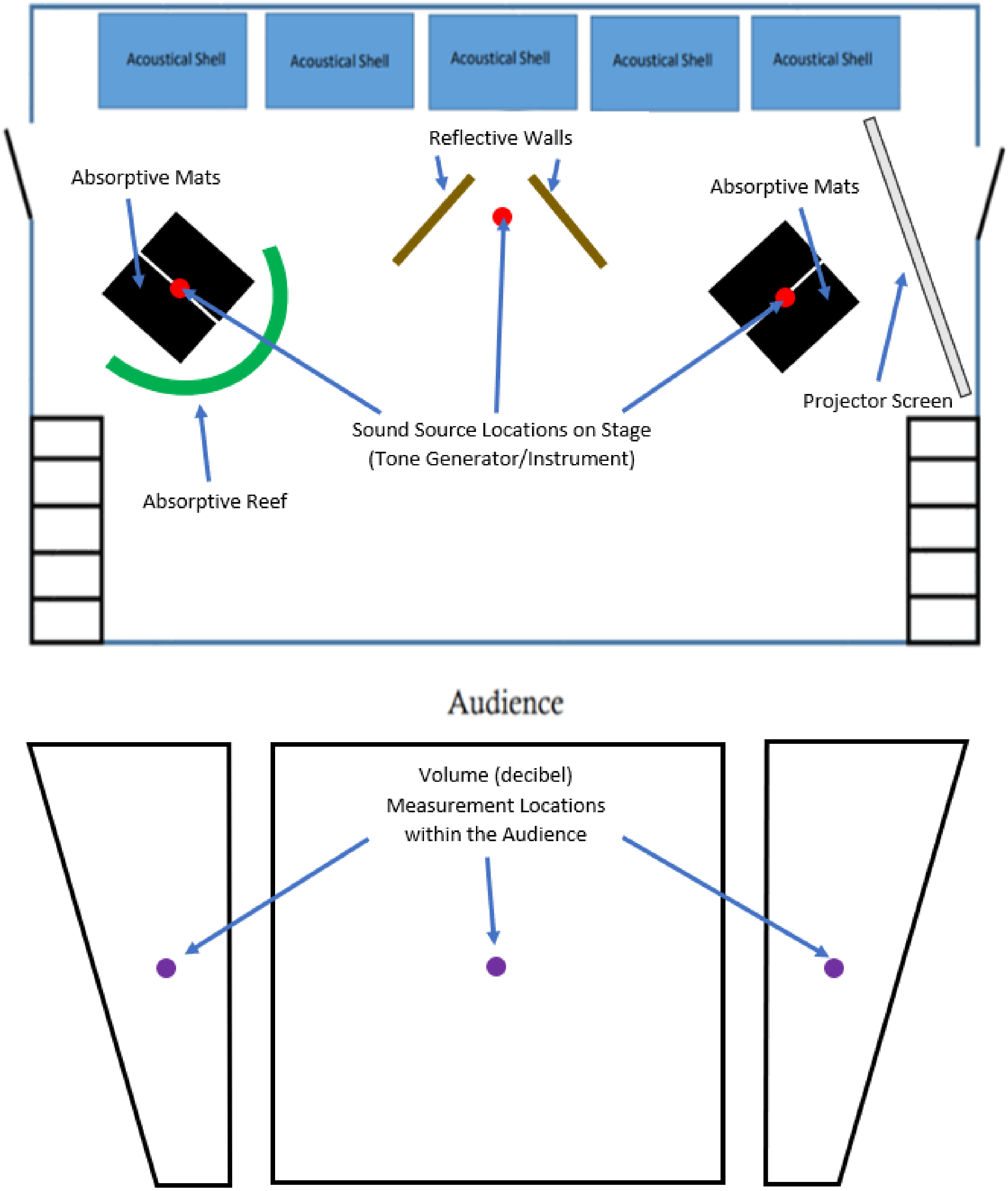

Figure 4. General diagram for visualizing acoustic testing in Ruth Taylor Recital Hall.

In general, the Reflective Walls were tested around/behind the source at the center of the stage (see Figure 5), the Absorptive Mats were tested on both sides of the stage, and the Absorptive Reef was tested in front of the source on the left side of the stage. These positions were selected to best match where these components would likely be in a typical orchestral arrangement.

Figure 5. Experimental set-up for Test 3 of the Reflective Walls. The tone generator and its stand are placed between the two walls, which flank the generator at a sharp angle.

Precise measurements of the tone generator and decibel meter's location was important to ensure consistent results with the baseline data (where the stage was empty except for the tone generator).

The decibel meters themselves were handheld devices, see Figure 6 for a visual reference. These devices were held in the center of the three audience sections and used to record the average sound intensities at that position. This was a potential source of error, as often these meters would fluctuate while the supposedly stable tone was playing. For this reason, our team members took multiple readings during a single frequency trial in order to find the most accurate representation of the volume at their position.

Figure 6. Visual reference of a standard decibel meter.

The acceptance criteria for this test was a three-decibel difference as measured in the audience in the appropriate direction for the component. This would mean an increase of 3 dB from the Reflective Wall components, and a decrease of 3 dB from the absorptive components. We selected this number of 3 dB due to the precision of our decibel meters (± 1.5 dB) and due to our research, which suggested that changes smaller than 3 dB would not be noticeable to most audiences [1].

Test Results and Evaluation

This section will separately discuss the results for the Full Component tests of the Reflective Walls, Absorptive Mats, and the Absorptive Reef. It will also discuss the results of the Wall Angle testing (similar procedure to Test 3, but with the only variable changing being the angle of the two Reflective Walls cupping the tone generator).

Reflective Wall Results:

Table 2: Results for Acoustic Testing of the Completed Reflective Wall Components.

	Source Position &Wall Conditions	**Tone Frequency**	**Audience Position**		
			Left Audience [dB]	**Center Audience [dB]**	**Right Audience [dB]**
Baseline	Center Stage, No Wall	250 Hz	49.4	51.3	44.9
		500 Hz	53.1	55.5	49.3
		1000 Hz	64.2	57.4	56.7
Test 3	Center Stage, Wall behind Source	250 Hz	49.4	51.4	47.1
		500 Hz	56.7	57.2	56.9
		1000 Hz	70.4	59.1	60.7
Difference	-	250 Hz	0	0.1	2.2
		500 Hz	**3.6**	1.8	**7.6**
		1000 Hz	**6.2**	1.7	**4.0**

The most important part of Table 2 is the last three rows: the comparison between the dB-level in the audience with and without the Reflective Walls. The Reflective Wall components were successful in increasing the volume of the source placed between them (See Figure 5 for experimental set up), though this change was only significant at certain frequencies and locations. These significant changes, I.e. greater than ±3 dB, are depicted in boldface in the table. In the Center position, and at the low frequencies in the Left and Right positions, the comparative increase is not large enough to exceed our acceptance threshold of ±3 dB from Baseline.

That being said, the only trial that did not yield at least some form of a net increase to the sound level was at 250 Hz, measured from the left position in the audience. This exception may have been due to the large screen we had to push against the right side of the stage (done so in order to have some semblance of an empty stage). The screen could have absorbed some of the lower-frequency sound which, otherwise, would have reflected off the components, then off angled surface of the exposed brick wall of the concert hall, and then out into left side of the audience.

In order to analyze how the *spread* of sound intensity within the audience was affected by these components, we generated Figure 7 from the raw data in Table 2. Figure 7 compares the sound intensity within the audience at different measurement positions, tone generator frequencies, and with/without the Reflective Walls.

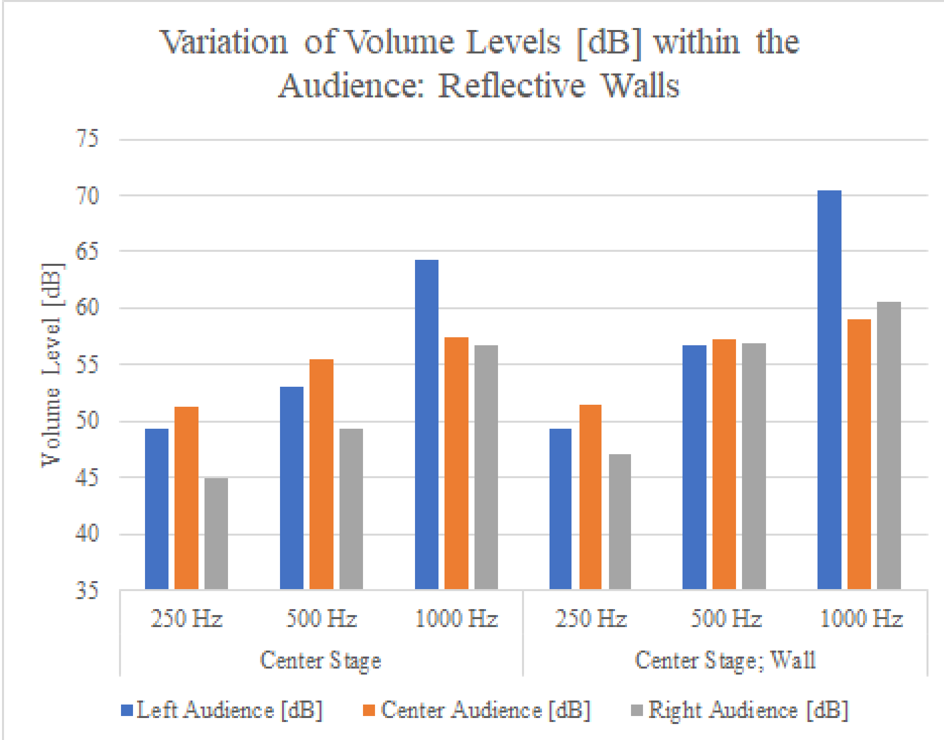

Figure 7. Comparison of volume levels within the audience with and without the Reflective Wall components flanking the sound source in the center of the stage.

From Figure 7 we can see that the Reflective Walls reduced the variation in sound within the audience at the 250 Hz and 500 Hz frequencies. This is most clear at the 500 Hz frequency, where the test without the walls had differences as large as 6 dB. With the inclusion of the walls, this spread was reduced to a much smaller 0.5 dB. However, the walls did not reduce this spread during the 1000 Hz tests. The left audience, which was already much louder than the other locations at this frequency, increased drastically, becoming even more of an outlier. The increase in the left side, 1000 Hz, outlier may have also been due to the effects of the screen pressed against the right wall of the stage. While this screen may have absorbed the lower frequencies, it is possible it may have reflected the higher ones. This could be due to the screen acting like a diaphragm, resonating and absorbing the lower frequency signals. At higher frequencies, however, the sound waves would be pulsing too quickly to move the screen material, making it act more as a reflector than as an absorber. This behavior would explain the outlier at 1000 Hz on the left of the audience.

