THE EFFECTS OF ACTUAL RECITAL HALL AND FOUR DIGITALLY-PRODUCED VARIABLE PRACTICE ROOM ENVIRONMENTS ON PHONATORY, ACOUSTICAL, AND PERCEPTUAL MEASURES OF VOCAL PERFORMANCES BY EXPERIENCED FEMALE SINGERS

BY

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the degree of Doctor of Philosophy.

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Abstract

Virtual acoustics practice rooms have been marketed as a means to simulate acoustics of larger performance venues, thus potentially allowing users to practice as if they were in a given performance venue. No study to date has examined singer phonation behaviors in such virtual acoustics environments, compared these behaviors to phonation behaviors exhibited by the same singers in an actual recital hall, and solicited singer perceptions of virtual acoustics environments.

The purpose of this study was to assess selected phonation behaviors and perceptions of female vocal soloists ($N = 20$) as they performed in two rooms: (a) a university Recital Hall, and (b) an individual practice room with 4 digitally-adjustable simulations of reverberation and reflections (Practice Room, Large Auditorium, Large Recital Hall, and Arena). Participants performed the same sung material at the same tempo in each environment, with the order of the 5 environments randomized among participants to control for potential order effect.

Primary results of this study indicated that participants on the whole (a) exhibited significantly greater mean distance dose and timbral spectral energy in the Real Recital Hall than in the virtual acoustic conditions and (b) perceived significantly greater hearing efficiency and singing efficiency in the Real Recital Hall compared to the four simulated conditions. Although (c) there appeared to be no significant relationships between participants' exhibited amplitude and their perceptions of hearing and singing efficiency, (d) participant comments favored singing in the Real Recital Hall over singing with the virtual acoustic conditions.

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"Think left and think right and think low and think high.
Oh, the thinks you can think up if only you try!"
--Dr. Seuss

Pursuing doctoral studies is one of the biggest "thinks" I have ever dared to dream. Achieving this goal has required endurance, patience, boldness, and perhaps most of all, community. I owe my thanks to many people who have come alongside and cheered me on throughout this process, and these few words will only scratch the surface of my appreciation.

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"You have brains in your head. You have feet in your shoes.
You can steer yourself any direction you choose.

You're off to Great Places! Today is your day!
Your mountain is waiting. So...get on your way!"
--Dr. Seuss

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Chapter One

Introduction

Developing Efficient Singer Technique in Practice and Performance

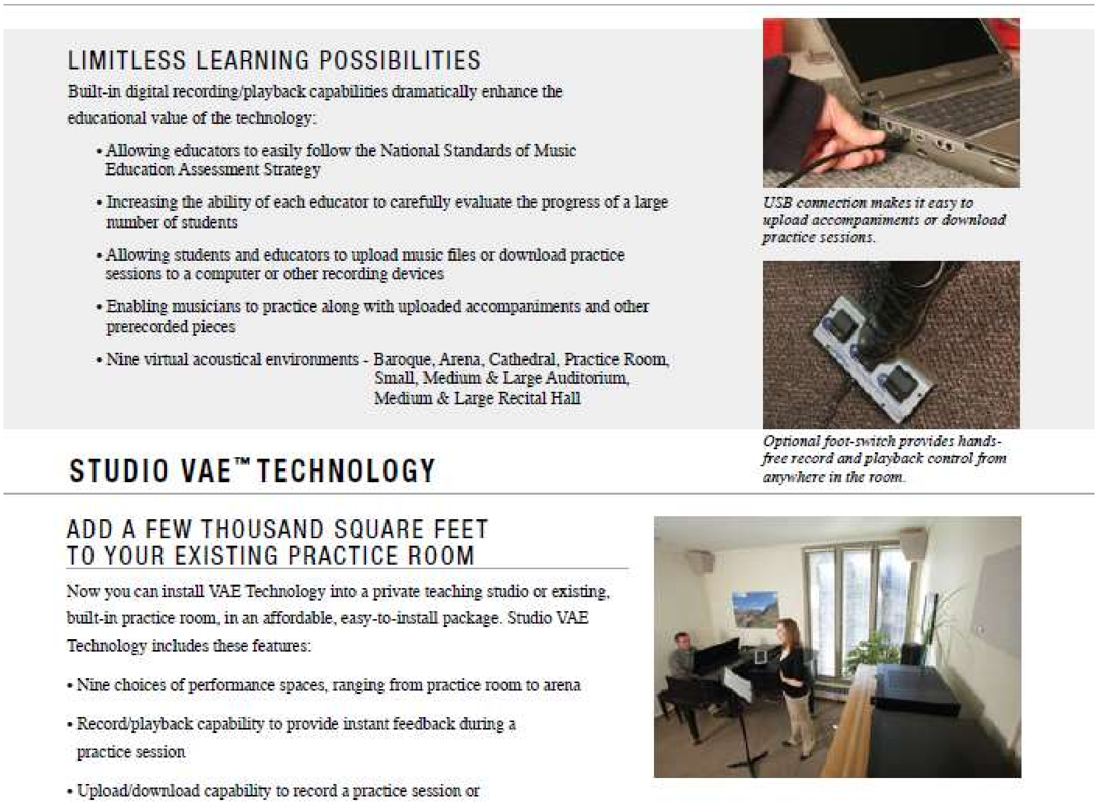
Efficient singing technique develops through consistent refinement of the complex interplay between hearing, proprioception, muscle memory, unconscious neurological processes, and psychology. Yet singers receive auditory feedback in larger spaces that is vastly different from that received in smaller rooms. Vocal adjustments needed to accommodate changes in auditory feedback experienced in larger venues can challenge technique carefully built through lessons and rehearsals occurring in small rooms and studios. One possible solution to the problem of changed auditory feedback and the resulting changes, whether conscious or reflexive, in phonation behaviors occasioned by larger performing spaces is using individual practice rooms designed to mimic the auditory feedback the singer would expect to receive while in a larger performance venue.

