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Effectiveness of Acoustic Design in Public Spaces

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EFFECTIVENESS OF ACOUSTIC DESIGN IN PUBLIC SPACES

by

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ABSTRACT

In this thesis, a discussion on the effectiveness of acoustic design in public spaces is made. The auditory properties of a location have noteworthy implications on the success of a building's design and how a room is perceived. Depending on the requirements of each location, either a reverberant or sound-absorbing approach is best suited for the environment. Moreover, public health is negatively affected by long-term involuntary noise exposure. Because of this, there is an obvious demand for continued and expanded study in acoustic design. This thesis aims to challenge interior design choices made in four testing locations: a classroom, a musical practice room, an ambient performance space, and an office. Reverberation time is tested at each site using both a Digital Sound Level Meter application (Decibel X) and a 732A Digital Sound Level Meter paired with a series of external source sounds at set testing frequencies. Depending on the results of each trial, an evaluation of possible improvements to each location's aural properties is made.

ACKNOWLEDGEMENTS

I dedicate this thesis to my family, friends, and dogs Mario and Bruce, who all supported me during my time in the HUT program. A special thanks to Dr. Kauffman, Dr. Mansy, and Dr. Lieser for your efforts and guidance throughout this process. I am grateful that I had this opportunity to pursue two of my interests: mechanical engineering and music. I have learned so much from the completion of this thesis and look forward to applying this knowledge in my future career.

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CHAPTER I: INTRODUCTION

Acoustics are an integral part of a building's design. Often seen as an afterthought, the ambiance or lack thereof of a room can make significant impacts on the public's opinion of a space. Additionally, public health is significantly impacted by external auditorial effects such as ambient noise and sound pollution. Examples of such health concerns include impaired hearing, lack of sleep, increased metabolic rate, cognitive performance, and more. Research on acoustic design continues to expand in new materials, applications, and the importance of this field of study. Within this thesis, an analysis of preexisting acoustic research is performed, with specific concentration on public use applications.

It is important to consider a building's intended purpose and to respect the intended goal of each setting when considering its acoustic design. The presence of ambient sound and extensive reverberation is not ideal for places such as offices, shared spaces, hospitals, etc. In spaces intended for performance, however, reverberation is a crucial aspect of the experience. Further analysis of how sound can be enhanced with appropriate design measures and various materials is to be conducted. Four locations of diverse intention will be examined using reverberation time, source sound, and recipient microphone.

The objective of this thesis is to quantify and record the acoustic properties of a variety of public spaces. This information will then be used to assess possible improvements in the acoustic design. If recorded data is reflective of desired benchmark standards that are recognized, the implemented design measures will also be acknowledged. Research regarding public areas is crucial for accelerating improvements in design, and such improvements can have great impacts on public health, wellness, and happiness.

By compiling the results of experimental data from four various testing locations, the goal of depicting the public trend of proper, or possibly improper, sound design can be fulfilled. These results, if determined unfavorable, are to be presented with the best intention, which is the improvement of the public environment, health, and experience.

CHAPTER II: LITERATURE REVIEW

Impacts on Health

In the article "Real Noise from the Urban Environment: How Ambient Community Noise Affects Health and What Can Be Done About It," Dr. Anne Moudon discusses the negative impacts associated with long-term, involuntary exposure to excessive noise [13]. An individual's environment can have great implications on one's health, and the analysis of how sound affects public health is no exception. Further investigation into the extent of health effects caused by noise exposure is limited. Research that is available, however, provides concerning insight into the severity of involuntary noise exposure. Sounds above 85 dB have the capability to cause long-term, irreparable damage to the inner ear hair cells that allow us to hear. Noise-Induced Hearing loss, or NIHL, is the damage of inner ear structures caused by sounds both impulsive or continuous (National Institute on Deafness and Other Communication Disorders). Any age group can experience NIHL. According to the CDC, anywhere between 6-24%, or 10-40 million adults in the U.S. under the age of 70 suffer from some amount of hearing loss due to noise exposure [14]. A significant prevalence such as this requires great urgency for prevention and solutions for involuntary sound exposure.

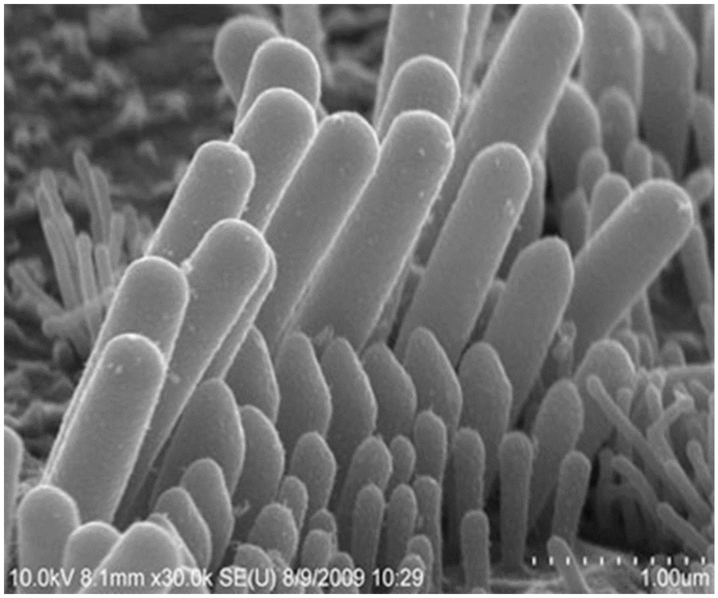

Figure 1: Image of Stereocilia perch atop sensory hair cells in the inner ear. Source: Yoshiyuki Kawashima, National Institute on Deafness and Other Communication Disorders [14].

Beyond the inner ear, long-term sound exposure has been proven to negatively impact other aspects of an individual's health. The psychological effects of sound exposure range from annoyance and reduced quality of life to amplified aggressive behavior; disturbance of natural sleep patterns can be connected to such reactions. Regardless of whether a person is unconscious or not, noise acts as an external stimulus to the brain, and distractions such as this can result in increased metabolic rate and insomnia. Additionally, undesirable noise such as that from traffic and city environments has a strong connection to increased stress/cortisol levels and depression. Finally, studies have shown that exposure to noise levels above 60 dB results in a dose-response relationship to cardiovascular risk and myocardial infarction. Public health is a complicated discussion, but the evidence supporting these damages is considerable and should be acknowledged. From this, a motivation to improve acoustic design in public spaces can be found.

Beyond adverse health effects, another consequence of noise exposure is diminished cognitive performance. In the article “Effects of noise and music on human and task performance: A systematic review,” Dalton and Behm analyze the negative impact background sound has on human performance [8]. Background noise is considered detrimental to tasks involving cognition, concentration, and attention. Acting as both a distraction and a source of stress, background noise has been shown to negatively impact attention span, reading skill, and comprehension. Excessive noise has also shown to negatively impact a child’s ability to learn and absorb information, as seen in Stansfeld’s study titled “Aircraft and road traffic noise and children's cognition and health: a cross-national study.” In a different experiment, traffic noise was related to a decrease in semantic and text memory as well as worsened attention spans. Overall, reading comprehension, memory, and general task performance decrease proportionally with an increase in excessive involuntary noise exposure. These effects have been noted in several age groups and in a variety of scientific studies. Because of these findings, an incentive for proper sound absorption is evident, and the existence of this study is ever more important.

