Vocal Adaptation:

An analysis of the impact of the acoustics of a space on a vocalist's performance

An Honors Thesis for the Department of Mechanical Engineering

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Abstract

Vocalists are very versatile musicians that are required to adapt the way they sing to the acoustical environment they are in. In this study four vocalists were brought into three different acoustical environments to observe what qualities of their voice changed due to the acoustical qualities of the spaces they were in. Given the small sample size and other limitations , no global adaptation pattern could be confidently concluded. However, from these case studies it was shown that adaptations were made on an individual basis and that there were a few room acoustic measurements and experiences of the vocalist that may be the cause for these vocal adaptation patterns.

Some of the causes of vocal adaptation that were measured in this study include, the genre of the piece, the reverberation quality of the room, the clarity of the space, and amount of stage support received during the performance. Some of the most common adaptation patterns that were observed included but are not limited to: more intentionality to the control and allocation of breath in dry acoustical environments, increased frequency of choosing to sustain notes in wet acoustical environments, and more consistent vibrato use for dynamic emphasis in wet acoustic space with R&B and Pop performances over Classical and Musical. From this study, we can start to observe what are the adaptation choices vocalists are making and why, to better inform both the designers of these space and the vocalist who perform in spaces on what experience has been like. The goal is to create a greater awareness and search for potential design and vocal adaptations that could enhance all vocal performances.

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Introduction

In my opinion, the goal of a vocalist is to deliver the most technical and entertaining vocal performance possible. From my experience, this is usually done through extensive training of the ear and voice over the period of years. A key attribute needed for a vocalist to consistently produce great performances across diverse venues is the experience of performing in various locations and developing a mental repertoire of how voice sounds and needs to adapt to the environment. Over the past few years, I have been curious whether singers are actively thinking about or developing this skill. From the vocalists I have spoken to and the vocalist participants in this research, it seems this adaptability is an unfamiliar skill to new singers and an unconscious ability that comes with time for experienced singers. This necessity to adapt the way sound is produced to compensate for a change in acoustical environment from which rehearsals have been conducted is a common experience for many vocalists. Even though this is a common lesson that must be learned by aspiring vocal performers, I have not been able to find much research surrounding this topic. Traditionally if someone is taking a course in voice, they would potentially be instructed on methods in which you can explore to aid in improving this skill of adaptation. This would require more attention on performance qualities involving but not limited to dynamics, breath control, pace, tonality, and intonation. However, in terms of architectural acoustics once again I have found very few studies that have been conducted surrounding the vocalist experience when performing and how they interact with varying acoustical environments, some of which will be discussed in the literature review section.

Motivation

As a vocal performer who is also a senior mechanical engineering undergraduate with a focus in architectural acoustics, I have always found the intersection between music and engineering fascinating. I am always trying to find ways to improve the experience of another musician through the means of an engineering solution. Although there is immense value to having the ability to naturally learn how to adapt the way a vocalist sings to any environment they are placed in, I feel that the burden shouldn't always be on the vocalist to produce a great performance. Rather, work should be shared with those who engineer the space. Being able to bridge the experience of vocalists with the current technology in architectural acoustics can enhance the vocalist's experience and capabilities to optimize on performance quality.

Research Questions

Many of my questions are around the experience of the vocalist, with the central question being how vocalist adapt the way they sing based on the acoustical environment they are in. Within that question I will be focusing on a few other questions such as but not limited to these. Are there dynamic changes, if so, what are they? Are there changes in pace of the composition? Are there changes technique and breath control?

I will also be checking to see how these changes are made based on the qualities of the room. Other questions that I would be interested in exploring would be what are potential ways in which their spaces could be improved to support vocalist better? What qualities of spaces makes vocal performances more difficult to execute? What information about acoustical spaces would be helpful for vocalist to have ahead of time? Given my interested in these questions I interviewed and measured three singers in various spaces as case studies to gain some perspective on the matter.

Definitions and Key Terms

Auralization – Procedure designed to model and simulate the experience of acoustic phenomena rendered as a sound field in a virtualized space.

Bass Ratio (BR) - Relation between the reverberation energy in the frequency range of 125 Hz to 250 Hz compared to the range of 500Hz to 1000Hz

Clarity (C) – Often represented as the early to late energy ratio in decibels. In this thesis I use C80 which is an acoustics parameter often used for music clarity taking the sound energy in the first 80 ms of an impulse.

Dynamics – The control of volume, silence & rests, and ad vowel placement. Used to set the mood of a piece and to tell an emotional story.

Electroglottograph - A device used for the noninvasive measurement of the degree of contact between the vibrating vocal folds during voice production

Interaural Cross Correlation (IACC) - measures the correlation over time between the sound pressure at the two ears of a listener and is influenced by the sound field around the listener's head, and the acoustic effect of the head.

Reverberation Time (RT) - To this day, this remains the primary indicator of room acoustics[1]. It is the time in seconds it requires for the level of sound to drop 60 dB. In this thesis I use RT20 to denote the reverberation time of the locations in this study, which uses the time it takes the level of sound to drop 20 dB then multiplies that number by three.

Sound Spectrograph - an instrument that obtains a sound spectrum by analyzing a complex sound into its component elements (time-frequency-intensity)

Stage Support (ST) – logarithmic ratio expressed in decibels of reflected sound to direct sound. ST_{early} looks at the ratio of early reflected energy (first 100 ms) and direct sound. This is typically associated with ensemble hearing conditions on stage. ST_{late} on the other hand looks at later reflected energy (100ms to 1s) from the room relative to the direct sound.

Speech transition Index (STI) – Provides the sound transmission with an objective value, focusing the physical phenomenon of sound mixing. In short, the easiness or difficulty of speech listening can be assessed by the resemblance of the original sound wave and transmitted sound wave to ears.

1) Berg, Morten Roar, et al. "Room Acoustic Descriptors: …"

***Strength (G)* –** Expressed in decibels, strength is the ratio of the sound energy that comes from a non-directive source measured at a seat, relative to the same sound energy from the same source measured in a free field at 10 m

Vocalist – Throughout this thesis you will see me use the word vocalist and singer interchangeably but that is based purely out of convince. When describing a vocalist, I am typically referring to someone who underwent advanced training in voice techniques and understands vocal health[2]. It's common for singers to share some abilities and to hold the title of professional which is why it is common for the two to be used interchangeable but throughout this entire body of work when I say singer, I am always referring to a vocalist.

2) Indeed Editorial Team. "Vocalist vs. Singer: …"

Literature Review

There were two studies that were very similar to the one conducted in this thesis. They both looked at how vocalist change the way they sing due to the acoustical environment they are in. In the first one[3] ,vocal intensity and glottal behavior were measured using a near-field microphone and an electroglottography. The room acoustics metrics examined were $IACC_{late}$, EDT, ST_{early}, BR, and STI. They had four singers singing a slow, medium, and fast song in 8 different locations with a near field microphone 3cm away from the corner of their mouths and an electroglottograph unit wrapped around their throat for measuring glottal activity. They wanted to see what physical changes are made in the structure of the vocalists throats when singing and how much power they must put behind their voice. Their conclusion was that singers use individual adaptation patterns to either follow or compensate for variations in room acoustics. The other study[4] was published two years earlier with the same number of acoustical environments and singers, also using the same equipment. Main difference were that in this publication there was less of an emphasis on glottal changes and intensity, the metrics we RT30, EDT, C80, G_{late} , and IACC, and the conclusion suggests that the duration (EDT) and tone color (BR) of the room reverberation are strong factors that cause performance adjustments, whereas $IACC_{early}$ and G_{late} minor relevance.

From these two studies I was able to gain a deeper understanding of what I wanted to use as my metrics and what instruments I wanted to use to test and analyze the audio data from the singers. I choose to use an audio spectrograph because it would allow for me to see visually how the vocality are changing the way they sing the

3) Paul Lizard et al. "Changes in the voice production of solo singers across concert halls"
4) Paul Luizard et al. “*How Singers Adapt to Room Acoustical Conditions: …*”

composition from a not so biological perspective like the other two studies using electroglottographs. I also put some focused on the C80 and ST_{late} metrics since they were not looked at in those studies.

In another source[5] it was discussed how musicians believe that some of the important acoustical qualities such as reverberance, support, timbre, dynamics, hearing self, and balance. They would use a questionnaire to measure statistical correlations to the qualitative data they received from the musician and the quantitative data they received from the room acoustics measurements. I explored the route of also creating a survey for my experiment but decided to leave all the questions as free response thus a statistically analysis was not done. From this source I see the importance of musician input because look at the data objectively cannot be done correctly when dealing with the subjectivity of music and performing. This same point is reinforced in another publication[6] where the world's greatest concert halls were evaluated and ranked qualitatively by music and conductors and compared to their quantitative acoustical qualities. One example of this is represented as a quote taken from the source. **"…'My understanding is that the Boston Hall is so good because the clear early reflections from the flat walls combine with the direct sound well in our hearing system making the total sound louder and maybe also wider.'"** Explaining why you like a space over another is a very subjective process as stated by another source[7] that used auralizations to see how personal taste influences qualitative attributes and preferences. What I like the most about the quote is the intersection between having an understanding of the room acoustic qualities and how those qualities may have been

5) Lilyan Panton *et al.* "Chamber musicians' acoustic impressions of auditorium stages: …"
6) Leo L. Beranek, "Concert hall acoustics: Recent findings"
7) Tapio Lokki *et al.* "Concert hall acoustics: …"

created given the size, materials, and placement of objects in the space. In my opinion this gives more merit to acoustical hypothesis', and I try to emulate that in my analysis when comparing qualitative to quantified data.