Reflective Wall Evaluation:

In terms of test objectives, Test 3 for the Reflective Walls partially achieved its intended results. The Reflective Walls increased the dB-levels in the audience at nearly every frequency and position, yet these increases were only significant at the mid-high frequencies and in the wings of the audience. Additionally, this pair of components managed to "smooth out" some of the variation in sound intensity within the audience, though not at every frequency range. While these results do not fully indicate success regarding the project requirements, they were an important indicator (before moving onto testing with real instruments) that these components may be useful as a tool to bolster the sounds of instruments in the center of the stage.

Wall Angle Results:

While testing the Reflective Walls, we decided to perform additional testing to see how the angle of the walls changed their effectiveness as reflective components. Figure 8 shows how we defined the "angle" of the Reflective Walls.

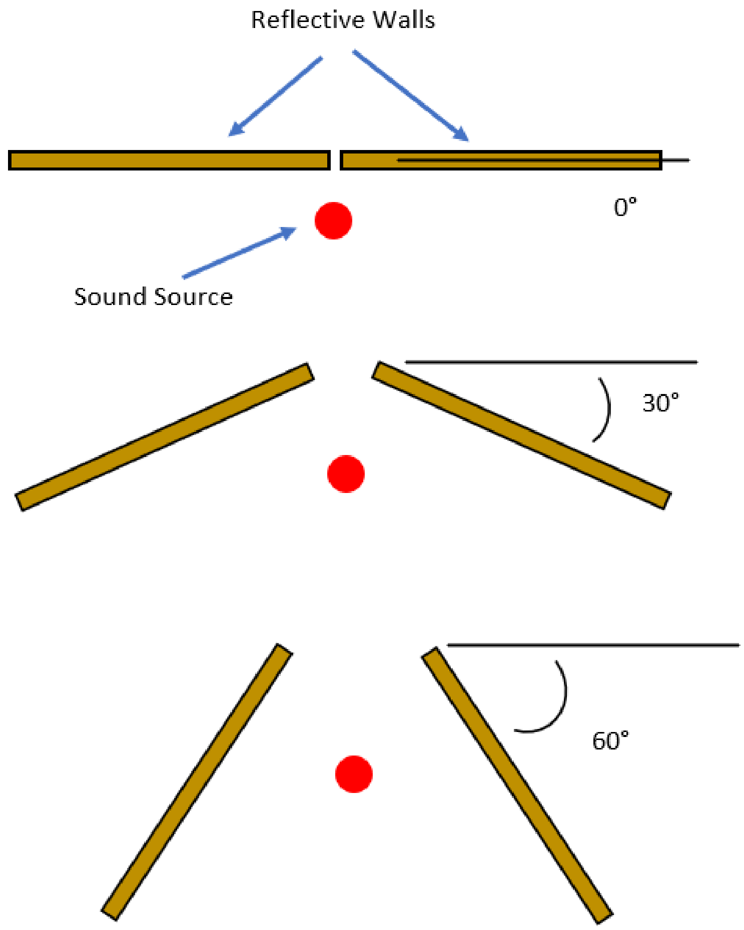

Figure 8. Visual aid for defining "angle" of the Reflective Wall components.

The results of this investigation are shown in Table 3. Since there were 5 angles tested (0°, 30°, 45°, 60°, and 90°), the numerical and graphical results are shown in Appendix C, while the main results are summarized in Table 3 below.

Table 3: Summarized Results and Analysis for Reflective Wall Angle Testing

Angle of Walls about Source in Center Stage Position	Combined Average Decibel Changes from Baseline	Maximum Volume Difference within Audience	Notes
No Component / Baseline	--	15.5 dB	Favors Center and Right sections at mid-high frequencies. Tends toward low volumes in Center section at low frequencies.
0°	+3.5 dB	6.8 dB	Most symmetrical. Favors the center of the audience with higher volumes.
30°	+4.2 dB	15.8 dB	Significantly increases volumes at mid-low frequencies in the Center and Left audience sections. Unevenness in the audience is quite large on average. Favors Center and Left sides.
45°	+4.2 dB	17.4 dB	Drastically increases volumes at mid frequencies. Reduces some of the unevenness in the audience at higher frequencies. Strangely low outlier at 250 Hz Right audience section.
60°	+5.5 dB	9.6 dB	Largest, consistent increases in volume in audience. Volume within audience is fairly evened out as well, though tends to favor Left section.
90°	+4.4 dB	8.9 dB	Fairly even increases. Generally favors Center and Right audience at mid-high frequencies.

Before discussing the results of Table 3, it is important to explain columns 2 and 3. The Combined Average Decibel Changes from Baseline value condenses the effects of the component across both frequency and position. The raw values (in Appendix C) were added together across the positions within the audience, averaged, and then averaged again across each frequency. This method, though very coarse, made sure to take into account the direction of the decibel change (increase or decrease), meaning generally lower values of these Combined results, but values that are more representative of the component's overall behavior. The Maximum Volume Difference within Audience data was similarly coarse, taking the absolute value of the largest volume difference between locations within the audience (though at the same frequency).

In essence, these two metrics are a very obtuse method of comparing the acoustic set ups and should be taken with a large grain of salt. However, the "Notes" section of Table 3 was generated directly from the original data in Appendix C. For more information on these results, and less *heavily* condensed data, please refer to Appendix C.

There are some important take-aways from Table 3. From these tone generator tests, it would seem that a 0° set up (essentially a flat wall directly behind the woodwinds section) would be ideal for maximizing an even "spread" of sound in the audience, while a 60° set up (cupping the section, similar to Figure 5) would be ideal for maximizing the raw sound projected by a central music section.

<u>Absorptive Mat Results:</u>

These components (as there were two 4x6 foot mats placed side-by-side to make one large surface, shown in Figure 4) were tested on both sides of the stage. They were first tested on the right side of the stage, though that put the sound source very near to the large projector screen against the stage's right wall, potentially skewing the data. The results of this test are shown in Table 4.

Table 4: Results for Acoustic Testing of the Absorptive Mat Components on the Right Side of the Stage.

	Source Position	Frequency	Audience Position		
			Left Audience [dB]	Center Audience [dB]	Right Audience [dB]
Baseline	Right Stage	250 Hz	51.4	53.6	53.1
		500 Hz	58.0	53.6	60.5
		1000 Hz	66.0	58.4	67.0
Test 3	Right Stage, Mat beneath Source	250 Hz	49.5	47.1	50.5
		500 Hz	56.3	53.8	61.2
		1000 Hz	61.2	64.4	72.0
Difference	-	250 Hz	-1.9	**-6.5**	-2.6
		500 Hz	-1.7	0.2	0.7
		1000 Hz	**-4.8**	**6.0**	**5.0**

The two main results shown in Table 4 are that the Absorptive Mats in the right stage position reduced the volume intensity at lower frequencies and in the left audience wing, while increasing the intensity at the 1000 Hz frequency in the center and right audience locations. The only significant changes (I.e., greater than a ±3 dB difference) were in the center audience at 250 and 1000 Hz, in the left audience at 1000 Hz, and in the right audience at 1000 Hz.

It was expected for the Absorptive Mats to decrease the amount of low frequency sound projected by the source. This is because the mats are intended to have high transmissivity, essentially increasing the amount of sound energy sent into the floor beneath the sound source. However, this phenomenon is most significant at lower frequencies due to the thickness and density of the material. At higher frequencies, unfortunately, it was found that the material was too dense and these sound waves were instead reflected off of the mat and into the audience. This explains why the Absorptive Mats reduced the sound intensity at the lower frequencies, and increased them at the higher.

In terms of how the mat in this location affected the spread of the sound intensity in the audience, Figure 9 shows this data comparatively.

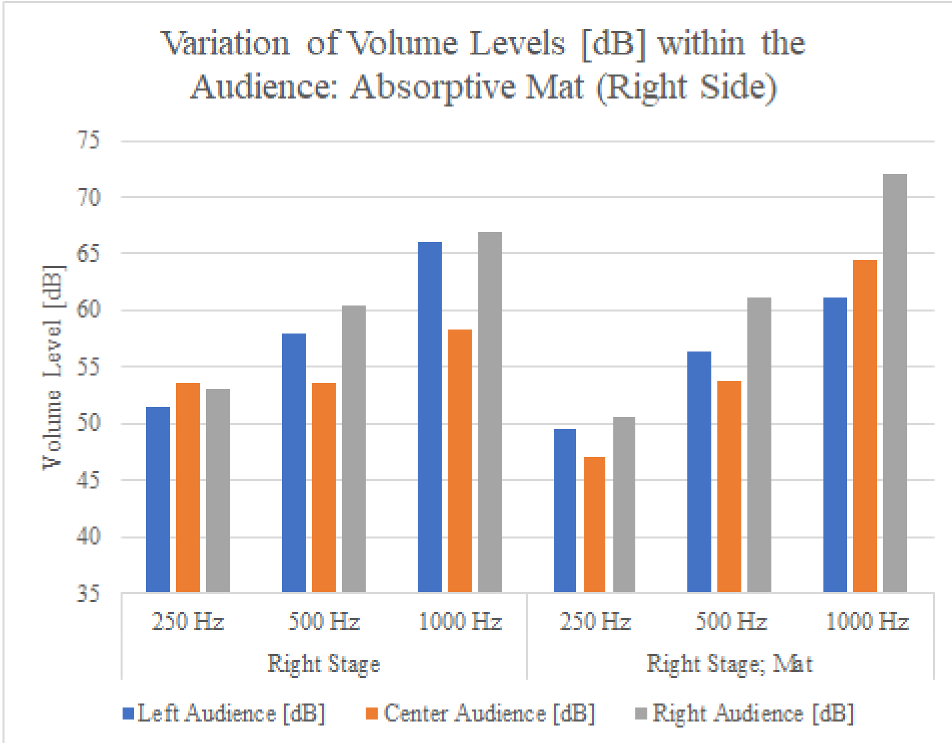

Figure 9. Comparison of volume levels within the audience with and without the Absorptive Mat component beneath the sound source on the right side of the stage.

From Figure 9, there were no significant reductions in volume variation across the audience. The only significant changes are from the strange decrease in sound intensity at 1000 Hz in the left audience discussed above, resulting in a change from an 8.6 dB variation without the mat to a 10.8 dB variation with it. There was also a slight increase in audience volume variation at 250 Hz, from 2.2 dB to 3.4 dB.

Moving on to the tests of the Absorptive Mats on the left side of the stage, these results are shown in Table 5.

Table 5: Results for Acoustic Testing of the Absorptive Mat Components on the Left Side of the Stage.

	Source Position	Frequency	Audience Position		
			Left Audience [dB]	Center Audience [dB]	Right Audience [dB]
Baseline	Left Stage	250 Hz	49.6	53.1	53.2
		500 Hz	58.3	57.1	61.9
		1000 Hz	62.4	60.5	67.8
Test 3	Left Stage, Mat beneath Source	250 Hz	48.4	52.4	54
		500 Hz	55.7	53.5	63.7
		1000 Hz	66	65.8	71.1
Difference	-	250 Hz	-1.2	-0.7	0.8
		500 Hz	-2.6	**-3.6**	1.8
		1000 Hz	**3.6**	**5.3**	**3.3**

The results shown in Table 5 are, in majority, insignificant. The only significant decrease in volume intensity was in the center position in the audience at 500 Hz, while the significant increases were at 1000 Hz throughout the audience. This is fairly consistent with the earlier discussion of the mat material, absorbing low frequency sound and reflecting high frequency sound. The main reason for the differences in the data (including which locations saw net increases/decreases and the extent of each) was most likely due to the sound source no longer being directly adjacent to the large projector screen.