Ideally, training singers in university music programs would include multiple opportunities to rehearse in a variety of performance venues. However, departmental policies, scheduling difficulties, time, and expense often prohibit student singers from utilizing performance venues for repeated rehearsals (Freiheit, 2003a). In many university schools of music, student singers and faculty performers are allotted only one or two rehearsals in the performance venue before scheduled performances. Students are rarely given the opportunity to take regular lessons in a dedicated performance space. The bulk of rehearsal and lesson time is spent in smaller rooms, such as studios or practice rooms with somewhat drier acoustical properties than larger performance venues.

Individual Practice Rooms with "Virtual" Acoustics

Some individual practice rooms have short reverberation times and fast reflections (Nelson, 2012). Large rooms give an auditory impression of spaciousness through longer reverberation times and slower reflections, which can affect how a speaker or singer perceives self-sound and thus affect phonation behaviors (Aretz & Orlowski, 2009; Bidelman & Krishnan, 2010; Bradley & Soulodre, 1995; Fry, 1980; Morimoto, Iida, & Sakagami, 2001). To create an impression of spaciousness in an individual practice room could allow for an easier transition from rehearsal to performance for student singers (Freiheit, 2007).

Currently, one manufacturer in the United States sells Individual practice rooms with digitally-altered acoustical outputs. Marketing materials invite potential customers to "add a few thousand square feet" to rehearsal spaces and individual practice rooms (Wenger Corporation, 2008). These individual practice rooms use digitally-processed sound, or "virtual" acoustics, to mimic the reverberation, reflections, and impression of spaciousness a student singer might experience in various venues, attempting to create a more realistic rehearsal experience (Freiheit, 2003b). Each room uses a complex system of speakers, microphones, and digital processors to take sound made in the room by the performer and create the "virtual" acoustical environment (Freiheit, 2010). Settings available in the virtual acoustics individual practice rooms include nine pre-programmed selections designed to imitate venues commonly found on large university campuses (Wenger Corporation, n.d.). Individual practice rooms utilizing virtual acoustics installed in university schools of music across the United States speak to the desire to bridge the gap between rehearsal and performance for students. The investment by these universities to install said rooms in terms of space and cost can be substantial. Figure 1 shows a portion of a marketing pamphlet describing the characteristics of this virtual acoustic technology.



LIMITLESS LEARNING POSSIBILITIES

Built-in digital recording/playback capabilities dramatically enhance the educational value of the technology:

- Allowing educators to easily follow the National Standards of Music Education Assessment Strategy
- Increasing the ability of each educator to carefully evaluate the progress of a large number of students
- Allowing students and educators to upload music files or download practice sessions to a computer or other recording devices
- Enabling musicians to practice along with uploaded accompaniments and other prerecorded pieces
- Nine virtual acoustical environments - Baroque, Arena, Cathedral, Practice Room, Small, Medium & Large Auditorium, Medium & Large Recital Hall

USB connection makes it easy to upload accompaniments or download practice sessions.

Optional foot-switch provides hands-free record and playback control from anywhere in the room.

STUDIO VAE™ TECHNOLOGY

ADD A FEW THOUSAND SQUARE FEET TO YOUR EXISTING PRACTICE ROOM

Now you can install VAE Technology into a private teaching studio or existing, built-in practice room, in an affordable, easy-to-install package. Studio VAE Technology includes these features:

- Nine choices of performance spaces, ranging from practice room to arena
- Record/playback capability to provide instant feedback during a practice session
- Upload/download capability to record a practice session or

Figure 1. Portion of marketing materials describing virtual acoustics (Wenger, 2008).

Individual practice rooms with virtual acoustics are constructed off-site in modular sections, allowing consumers to choose the size and shape of the room based on available space, thus helping consumers to avoid costly renovations. Room components are shipped to the location and installed by trained technicians. Each individual practice room contains its own heating, air conditioning, and ventilation (HVAC) system, which reduces the possibility of noise bleeding into the room from the outside and affords greater sound isolation on the inside. Doors and wall components are constructed with sound insulating materials, and each room is wired for electrical outlets in one or more walls (Wenger Corporation, 2008). Figures 2 and 3 show portions of marketing pamphlets describing the sound isolating properties of the individual practice rooms.

Figure 2. Portion of marketing materials highlighting sound isolation (Wenger, 2008).

Figure 3. Portion of marketing materials that describes sound-isolating properties (Wenger, 2012).