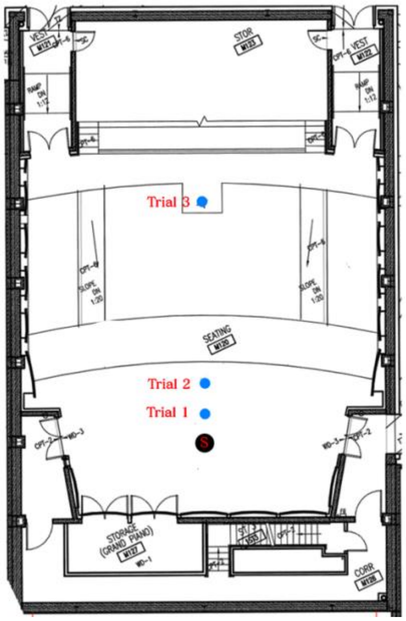
Methodology

Room Data Collection

Prior to any interactions with subjects, data was collected from each research location. A dodecahedron loudspeaker and subwoofer was used to produce a sine sweep to collect impulse response data. An omnidirectional Blue Yeti microphone was used as the receiver of the audio data and the data was processed through a MOTU Monitor into the software Fuzz Measure for producing reverberation time and clarity graphs. From that, the recorded impulse was imported into a pre-written MATLAB script to produce early and late-Stage Support graphs which can be produced using the equations for early and late-stage support found in the ISO standards for collecting stage support measurements[8]. Also coming from the ISO standard, we have the positioning of the source and receiver. For each research location, the microphone (receiver) position and the speaker (source) position will 1.5 meter from the floor and the distance between them will be changed after every set of trials. A singular trial consisted of three sine sweeps with the data averaged in Fuzz Measure, and a set is completed when this is done three times. The position of the source will be in the center of the stage where a performer would typically stand to sing, having the receiver be the object that moves. The first set of trials will always have the source and receiver positioned 1 meter from each other while

8) GADE, A.C. Practical Aspects of Room Acoustical Measurements on Orchestral Platforms

the second set of trials will be 2 meters. Since Distler and Curtis allow for testing in the center of the room at a great enough distance to provide some difference in results, a third set of trials was collected at 7.3 meters and 6 meters for Distler as shown in Fig. 1(A) and Curtis as shown in Fig.1 (B) respectively.

(A) 

(B) 

Figure 1. Layouts of Distler Hall and Curtis Multipurpose room. Black circle with S are source position. Colored dots are the relative positions of the receivers for each set of trials.

Quantitative Subject Data Collection

Three singers including myself have been taken to various locations on the Tufts University Campus that have historically been used as performance or practice spaces. Each singer received a university pre-approved COVID singing mask provided by the Tufts Music Department. Due to the regulations of having singers wear masks during data collection, there is a level of uncertainty of how it affects the data and singers performance, all of which is discussed further in the limitations section. Each singer was asked to prepare two songs of their choosing and from any genre they were comfortable with. The reason I didn't restrict them to a homogenous repertoire is because I did not want variations between performances to be due to the effects of having to learn the piece quickly[9]. The only requirement was that it was sung acapella, and that one song was faster than the other. For each location, the singers were placed in the same spot that the source was placed when collecting room acoustics data, and the receiver being a Shure SM58 cardioid microphone would be placed about 3-6 inches away from the singers as shown in Fig.2 . The microphone was plugged into a MOTU Monitor which feed into Garage Band to collect the audio recordings. Once in their position and ready to perform, the singings would be cued in to start, and the recording would begin. The gain level was monitored off stage and was calibrated ahead of time for each singer. After the song has concluded the singers were given a short 2-minute break before starting the next song. Once both songs were completed singers gave feedback on their experience in the room which were compared to the data and official survey answers they gave. The singer would do the same process in the remaining locations, and once data had been collected in all locations, all singers received a survey to answer targeted question.

9) Paul Lizard et al. "Changes in the voice production of solo singers across concert halls"

Figure 2. Example set up of the singers in Distler Hall with mask and audio equipment

Qualitative Subject Data Collection

As mentioned, the singers were given the survey that is found in the Appendix under Survey Questions. The purpose being to give the participants an opportunity to give an account of how they felt about the space in comparison to other spaces they have sung in either that day for this research or in the past. I wanted to see if they were actively making changes in their vocal performance due to acoustic qualities of the rooms, they were in. There is only so much I can observe in terms of mouth shape and breath intake given the singers are wearing masks, so this was an opportunity for the singers to let us into the vocal choices they made while performing.

Data Analysis Procedure

I used Fuzz Measure to compare the graphs of RT20 and C80 for all rooms at 1m. I then took the impulse response collected in Fuzz Measure from the dodecahedron loudspeaker at 1m from each location and imported it into my Stage Support MATLAB code as seen in the Appendix. To analyze the singers audio recording, I used the iZotope RX 8 Audio Editor spectrograph viewer. This allowed for me to compare the intensity, harmonic information, pitch, dynamics changes, and pace between distinct songs per location sung by the participant. This approach really worked best for vibrato changes and pace because time and pitch are tracked with a spectrograph. I would look specifically at places in the song where notes were sustained, vocal agility was demonstrated, pitch slides and crescendo, etc. All to see if those same techniques were used in the other locations or across song genres. The survey responses were then compared to the quantitative data gathered to see if what the vocalist experienced is represented well by what the data suggest such as clarity hear by the singer versus what they clarity value of the room was from the impulse testing.

Findings

Vocalist Profiles

Below in Fig.3 you will find profiles of the vocalists who participated in this study. All of them were selected for their demonstrated vocal abilities around Tufts campus or through a recommendation from a trusted source. They all have performed in a variety of spaces and have diverse singing backgrounds. They also have had some professional training and over a decade of performing experience.

Singer & Vocal Part	Years Preforming	Typical Genre	Song Selection Faster Song	Professional Training	Previous Performance Spaces
Jenah Gabby (Soprano)	18 Years	R&B	"Learn to Love" –Anaiis (ft. Azekel) "Sandstorm" –Mereba (ft.JID)	10 Years	Auditoriums, Theaters, and Grand Halls
Mona Tavangar (Mezzo-Soprano)	10 Years	Classical, Opera, Musical Theater, Jazz ,and Pop	"If I Loved You" –Richard Rodgers "When He Sees Me" -Sara Bareilles	9 Years	Concert Halls, Auditoriums, multipurpose rooms
Charlotte Nanteza (Contralto)	18 Years	R&B and Choral	"Don't Judge Me" – Chris Brown "Catch Me" – Demi Lovato	1 Year	Concert Halls, Auditoriums, and Outdoor Venues
Kamar Godoy (Tenor)	15 Years	Funk, Soul, Alternative Rock, and Classical	"Elastic Heart" –Sia "Black & Gold" –Sam Sparro	3 Years	Concert Halls, Auditoriums, and Outdoor Venues

Figure 3. Table of all the participants, their pieces for the study, and their experience

Room Information

Distler Hall

This hall (Fig. 4) is an acoustically separated "box-within-a-box" designed for live acoustic performances, seating about 300 people. Measuring at around 11m long, 8m wide and, 6.7m tall; it is completely sealed preventing sounds from outside the hall interrupting performances. All electrical and mechanical systems in the room also designed to be silent[10]. The walls are hollow causing lower frequencies to blend and become muddled decreasing discernment between those lower frequencies. The floors and walls are all wood and the seat are upholstered. Distler has a reverberation time of a little over 2 seconds as see from the RT20 octave band graph in Fig.9, with a clarity value of about 7.6

10) BMOP. "Distler Performance Hall at Tufts University." *Boston Modern Orchestra Project*,

decibels as shown in the C80 octave band graph in Fig.12 . This makes since given that this is one of the more reverberate performance spaces on the Tufts University campus. With a large and wet space containing many reflective surfaces, we are bound to have more late sound energy over early causing the clarity to be the lowest out of our three spaces. Especially for the lower frequencies as mentioned earlier. Having strong and close early reflections makes it harder to hear direct sound which is responsible for distinguishing between succession of musical notes[11] . This is the cause of the lack of intelligibility for lower frequencies in Distler Hall.

Figure 4. On stage in Distler Hall setting up equipment to collect room acoustics data

Curtis Multipurpose Room:

This room (Fig.5) has been used for all kinds of events ranging from vendor fairs, science fairs, dance showcases, plays, and vocal performances. Because the space is so versatile there is less attention to the room overall for vocal performances only. It appears

11) Leo L. Beranek, "Concert hall acoustics: Recent findings"

the focus could have been to limit the amount of sound that travels not just in the space but also to neighboring rooms. Measuring at 11.5m long, 10.85m wide, and 4 m tall; the floors are wooden panels with a carpet covered stage, and about 2.5m of the wall are wooden panels from the floor and the rest being plaster. The space seems to have some acoustical treatment on the walls to make it less reverberant but from the floors, walls, and diffuses scattering of the light fixture we have quite of bit of reflection happening in this space. Every space behind the stage is also covered in fiberglass panels. To understand how reverberant this location is, imagine if Distler is the most reverberant space and the practice room is the least reverberant space, Curtis would be right in between with a reverberation time of a little over 1 second as see from the RT20 octave band graph in Fig.8, and a clarity value of about 7.6 decibels just like Distler as shown in the C80 octave band graph in Fig.11. Just from being in the room, much of the sound gets captured near the top of the room where most of the reflective surfaces are without acoustical treatment. When the data for this room was collected there was a curtain that spanned the entire wall parallel to the front of the building facing the street (refer to Fig.1 B). This could be causing most of the absorption of the room since the gap behind it is at least 10 meters for storage of chairs and tables. The greatest drawback to this room was the outside noise consistently bleeding into the room during the day. Since College Ave is a busy street in the afternoon around Tufts University, any data collection needed to be taken either in the morning or the evening.