In terms of volume variability within the audience, Figure 10 presents this comparative data.

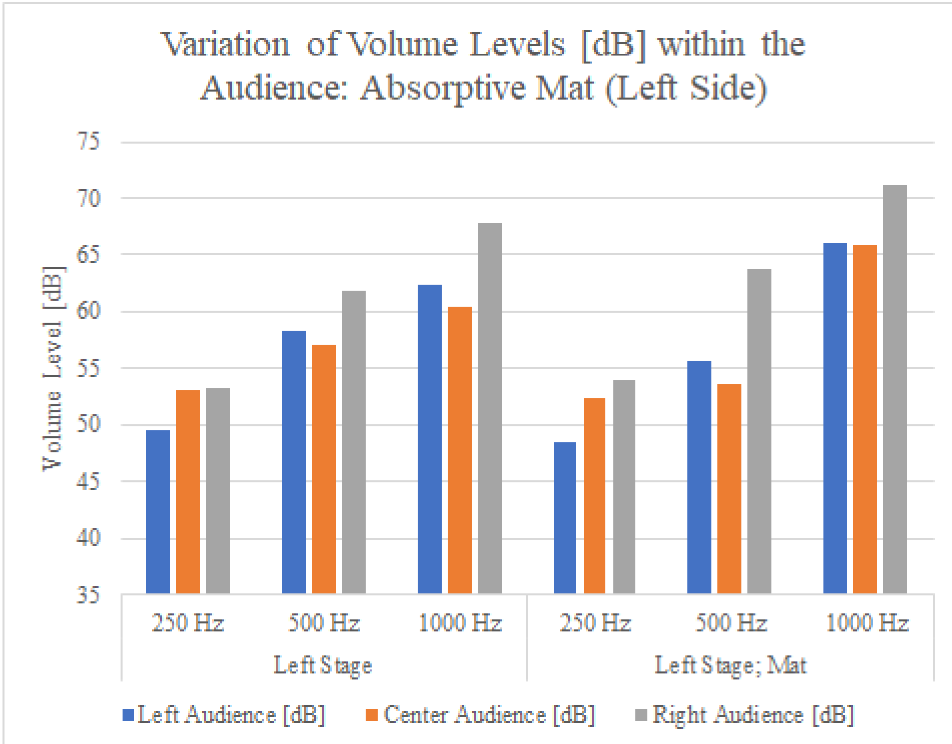

Figure 10. Comparison of volume levels within the audience with and without the Absorptive Mat component beneath the sound source on the left side of the stage.

Like the volume variation with the Absorptive Mats on the right side of the stage, Figure 10 does not show much significant change. The largest change in the magnitude of the volume variation in the audience was at 500 Hz, where the addition of the mats on the left side of the stage caused an increase in the sound intensity spread, from 4.8 dB without the mats to 10.2 dB with the mats. Though the mats caused a small decrease in this variation at 1000 Hz, this difference is minimal, 7.3 dB without mats to 5.3 dB with mats.

<u>Absorptive Mat Evaluation:</u>

For these tests of the Absorptive Mats on both sides of the stage, we can only call the results partially successful. This test proved that the placement of the mats must be more informed and intentional than just simply “place under percussion to reduce sound”. There is a clear frequency dependence on the effects of the mats. While this use of the mats might be viable for lower register instruments, such as a bass drum, doing so for higher register instruments could end up increasing, rather than decreasing, their sound projection into the audience. This still could be used to the advantage of the orchestra, placing one of these mats under high register woodwinds, such as flutes, to increase, rather than “absorb”, their sound, though this is not in line with the original intention of the mat components. In addition, the mats also did not impact the variation of the sound level in the audience with any real significant/consistent changes.

Absorptive Reef Results:

The absorptive reef was found to be the least useful of all the tested components, which eventually led to it being scrapped from later testing. This was within expectations since it had the lowest effective surface area of all the prototypes. Figure 11 demonstrates the recorded effects, showing only slight changes to the acoustic balance of the hall.

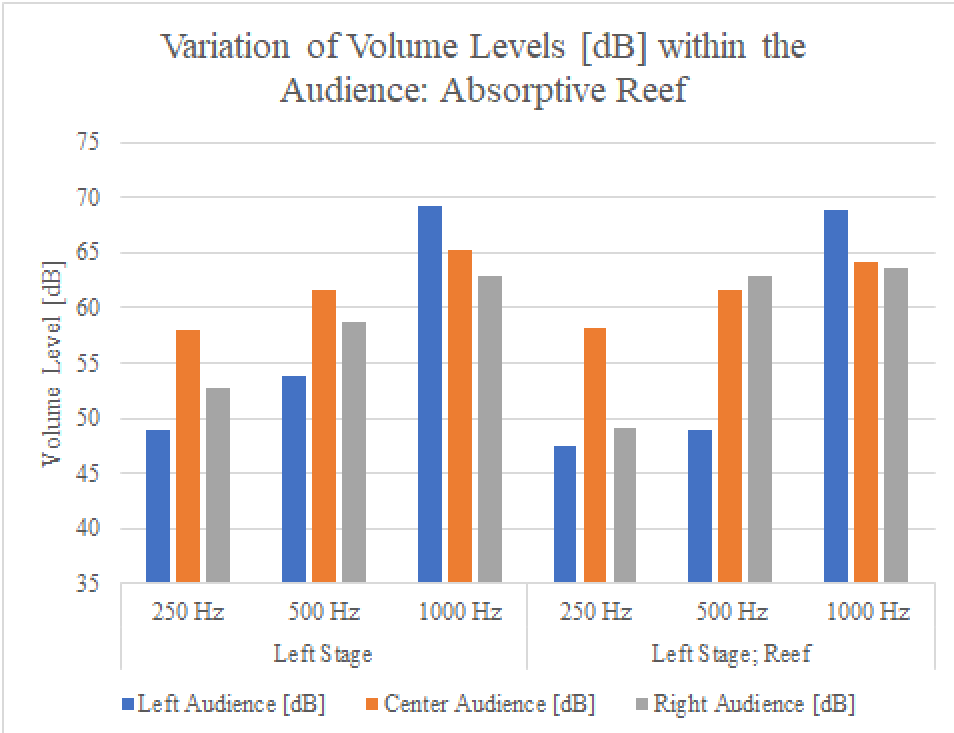

Figure 11. Comparison of volume levels within the audience with and without the Absorptive Reef component placed in front of the sound source on the left side of the stage.

Due to the lack of impacts, and to better focus our efforts on the more promising prototypes, we did not conduct any further testing on the Absorptive Reef. We did not feel that these results warranted further testing with actual instruments so the group elected to drop this component from the final system presented.

In summary, the Reflective Wall components were the closest of our components to success, increasing the volume of the source between them across the board. However, only some of these positive changes were significant (outside a ±3 dB difference range). This was less true with the Wall Angle tests, where a wide variety of angles showed significant increases or decreases in the volume levels in the audience, with the 0° and 60° variations potentially being the most useful. This also suggested that finding an ideal *configuration* of the Reflective Walls was more important than potentially rebuilding/redesigning them. The results for the Absorptive Mats were much more mixed, revealing the extreme frequency-dependence of the mat material, and the magnitude of the acoustic impact of the projector screen that we were required to keep on stage during testing. The Absorptive Reef had almost no statistically significant changes, so no further tests were conducted with it.

Test 4/5: Full Components and Representative Sources

These tests were very similar to those performed in Test 3, but with real musicians and instruments as opposed to a single-frequency tone generator. Much of the testing procedure is identical, except that combinations of components were occasionally used (Walls + Mats, etc.) in these tests.

This test was used to verify that the acoustic components generate their expected results (Reflective Walls increase sound levels within the audience, Absorptive Mats, ideally, reduce sound levels) with sound sources that were more accurate to the orchestra ensemble.

Replacing the tone generator in Test 3, a musician will be placed in various key positions on the stage with a reflective or absorptive component nearby. At each position, there will be nine recorded readings: a relatively low, medium and high frequency recorded in the left, middle and right section of the audience. The Reflective Walls were mainly tested at the center of the stage and the mats were primarily tested on the left and right sides of the stage. We also tested combinations of components: a wall with a curtain attached to the back placed behind the percussion in an attempt for more dampening (see Figure 12), and the mats beneath the woodwind players in the center of the hall (see Figure 13).

Figure 12. Visual aid for combination of Absorptive Mat and curtain attached to the back of a Reflective Wall, used in percussion testing (timpani).

Figure 13. Visual aid for combination of Absorptive Mat and Reflective Walls, used in woodwind testing (oboe).

These tests combined the finished components with actual instruments to simulate the full orchestra at a reduced scale. Specific attention was paid to how the musicians were playing, typical instrument height above the stage, and the previous test's instrument placement. The main assumption for Test 5 was that the individual instruments will more accurately model the expected behaviors of the full orchestra. It also assumed that the musicians would be able to produce a steady tone, which eventually proved to be true only for the woodwind tests. As with all other comparison tests (I.e., Test 3), we deemed a three-decibel difference in the appropriate direction to be acceptable for this test.

Test Results and Evaluation

The results of this test are separated by instrument: Oboe (Woodwind), Marimba (Percussion), Snare Drum (Percussion), and Timpani (Percussion).

Woodwind Results:

The tests with the woodwinds used oboes and oboe-players as representative sources. There were six test set-ups investigated (Baseline, Walls 25°, Walls 60°, Walls 75°, Mats, Mats & Walls 60°), with the numerical and graphical data being shown in Appendix D. The results of these tests are summarized in this section.

Table 6: Summarized Results and Analysis for Woodwind Component Testing

Component Set-Up around Center Stage Position	Combined Average Decibel Changes from Baseline	Maximum Volume Difference within Audience	Notes
No Component/Baseline	--	9.1 dB	Heavily favors Right and Left sections at low pitches.
Walls 25°	+3.6 dB	4.2 dB	Best total volume gains for the oboes across all pitches and locations. Reduced sound "spread". Still slightly favors the Left and Right Audience sections at low pitches.
Walls 60°	+2.8 dB	5.0 dB	Decent volume increases but with significant spread/variation within the audience
Walls 75°	+2.1 dB	6.9 dB	Maintains the Baseline pattern of favoring Right and Left sections at low pitches. Shows large volume increases at mid-range pitches.
Mats	+2.3 dB	2.5 dB	Significantly reduced "spread" of volumes within the audience at the price of, overall, smaller increases in volumes.
Mats + Walls 60°	+2.7 dB	4.1 dB	Fairly significant volume gains across all pitches. Tends to favor Right audience section at low and high pitches (best balance at mid-range pitches).