Reverberation

The applications of this thesis are within spatial design and potential improvements to be made for maximum efficiency and optimal performance. To properly quantify such a concept, a definition of what affects sound perception and noise control must be made. Reverberation is the persistence of sound after a sound has been produced. Sound waves propagate from a source and reflect off the walls and items in a room, resulting in reverberation. Several factors contribute to the presence or lack of reverberation, such as room size, furniture, occupants, and more. Scientifically, reverberation is the occurrence of reflections that arrive in less than 50 ms [6]. To determine the reverberation time of a room, or how much a room experiences the effect of reverberation, the standard forms of measurement are the T_{20}, T_{30}, and T_{60} times. These refer to the time it takes a room to drop 20 dB, 30 dB, and 60dB from the original sound, respectively, and these measurements begin after the initial source sound has dropped 5 dB for a more accurate representation of the room's acoustics [4]. The Sabine equation, often used for calculating reverberation time, is referenced below.

$$\boldsymbol{A = 0.921\frac{Vd}{c}} \qquad (2\text{-}1)$$

Where A= sound absorption, m^2, V= volume, m^3, c= speed of sound, m/s, and d= decay rate, dB/s [4]. An alternative version to this formula using T_{60} value is:

$$\boldsymbol{T_{60} = 0.161sm^{-1}\frac{V}{S\alpha}} \qquad (2\text{-}2)$$

Where T_{60} is the time in seconds required for a sound to decay 60 dB, V is the volume of the room, S is the boundary surface area, and α is the average absorption coefficient. The average absorption coefficient can be determined using the following equation:

$$\boldsymbol{\alpha = \frac{(s_1\alpha_1 + s_2\alpha_2 + \cdots s_n\alpha_n)}{S}} \qquad (2\text{-}3)$$

These equations provide great insight into the effects each factor has on the overall T_{60} value and will be used in subsequent sections to compare selected recorded T_{60} values to their theoretical calculated value. Referencing these equations reveals a proportional relationship between volume and T_{60}.

Reverberation times of a room can be affected by a variety of factors. Kaplanis et al. discuss reverberation as a perceived phenomenon as well as its physical implications. Reverberation is a multifaceted effect impacted by depth, distance, width, size, and acoustic tendencies including timbre, loudness, distance, perceived room size, clarity, etc. [11]. In this study, the approximate square footage of each evaluated room was recorded, and details such as floor material and the number of miscellaneous items in the area were also documented. It is therefore a culmination of many effects that result in variations of a room’s reverberation time. Figure 2 below details the absorption coefficients of different materials used during construction.

Materials	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Carpet	0.01	0.02	0.06	0.15	0.25	0.45
Concrete (unpainted, rough finish)	0.01	0.02	0.04	0.06	0.08	0.1
Marble or glazed tile	0.01	0.01	0.01	0.01	0.02	0.02
Vinyl tile or linoleum on concrete	0.02	0.03	0.03	0.03	0.03	0.02
Wood parquet on concrete	0.04	0.04	0.07	0.06	0.06	0.07
Fiberglass board (25mm(1”) thick)	0.06	0.2	0.65	0.9	0.95	0.98

Figure 2: Absorption Coefficients of Common Building Materials and Finishes. Source: JCW Acoustic Supplies [1].

Applications of New Materials

When considering typical sound absorption techniques, the most often techniques involve the implementation of a sound absorption panel made of either fiberglass, polyester, or wood. While semi-effective, these materials are not optimized for sound absorption and are often wasteful and nondegradable when no longer in use. The following reviews some of the new and innovative materials in discussion for sound absorption purposes.

Acoustic metamaterials are new, engineered materials capable of acoustic behaviors not found in naturally occurring substances. These materials are formed with a composite of many individual materials to achieve a unique result. By altering the precise microstructures in each material, researchers can produce materials that exceed properties of stiffness, density, elasticity, tensile strength, etc. found in these materials separately, capable of surpassing the bounds of its separate constituents [9]. A note of interest for these materials is their ability to manipulate the speed of an acoustic wave. These materials can propagate waves with varying speeds; if done with negative speed, a metamaterial can serve as excellent sound absorbers capable of rapidly decaying an external sound wave. An acoustic cloak can bend waves around its interior to hide an internal object from the field of sound, a process only possible with an acoustic metamaterial. Further research into metamaterials, including their applications and limits, is crucial for improving the study of acoustic design and its relevancy, and these materials could better dampen and reverberate sound in the public space if this research is supported.

In current research, acoustic metamaterials are experimental and found in academia, but lack experience in application. This is due to their necessary preciseness and need to vary across a large scale. However, cloaking is possible in a three-dimensional space practically using broadband acoustic metamaterials using a pyramid or cone shaped cloak, both using homogenous parameters [19]. There is potential for metamaterials to become applicable on a larger scale given the proper supporting research.

Figure 3: Image of sonic crystal metamaterial from "Acoustic metamaterials" by Haberman and Guild [9].

Another creative material being considered for sound optimization is bio-based foams. Due to the excessive waste often produced in noise control settings, bio-based foams (PLA foams) that degrade to water and CO_2 when exposed to landfill humidity have been researched. Issues with this material include brittleness and inferiority to nonrecyclable alternatives. Due to these issues in structure, polymer composites of PLA and Polyhydroxyalkanoate (PHA) were created using salt as the particulate [12]. Because of this unique composite, acoustic performance was significantly improved along with its structural integrity, rivaling its traditional sound absorbing materials. These foams are applicable to many forms of noise cancellation and absorption, including sound dampening and vehicle sound barriers.

In the same understanding of sustainability in acoustic study, Buratti et al. discuss the application of recycled materials for sound absorption. A composite of wastepaper and wool fibers was tested in a classroom and compared to traditional forms of sound absorption (glass wool and extruded polystyrene panels). In experimentation, it was determined that in frequencies above 1000 Hz, panel G was capable of an absorption coefficient similar to that of conventional methods [5]. Figure 4 depicts the absorption coefficient data collected from this study. The accessibility and sustainability of this waste/wool composite material is a positive when considering new materials to improve sound absorption in current and future public spaces.

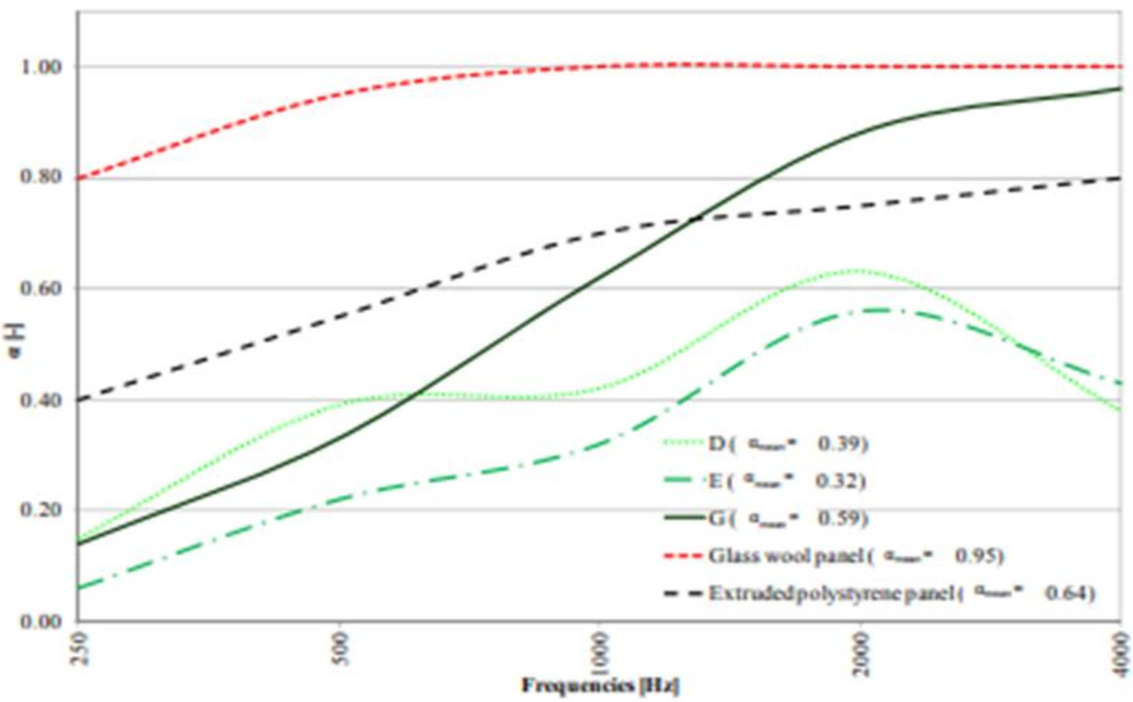

Figure 4: Mean acoustic absorption values obtained for the sustainable panels (D, E, and G) and two additional traditional systems. Source: Sustainable panels with recycled materials for building applications: environmental and acoustic characterization, Buratti

Cox and D'Antonio expand upon Schroeder diffusers, which are arrangements of scattering surfaces originally invented in the 1970s. Diffusers are favored over absorption techniques in orchestral halls to preserve the "energy and reverberance" of the performers. Wells of varying and consistent depths are used to make single- or two-dimensional diffusers capable of reflecting sound in multiple paths at once. For this to succeed, there must be plane wave propagation within the wells. The necessary depth of each well is determined by the sequence S_n number, λ_{min}, and the number of wells per period [7]. The authors of this paper suggest removing fins in traditional Schroeder diffuser designs to produce a simpler geometry with lower absorption tendencies. Schroeder diffusers are a considerable option for locations such as performance halls requiring amplified reverberation times. An example of a Schroeder diffuser is shown below in Figure 5.