The virtual acoustics system uses microphones imbedded in the walls to pick up sound from the performers and convert the sound to electronic signals. The electric signals are then processed digitally to alter the impression of acoustical reflections and reverberation time to mimic various performing venues, and broadcast into the room through speakers in the ceiling and walls (Wenger Corporation, 2013). The design focuses heavily on speaker placement in order to create a uniform sound throughout the room (Freiheit, 2010). Marketing materials and technical papers from the manufacturer highlight how speaker placement creates a fairly even distribution of sound throughout the room, such that a performer should be able to stand or sit in any part of the room and perceive no difference from standing or sitting in any other part of the room (Freiheit, 2010; Wenger Corporation, 2013). A suggested advantage of this kind of homogenous sound is that each performer in an ensemble rehearsing in the same room, such as a string quartet or vocal trio, could expect to hear essentially the same thing as his or her colleagues. A possible disadvantage to the distribution of sound is that rarely do performing spaces have uniform acoustics in every area of the stage. In real performing and rehearsal spaces members of an ensemble may hear differing acoustical feedback based on where they are sitting or standing.

Marketing materials offer both descriptions of how the rooms are intended to function and testimonials from users who expressed satisfaction with the rooms. The manufacturer describes several educational advantages to using the virtual acoustics rooms for university music students. Included in those advantages is the ability to record and playback rehearsals through the digital processor. Users then can immediately hear the performance through the speakers in the walls and ceiling, or download the recordings to a removable drive using a USB port. Figure 4 shows a portion of a marketing pamphlet describing record and playback capabilities for music educators.

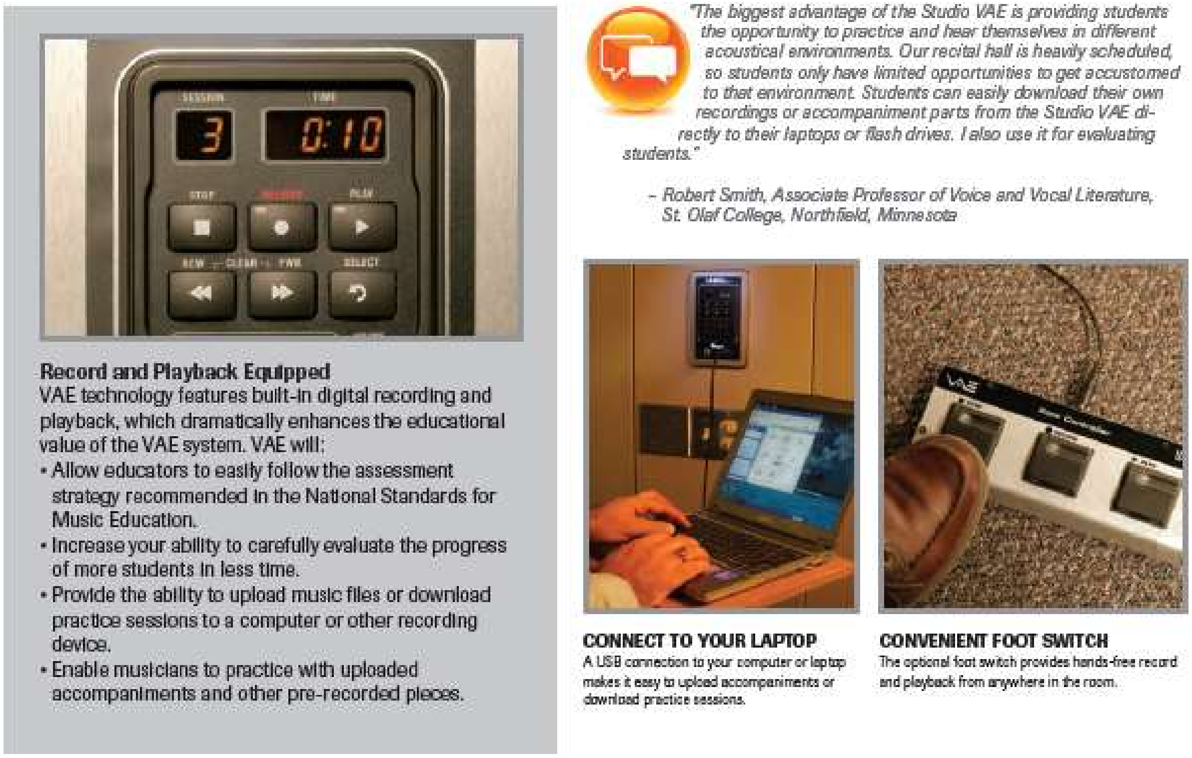


Figure 4. Marketing materials describing record and playback features (Wenger, 2012).

The marketing materials also suggest a student could take those recordings to a teacher during a lesson, offering the teacher a better understanding of how the student is engaged in rehearsals outside of lesson time (Wenger Corporation, 2008; Wenger Corporation, 2012). The same USB port can also be used to upload recordings of accompaniments or other ensemble members for the student use in rehearsal (Wenger Corporation, n.d.). What is not immediately clear is whether those recordings exhibit the characteristics of the variable acoustics, or whether the recordings are essentially “dry” with no digital enhancement.