As with Table 3, the results of Table 6 neglect many important factors (frequency, location, etc.) that can be better shown in Appendix D. However, they are useful to show very general comparisons between component set-ups, with the conclusion that the Reflective Walls at an angle of 25° provided the largest increase in volume within the audience, with only a fairly minimal spread across the audience.

Woodwind Evaluation:

These tests were largely successful. Using actual instruments and musicians, we were able to generate various component set ups that were able to address both increasing the sound projected into the audience, and evening out the spread of the sound within the audience. This test also proved one of our assumptions to be incorrect: that a tone generator would be more consistent as a sound source than a human woodwind musician. Qualitatively, each member of the team taking data in the audience was surprised at how even and sustained the decibel readings were, even between tests with long pauses in between. If we had discovered this sooner, we most likely would have performed fewer tests with the tone generator that we assumed would provide better data than a human playing an instrument.

Percussion Results:

Overall, the results from our tests with the three percussion instruments (the marimba, snare drum, and timpani) were less conclusive. This is primarily because while the pitch/sound was being played by the musician, there was a much larger variation in volumes. "Rolling", or attempting to make a sustained sound, on a percussion instrument is not as simple as just continuing a flow of air (as is the case with wind instruments). Instead, the player is merely hitting the instrument very quickly, so that there is an illusion of a sustained sound. This is not really the case, however, and, as a result, the decibel readings for the percussion tests varied significantly during measurement.

The first instrument investigated was the marimba, as it would allow us a similar 2-octave range of frequencies. One important factor to note is that the resonance at the highest marimba key, F6, was fairly poor due to the nature of the instrument. This may have exacerbated some of the inconsistencies in the tone at this pitch.

Table 7: Results from Marimba Component Testing

Stage Position: Left	**Pitch (Frequency)**	**Audience Position**		
Marimba		**Left Audience [dB]**	**Center Audience [dB]**	**Right Audience [dB]**
Baseline	F4 (~349 Hz)	59.3	59.6	59.1
	F5 (~698 Hz)	71.8	66.1	64.9
	F6 (~1397 Hz)	57.8	58.0	63.2
Mats	F4 (~349 Hz)	58.4	60.1	63.8
	F5 (~698 Hz)	65.9	62.7	67.5
	F6 (~1397 Hz)	60.3	61.7	60.1
Difference from Baseline	F4 (~349 Hz)	-0.9	0.5	**4.7**
	F5 (~698 Hz)	**-5.9**	**-3.4**	2.6
	F6 (~1397 Hz)	2.5	**3.7**	**-3.1**
Back of Wall + Mats	F4 (~349 Hz)	64.7	62.8	65.8
	F5 (~698 Hz)	65.8	64.9	65.8
	F6 (~1397 Hz)	62.8	57.5	60.2
Difference from Baseline	F4 (~349 Hz)	**5.4**	**3.3**	**6.7**
	F5 (~698 Hz)	**-6**	-1.3	0.9
	F6 (~1397 Hz)	**5**	-0.5	-3

These results are fairly inconclusive, with seemingly random spikes either in the positive or negative direction. This was most likely due to the inconsistencies in the tone mentioned above. As mentioned above, the Back of Wall + Mats test were an attempt to absorb more sound from the marimba, see Figure 14. However, due to the relative thinness of the curtain material used, this likely did not introduce any significant dampening and, as suggested by the data above, instead *amplified* the sound of the marimba.

Figure 14. Visual aid for combination of Absorptive Mat and curtain attached to the back of a Reflective Wall, used in percussion testing (marimba).

Figures 15 and 16 show the investigation of how different component set ups influenced the spread of the sound within the audience.

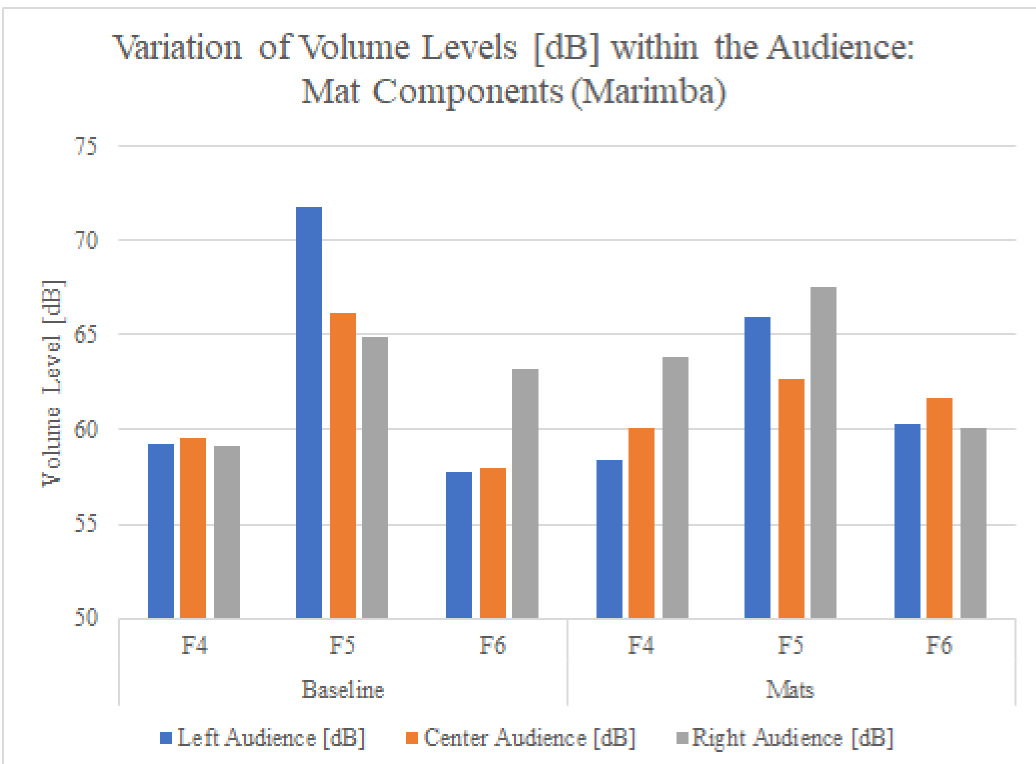

Figure 15. Comparison of volume levels within the audience with an Absorptive Mat beneath the marimba.

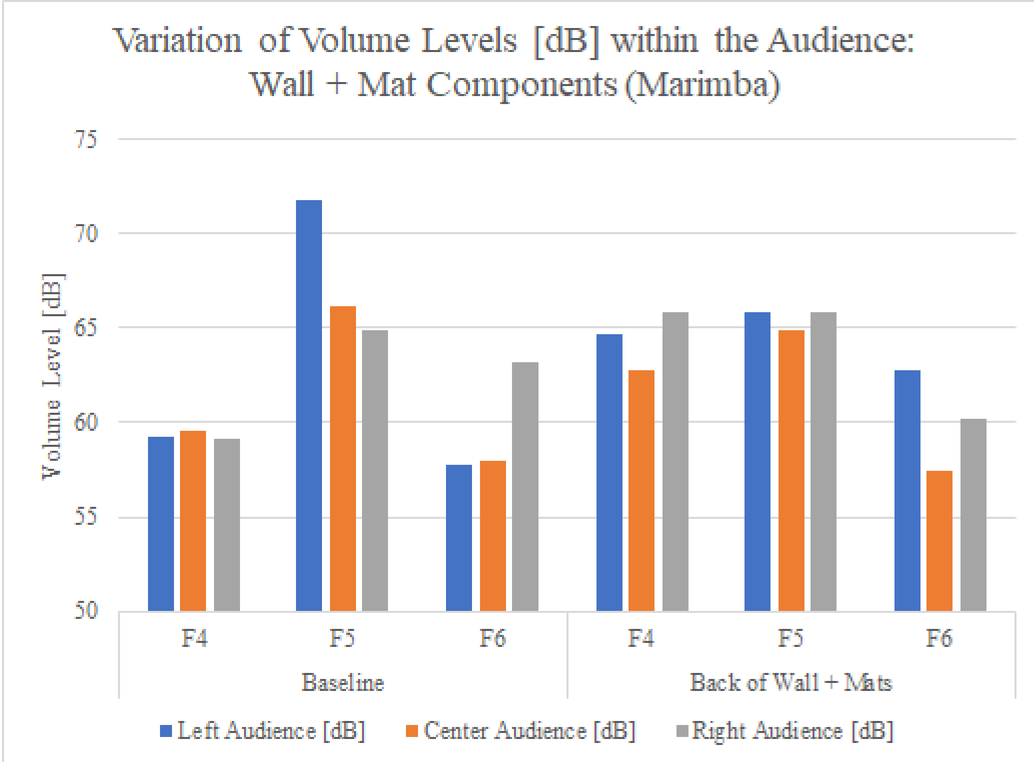

Figure 16. Comparison of volume levels within the audience with an Absorptive Mat beneath and a Reflective Wall behind the marimba.

From these results we can see that adding a wall behind the marimba generally made the instrument louder, but also more even across the audience. This conclusion is still fairly uncertain, as the percussion tone was much more uneven than the woodwind tones, varying over a range of 5-10 dB as opposed to only ~1 dB.

The results of the snare drum testing were similarly uncertain.

Table 8: Results from Snare Drum Component Testing

Stage Position: Left	**Pitch**	**Audience Position**		
Snare Drum		**Left Audience [dB]**	**Center Audience [dB]**	**Right Audience [dB]**
Baseline	N/A	78.5	77.1	79.8
Mats	N/A	77	75.7	77.2
Difference from Baseline	N/A	-1.5	-1.4	-2.6
Back of Wall + Mats	N/A	75.8	74.9	76.2
Difference from Baseline	N/A	-2.7	-2.2	**-3.6**

From Table 8, we can see that there was really only one test result that was significantly different (I.e., greater than 3 dB). The lowering of the volume level of this instrument was consistent though, and so it may be worth further investigation by Dr. Kneer to see these mats are able to make noticeable changes to the dynamics of the snare drum.