Figure 5. On stage in Curtis Multipurpose Room setting up equipment to collect room acoustics data from 20 ft away from source is the photo on the left and to the right is the stage

Practice Room:

This room (Fig.6) was designed specifically to be as dry as possible to make sure as much sound as possible can be absorbed and not bleed into the other rooms. Measuring at 4.5 m long, 3.5m wide, and 2.7m tall; all the walls and ceiling are fiberglass panels insulation, and the door is insulated completely. Most of the sound that is being reflected is coming from the linoleum tiles in the floor. Practice Room 022 has a reverberation time of about 0.2 seconds as see from the RT20 octave band graph in Fig.7, and a clarity value of about 21.6 decibels as shown in the C80 octave band graph in Fig.10. It makes sense that the clarity value is so high because we are getting more early reflections than late given that the absorption in the room is so high.

Figure 6. Inside of Practice Room 022 setting up equipment to collect room acoustics data from 2 meters away from source

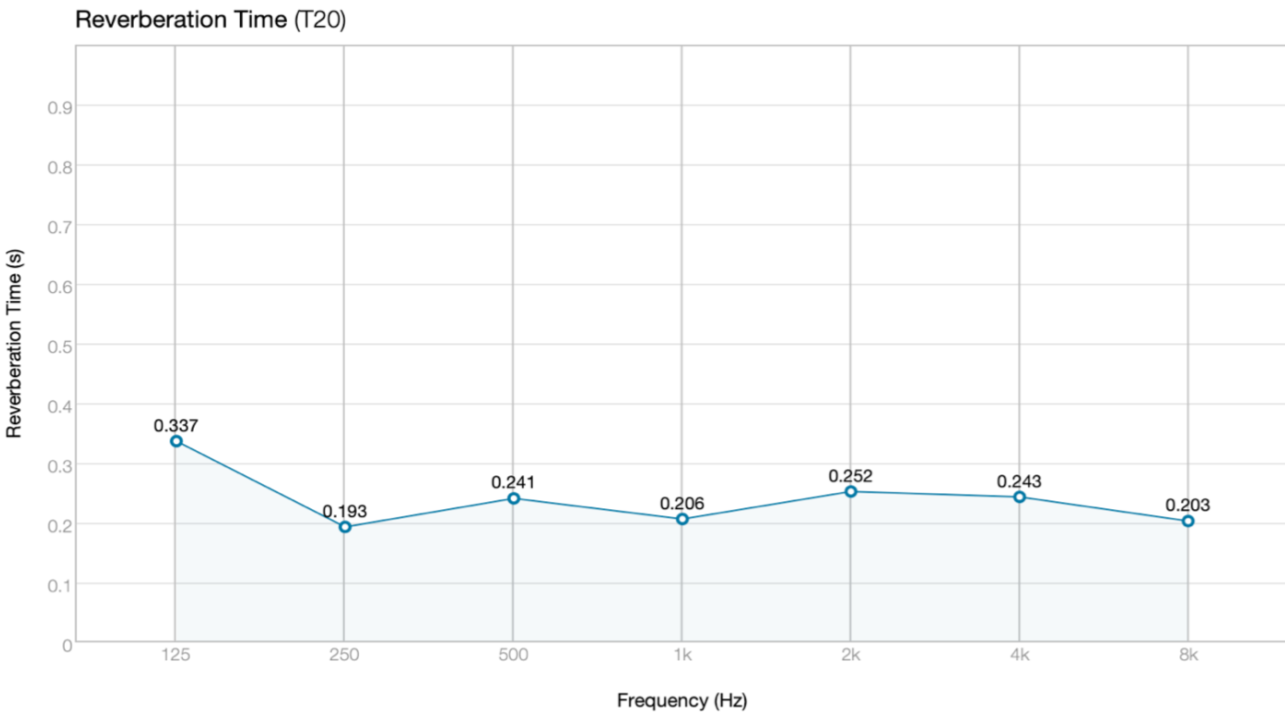


Figure 7. Practice Room RT20 Graph

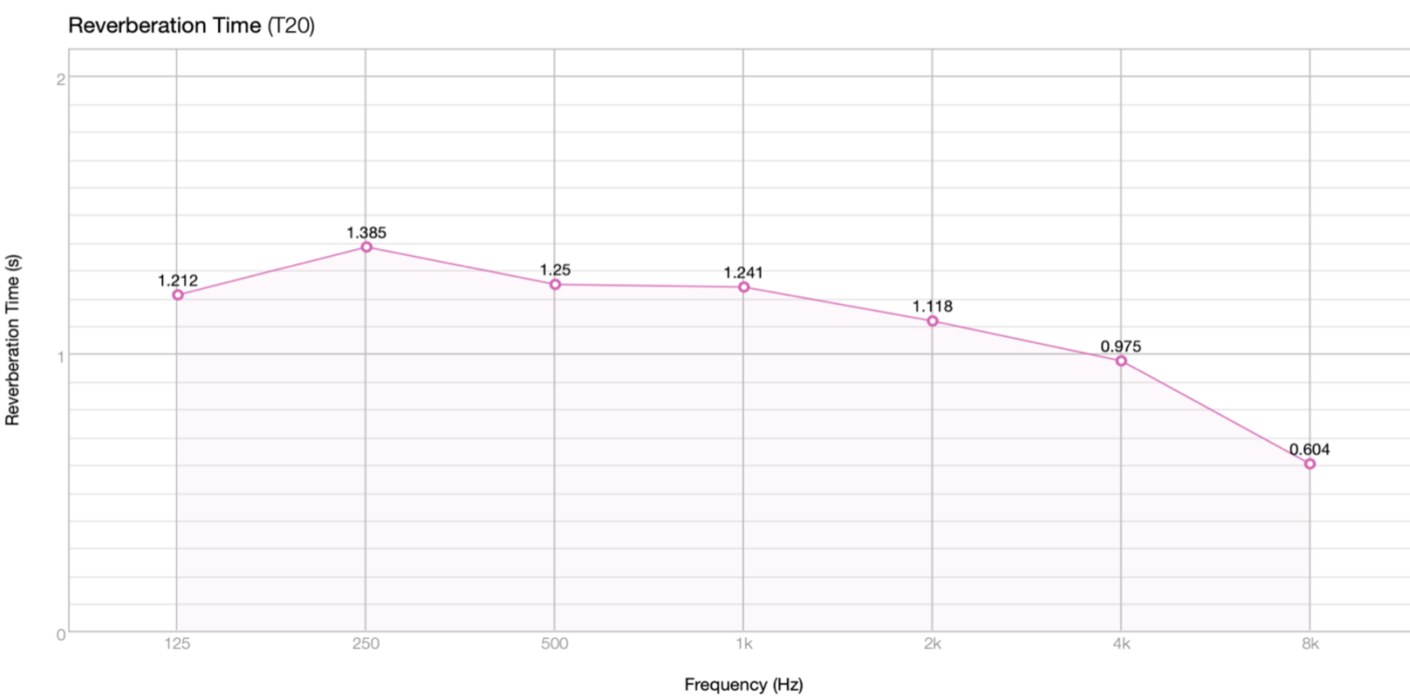


Figure 8. Curtis Multipurpose Room RT20 Graph

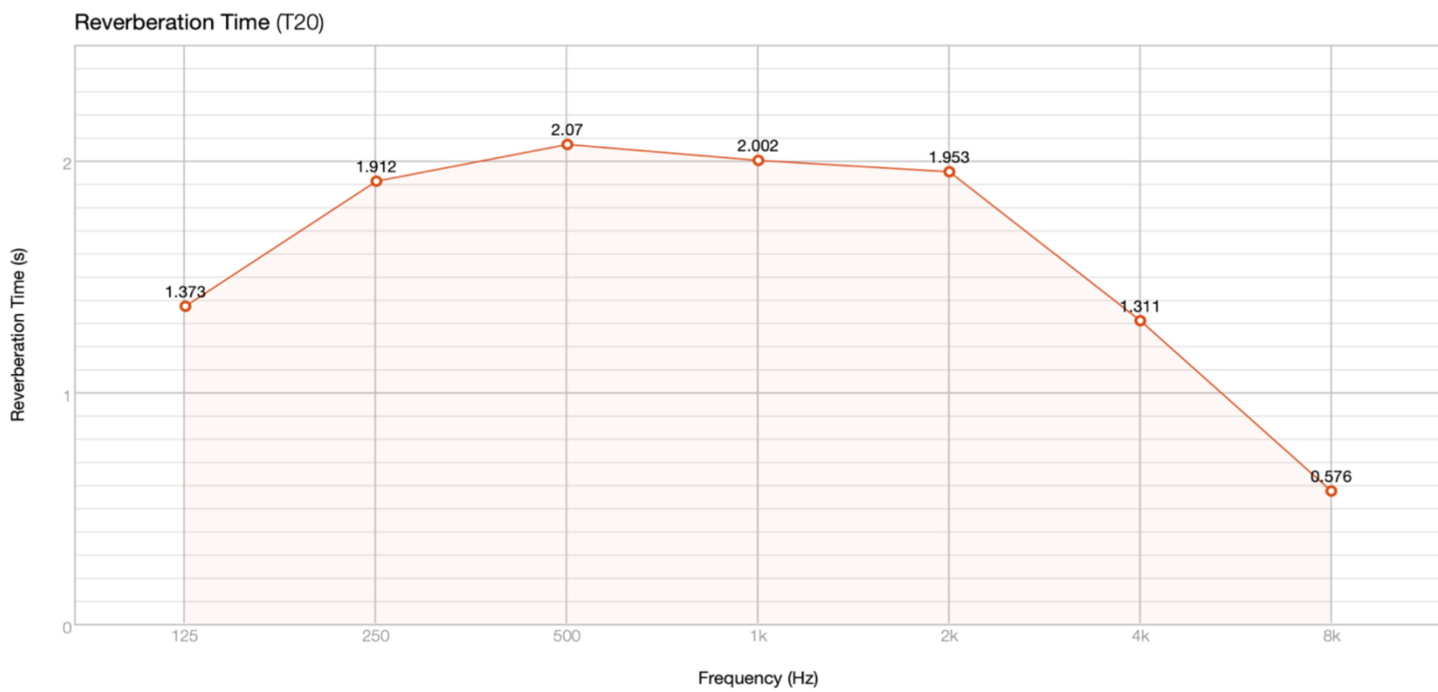


Figure 9. Distler Hall RT20 Graph

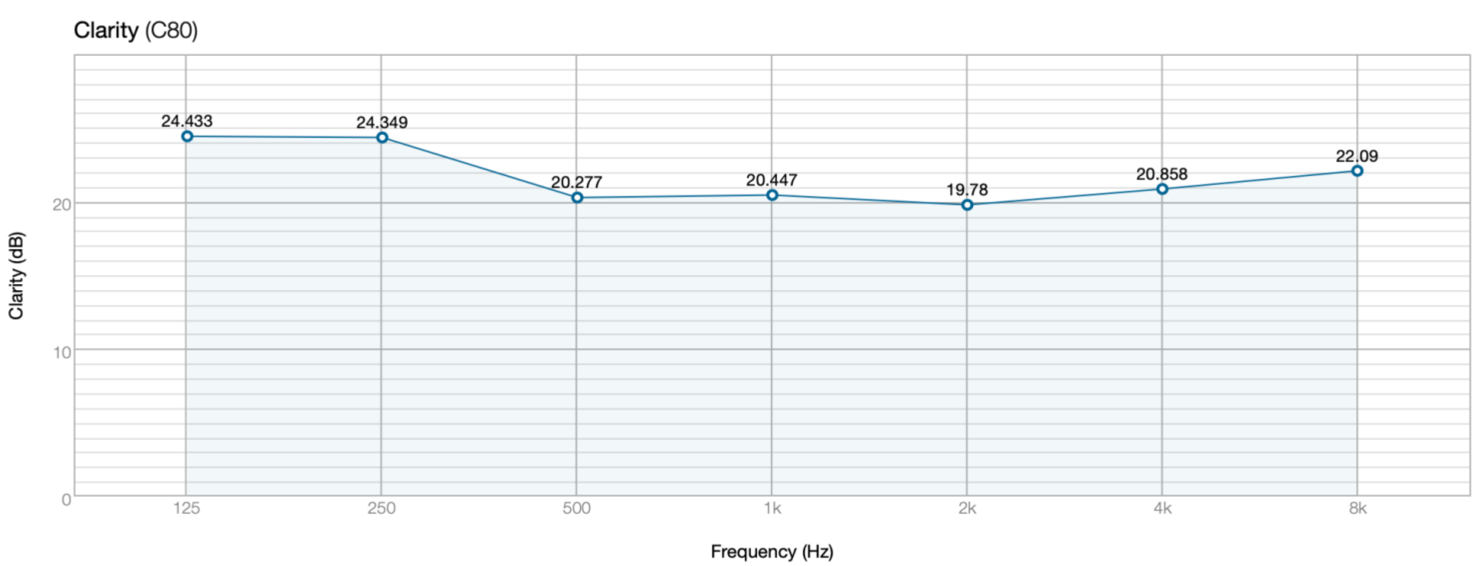


Figure 10. Practice Room C80 Graph

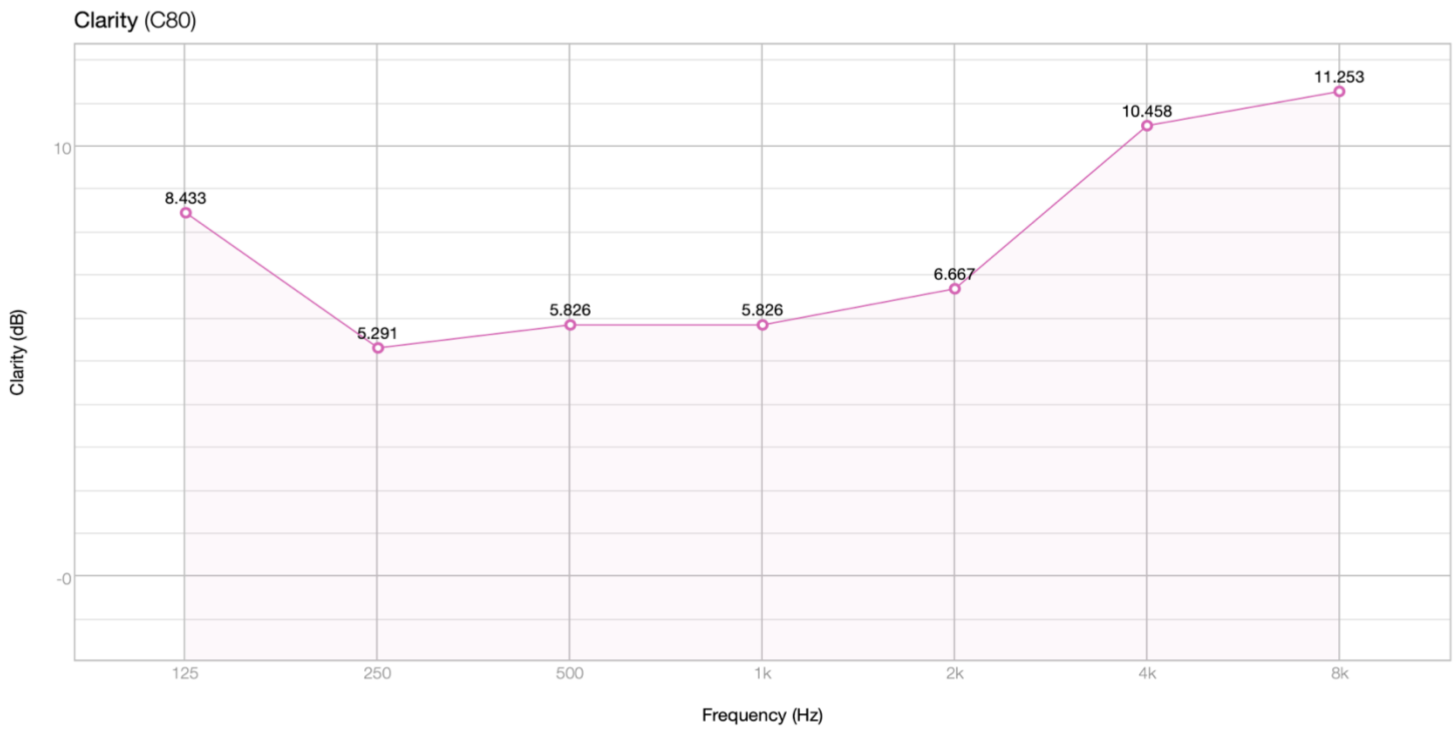


Figure 11. Curtis Multipurpose Room C80 Graph

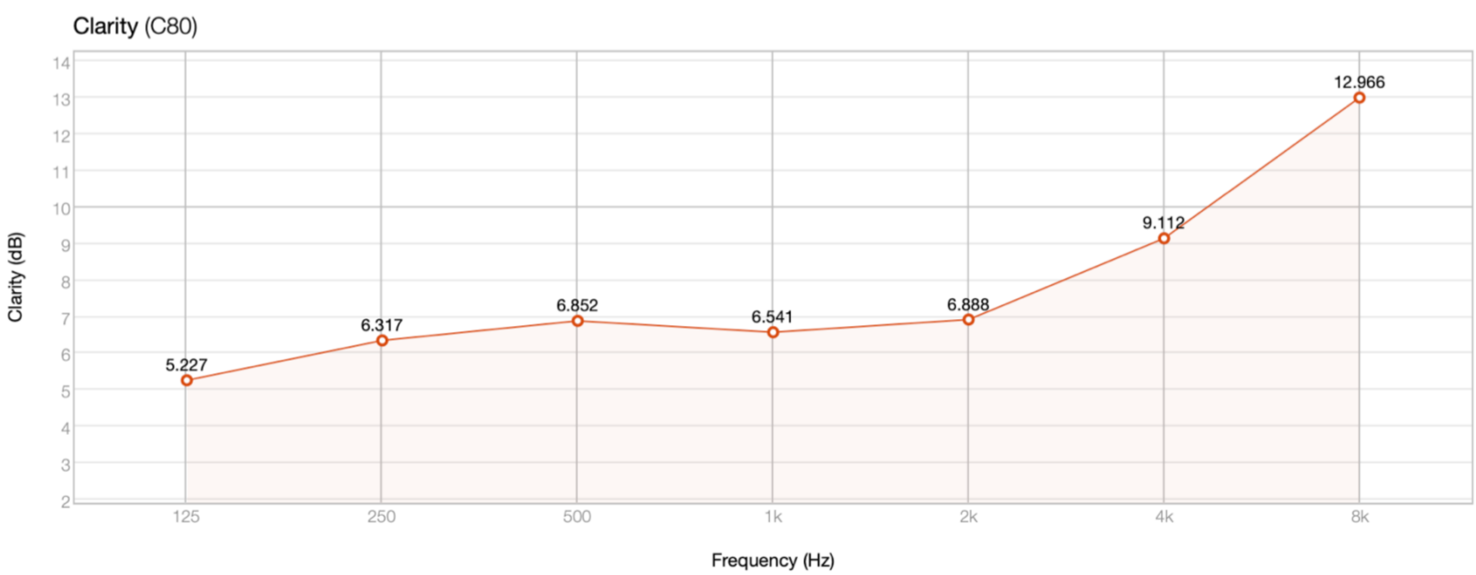


Figure 12. Distler Hall C80 Graph

Stage Support:

One of the most important things that I wanted to analyze in terms of the rooms acoustics has to be the early and late stage support. I wanted to understand this metric and how it compares to the vocalists experience. ST_{Early} & ST_{Late} are the most common room acoustic metric to investigate stage acoustics[12] and has an impact on how much the performer can hear themselves on stage and if performing with other, how much that can hear each other.