Another potential educational advantage listed in the marketing materials is the opportunity for accelerated learning by using a rehearsal space that more closely resembles the performing space where the student will ultimately present his or her work. The manufacturer's website lists no references to any studies that might support this contention. Of the few customer testimonials specifically about the variable acoustics systems listed on the website, only anecdotal comments previously given in a presentation at a professional conference by a representative of the manufacturer point to an increase in student rehearsal time or accelerated learning by using the variable acoustics rooms (Freiheit, 2003a).

A third potential educational advantage the manufacturer mentions is more time spent in rehearsal by student users of the variable acoustics rooms due to the variability provided by the virtual acoustics system (Freiheit, 2003a). The prospect of enticing students to longer and more effective rehearsals would likely be very attractive to most teachers of singing. However, there is no empirical research cited by the manufacturer or any cited testimonials included in the marketing materials to confirm the assertion that students have indeed increased practice time by using the variable acoustics rooms.

Neurological Considerations in Developing Singer Technique

A factor unaddressed by the manufacturers in the published marketing materials or in published research is whether the virtual acoustics used in these individual practice rooms produce the same or similar neurological reactions as the acoustics produced in a "real" environment. The lack of examination of the neurological component of singing in this type of virtual acoustic environment opens for consideration neurological processes or reflexes that could affect phonation behaviors in student singers.

Neurological auditory reflexes could play a role in how singers react to differing acoustical environments, but the extent of that possible reflex is not well defined. Amplitude, in particular, is one factor in speech and singing that is partially controlled by neurological reflex (Eliades & Wang, 2012). The Lombard Effect, a well-documented example of neurological reflex affecting vocal amplitude, explains the tendency for speakers to increase their amplitude in the presence of ambient noise (e.g., Brumm & Zollinger, 2011; Junqua, 1996; Keough & Jones, 2009; Lane & Tranel, 1971). A question arises of whether the digitally-processed voice is close enough to the singer's actual voice that the brain perceives both as being the same, or whether the digitally-processed voice is perceived more as ambient noise or auditory stimulus. Characteristics of singer self-sound, such as frequency composition and the presence of formants in the frequency composition of self-sound, could be present to different degrees, altered, or completely absent based on how the sound is digitally processed. The assumption that sound from the speaker system is perceived in the same or in a similar manner as self-sound that has not been digitally altered seems to be taken for granted by proponents of the virtual acoustics system. However, to date no research is present to support this assumption.

Need for the Study

Vocal pedagogy literature and tradition suggest consistent, monitored practice contributes to development of a reliable and efficient vocal technique that can be adjusted to any performance environment. Thus, university students majoring in vocal music may spend the bulk of their singing time in rehearsal and practice.

Less frequently addressed by the pedagogical literature is the particular acoustical environment in which student vocal practice occurs. Most university music buildings provide facilities for individual practice. Typically, however, these small practice rooms may be constructed more with an eye toward economy than the notion of creating optimal acoustical environments for student training.

Some research studies (e.g., Eliades & Wang, 2008; Keough & Jones, 2009; Nelson, 2014) have indicated that muscle memory carefully developed in a dry practice room potentially can be overridden by neurological reflex from auditory feedback in a more reverberant space.

The introduction of individual practice rooms with virtual acoustics into the music education marketplace has raised an interesting question, namely whether practice rooms with digitally adjusted acoustics might assist in bridging the difference between practicing in a small rehearsal space and performing in a larger venue. To date, however, no study has examined phonation behaviors of singers using the individual practice rooms under various virtual or digitally adjusted conditions, compared the phonation behaviors of singers performing in a room with virtual acoustics with the phonation behaviors exhibited by the same singers performing the same vocal material in an actual recital hall, or systematically compared singer perceptions of the virtual acoustics systems with their perceptions of an actual recital hall environment.

Purpose of the Study

The purpose of this study was to assess selected phonation behaviors and perceptions of female collegiate vocal soloists ($N = 20$) performing in two rooms: (a) a university Recital Hall, and (b) an individual practice room with four digitally-adjustable simulations of reverberation and reflections (Practice Room, Large Auditorium, Large Recital Hall, and Arena).

Research Questions

To that end, the following research questions guided the investigation:

1. Do participants' measured phonation distance dose, dosimeter-acquired amplitude, and long-term average spectra differ significantly according to the five performance contexts?
2. Do participants' perceptions of hearing and singing efficiency vary significantly according to the five performance contexts?
3. Are there significant positive or negative correlations between participant reports of perceived singing effort and dosimeter-acquired amplitude measures, and between perceived hearing efficiency and dosimeter-acquired amplitude measures?

4. What do participant comments suggest about singing in both the recital hall and the practice room with virtual acoustical settings?

Definitions

Ambulatory Phonation Monitor. The KayPENTAX Ambulatory Phonation Monitor (APM), Model 3200, used for this study consists of a portable monitoring device used to extract information on certain vocal parameters, including distance dose (Dd), mean sound pressure level (SPL), cycles of vibration, and mean fundamental frequency. Measurements are taken through a sensor containing an accelerometer attached to the skin on the front of the neck and transferred via a wired connection to a microprocessor.

Distance dose (Dd). Distance dose (Dd) is a calculation of the distance in meters the vocal folds travel from the midline. Distance dose can be affected by amplitude (higher amplitude results in greater distance traveled from the midline), frequency (determines the number of times the vocal folds travel from the midline), and duration.