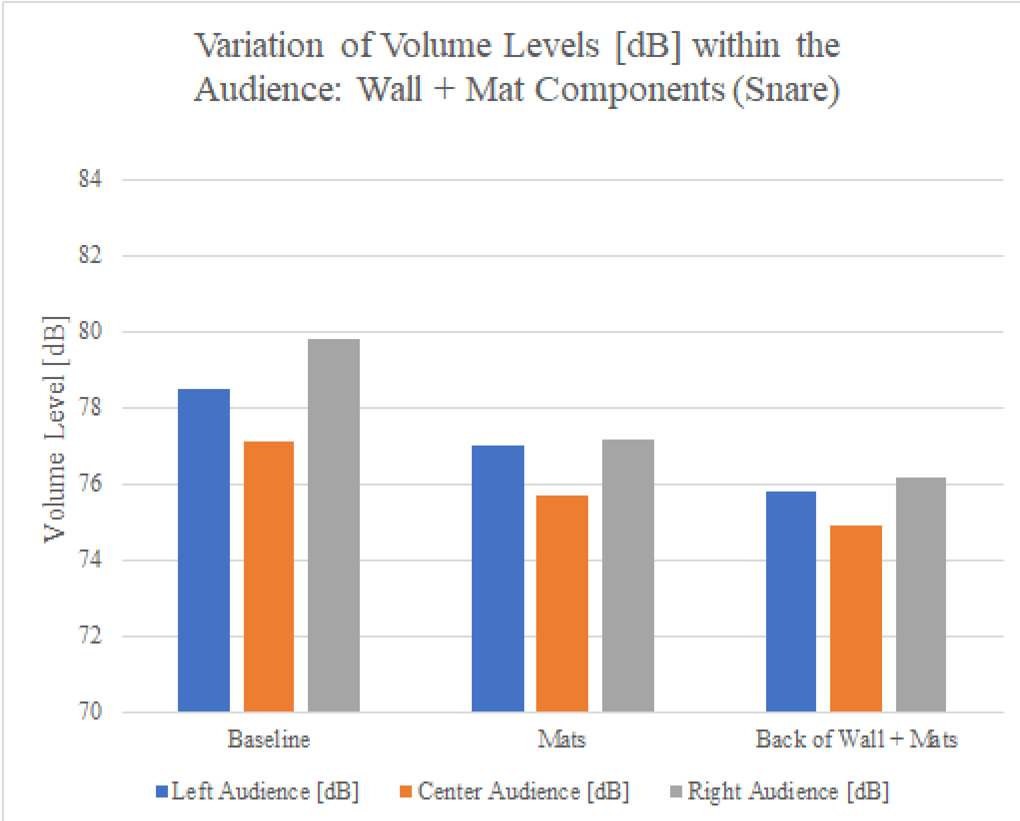

Figure 17. Comparison of volume levels within the audience during snare drum testing.

In terms of audience spread for the snare drum testing (shown in Figure 17), the loudest sections continued to be the Right and Left parts of the audience, though these effects were slightly reduced by the component configurations.

For the timpani test results, there was a tendency to boost the sound of the drum, though most of our results did not exceed our 3-dB threshold for significance. This meant the mats were more reflective than expected, or perhaps the pitches we used were too high to be absorbed. Thus, it may be wise to continue experimenting with a bass drum, which has pitches much lower than those used with the timpani. These unexpected results also could have been due to the unevenness of the tone.

Table 9: Results from Timpani Component Testing

Stage Position: Right	Pitch (Frequency)	Audience Position		
Timpani		**Left Audience [dB]**	**Center Audience [dB]**	**Right Audience [dB]**
Baseline	F3 (~175 Hz)	60	62.5	62.6
	D4 (~294 Hz)	65.6	65.1	67
Mats	F3 (~175 Hz)	61.9	64.3	64.4
	D4 (~294 Hz)	66.1	65.1	67.3
Difference from Baseline	F3 (~175 Hz)	1.9	1.7	1.8
	D4 (~294 Hz)	0.5	0.0	0.3
Back of Wall + Mats	F3 (~175 Hz)	62.1	64.5	62.1
	D4 (~294 Hz)	68.2	69.1	65.8
Difference from Baseline	F3 (~175 Hz)	2.1	1.9	-0.5
	D4 (~294 Hz)	2.6	**4.0**	-1.2

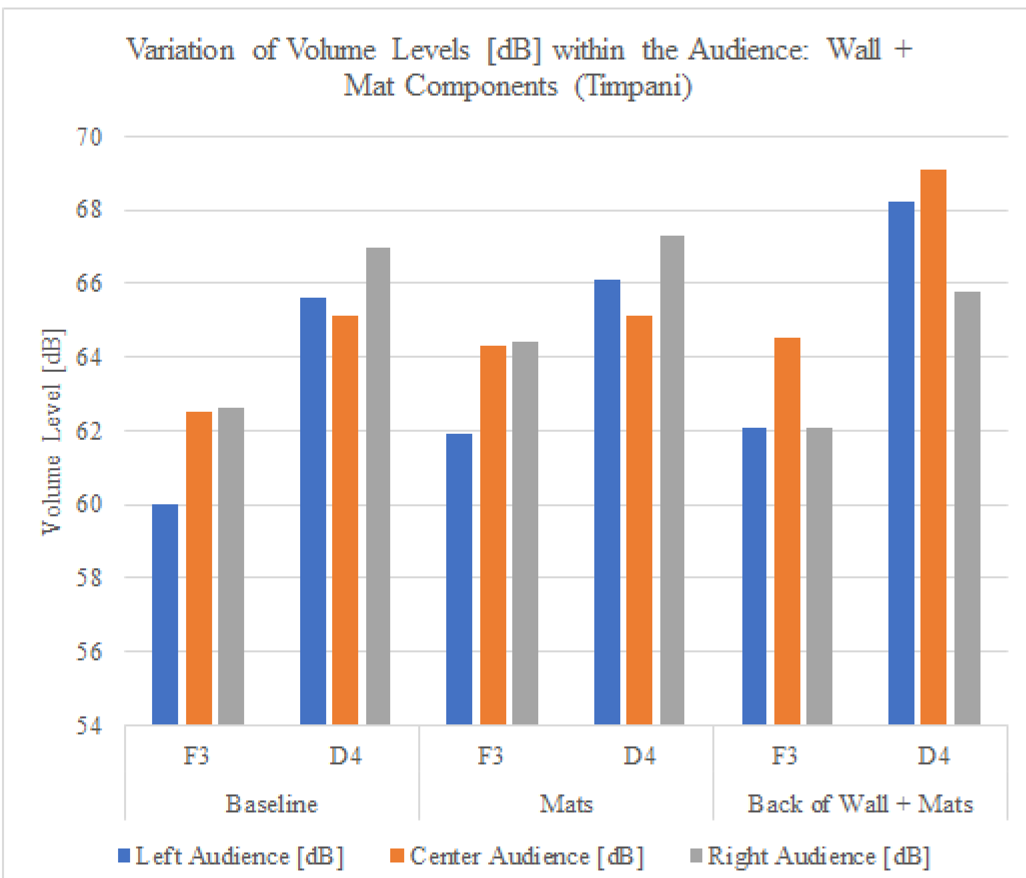

Figure 18. Comparison of volume levels within the audience during timpani testing.

Percussion Evaluation:

These tests were not nearly as conclusive as the woodwind testing, most likely due to the nature of a percussion "steady tone". The mats, the main component being tested, seemed to affect each instrument differently. In the marimba testing, the mats seemed to cause random increases and decreases. With the snare drum, the decreases were small yet consistent, making it the best example of the mats working as absorptive components. The timpani results were also widely varied, yet, in general, saw more increases in volume than expected. For these reasons, the percussion testing was only partially successful, and we recommend some qualitative experimentation by Dr. Kneer to see how these mats interact with the volume and timbre of the various percussion instruments.

3.2 Storage and Safety

Associated Tests:

Storage Test:

The only requirement for this test was that all system components fit in their allotted space in RTRH without disrupting the normal functions of everyone who uses the space. A spacer was included to the initial wall designs in order to allow for a smaller overall storage footprint.

Figure 19. Demonstration of Reflective Wall storage.

This placement was shown to both Dr. Kneer and the stage manager of RTRH, who both validated that its location did not pose a hindrance to those using backstage storage.

OSHA/Safety Testing:

The only component that was determined to have any potential safety concerns was the reflective walls. Due to their larger size and weight, the group wanted to test their performance under two possible conditions: sliding and tipping. We wanted to understand the force needed to displace the walls when applied from each side. This was tested at both the center and the top of the structure.

Figure 20. Tipping tests for the Reflective Wall components.

These tests were predominantly designed to offer safety information for handling these structures. Since we do not know who in the orchestra will typically be transporting them, we wanted to ensure that they were reasonably stable. The tilt angle was measured to be around 20 degrees, and the force required for the walls to begin sliding was 25 lbs.

Conclusions

The project was initially presented to the team as finding a way to address the current acoustic imbalances within Ruth Taylor Recital Hall. We attempted to quantitatively measure this imbalance and provide a framework by which we could assess our component designs. Due to limitations with time and testing with a full orchestra, the group changed its focus to, instead, providing Dr. Kneer with a system of tools to be used at his discretion. We kept the same three decibel change as our criteria for significance, but we now focused more on documenting the real-world effects of the structure as opposed to just optimizing their properties. Ideally, these findings will be updated as the components are used with larger ensembles. The primary deliverable of this project, aside from the two component types, is the user manual given in Appendix A. This lists the relevant conclusions from the five tests conducted as well as general guidelines for safety and storage. Overall, the project met most recent requirements put forth, though additional testing will be required to completely solve the originally proposed problem.

Appendices

Appendix A.

SOUND DYNAMICS USER MANUAL

This document contains the most pertinent information gathered by the team during testing. This is to serve as a reference guide only and should be updated as findings are made with the full orchestra. Full testing documentation is provided in Section 3 of the Final Project Report. For any questions or concerns, please contact the group leader at: alove2@trinity.edu

GENERAL FUNCTIONS & STAGE PLACEMENT

- Walls: used to increase projection of sound sources in front of the component
  - Stage Position:
    - Generally, place behind sections that are quitter than the surrounding ensemble
  - Frequency Dependence:
    - Most effective at mid frequencies,
  - Angle: angles are described between backstage and wall (ex. 0˚ indicates wall placement parallel with back of stage)
    - 0˚ provides most symmetry across audience & moderate increases to sound level
    - 60˚ angle provided the greatest overall sound level increase in audience, favors left side
- Mats: absorb vibrations at stage surface, reflects higher frequencies
  - Stage Position: placed under instruments with large contact are to the stage
  - Frequency Dependence:
    - Suited for lower ranges, provides some reflection of higher frequencies when used with the walls

COMPONENT STORAGE

- Both components stored behind stage, opposite of garage with chairs
- Walls should be stored flat against the wall, flush with each other, and with locked wheels
- Mats may be rolled up and transported with two people
  - Should be stored upright beside walls
- If any problems are encountered with the storage of these devices, please contact the current stage manager of Ruth Taylor Recital Hall

SAFETY CONSIDERATIONS

- The tilt angle of the walls is 25˚
  - Please do not transport the walls in any way that exceeds this threshold
- Though all wheels are capable of locking, only two opposite wheels should be locked during use.
  - This reduces the likelihood of tipping in the event of an accident
- Do not stack, lean, or otherwise support any objects using the walls.
- Walls should be used next to mats, not directly on top of them

Appendix B.