Starting with Practice Room 022 (Fig. 13), as we can see both ST_{Early} & ST_{Late} are negative which means we have more direct energy than reflected overall. We will see that this is true for all the locations. There is significantly more direct sound for ST_{Late} than ST_{Early}. This makes sense because ST_{Early} captures the first 100ms of sound energy. With the room having a reverberation time of 0.2s there is enough time for more reflections to reach the receiver before the energy drops below 60 dB. Whereas in ST_{Late} we see that it take the sound energy from 100ms to 1s. After 200ms you will not get much of any reflections. This would suggest that people would be able to clearly hear themselves in this room but there is no support in reflection potentially making it difficult for people support themselves over an extended period.

12) Wenmaekers et al. “Early and Late Support Measured over Various Distances: …”

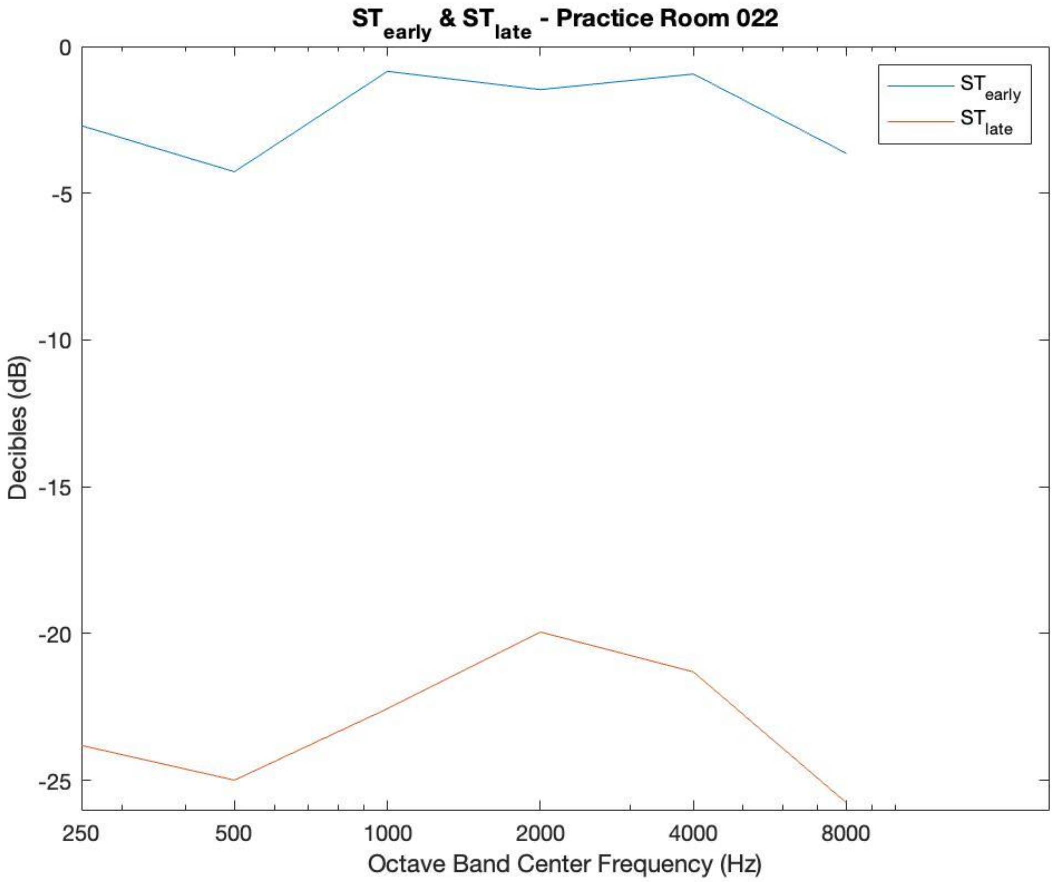


Figure 13. Stage Support Graph for Practice Room 022 with source and receiver 1m apart

Now looking at Curtis Multipurpose Room (Fig.14), it seems as though both the late and early stage support lines follow the same trend until it reaches 4000Hz. Having similar trends can be attributed to the fact that the reverberation time is about 1 second which is greater than or equal to the time integration for both early and late reflected energy. The split at 4000Hz could suggest that there are properties of the room either in absorption or reflection of materials that favor the 8000Hz frequency band causing the decrease in reflective sound energy and increase sound energy.

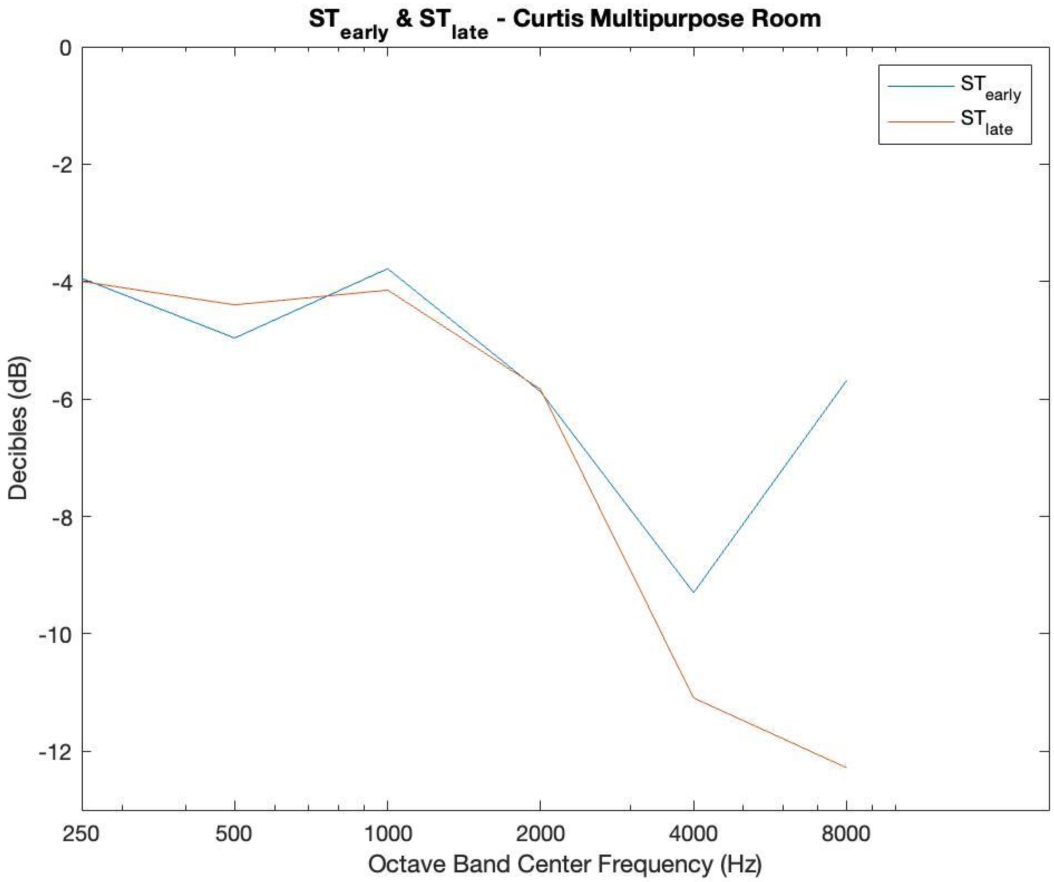


Figure 14. Stage Support Graph for Practice Room 022 with source and receiver 1m apart

Lastly looking at Distler Hall (Fig.15), We can see somewhat of a similar trend where at 1000Hz and after 2000Hz the early and late lines diverge from each other, and I would once again hypothesis that this is due to are properties of the room either in absorption or reflection of materials.

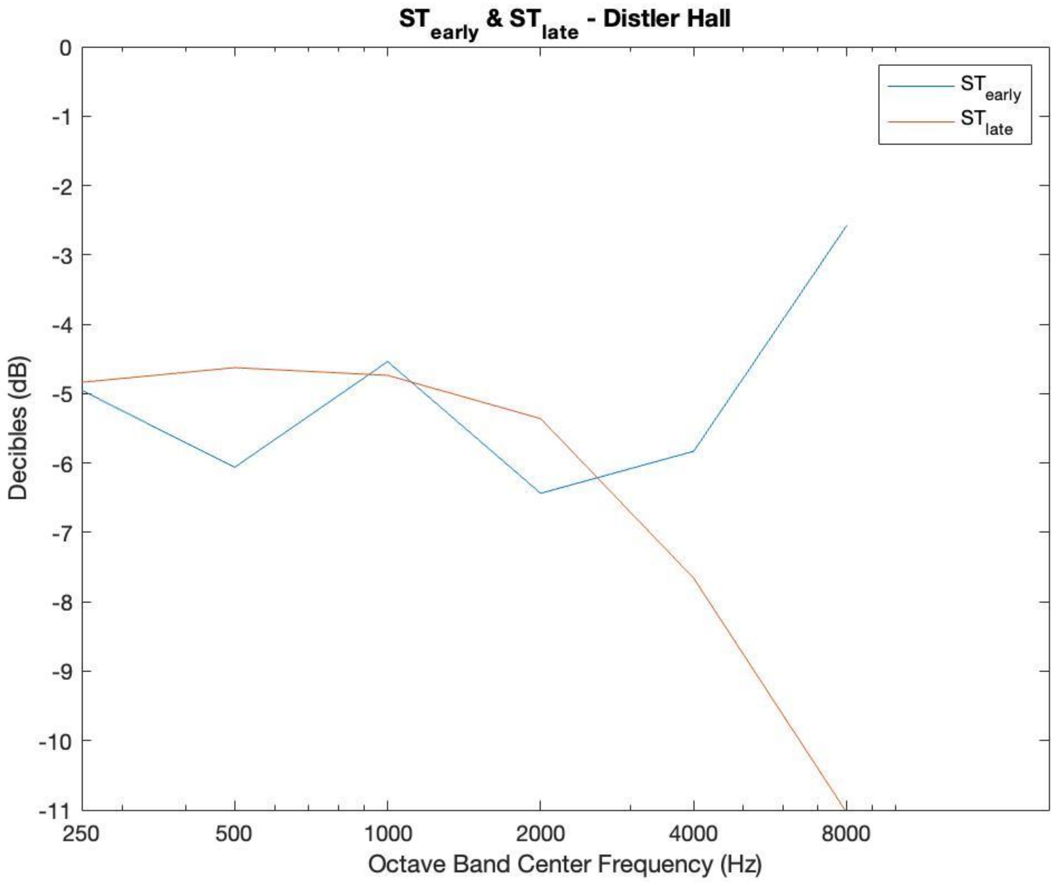


Figure 15. Stage Support Graph for Practice Room 022 with source and receiver 1m apart

Qualitative Survey

In terms of what space was more favorable, it seems most of the vocalist preferred Distler over the two other spaces, saying that it supports vocal resonance and provides a richness and depth to their voice. Although they all expressed singing in Distler was easier because it required less breath to produce power, the Mezzo-soprano brought up some good points about the drawback of Distler compared to the other spaces. When singing her classical piece, she was less concerned about her dynamics than with the music theater piece which was her faster song.