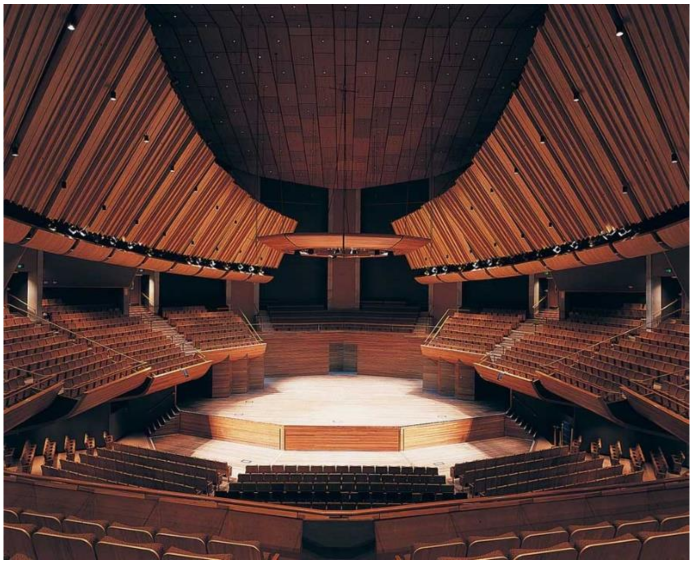

Figure 5: Image of the Michael Fowler Center in Wellington Town Hall, New Zealand. Source: Marshall Day Acoustics.

Sound Design for Specific Environments

When evaluating the effectiveness of a room's acoustics, one must consider the specific applications of said room. In the *Choice of the optimal acoustic design of a school classroom and experimental verification*, Russo and Ruggiero study the impact a decreased reverberation time can have on a classroom and possible techniques to implement this concept. Sound absorbing panels composed of a low-density expanded polyethylene, referred to as Stratocell Whisper panels, were used in these experiments. To find the optimal size for these panels, an algorithm can be applied. By applying absorption panels away from the sound source and throughout the room's walls and ceiling, a satisfactory acoustic outcome for the classroom was achieved [17].

Watson provides suggested reverberation times for performance and auditorium settings. Reverberation times around 2.3 seconds were considered ideal for such locations. However, some sources suggest a range between 1.8-2.2 seconds at mid-frequencies is sufficient for a positive musical experience [15]. For the purposes of this study, this range of values will be considered ideal for the T_{60} times of the Rehearsal Hall. In spaces necessary for soundproofing, such as an office or classroom, there are two types to consider: those generated in the air, and those that originate in the structure of the building [18]. An example of a type one sound would be an individual's voice carrying throughout a building. These sounds can affect adjoining rooms if proper soundproofing is not implemented, and this is most often through connecting ventilation ducts. Machinery such as motors, elevators, and street traffic are examples of type two sounds to consider when evaluating an office building. Factors such as a rigid building structure and walls, inclusion of absorbing materials such as flax or sand between walls, and a disconnected ventilation system can all improve the dampening of a shared office space.

CHAPTER III: METHODOLOGY

Acoustic testing was conducted at three locations at the University of Central Florida: a classroom (room M260), a musical practice room (M254), and performance space Rehearsal Hall (RH). Despite its name, the RH is a space often used for performance, most often for student recitals and small chamber concerts. The final testing location was an offsite office location at Southern Healthcare Management in Casselberry, FL. This location was chosen due to its cubicle arrangement and shared space for employees to properly investigate the ramifications of such a workspace on employees. Each testing location was selected to offer a variety of acoustic intentions. Data was collected using both a Digital Sound Level Meter application (Decibel X) and a BK PRECISION 732A Digital Sound Level Meter (dB) with a set of pure tone testing source sounds at a set of specific frequencies. These frequencies were exported using a Bose Soundlink Revolve II speaker featuring a 360° sound orientation that was connected to a HP Spectre x360 Laptop. The frequencies evaluated were 125, 250, 500, 1000, 2000, 3000, 4000, and 8000 Hz. According to the American Speech-Language-Hearing Association (ASHA), these specific frequencies are ideal to test for the perception and understanding of vocalizations [2]. Additionally, the International Organization for Standardization (ISO) states that 125, 250, 500, 1000, 2000, and 4000 Hz frequencies are standard measurement frequencies for reverberation time calculation [10]. Because of the consistency in tested frequencies and the applications of this thesis, all eight frequencies cited above were tested in each location to have as much of a perspective on the room's acoustics as possible. Three trials at each frequency were performed and the reverberation time results were averaged together to attain as accurate results as possible.

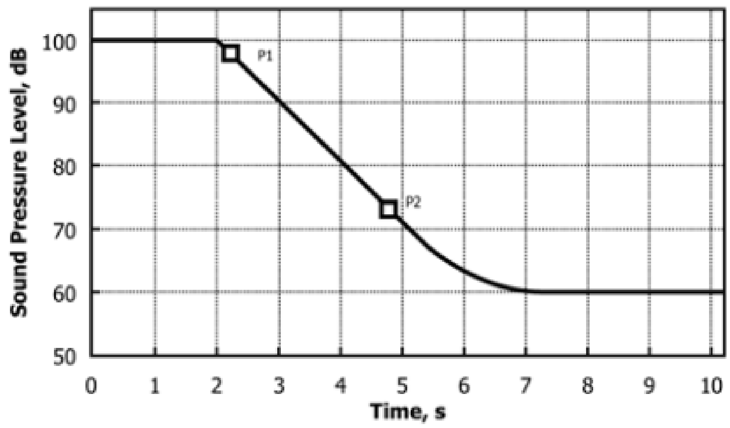

Figure 6: Sound pressure level graph used for reference when calculating RT. P1 is the first point used for calculations and is 5 dB below the maximum value. P2 is 25 dB below point 1. Source: ASTM E2235 – 04 [4].

By comparing the Y value of the sound pressure chart from when the sound is first stopped to when the room reaches the noise floor, one can calculate the reverberation time of the space in question. T_{20}, T_{30} and T_{60} (decay times of 20, 30, and 60 dB after ending the source sound) are the standard measurement values for reverberation time. Calculation of these values begins once the source sound has decayed 5 dB and ends after the sound level has fallen by the subsequent amount of dB.

Start Time: 2023/03/13	19:22:43.196
Export Time: 2023/03/13	19:24:35.387
Min (dBA): 49.3	
Max (dBA): 86.6	
Peak (dBA): 86.7	
Avg (dBA): 83.1	
TWA (dBA): 43.8	
Dose (%): 0.0	
Recorded Value (dBA)	Response Time (seconds)
49.7	0
51.1	0.2
51.7	0.4
49.7	0.6
80.3	0.8
86.6	1
86.4	1.2
86.4	1.4
86.4	1.6
86.4	1.8
86.3	2
86.2	2.2
86.2	2.4
84.9	2.6
66	2.8
49.3	3
51	3.2
50.4	3.4
50.9	3.6

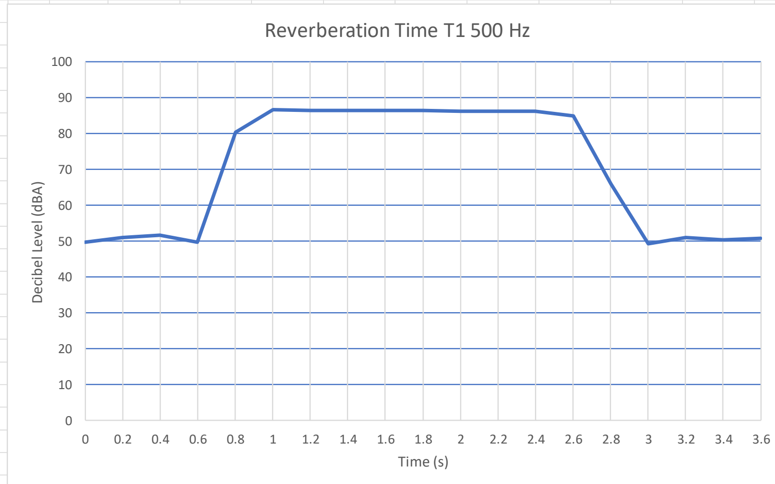

Figure 7: Example of raw data from Decibel X (Trial 1, 500 Hz, Office).