Dosimeter-acquired SPL. Dosimeter-acquired SPL is an estimate of the intensity created by the force of the contact of the vocal folds measured in decibels (dB) as calculated by the Ambulatory Phonation Monitor using the accelerometer attached to the skin on the front of the neck. The APM is calibrated for each individual, and thus the accelerometer is able to estimate the amplitude of each recorded phonation event by comparing the intensity of the vocal fold vibration as measured by the accelerometer to the calibration file obtained at the beginning of the data collection period.

Long-Term Average Spectrum (LTAS). Human sound is comprised of an array of spectral energy occurring simultaneously which combines to create the whole. Each frequency in the spectrum constitutes a part, or partial, of the whole. The amplitude of certain partials and the dampening of others results in timbre, or resonance. LTAS measures the average amplitude of partials, and the resulting graphs of spectral energy can be helpful in determining characteristics of vocal quality.

Virtual acoustics. Virtual acoustics refers to sound signals retrieved from an individual practice room via microphones, digitally-processed, then distributed back into the room through loudspeakers. Digital processing produces sound signals intended to imitate various performance environments with the intent of allowing the user to virtually rehearse in a performance environment while still in an individual practice room. While perhaps not truly "virtual," this term is used by the manufacturer of the individual practice rooms employed by this study, and therefore is the term used by the author. Other terms found in the literature to describe electronic means of manipulating sound in rehearsal or performance venues include "active," "adjustable," and "variable" acoustics.

Chapter Two

Review of Literature

This review of literature focuses on two avenues of singing important in vocal training: (a) the acoustical environment singers use to develop technique, including student use of individual practice rooms and the design of individual practice rooms, and (b) the neurological processes involved in the regulation of vocal amplitude, including the Lombard Effect and sidetone amplification. Additionally, it looks at (c) acoustical measures of vocal production that can indicate vocal quality and vocal loading.

Student Use of Individual Practice Rooms

Students may consider various factors in choosing rooms to use for individual practice including availability, condition of the equipment or instruments provided, and, to a lesser extent, acoustics. Although some acoustical studies address large performing spaces for instrumental and vocal music, few studies to date have examined individual university music practice rooms and how the acoustical qualities of these rooms may affect the musicians who use them.

Section II.F.1 of the Handbook for Schools of Music published by the National Association of Schools of Music (NASM) stipulated that adequate practice facilities with appropriate acoustical treatment should be provided for student use (NASM, 2013). However, NASM did not define what is considered appropriate acoustical treatment, nor did the handbook differentiate between common rehearsal spaces used by students in schools of music to suggest what might be appropriate in varying environments.

Scant attention existed in the literature regarding architectural or acoustical considerations for small individual practice rooms. Mehta, Johnson, and Rocafort (1998) suggested individual practice rooms be built with non-parallel walls, short-pile carpet to reduce footfall noise, and absorption panels present on one wall to reduce flutter echo. The authors stated ideal reverberation time for individual practice rooms measuring 9 ft x 6 ft was around 0.4 s at 500 Hz, however it was not specified if these suggestions were intended for singers, instrumentalists, or both. Furthermore, the authors did not provide the source data from which they determined the ideal reverberation rates for practice rooms. The authors did not discuss ideal decay rate.

In a case study at a large Midwestern university school of music, Nelson (2012) surveyed vocal music majors to determine their most preferred practice room in the music building and which room was least preferred. The most preferred individual practice room measured 51 ft^2, 408 ft^3, with 8 ft ceilings, short pile carpet, painted cinder block walls, and no acoustical absorption panel present. The least preferred room measured 54 ft^2, 432 ft^3, with the same construction materials, and an acoustical absorption panel present on an angled wall. Impulse response testing using pink maximum length sequence (MLS), which is equal energy across all octave bands in pseudo-random pulses used to calculate reverberation rate across all octave bands, and reverse Schroeder integration, a calculation method that measures reverberation and decay time using an impulse response, revealed the most preferred practice room to have a reverberation rate of 0.4 s at 2 kHz, near the area of the singer's formant, and a slower decay rate over 50 ms. The least preferred individual practice room had a reverberation rate of only 0.2 s at 2 kHz with a more rapid decay rate. Interestingly, students' stated reasons for their preference of one room over another had more to do with equipment available in the room than acoustical properties.

Acoustical Design of Performance and Rehearsal Spaces

Reverberation in Performance Spaces. Shankland (1979) asserted optimal acoustics for the audience should begin with determining preferences of the performers because the propagation of sound in a room can affect how acoustical characteristics are interpreted by the performer. This is of particular importance to singers as the interpretation of sound may affect phonation behaviors. Numerous guidelines have been published by acoustical experts regarding the optimal reverberation rates in performance spaces (Aretz & Orlowski, 2009; Beranek, 1992; Bradley, 2005; Hartman, 2007; Parkin & Humphreys, 1979). Recommendations have suggested listeners and performers preferred reverberation rate for music performances to range between 1.5 s and 2.0 s, depending on the stylistic period of the music being performed and the size of the ensemble. For instance, a Baroque chamber fugue that would require clarity to perceive each individual fugal voice would retain the crispness of each line in a more dry condition, in contrast to a large Romantic choral work with generally chordal structures and fewer moving lines that would benefit from the fullness added to the sound with greater reverberation. Table 1 provides a list of suggested reverberation times for differing musical genres and performing events.