Applicable OSHA Codes and Standards

- Structure/cart needs to be properly maintained to avoid injury to the handler.
- Make sure that the structure/cart has the design and capacity for the job tasks.
- Use structure/cart for the intended purpose; reckless horseplay can lead to injuries.
- Unless the structure/cart is designed to carry people, do not allow passengers.
- The floor or ground surface determines the best wheel type for the structure/cart.
- For tight spaces and crowded work conditions, four swivel wheels or casters add maneuverability.
- For pushing long distances, two swivel wheels and two straight wheels ease movement.
- Structure/cart needs a wheel-locking mechanism to park them.
- Take care where you park your cart; do not block walkways, exits, or doorways.
- A braking system adds additional control over slopes and ramps.
- Handles should be located at the rear of the structure/cart and at the proper height for pushing.
- Do not overload the structure/cart.
- Do not attempt to carry extra items while you are pushing the structure/cart; when pushing, keep both hands on the cart handle.
- Inspect the structure/cart each time you use it; it should be properly functioning and in good repair.
- Wheel bearings require periodic inspections and maintenance, and damaged wheels should be replaced.
- Always use the structure/cart in a responsible manner and maintain the vehicle in safe operating conditions.
- Always reduce speed to compensate for poor terrain or conditions.
- Always apply service brake to control speed on steep grades.
- Always maintain adequate distance between structures/carts.
- Always reduce speed in wet areas.
- Always use extreme caution when approaching sharp or blind turns.
- Always use extreme caution when operating over loose terrain.
- Always use extreme caution in areas where pedestrians are present.
- Must ensure that all passageways used remain clear of obstructions and tripping hazards.

Materials List

Catalog / Part Number	Description	Qty	Unit Cost	Extended Cost
750298707005 92-5/8 STUD	2X4-92 5/8" PRIME WHITEWOOD STUD	14	6.75	94.50
887480007305 5/16X2HEXBLT	HEX BOLT ZINC 5/16 X 2 50PC	1	12.15	12.15
887480072204 ZINCWASHER	FLAT WASHER ZINC 5/16 100PC	1	13.50	13.50
887480017403 HEX NUTS	HEX NUT ZINC 5/16 100PC	1	11.70	11.70
885785499573 PULL 4PK	3-3/4"(96MM) BAR PULL SS 4 PK	1	20.98	20.98
887480011555 CASTER	CASTER RUBBER 3" SWIVEL W/BRAKE	8	10.41	83.28
030699153077 CORNER BRACE	BRACE, CORNER_3"_ZINC_4PK	4	3.98	15.92
Model# 235552	1/4 in. x 4 ft. x 8 ft. BC Sanded Pine Plywood	3	30.33	90.99
Model# 31880	5 in. Galvanized Corner Brace	8	3.98	31.84
Total				**374.86**

Appendix C.

More detailed test results for Wall Angle Testing.

Table C1: Results for Acoustic Testing Changing Only the Angle of the Reflective Wall Components

Source Position	Frequency	Audience Position		
		Left Audience [dB]	Center Audience [dB]	Right Audience [dB]
Center Stage	250 Hz	49.4	39.4	50
	500 Hz	44.3	59.8	52.26
	1000 Hz	55.9	67.5	66.6
Center Stage; Wall 0°	250 Hz	53.7	54.5	50
	500 Hz	56.1	54.0	56.5
	1000 Hz	61.95	68.3	61.5
Difference - 0°	250 Hz	**4.3**	**15.1**	0
	500 Hz	**11.8**	**-5.9**	**4.24**
	1000 Hz	**6.05**	0.8	**-5.1**
Center Stage; Wall 30°	250 Hz	58.5	52.4	46.1
	500 Hz	58.7	68.7	52.9
	1000 Hz	65	62.2	58.5
Difference - 30°	250 Hz	**9.1**	**13.0**	**-3.9**
	500 Hz	**14.4**	**8.9**	0.64
	1000 Hz	**9.1**	**-5.3**	**-8.1**
Center Stage; Wall 45°	250 Hz	54.6	53.6	37.2
	500 Hz	59.3	68.3	63.4
	1000 Hz	66.1	61.1	59.35
Difference - 45°	250 Hz	**5.2**	**14.2**	**-12.8**
	500 Hz	**15**	**8.5**	**11.14**
	1000 Hz	**10.2**	**-6.4**	**-7.25**
Center Stage; Wall 60°	250 Hz	56	52.8	46.4
	500 Hz	61.6	61.1	59.8
	1000 Hz	68.5	66.8	61.7
Difference - 60°	250 Hz	**6.6**	**13.4**	**-3.6**
	500 Hz	**17.3**	1.3	**7.54**
	1000 Hz	**12.6**	-0.7	**-4.9**
Center Stage; Wall 90°	250 Hz	49.4	47.3	55
	500 Hz	54.3	63.2	62.1
	1000 Hz	61	67.1	65.52
Difference - 90°	250 Hz	0	**8.0**	**5**
	500 Hz	**10**	**3.4**	**9.84**
	1000 Hz	**5.1**	-0.4	-1.08

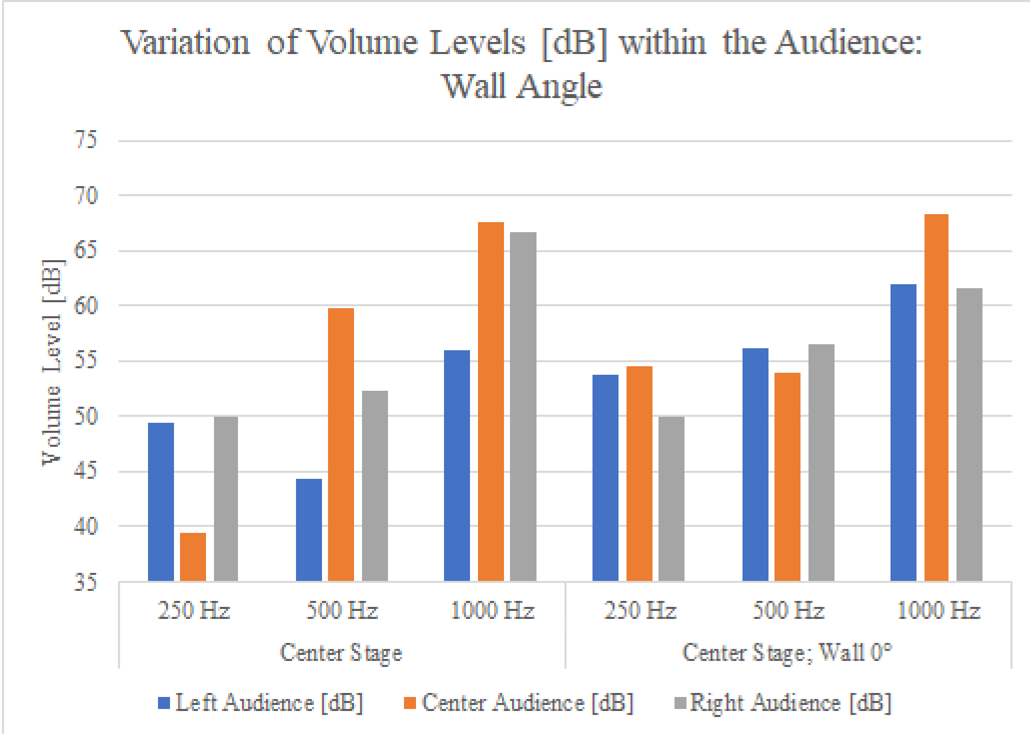

Figure C1. Comparison of volume levels within the audience with the Reflective Walls set to 0°.

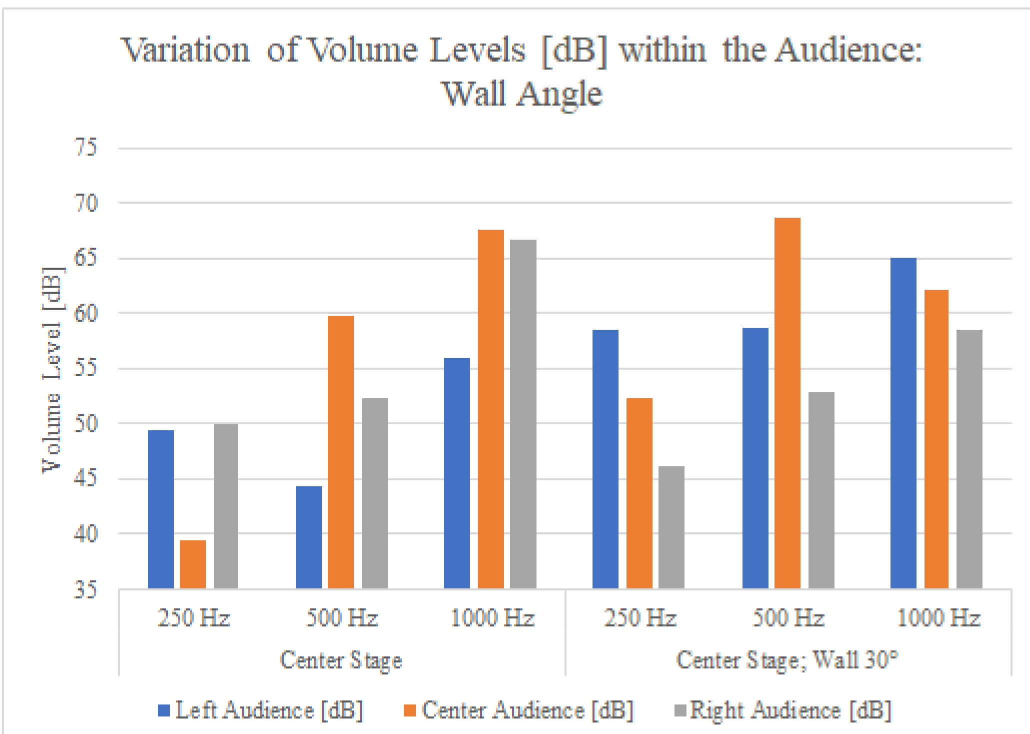

Figure C2. Comparison of volume levels within the audience with the Reflective Walls set to 30°.

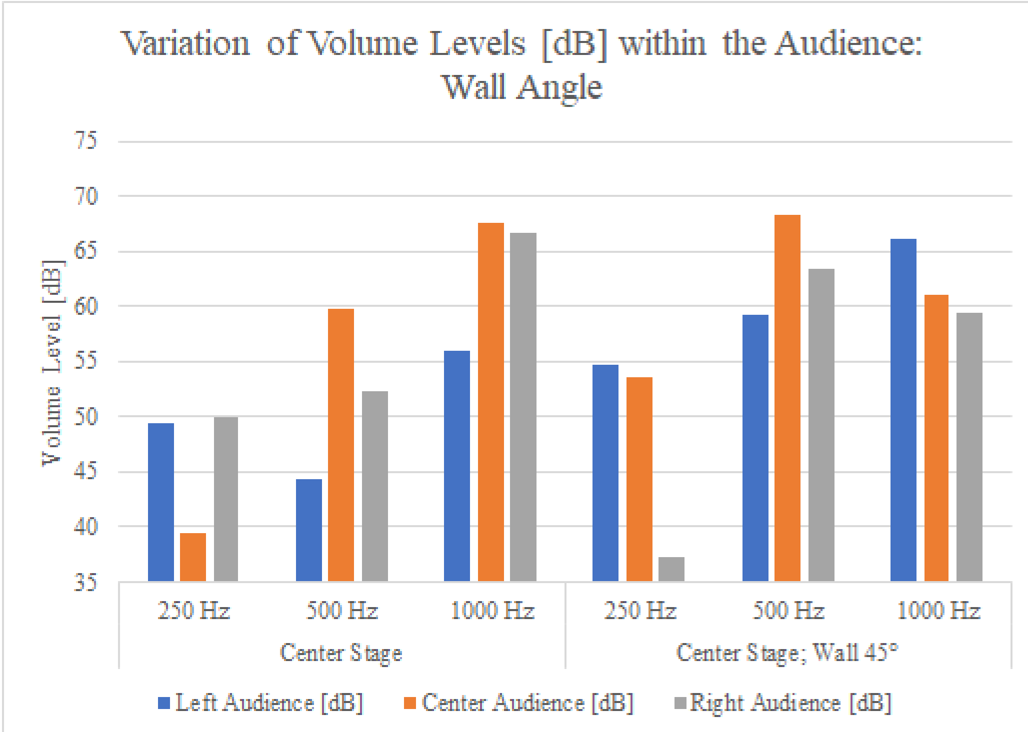

Figure C3. Comparison of volume levels within the audience with the Reflective Walls set to 45°.