Figure 7 displays an example trial of raw data from the Decibel X application. The graph corresponding to this data was generated and is used to calculate the rate of decay in sound. In this sample, the noise floor is about 51 dB, and the peak dB level recorded is 86.6 dB. After subtracting 5 dB from the head value, 81.6 dB is the first value necessary in calculating the T_{60} time, identified with a green dot in Figure 8. Subsequently, 20 dB is subtracted from this value, resulting in 61.6 dB shown with a red dot in Figure 8.

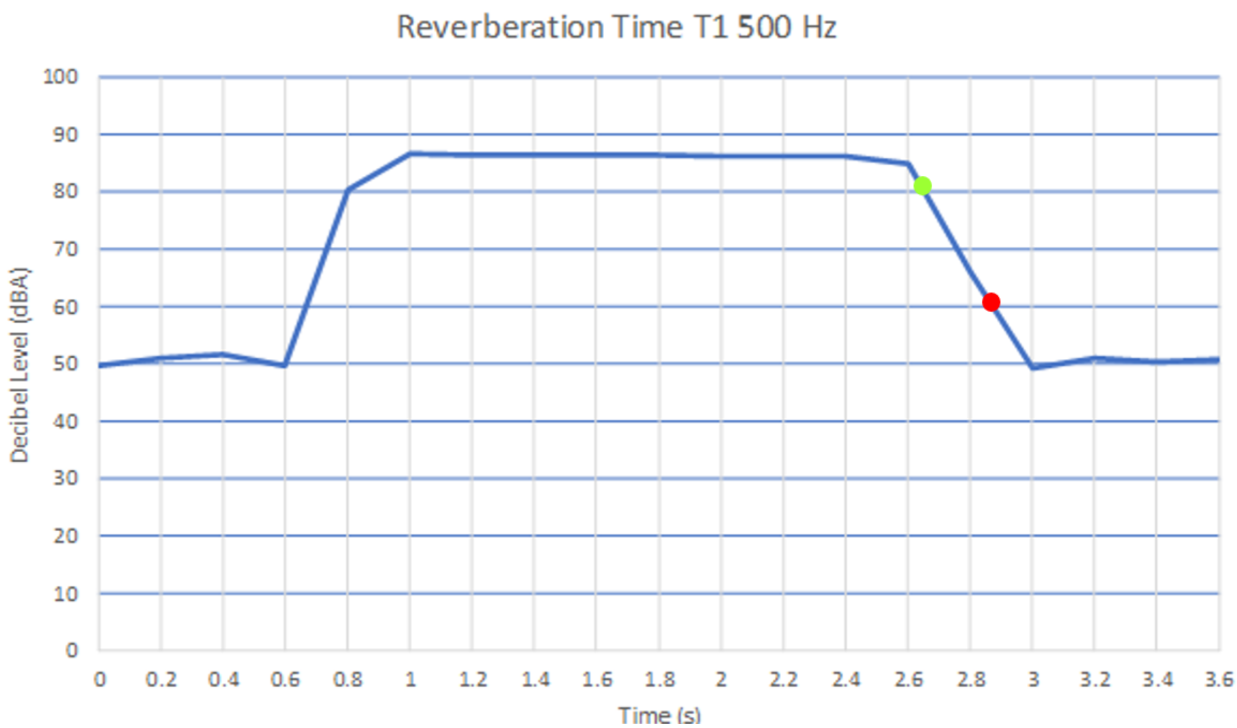

Figure 8: Up-close image of graph generated from data shown in Figure 7. (Trial 1, 500 Hz, Office).

From the data points above, linear interpolation is used to determine the exact times these dB levels occur, which are at 2.837 and 3.0551 seconds. Subtracting 3.0551 seconds by 2.837 yields the T_{20} result of 0.2181 seconds. To determine the T_{60} time, T_{20} is multiplied by 3, resulting in a reverberation time of 0.6543 for this sample. In most environments, it is not feasible to produce a source sound loud enough to showcase a differential of 60 dB between itself and the noise floor. Because of this, extrapolation was conducted, as is supported by ISO 3382-1, Standard 3.5: "T can be evaluated based on a smaller dynamic range than 60 dB and extrapolated to a decay time of 60 dB" [10]. This process is repeated three times for each frequency and the results are averaged together to find a final RT value at this location and specific frequency. This results in 24 samples of data for each location, or 96 total files.

To evaluate the acoustic effectiveness of each investigated room, benchmark T_{60} times are compared to the recorded values. Performance halls are most effective when designed with a reverberation time of $1.8 < T_{60} < 2.2$ [15]. If the test results yield a result that varies far from this goal, i.e., more than ±0.25 seconds, then an analysis on suggested improvements for acoustic performance is made. For the musical practice room, performers of different instruments may have varying preferred reverberation times due to the volume and timbre of their respective instruments. Percussion players tend to prefer 0.3-0.5s, string players 0.6-0.9s, and wind players 0.4-0.7s [16]. In the life of a musician, a significant amount of time is spent in these practice spaces, which can alter the perception of their true sound if sound absorbent enough. However, given the number of students at UCF, the classrooms that are nearby the practice rooms, and the variety of musicians using these facilities, the benchmark reverberation for this study will be considered $0.3 < T_{60} < 0.5$ seconds as its maximum averages between the range of preferred times. According to ANSI/ASA S12.60, $T_{60} < 0.6$ seconds is considered ideal for classrooms smaller than 10,000 ft^3 [3]. When considering the intents of these rooms and the applications of this study, this benchmark will also be applied to the office location as it is also a shared space most often occupied by discussion.

An additional factor to consider when assessing this data is the frequencies of sounds produced in each room. For example, instruments are capable of different frequency ranges depending on their size and shape. The horn has a range of A2-A5 (110-880 Hz) and a piccolo can play from C5-B7 (523- 3951 Hz). Because of this, the most relevant frequency range for both a practice room and performance hall are between 125-4000 Hz. The average frequency of a person's normal speaking voice can range from 60-300 Hz; therefore, lower frequency optimization should be a priority for both the classroom and office locations.

For each room, a standard distance of 4 ft between the input device and source sound was implemented to ensure consistency between trials and have ample distance to avoid noise distortion. Figures 9-15 showcase the testing setups for each of the four evaluated locations.

Figure 9: Image of Rehearsal Hall during testing.