“I clearly love Distler, but it’s definitely more suited for some styles than others – I think it’s best suited for more classical styles. I’ve been thinking back to when I was singing “*Till There Was You”,* for “*When He Sees Me”* it was also good of course but I think some of the nuances of musical theater/pop styles get swallowed up by the big space.”

I would have to agree with her, because of the longer reverberation time, you may get distracted when hearing some of your reflected sound up to 2 seconds later. This lowers the clarity of the lyrics and causes intonation issues as brought up by another singer.

“The only disadvantage is that you won't hear the accuracy of the notes as much as when you are singing in the practice rooms. “

It seems as through the main reason the vocalist didn’t like the practice room is because they all went from a more reverberant space (Distler Hall or Curtis Multipurpose Room) to this dry space. Although they all expressed that having the space amplify their voice was desired, the Soprano brough up the point that having to be aware of your breath and pushing yourself to be heard is good practice for when you are not in a luxurious space like Distler all the time.

“I feel like in a practice room I need to put more of a strain on my voice because the wall takes up so much sound. I needed to be cognizant of how I breathe and how loud I must be to get the sound across… I do like that I can hear the notes clearly in the practice room. It allows me to challenge myself. Distler just makes

me sound prettier and louder which is always great when you do not want to put in that much effort."

What the practice room lacks in supporting the intensity of the vocalist voice, it makes up in clarity and forcing intentionally of breathing and dynamic changes. Therefore the Mezzo-Soprano enjoyed Curtis a lot due to the space sharing the best qualities of both Distler and the Practice room.

"**I was surprised by Curtis! I thought my voice sounded more resonant than I thought it would… this had some qualities similar to Distler! On a much smaller scale, of course, but that was to be expected"**

As a Tenor I enjoyed singing in Curtis the best because I could more easily hear my lower register in this space compared to Distler and the reverberance was not overbearing. Curtis still has the drawback of outside sound bleeding into performances but with the fiber glass panels behind the stage improving clarity by increasing the amount of direct sound you get, while also receiving reflective sound from the rest of the room I think that is makes for a great space overall for vocal performance.

Spectrographs Analysis

What sets this research apart for others that I have seen in the past is that for my analysis on vocal adaptation I am using spectrographs and comparing them visually against each other. This allows for us to visualize of the descriptors used in explaining how a vocalist adapts the way they sing per location. Here we see in Fig. 16 the difference between the mezzo-soprano in Distler versus the practice room. It is typical for a classical singer to hold out a pure note and add vibrato to it at the end of a phrase for emphasis as we see in (A), but in the practice room we can see that the choice was made to remain heavier on the vibrato earlier and limit how long she stays on the note as seen in (B). When in a concert hall letting a note sustain before intensifying it with a vibrato is in my opinion pleasing to the ear and accompanies the space.

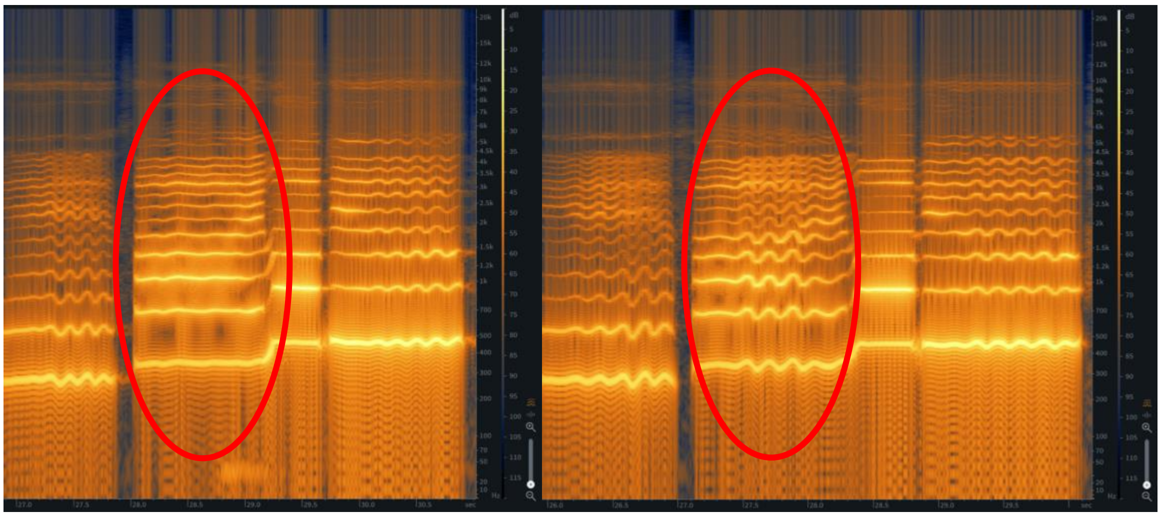


Figure 16. Spectrograph of Mezzo-Soprano slower song. The phrase is “If I Loved You”. On the left we have the audio from Distler Hall and on the right we have Practice Room 022

We get a similar effect with the mezzo-soprano’s faster musical theater song Fig.17 where the end of the phrase is held out as a sustained note completely in more reverberant spaces and in in the practice room, more vibrato is added for artistic effect to fit the location. The graph for Curtis resembled a mixture of the two with some vibrato and some sustain of notes.

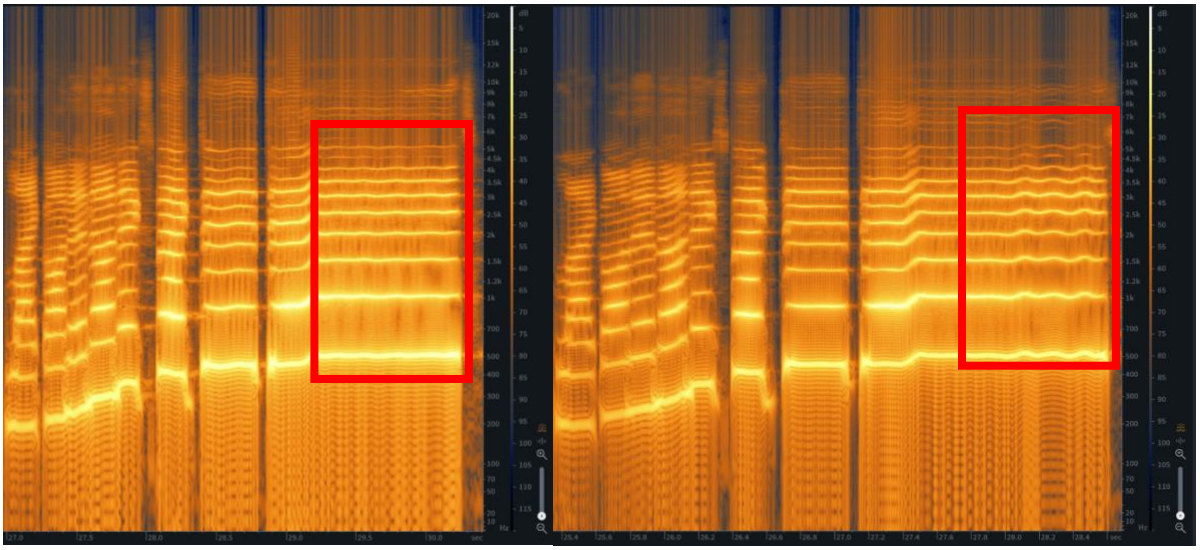


Figure 17. Spectrograph of Mezzo-Soprano faster song. On the left we have the audio from Curtis Multipurpose Room, and on the right we have Practice Room 022

Sometimes the vocalist will make a stylistic choice based on the space they are in as well. We can see in Fig.18, the Soprano vocalist choose to bridge the space between two phrases giving a legato effect in Distler where as they kept the open space in the practice room. Since the reverberation in Distler is long it make sense that this was a choice the vocalist made. The reflections are already blending in your ear adding color to the space, so from my experience, you would naturally want to do the same with your singing. In the practice room the reverberation in dry and clean cut so cutting phrases short is common especially when trying to conserve on energy to get through a piece.