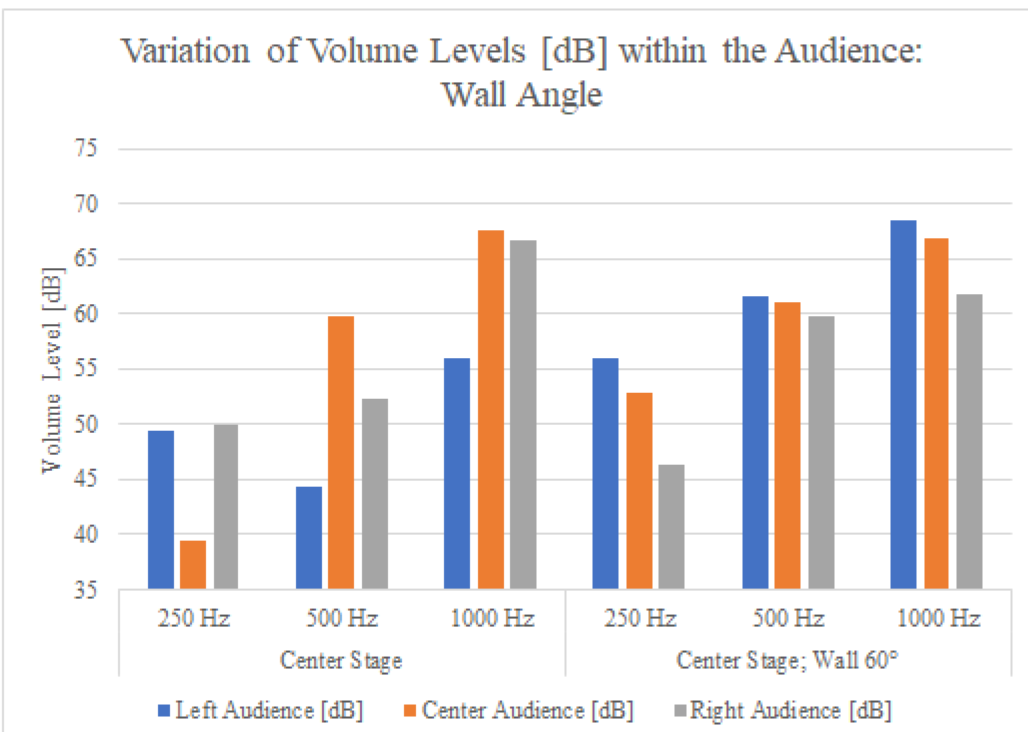

Figure C4. Comparison of volume levels within the audience with the Reflective Walls set to 60°.

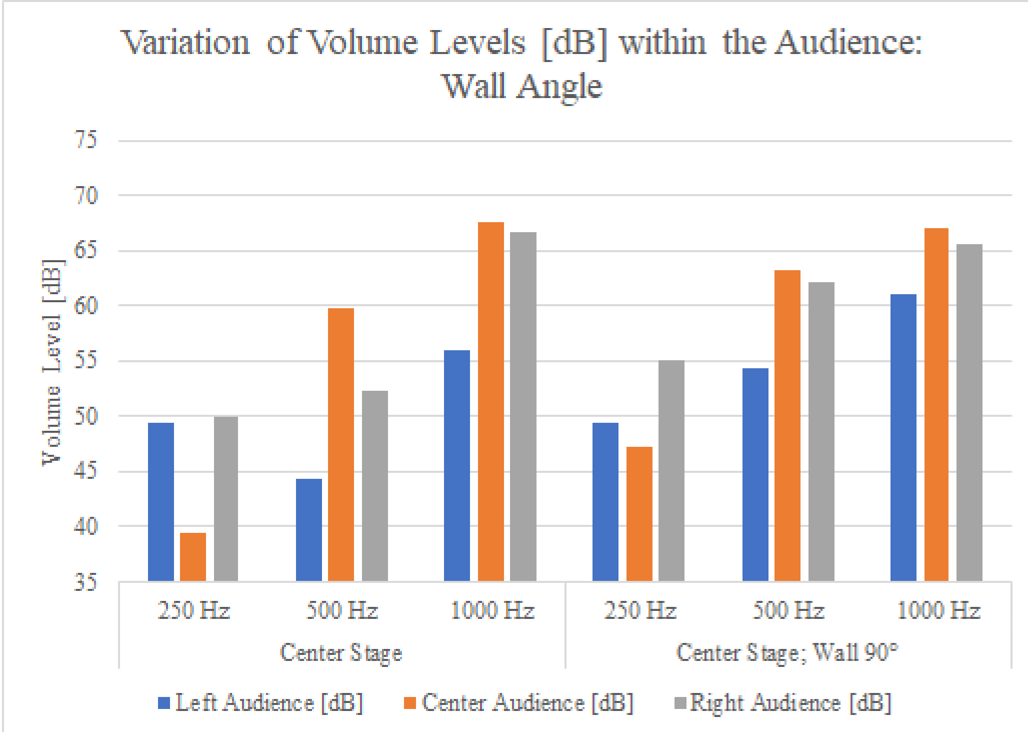

Figure C5. Comparison of volume levels within the audience with the Reflective Walls set to 90°.

Appendix D.

Component Testing with Oboe.

Table D1: More Detailed Results for Component Testing (Isolated and Combined) for Oboe.

Stage Position: Center	Pitch (Frequency)	Audience Position		
Oboe		**Left Audience [dB]**	**Center Audience [dB]**	**Right Audience [dB]**
Baseline	C4 (~262 Hz)	71.1	62.0	69.5
	C5 (~523 Hz)	60.9	59.5	60.7
	C6 (~1047 Hz)	65.3	67.4	65.4
Walls 60°	C4 (~262 Hz)	72.1	67.8	72.8
	C5 (~523 Hz)	63.5	65.4	63.4
	C6 (~1047 Hz)	67.5	69.0	65.9
Difference from Baseline	C4 (~262 Hz)	1	**5.8**	**3.3**
	C5 (~523 Hz)	2.6	**5.9**	2.7
	C6 (~1047 Hz)	2.2	1.6	0.5
Mats	C4 (~262 Hz)	70.7	69.8	72.3
	C5 (~523 Hz)	63.5	63.4	65
	C6 (~1047 Hz)	66.3	65.4	66.2
Difference from Baseline	C4 (~262 Hz)	-0.4	**7.8**	2.8
	C5 (~523 Hz)	2.6	**3.9**	**4.3**
	C6 (~1047 Hz)	1	-1.9	0.8

Wall (60°) + Mats	C4 (~262 Hz)	68.5	68.7	72.8
	C5 (~523 Hz)	64	63.3	64.2
	C6 (~1047 Hz)	67	68.2	69.8
Difference from Baseline	C4 (~262 Hz)	-2.6	**6.6**	**3.3**
	C5 (~523 Hz)	**3.1**	**3.8**	**3.5**
	C6 (~1047 Hz)	1.7	0.8	**4.4**
Walls 25°	C4 (~262 Hz)	74.5	71.2	72.8
	C5 (~523 Hz)	65.8	65.7	64.5
	C6 (~1047 Hz)	66.7	68.6	64.4
Difference from Baseline	C4 (~262 Hz)	**3.4**	**9.2**	**3.3**
	C5 (~523 Hz)	**4.9**	**6.2**	**3.8**
	C6 (~1047 Hz)	1.4	1.3	-1
Wall 75°	C4 (~262 Hz)	72	66.3	73.2
	C5 (~523 Hz)	64.7	64.4	64.2
	C6 (~1047 Hz)	65.5	67.1	63.7
Difference from Baseline	C4 (~262 Hz)	0.9	**4.3**	**3.7**
	C5 (~523 Hz)	**3.8**	**4.9**	**3.5**
	C6 (~1047 Hz)	0.2	-0.3	-1.7

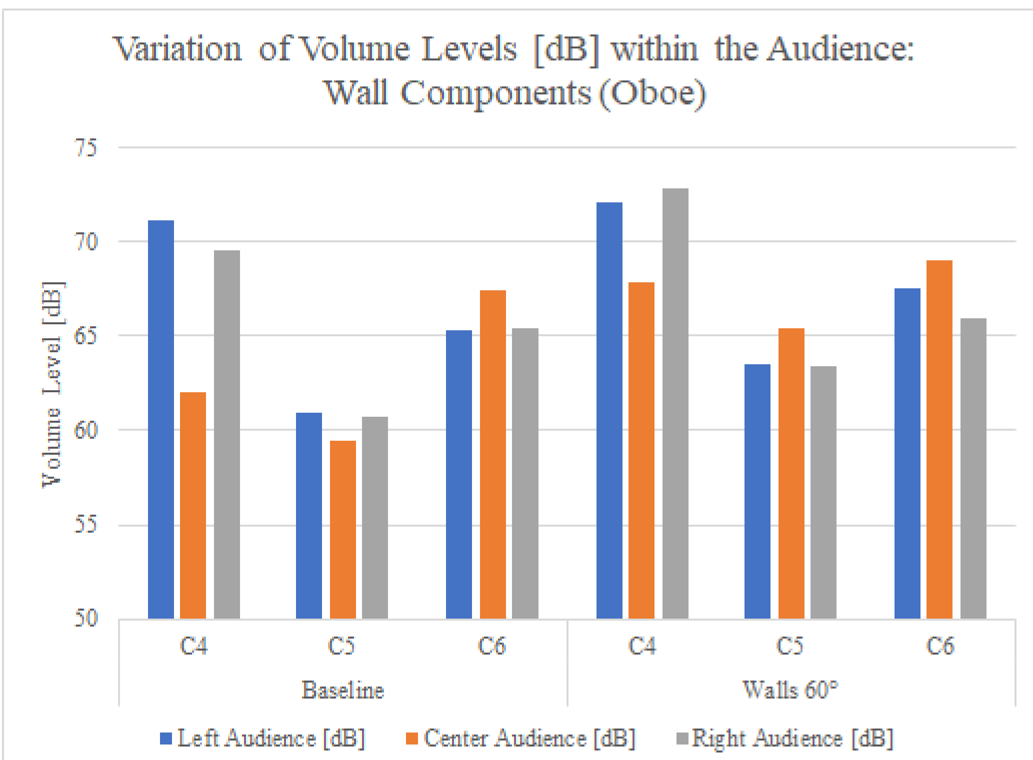

Figure D1. Comparison of volume levels within the audience with the Reflective Walls set to 60°.