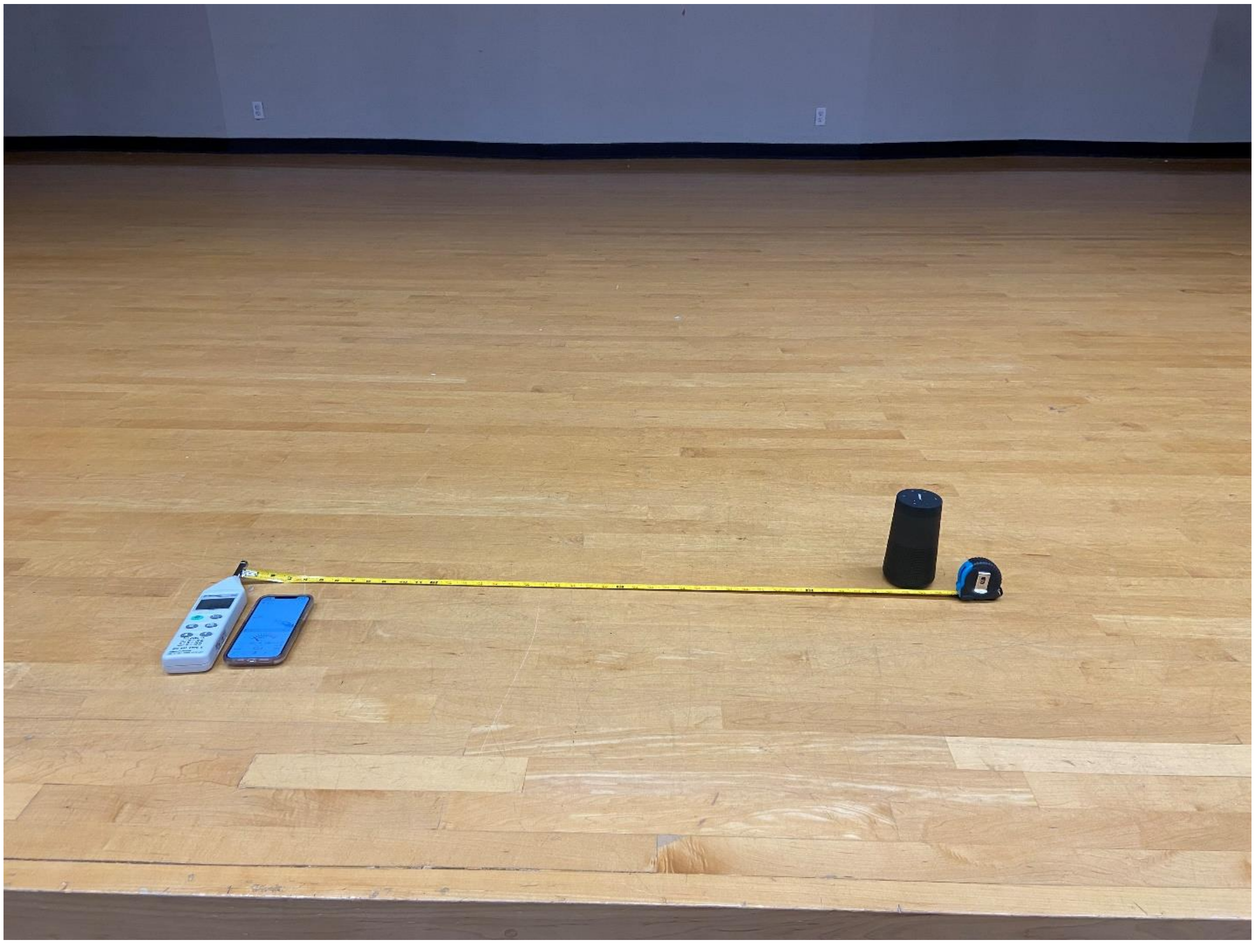

Figure 10: Up-close image of testing setup for the Rehearsal Hall.

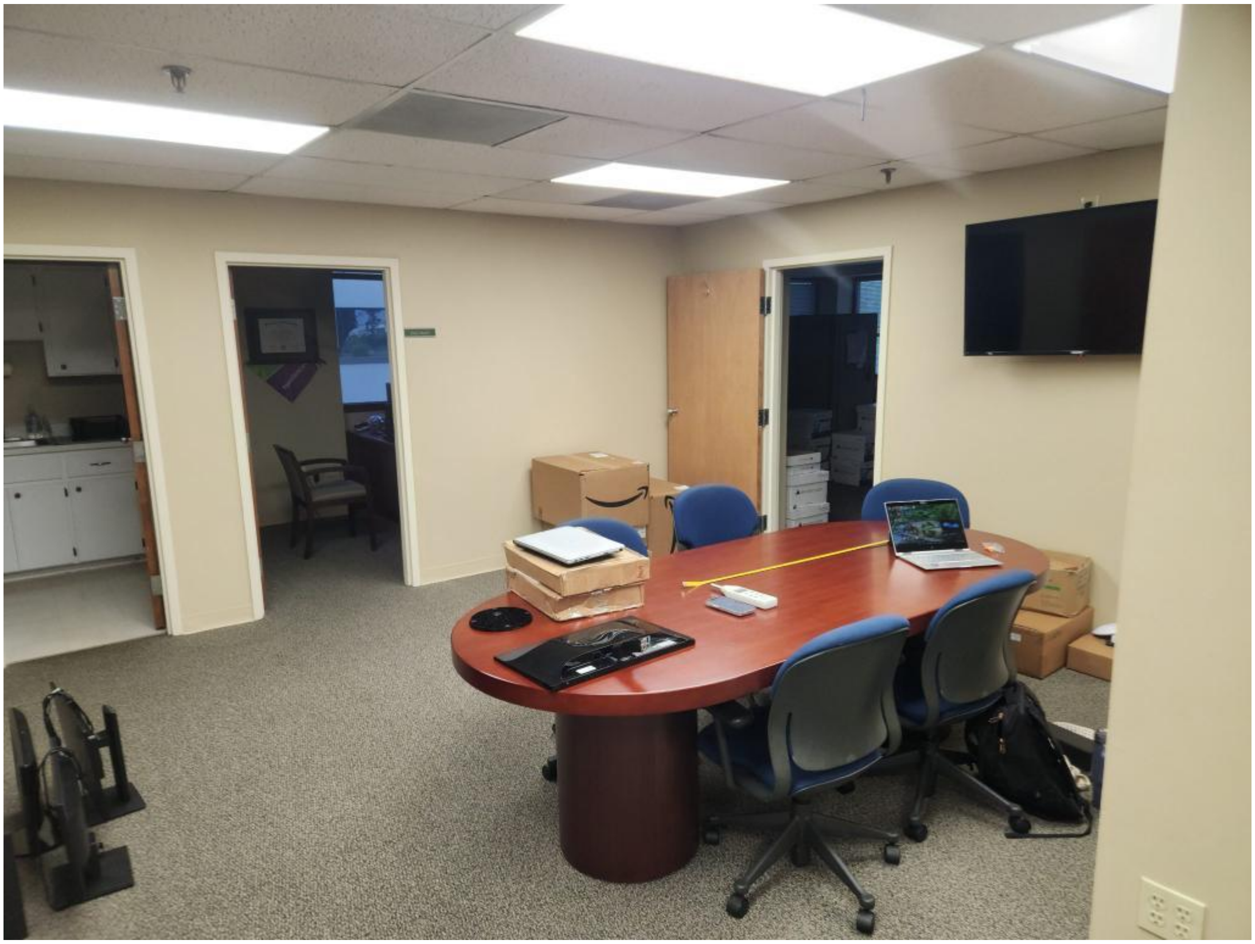

Figure 11: Up-close image of testing setup for the office.