Table 1

Reverberation Goals for Differing Music Stylistic Periods and Other Performances

Music Style or Performance Type	**T60 goals in seconds at mid-frequencies**
Organ or choral	2.1-4.2
Baroque	1.3-1.5
Early Classical	1.6-1.8
Late Classical/Romantic	1.8-2.2
Later 20th Century	1.4-2.0
Amplified Music	0.5-1.2
Dramatic Theater	0.7-1.1
Cinema	0.4-1.0

Decay Time. Decay time is the amount of time in milliseconds needed for the initial sound source to decrease in amplitude by 60 dB. Depending on the venue, the decay time can last anywhere from a few milliseconds in small rooms to over four or five seconds in large cathedral-like spaces. Longer decay rates could allow for dissipating sound to be interpreted as ambient noise. In addition, sound signals with longer duration can be perceived as louder than they actually are (Epstein & Florentine, Gelfand, 2010; 2006; McFadden, 1975; Richards, 1977;Stevens & Hall, 1966).

Early Reflections. Fry (1980) determined high frequency early reflections are needed by singers on a stage in an auditorium for optimal acoustical feedback. Marshall and Meyer (1985) reported early reflections delayed by 40 ms or more adversely reacted with the reverberation for participants (*N* = 3). The researchers suggested reverberation time contributed both to “ease of ensemble” and singing comfort.

Noting some difficulties with the Marshall and Meyer study, Noson, Sato, Sakai, and Ando (2000) sought to determine the preference of singers ($N = 9$) for single delayed early reflections by creating simulated reflections in a church undergoing acoustical renovations. The researchers asked solo singers to sing a fast tempo song and a slow tempo song on the stage, and then paired singers and asked them to sing in unison a fast tempo passage and a slow tempo passage. Four simulated delayed reflection categories were presented: no reflection, and reflections at 10 ms, 20 ms, and 30 ms. When singing the slow tempo songs, the soloists came to no consensus as to which length of reflection was preferred, however when paired in duets there was a strong preference for a short-delayed reflection of 10 ms. However, in the fast tempo song the duet pairs did not reach a consensus while the soloists preferred a delay in the range of 20 to 30 ms. A third group of singers ($N = 5$) sang the fast tempo songs with a simulated delay fixed at 10 ms from either the left side or from the rear with a gain of +0, +6, or +12 dB. Singers showed a strong preference for a left side reflection over the rear reflection at +0 dB and +6 dB, but not at +12 dB. A third part to the study put singers ($N = 4$) in an anechoic chamber wearing a headset microphone to capture the participant's voice. An electronic speaker placed 1 m behind the participant simulated delayed reflections at 5 ms, 10 ms, 20, and 40 ms in random-ordered pairs. Each participant sang the same fast and slow tempo songs as in the previous portion of the study in pairs and then assigned a preference to one of the acoustical conditions in each pair. Results showed during the slow tempo songs participants showed no clear preference for delayed reflections, but did show a trend in preferences for delays averaging 17.5 ms. The researchers noted that most rooms will have more than one source of reflections and may have up to twelve possible occurrences of reflections from the space. However, the results suggested a possible importance of side reflections for solo and duet singers in producing a preferable acoustical environment.

Late Reflections. Other studies have found late reflections to be important in creating a sense of spaciousness to the listener and the performer. Bradley and Souldre (1995) showed later arriving reflections reduced listeners' sensitivity to early reflections. They concluded early reflections were likely temporally organized along with the direct sound, creating a localization of the sound source, whereas later reflections did not merge temporally with the sound source. The later reflections thus created the perception of a more spatially distributed sound.

Furuya, Fujimoto, Ji, and Higa (2001) found a strong connection between lateral late reflections and a perceived feeling of listener envelopment, and thusly front, back, and overhead reflections contributed to perceived listener envelopment to lesser degrees. Morimoto, Iida, and Sakagami (2001) found a strong link between late reflections from behind the listener and a perceived sense of spaciousness. Wakuda, Furuya, Fujimoto, Isogai, and Anai (2003) confirmed those results by finding reflections from overhead, laterally, and behind produced perceived spaciousness for listeners. Heller (2013) described how, in some instances, reflections of sound can deliver greater energy to the listener than the initial sound source because of the addition of sound energy through subsequent reflections.

Variable Acoustics in Performance Spaces. Performing spaces are generally static spaces with little variation in how the room can be arranged. Thus, the natural acoustics of the space are predetermined. However, many halls and auditoria are used for performances and presentations that can be widely variable in nature and can benefit from adjustable acoustics to accommodate various needs. Modifications to adjust acoustics in an otherwise static space without extensive remodeling, such as curtains or drapes, is known as passive variable acoustics (Poletti, 2010). As an example, curtains that are fully or partially deployed will reduce the reverberation, decay time, and reflections heard by the audience and the performers. However, to increase these measures demands a different kind of modification to the room, namely adding more space (Elson, 1921). Some halls, such as the Eugene McDermott Concert Hall at the Meyerson Symphony Center in Dallas, Texas, included passive variable acoustics in the design by adding spaces around the ceiling of the hall accessible by 2.5 ton concrete doors. Opening the doors allowed for more space for lower frequency sounds with longer wavelengths, which increased both reverberation rate and decay time in those lower frequencies, adding a “blooming” quality to the sound (Barron, 2008).