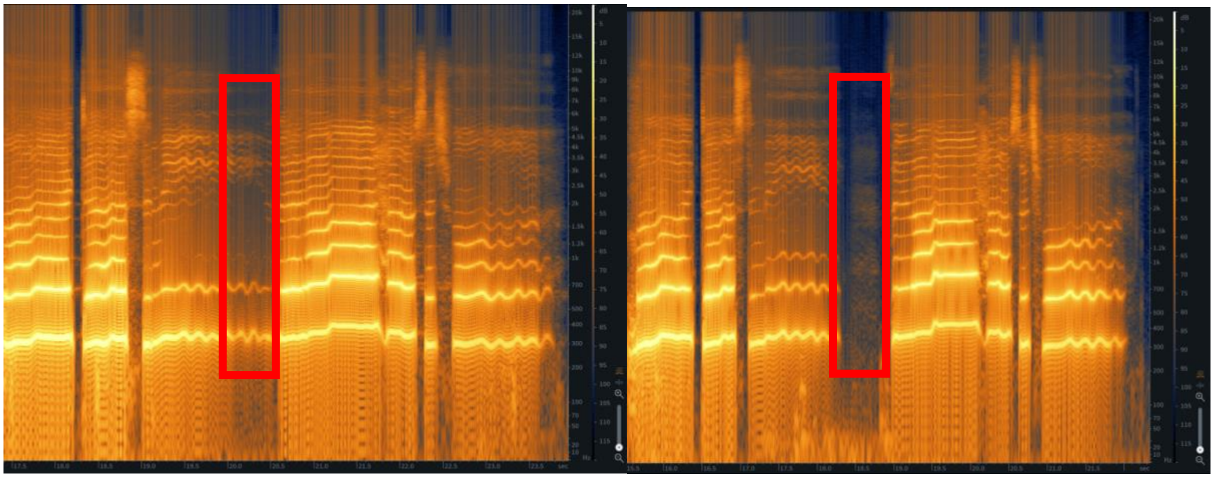
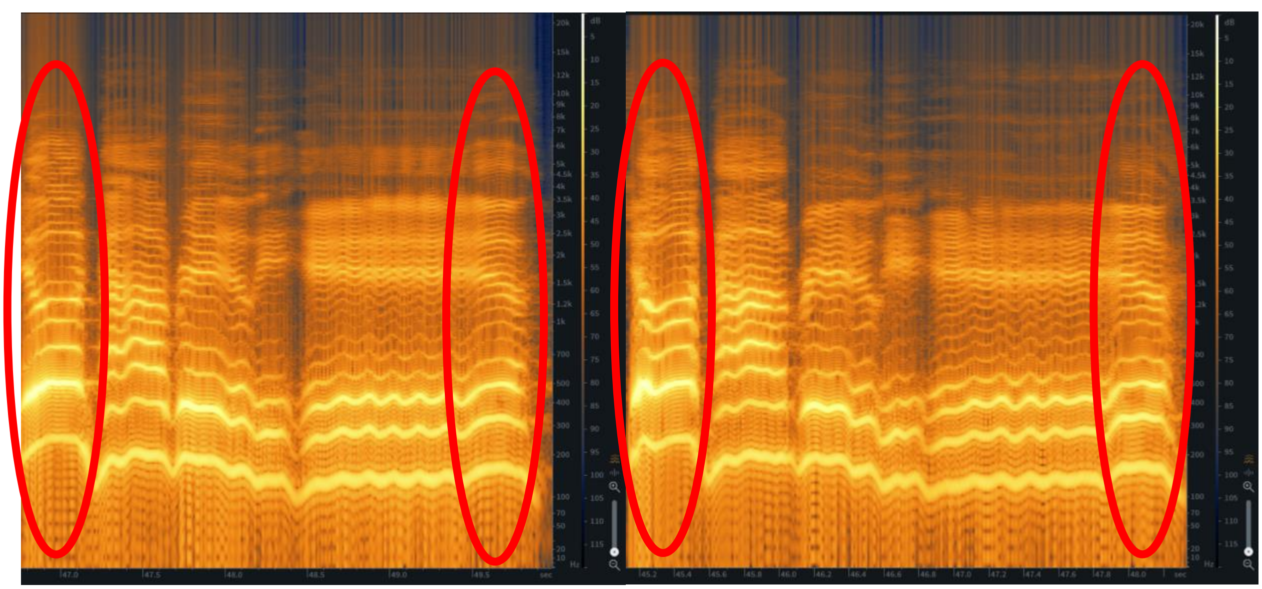


Figure 18. Spectrograph of Soprano slower song. On the left we have the audio from Distler Hall and on the right we have Practice Room022

When it came to my tenor voice, I felt more supported in Curtis Multipurpose Room. You can see from Fig.19 that I had much more control of bending my pitch to match the style of the song compared to the practice room and Distler. You can also notice that more harmonics are present in the mid and high frequencies of the spectrograph, showing the space is adding color and depth to my voice.



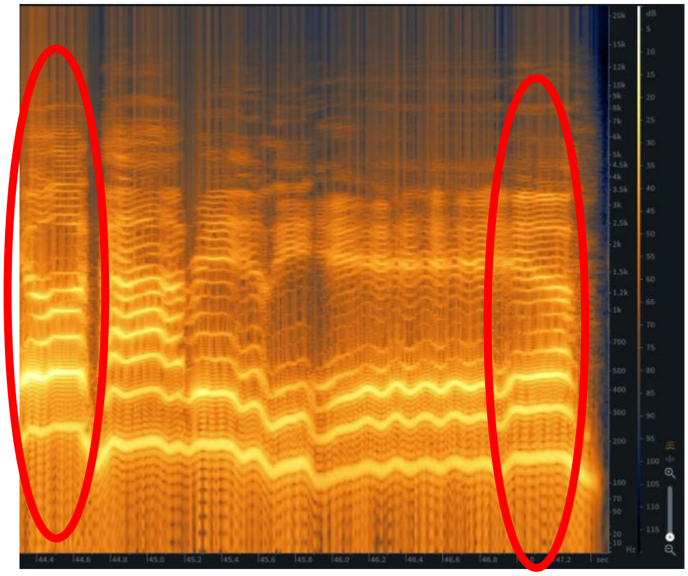


Figure 19. Spectrograph of Tenor Faster song. On the top left we have the audio from Curtis Multipurpose Room, on the top right we have Distler Hall, and on the bottom we have Practice Room 022

The thing that is the hardest to quantify from the setup of this study is dynamic changes. We know that the most prominent factors that differentiate dynamics of a hall and the cause of dynamic variations between acoustical environments is attributed to Hall Loudness, reverberance, and width. You will notice that for many of the singers they would alter their dynamics slightly to accommodate for the space. In Fig.20 we see that the Contralto clearly made different vocal and stylistics choices between locations and some of that could have been attributed to the acoustical space.

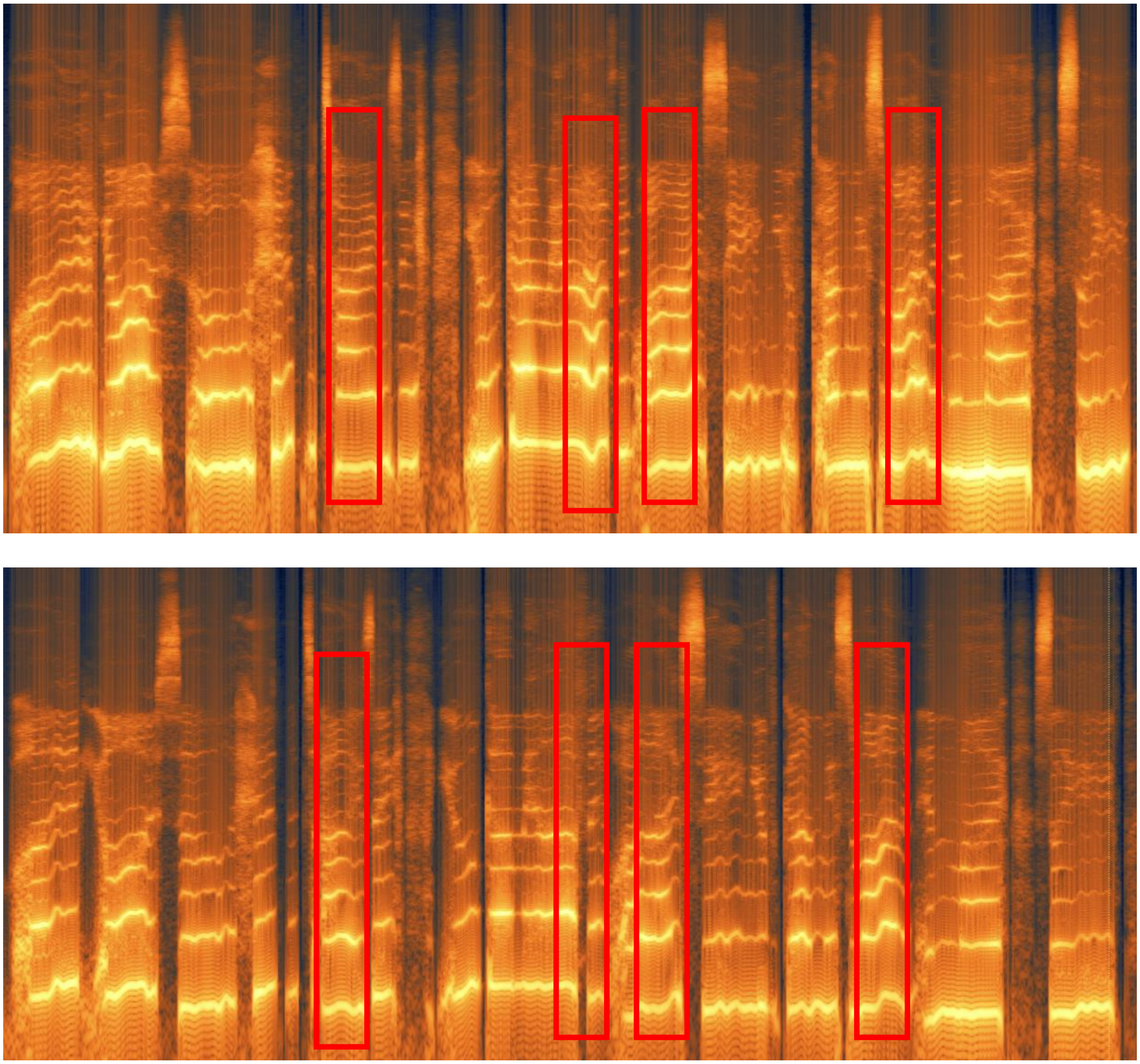


Figure 20. Spectrograph of Contralto faster song. The top audio source is from Curtis Multipurpose Room, and the bottom is Practice Room 022.