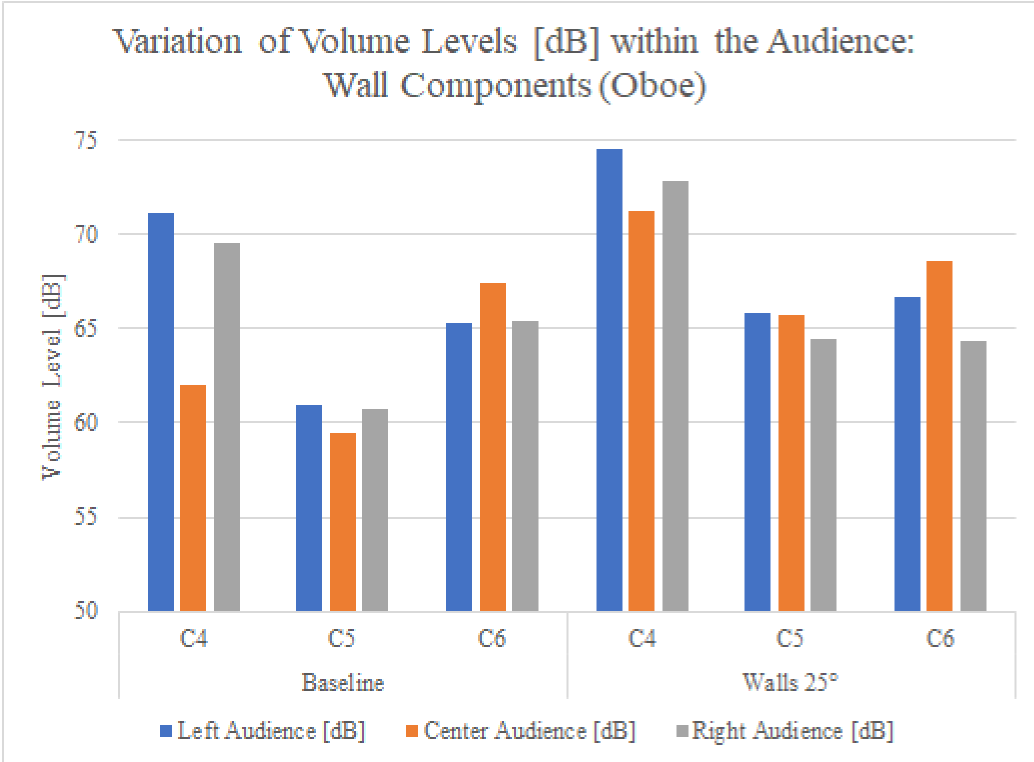

Figure D2. Comparison of volume levels within the audience with the Reflective Walls set to 25°.

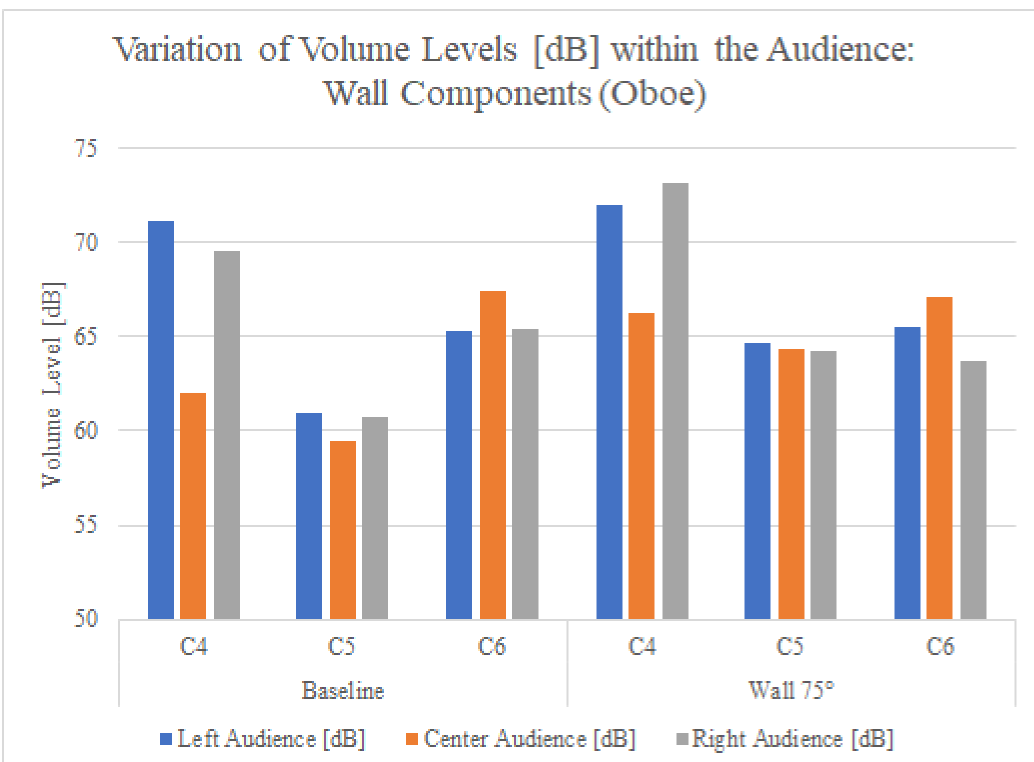

Figure D3. Comparison of volume levels within the audience with the Reflective Walls set to 75°.

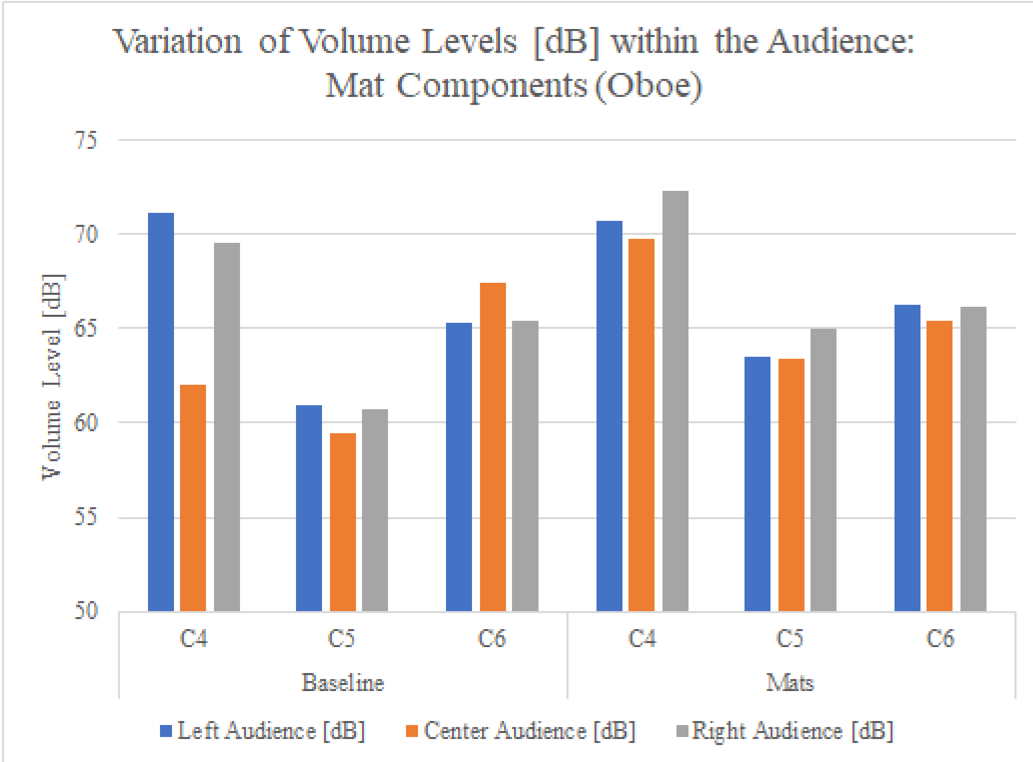

Figure D4. Comparison of volume levels within the audience with the Absorptive Mats.

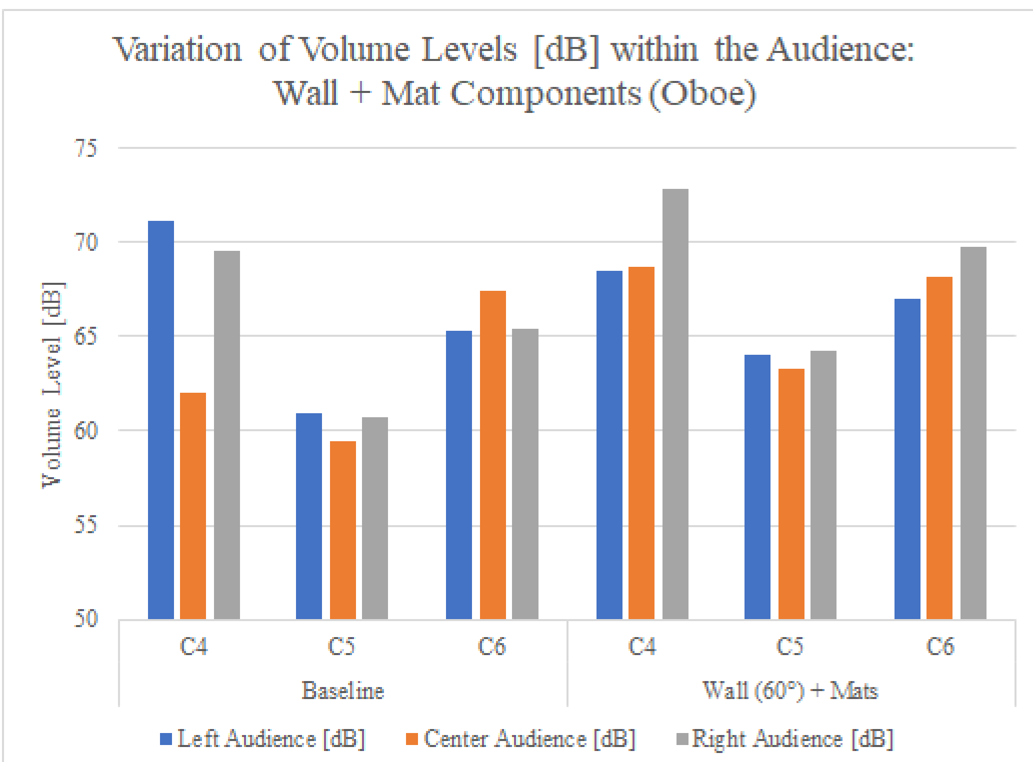

Figure D5. Comparison of volume levels within the audience with both the Absorptive Mats and the Reflective Walls set to 60°.

Figure D6. Further visual aid for oboe testing.

Bibliography

[1] "Architectural." *IAC Acoustics*, 29 Sept. 2020, www.iacacoustics.com/blog-full/comparative-examples-of-noise-levels.html.