Methods of adjusting and expanding certain acoustical characteristics without modifying physical structures became a desirable solution to both new and older concert halls. Using electronic enhancement systems, often out of the eye of the listener, performing spaces could be adjusted to accommodate multiple uses. Separate systems can be installed to enhance stage acoustics, providing musicians with the acoustical feedback desired without hindering the audience experience. Hoover and Ellison (2013) described stage systems that utilized microphones to collect sound from the musicians and then process the sound through a digital processor to control for early and late reflections, reverberation time, decay density, and frequency response. Speakers above and to the side of the performers were placed in such a way that musicians could not localize to any individual speaker while the system was functioning.

Ellison and Schwenke (2010) described characteristics of room construction necessary for adjustable acoustic systems to function properly without any undo interference from the environment. Some acoustical anomalies, such as echoes or ringing, can be disguised by active acoustical systems if the simulated reflections produced by the system are greater than those that naturally occur in the room. However, designing the space to reduce acoustic anomalies such as flutter echoes would prevent those undesirable sounds from being accidentally enhanced by the system. Ambient noise should be consistent with recommended values for activities that would be commonly hosted in that room. For instance, rooms used for cinema, an activity that could be greatly hindered by ambient noise, should have an ambient noise level below NC25 with a sound isolation of at least STC 60. The authors concluded that pursuing adaptable acoustic solutions for spaces utilized for multiple purposes was worthwhile.

Reverberation in Rehearsal Spaces. Various writings have addressed optimal acoustical characteristics for larger rehearsal rooms (Beranek, 1992; Elson, 1921; Manternach, 2010; Mehta, 1998; Pancharatnam & Ramachandraiah, 2005), often with differentiating suggestions depending on the size of the ensemble, the voice or instrument type, or the genre of the music being rehearsed. Authors considered reverberation rate an important acoustical characteristic of rehearsal spaces, with some attention paid to decay rate, room gain, or other factors that could influence the performers' perception.

Young and Gales (1956) surveyed school music teachers in San Diego to determine preferences for rehearsal spaces for different kinds of ensembles. Generally, directors stated marching band should have the least reverberant space for rehearsal while choir space should be the most reverberant. The preferred reverberation time for an occupied choral rehearsal space was around 1.1 s.

Manternach (2010) surveyed choral directors ($N = 33$) to determine what acoustical characteristics were desirable in a rehearsal space for choirs and performed acoustical testing in rehearsal spaces ($N = 3$) used for choir. Participants used a Likert-type scale to describe their current rehearsal space from Very Dry to Very Reverberant. Responses split fairly evenly, with 36% reporting a reverberant space, 45% reporting a dry environment, and 15% reporting a moderate space. When asked what kind of reverberation they would prefer to have in their rehearsal space, the vast majority (95%) reported a preference for a moderate reverberation. The majority of directors (52%) reported a preference for a rehearsal space that was slightly drier than their performance space, and 76% reported a preference to have some control over adjusting the reverberation in the rehearsal space. Only one director already had adjustable acoustics in the rehearsal space. A second part to the study tested rehearsal rooms (N =3) and found reverberation times of 0.5 s, 0.9 s, and 3.4s. None of these rooms had adjustable acoustics.

Electronic Virtual Acoustics for Rehearsal and Individual Practice Rooms. The success of electronic active acoustics in performance venues brought a demand for active systems in rehearsal venues. Freiheit (2003, November) described active acoustics systems for rehearsal spaces in similar terms to those used for performance venues. Manufacturers designed processing systems that would employ many of the same principles used in larger performance venues, but eliminated auditory artifacts, such as distortion and speaker noise, that might be more apparent in smaller venues. Careful speaker placement provided musicians with a sense of immersion in the sound without localizing to any one point of output. The digital processing systems also contained numerous presets that would mimic different performing spaces, including customizing a setting that would mimic the performing space most often used by the ensemble.

Individual practice rooms are used by soloists and small ensembles for rehearsal and provide different acoustical challenges than larger performance venues. Klepper (1989) described small rooms for music rehearsal as “unnatural environments for music production.” He stated that because of their size, individual practice rooms with too much absorption could sound overly dry or anechoic, but with too little absorption would sound “boxy” with uneven frequency response.

Freiheit (2003, April) described virtual acoustical systems for individual practice rooms similar to electronic active acoustics systems used in larger rehearsal spaces. The rooms were self-contained units with separate electrical and HVAC systems to avoid noise pollution from outside sources. Perforated walls and ceiling tiles housed speakers spread throughout the room in such a way as to reduce the possibility of the user localizing to any signal output. Adjacent speakers connected to separate channels to avoid a concentration of sound, intending rather to provide the user with the perception of being enveloped in sound. The digital processing system adjusted gain in the speakers to lessen the chance of feedback from the microphones placed in the walls. A digital interface allowed for the user to select the virtual environment in which to rehearse.