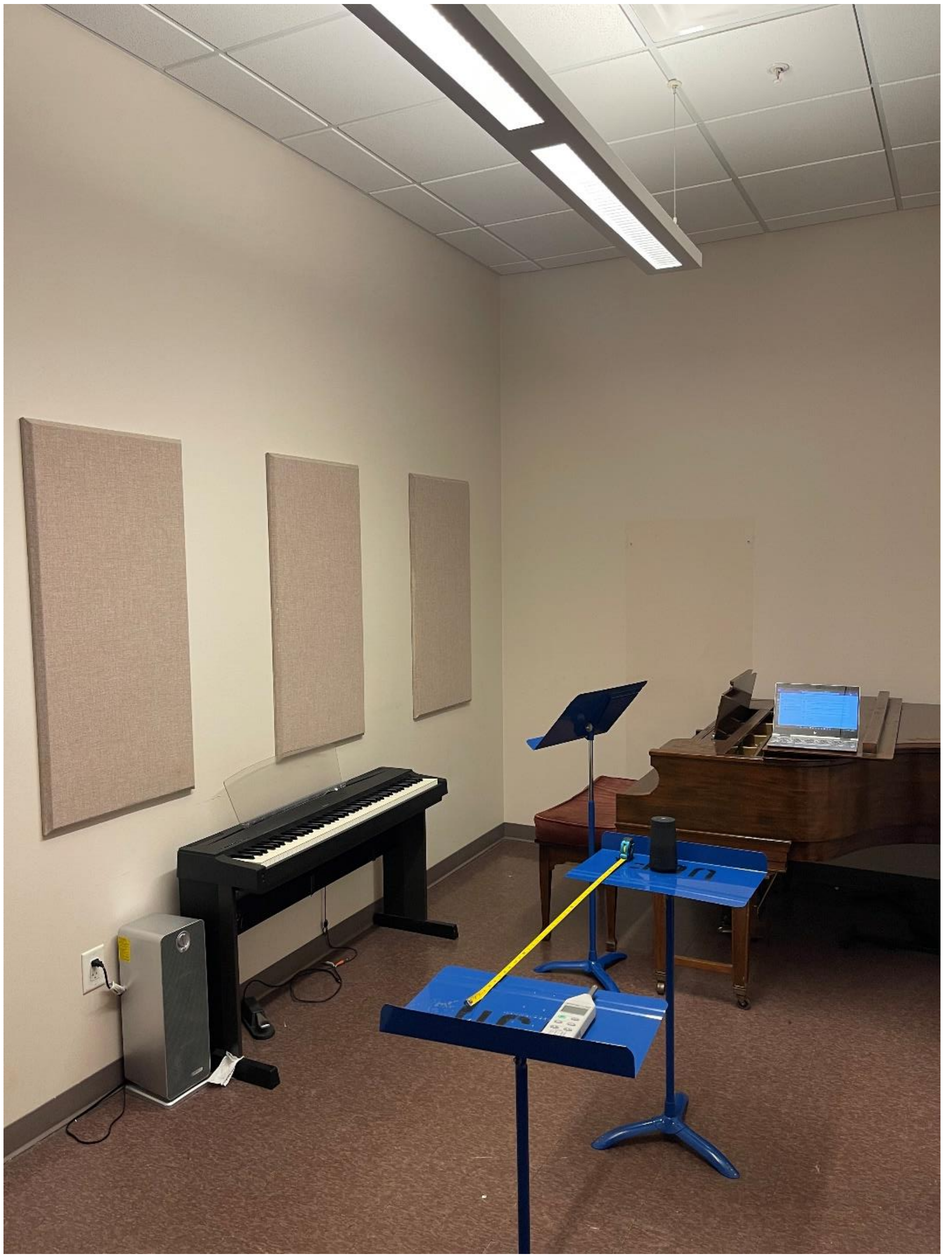

Figure 12: Image of practice room during testing.

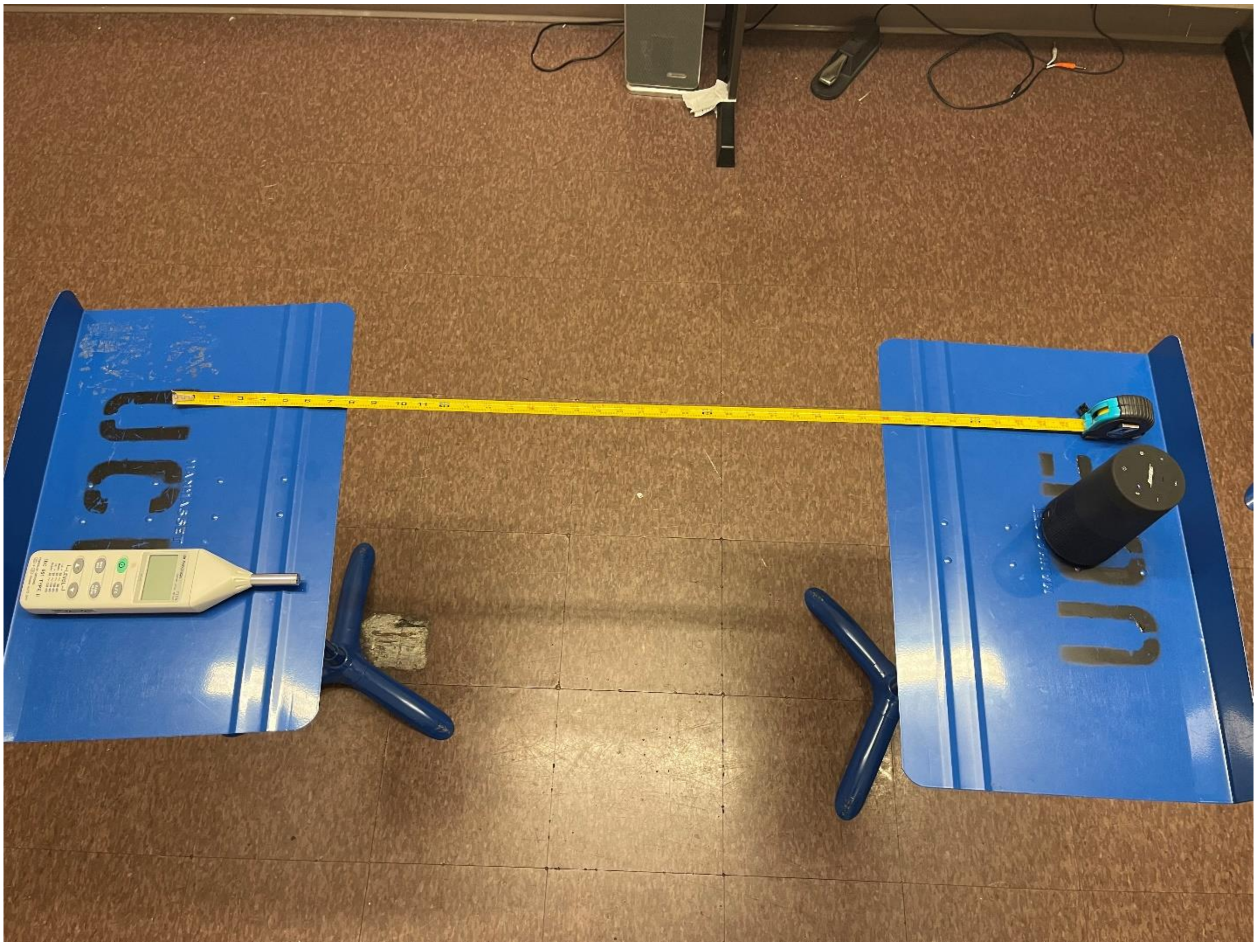

Figure 13: Up-close image of testing setup for the practice room.

Figure 14: Image of classroom during testing.