Discussion and Conclusion

Limitations

Although I tried as much as I could to eliminate error from his study, there were a few things that were out of my control that prevent me from making definite conclusions. First, COVID face masks can reduce the volume of lower frequencies and can reduce the power of higher frequencies. Although pitch may not be affected, clarity and timbre is[13]. So, this may present inaccuracies in the singers spectrographs, but the error remains consistent across all spectrographs since they consistently wore the same masks across locations.

Another issue was simply timing. Many singers dropped last minute and not all spaces were available for all the singers when they were available. This means that only the Mezzo-soprano and I were able to get to all three locations to collect data on the same day. The Soprano was only able to make it to Distler Hall and the Practice Room and the Contralto was only able to make it to the Practice Room and Curtis Multipurpose Room. Due to these inconsistencies of location for all singers as well as too small of a sample size I cannot confidently make a conclusion around how the spaces affect vocal ranges. On the other hand, I can speak to what I observed regarding these case studies.

If I were to complete this study again, it would be during a time where I could have singers maskless. Also, if it were at Tufts, I would collect data during the summer when singers would have more availability and so would the spaces. I would lastly have more vocalist and would give them an additional survey where they rank the qualities of a

13) Acoustics Society of America. “Sing on: …”

space so that I can do statistical analysis on the correlation between some of the metrics I tested for quantitatively and some of the responses the vocalist gave[14].

Final Thoughts

From the results of the spectrographs and the responses I got for using the surveys and conversations with the vocalist, I was able to compare that to the quantitative results from the room acoustics measurement to see how the changes the vocalist made across location could be attributed to the acoustical quality of the rooms. As mentioned in the limitations, it is beyond my abilities to make any generalizations about singing adaptation behaviors, but with a larger sample size and more consistent conditions, more specific adaptation patterns can be concluded. I can say that the way in which each person exhibited vocal adaptions, was done based on their individual experience with the space.

As an R&B singer, the Soprano focused on how the room support her breathy vocal texture and enjoyed letting her notes connect to the next phrase utilizing her vibrato emphasis in more reverberant space which is exactly what we saw in Distler Hall from the spectrographs. We see from the C80 graphs for Distler that the clarity gets higher for higher frequencies, thus the Soprano and the Mezzo-soprano could hear themselves much better than I, being a tenor. Being classically trained, the Mezzo-Soprano to take advantage of wetter spaces differently holding notes pure notes and exploring dynamic changes such as crescendos with these notes appropriately. For both, when in the practice room we see more focus on breath control due to the cutting from phrases early and more intentionality on vibrato placement. You use more breath to

14) Lilyan Panton *et al.* "Chamber musicians' acoustic impressions of auditorium stages: …"

sustain a note and constrict your glottis to enable a vibrato, which is the choice that seems to be explored in the spectrographs to accommodate for the high absorption in the room and lack of stage support.

As a pop singer the Contralto really relied on the rooms ability to support the intelligibility of the notes. Also, for the faster song's chorus, the intensity was supposed to consistently grow. In Curtis, the space had a large enough reverberance in the mid and high octave bands to support her and the late stage support value increases in direct sound energy over reflected the higher the frequency, but in the practice room the Contralto introduced more pauses like the other singer as well as kept the intensity at the same level across the chorus.

In the future I believe testing for the Bass Ratio of each room may be helpful especially for gaining a deeper understanding of the lower frequencies interact with the space which is often attributed to the color quality of the space. I hypothesize that the reason for the roundness of my pitch from the spectrograph come from the increased clarity in the lower frequency allowing me to hear more of my fundamental note giving me more control over how I produce it.

Overall, we can see that the way that the vocalist in this study adapt the way they sing was on an individual basis and had some dependency on genre/personal singing style. Even though we cannot make certain correlations room acoustic between vocal choices and environment qualities, we can make educated hypothesis based on some of the room acoustic metrics observed in this thesis as well as some knowledge of the martials and size of the spaces and how their physical properties can affect the sound of the room for the vocalists performance.

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Last but not least, to my Mom and family, thank you for being the village that supported me for so many years to get to this point. We finally made it to another chapter, and I can’t wait to see what new heights we reach together.

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Appendix

Survey Questions

Question 1:
"Can you describe the way your voice sounds in this space compared to other spaces you have sung in either today or in the past.

Question 2:
"Do you feel this space adds to your voice quality, if so, how?"

Question 3:
"Compared to singing in a practice room /dry room do you feel like you had to place more of a strain on your voice or got tired sustaining notes more or less in this space?"

Question 4:
"How well (clear) do you think you were able to hear yourself in this room"

Question 5:
"Does the room support dynamic changes in your voice?"

Question 6:
"Do you feel you voice is properly amplified with this space?"

Question 7:
"Do you have to provide a lot of breath support to deliver a powerful note?"

Question 8:
"What are some qualities of this space that you like?"

Question 9:
"What are aspects of this space that you dislike?"

Question 10:
"Is there anything else about your experience singing in this space that you would like to add?"

Reverberation Table

Space	Location	Trial	125	250	500	1000	2000	4000	8000
Practice Room 021	1m	1	0.309088	0.194919	0.238861	0.207538	0.251639	0.242814	0.20832
		2	0.351861	0.195492	0.23857	0.204786	0.255115	0.242973	0.204845
		3	0.336597	0.193095	0.240818	0.206329	0.252361	0.243312	0.202936
	2m	1	0.430988	0.302748	0.270116	0.244436	0.265728	0.229769	0.21235
		2	0.99843	0.296526	0.273615	0.250049	0.263814	0.232491	0.208599
		3	0.713425	0.317192	0.24586	0.250441	0.263837	0.226805	0.206214
Curtis Multipurpose Room	1m	1	1.185957	1.371994	1.251677	1.23744	1.120247	0.977186	0.602639
		2	1.201267	1.377675	1.246592	1.241904	1.120198	0.974569	0.604755
		3	1.212336	1.385291	1.250006	1.240535	1.118462	0.974988	0.603965
	2m	1	1.538806	1.440772	1.407147	1.295262	1.220773	0.990319	0.604484
		2	1.56641	1.440423	1.403462	1.307675	1.217836	0.992134	0.606358
		3	1.571396	1.410794	1.407386	1.309497	1.222785	1.001968	0.601901
	6m	1	1.187881	1.526822	1.431292	1.376169	1.221654	1.039089	0.634051
		2	1.243816	1.513578	1.428844	1.374332	1.218216	1.035878	0.627788
		3	4.929146	1.530666	1.442777	1.362515	1.228404	1.036097	0.635668
Distler Hall	1m	1	1.433492	1.902785	2.041486	1.963532	1.954873	1.322466	0.580595
		2	1.305825	1.914121	2.108953	1.967663	1.963412	1.309644	0.58463
		3	1.265386	1.937721	2.07425	1.976222	1.968862	1.332722	0.563821
	2m	1	1.475905	1.657748	2.023741	2.110937	1.908455	1.310869	0.604249
		2	1.481192	1.672089	2.033242	2.097885	1.924456	1.287023	0.589572
		3	1.488827	1.665585	2.0248	2.094743	1.915201	1.297806	0.58532
	7.3m	1	1.553937	2.009172	2.094613	2.024159	1.866294	1.364739	0.647007
		2	1.585809	2.032029	2.07074	2.012268	1.86741	1.353813	0.638439
		3	1.557727	2.031083	2.081677	2.018676	1.870565	1.352781	0.651935

Stage Support MATLAB Code

```
close all
clear variables

% establish variables before loop
OctBand = [250; 500; 1000; 2000; 4000; 8000];
ST_early = [];
ST_late = [];

for n = [250 500 1000 2000 4000 8000]
    % load IR
    [pdata,samplfreq] = audioread('Distler_1m.wav');
    total_time = length(pdata)/samplfreq;
    t = linspace(0,total_time,length(pdata));

    % filter by octave band
    filteredpdata = octave_band(pdata,n,samplfreq);

    % calculate filtered sound energy decays
    energy = (filteredpdata).^2;
    energy_norm = energy./max(energy);
    log_energy = 10*log10(energy_norm);

    % calculate ST for each octave band
    direct = find(log_energy==0);
    ST_early_top =
trapz(energy(direct+0.020*samplfreq:direct+0.100*samplfreq));
    ST_early_bottom = trapz(energy(direct:direct+0.010*samplfreq));
    ST_early_new = 10*log10(ST_early_top/ST_early_bottom);
    ST_early = [ST_early;ST_early_new];

    ST_late_top =
trapz(energy(direct+0.100*samplfreq:direct+1.000*samplfreq));
    ST_late_bottom = trapz(energy(direct:direct+0.010*samplfreq));
    ST_late_new = 10*log10(ST_late_top/ST_late_bottom);
    ST_late = [ST_late;ST_late_new];
end

% create table with all values for each octave band
T = table(OctBand,ST_early,ST_late)

% plot all octave bands ST_early & ST_late on one figure
figure
semilogx(OctBand,ST_early)
hold on
semilogx(OctBand,ST_late)
set(gca,'XTick',[250 500 1000 2000 4000 8000])
xlim([250 20000])
ylim([-8 -3])
title('ST_e_a_r_l_y & ST_l_a_t_e - Distler Auditorium')
xlabel('Octave Band Center Frequency (Hz)')
ylabel('Decibles (dB)')
legend('ST_e_a_r_l_y','ST_l_a_t_e','Location','northeast')
```