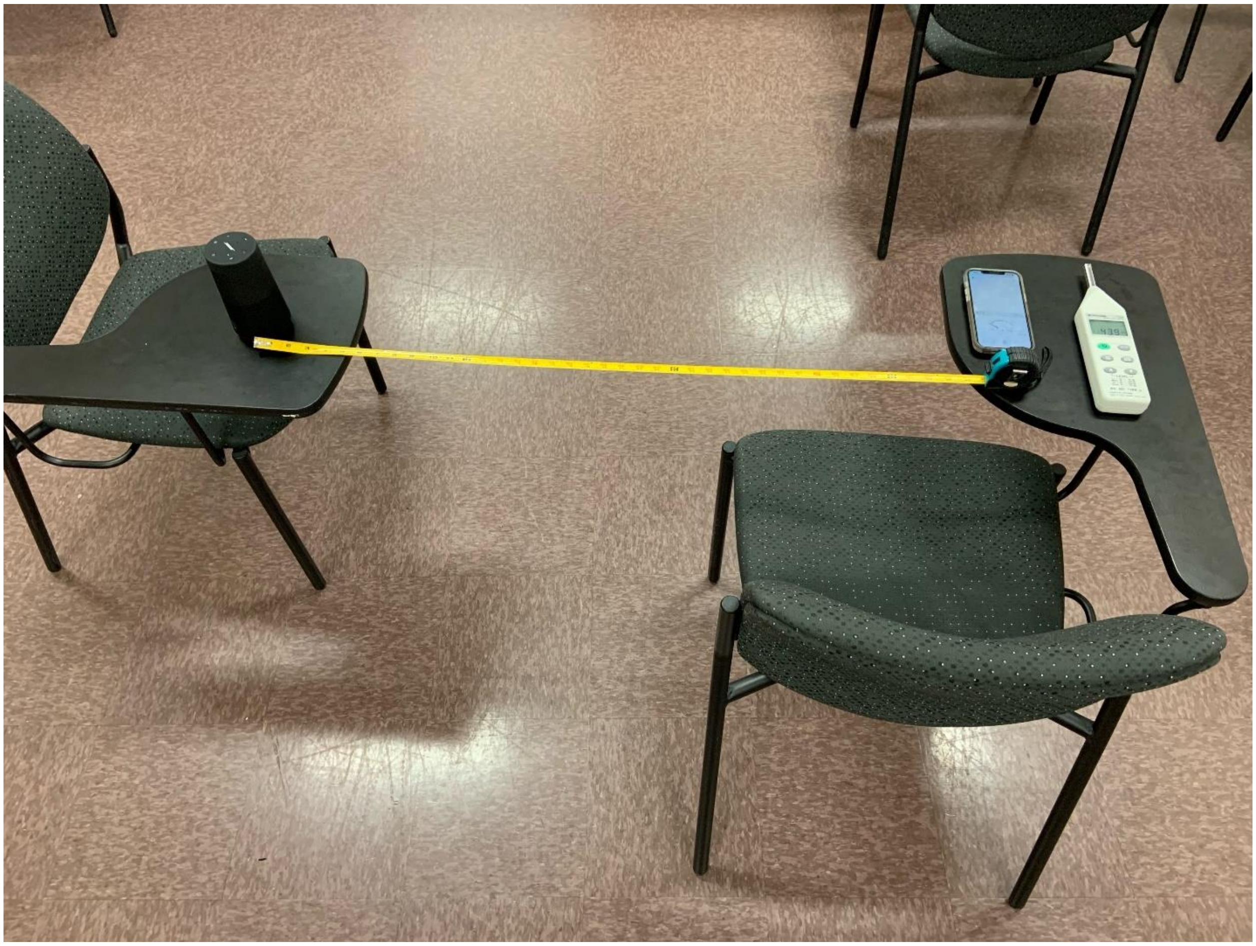

Figure 15: Up-close image of testing setup for the classroom.

CHAPTER IV: RESULTS

Data for the T_{20} and T_{60} times calculated for each frequency is compiled on Figures 16 and 17, respectively. Discrepancies in the recorded reverberation time can be seen from the distinct drop in values across all locations between 125 and 250 Hz. This is a result of an inadequate amount headroom between the T_{20} time and the noise floor, which should be at least 10 dB for this calculation to be accurate [4]. At such a low frequency, it was not possible to produce a source sound loud enough to create this necessary headroom despite all frequencies being recorded at the maximum volume settings on all equipment. This data was not excluded as it still offers value through comparison. However, with this in consideration, all peak reverberation times recorded at 125 Hz were excluded from analysis. In these graphs, RH refers to the Rehearsal Hall and PR is short for practice room.

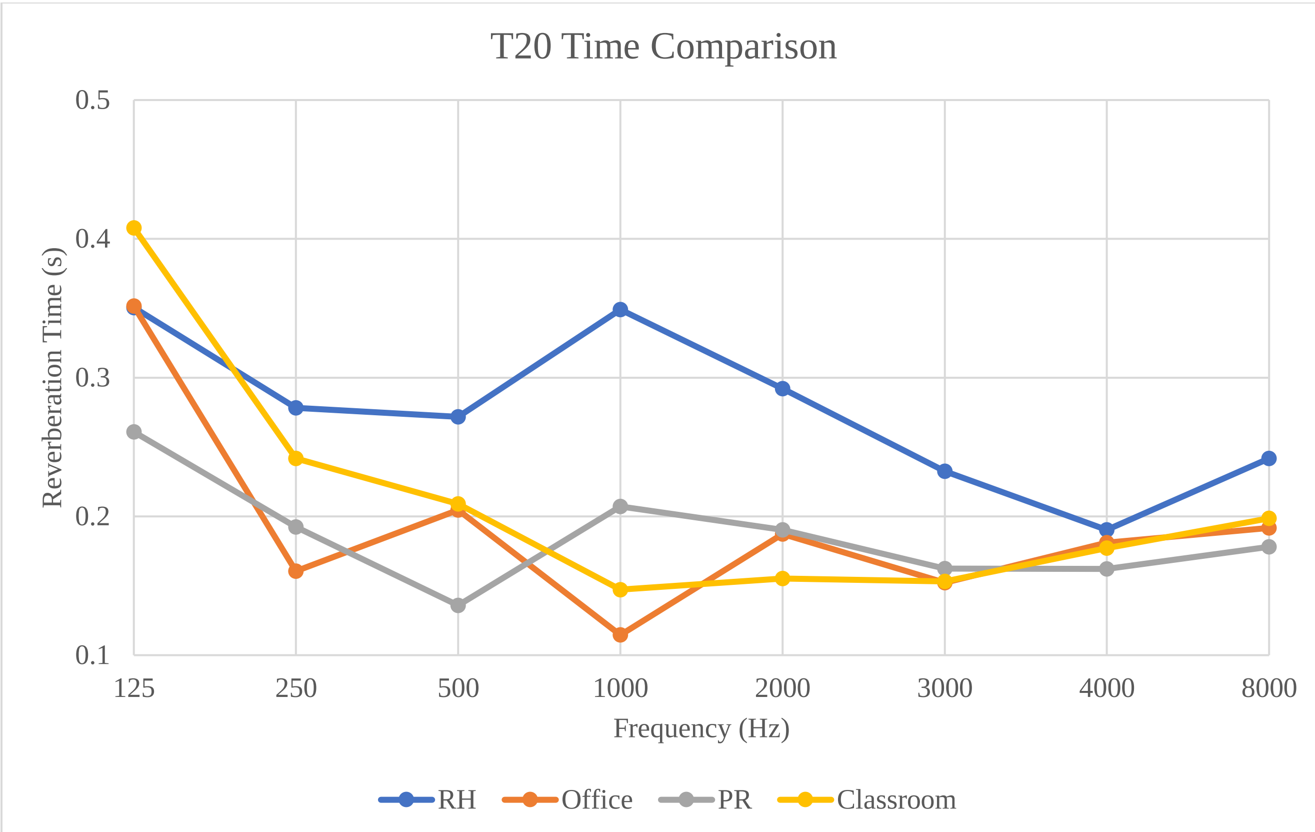

Figure 16: Graph of calculated T20 times for each tested location.

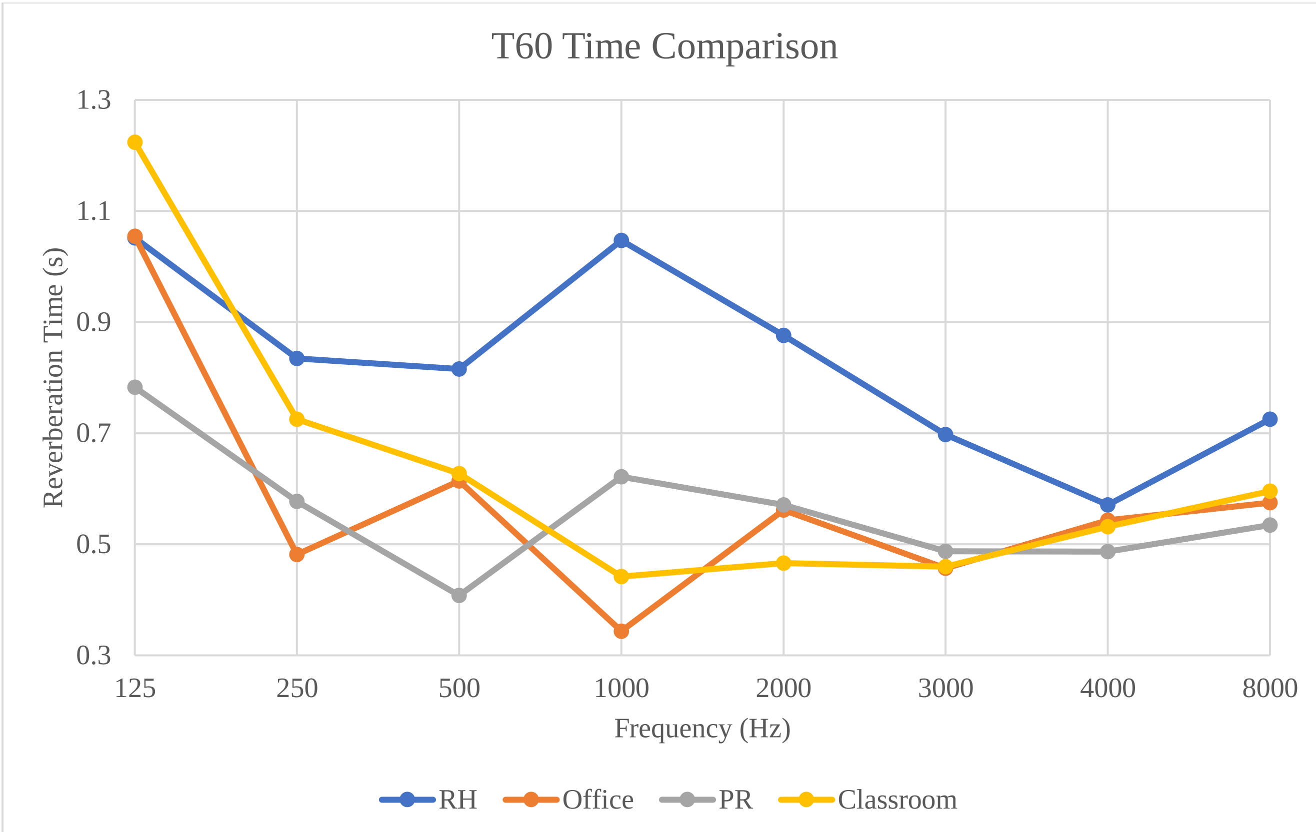

Figure 17: Graph of calculated T60 times for each tested location.

Location	Volume (m^3)
RH	1,156.66
Office	218.32
PR	57.68
Classroom	136.76

Table 1: Approximate cubic volume of each tested location.

Location	Ideal RT	Relevant Frequency Range
RH	$1.8< T_{60}<2.2$	125-4000 Hz
Office	$T_{60}<0.6$	60-300 Hz
PR	$0.3<T_{60}<0.5$	125-4000 Hz
Classroom	$T_{60}<0.6$	60-300 Hz

Table 2: Summary of ideal reverberation times and relevant frequency ranges for each location.

Reviewing this data highlights both acoustic achievements and faults in each location. In the RH, for example, the peak reverberation time is at 1000 Hz, which is within the most relevant frequency range of 125-4000 Hz identified in Chapter III: Methodology. The T_{60} time at this frequency, however, was 1.05 seconds. According to sources mentioned in Chapter II: Literature Review, Sound Design for Specific Environments, a reverberation time between 1.8-2.2 seconds is considered ideal for a performance hall. Because of this discrepancy, it is recommended that the Rehearsal Hall incorporates techniques to increase reverberation times, such as switching to hardwood floors, removing sound absorbing panels on exterior walls, and potentially integrating additions such as Schroeder diffusers to improve the ambience of this space.

When analyzing the office data collected during this investigation, a series of peaks at 500 and 2000 Hz are present. However, when considering the most relevant frequency range of 60-300 Hz, this is not a point of concern for this room. Within this range, the peak reverberation time recorded was 0.61 seconds at 500 Hz. Compared to the benchmark values of $T_{60}<0.6$s, the office location performs the best among all tested locations in terms of theoretical RT versus recorded RT. An additional point to consider is the elevated noise floor at this location. An AC unit resulted in an elevated noise floor averaging around 50.5 dB, the highest out of all locations. Within Chapter II: Literature Review, Impacts on Health, the negative long-term effects of involuntary sound exposure were evaluated. The sound dampening of the office performs well for its intentions, however the elevated noise floor is a point of concern for employees. Suggestions for improvement are isolated only to this consideration, which could be improved from increased dampening around the AC unit or a new system altogether.

Between the frequencies of 125-4000 Hz, the practice room experienced a peak reverberation time of 0.78 seconds at 125 Hz, and a second peak of 0.62 seconds at 1000 Hz. Additionally, the noise floor averaged 27 dB, the lowest out of all locations. This reveals that external noise suppression is present, a positive note to make for the acoustic parameters of this space. When comparing these values to the benchmark of $0.3<T_{60}<0.5$, the recorded RT exceeds this recommendation. Additionally, considering the margin of discrepancy ±0.25 seconds from the suggested value, there is improvement to be made in terms of the sound absorbency of this room. While potentially leaking sound from these practice rooms to neighboring classrooms, offices, and student workspaces, this can affect the day-to-day actions of many individuals in the building. Additional forms of sound absorption are recommended for the practice rooms to improve their effectiveness.

For the classroom location, the peak T_{60} between 60-300 Hz was 1.22 seconds at 125 Hz, and 0.73 seconds at 250 Hz. Both RTs are beyond the recommended range of $T_{60}<0.6$s for an acoustically optimized classroom. If excluding the 125 Hz due to the absence of necessary head room in the sample, this location does not stray more than ±0.25 seconds from these advised parameters. However, there is opportunity for acoustic improvement via increased sound dampening, which could appear in the forms of increased absorption materials like those mentioned in Chapter II: Literature Review, Applications of New Materials.

Location	Maximum T60 (s)	Frequency (Hz)	Noise Floor Averages (dB)
RH	1.05	1000	32.2
Office	0.61	500	50.5
PR	0.62	1000	27.1
Classroom	0.73	250	38.1

Table 3: Maximum recorded T60 value and average noise floor at each location.

Table 1 showcases the approximate volume of each location. The size of a room can have considerable effects on the recorded reverberation times. However, this factor is not always indicative of a room's reverberation time. Despite a large difference between the volume of the office and the classroom, the office has a lower reverberation time than the classroom within its most relevant frequencies of 60-300 Hz.

The Sabine equation (2-2) was used to compare the theoretical T_{60} value of the practice room to the actual recorded value. At 1000 Hz, the absorption coefficient of linoleum is 0.03, drywall is 0.1, and the six 1" fiberglass boards in the room are 0.9. The volume of this location is 57.68 m^3. Using equation (2-3) and accounting for the absorption panels, the average absorption coefficient α is:

$$\alpha = \frac{(17.2 * 0.03) + (54.675 * 0.1) + (19.2 * 0.9)}{91.075}$$

$$\alpha = 0.255$$

With this information, the theoretical T_{60} time for the practice room at 1000 Hz is:

$$T_{60} = 0.161sm^{-1}\frac{(57.68\ \mathrm{m}^3)}{(91.075)(0.255)}$$

$$T_{60} = 0.3998 \approx 0.4$$

It is important to note that the Sabine equation can only offer a rough estimate of a room's reverberation time. However, comparing this to the recorded value of 0.62s offers an interesting observation. Considering the materials used in this space and its dimensions, the hypothetical T_{60} time is less than the recorded. Typically, theoretical values outperform actual values due to inconsistencies in material placement and changes in room layouts with furniture. This study shows a benefit to implementing data collection through testing as these values can misrepresent the true performance of a space if evaluated independently.

The formula for the wavelength of a wave is $\Lambda = \frac{c}{f}$, where c is the speed of sound (343 m/s) and f is the evaluated frequency. At 8000 Hz, for example, the wavelength is 0.043 m long, while at 125 Hz the wavelength is 2.744 m. With such a large difference in wavelengths between the maximum and minimum measured frequencies, one can understand the difference in reverberation time between each sample. As the frequency of the sample increases, the wavelength of the produced sound decreases significantly. A proportional relationship between the wavelength of the sample and the reverberation time can be seen. As the waves become shorter, their ability to reflect off objects and walls in the room diminishes. This relationship is evident in Figures 16 and 17, showcasing an overall decline in reverberation time as the frequency approaches 8000 Hz.

CHAPTER V: CONCLUSION

Three main objectives were outlined and accomplished through the completion of this thesis. By recording the T_{60} values across a range of frequencies at four selected public locations, an understanding of the acoustic performance of each location was made. From this data followed an assessment for possible improvements in acoustic design which was done through comparison of ideal T_{60} values to those that were recorded and calculated. Depending on the data and the intents of each space, different materials and adjustments to current designs were suggested to improve the aural perceptions of the room. Finally, for locations meeting these benchmarks, an acknowledgement of design measures currently in use was made for design measures positively impacting T_{60} values. For future works, a study of great potential would involve incorporating suggested design and material improvements and recording the change in T_{60} time because of these implementations. An additional expansion upon this research includes investigating other locations of relevance, such as a professional performance hall, a percussion practice room, and various healthcare locations such as hospitals and nursing homes.

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