Barbar (2013) detailed the general pathway of the sound signal in an active acoustical system designed for small rooms. Microphones installed in the walls or ceiling of the room picked up the signal from the user and transferred the sound to a microphone pre-amplifier and then to an analog equalizer. From there the sound signal passed through an audio/digital converter before processing in the digital signal processor. The new digital signal was then converted to audio and passed to a power amplifier that sent the signal to speakers throughout the room. Figure 5 illustrates the signal pathway from input to output.

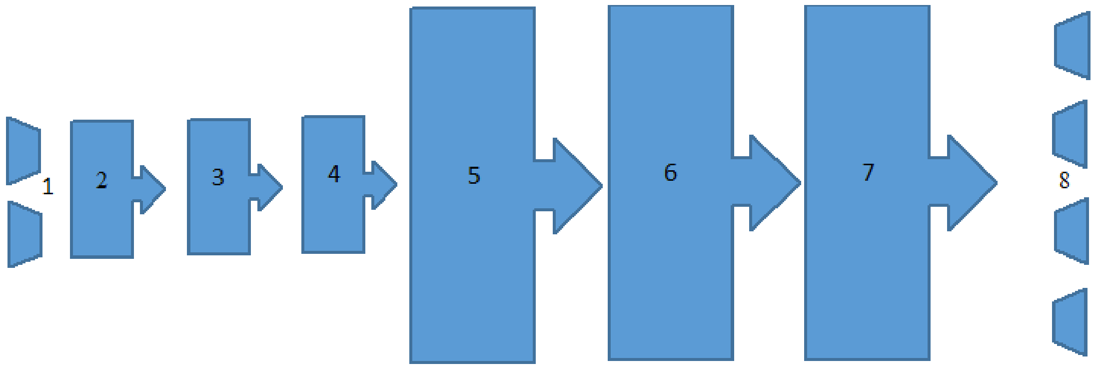


Figure 5. Schematic of the signal pathway in an active acoustic processing system. 1) Microphones pick up user sound, 2) Microphone pre-amplifier, 3) Audio/digital converter, 4) Calibration equalizer, 5) Digital signal processing, 6) Digital/audio converter, 7) Power amplifier, and 8) Speakers.

Summary. The acoustical design of many modern performance spaces has included both passive active acoustics and electronic active acoustics to manipulate certain acoustical characteristics, such as reverberation time and early and late reflections. Due to the success of active acoustics systems in performance spaces, adjustable acoustical measures were introduced into rehearsal spaces in order to better simulate the performance environment. Similar systems are now being used in individual practice rooms. The design of the self-contained individual practice rooms with electronic acoustics systems serve to envelop the user in sound and prevent localization to any single sound source.

Lombard Effect and Vocal Production

Singing is dependent on cognitive motor planning, proprioception (awareness of position and movement of the body), and auditory perception. Howell (1985) showed altered auditory feedback affected amplitude of speech. Lane and Tranel (1971) suggested speakers generally lowered their amplitudes when their own auditory feedback increased and increased their amplitudes when auditory feedback decreased, a phenomenon known as “sidetone-amplification effect.” This effect was temporary, and speakers’ voices returned to normal after a time. By contrast, in the presence of noise, speakers showed evidence of the Lombard Effect and did not normalize amplitude over time.

Siegel and Pick, Jr. (1974) showed similar results. Adult speakers ($N = 20$) spoke aloud on any topic they chose while wearing headphones which played back their own voice with adjustments of sidetone amplification of +0 dB, +10 dB, and +20 dB in randomized orders. In the first phase, participants received no instructions during the three conditions (neutral). In the second phase, participants were instructed to pay attention to the sound of their own voice through the headphones and adjust their volume to maintain a constant amplitude (maximizing condition). For example, if the sidetone became louder, the participant should speak more softly to compensate. For the third phase, participants received instructions to pay attention to how their voices felt during their speech and maintain the same feeling throughout the speech exercise (minimizing condition). Results showed participants changed their output by a small but significant ratio in the maximizing condition, with a smaller ratio of change with the neutral and minimizing conditions. A second experiment asked female participants ($N = 24$) to speak on any topic while noise played through headphones at varying degrees of intensity. The participants received the same directions given to participants in the first experiment. The participants did not show an ability to compensate their own vocal production in the presence of noise, suggesting speakers are not likely able to resist the sidetone-amplification effect in the presence of noise.

Egan (1975) presented noise binaurally through earphones to male ($N = 15$) and female ($N = 15$) participants in four different frequency regions at differing amplitudes. Noise frequency regions were 0.05-0.5, 0.5-2.0, 2.0-6.0, and 0.05-6.0 kHz at 11 different sound pressure levels from 20 to 120 decibels. Participants read aloud passages in quiet and noise conditions. Results revealed an increase in vocal amplitude in noise conditions above 50 dB SPL, and greater increases in noise frequency bands of 2.0-6.0 and 0.05-6.0 kHz. Interestingly, females showed a 2-4 dB greater increase in vocal amplitude than male participants. Castellanos, Benedi, and Casacuberta (1996) also noted sex differences in Lombard Effect. Data from Junqua (1996) suggested the overall magnitude of Lombard Effect was highly variable between speakers and could be affected by gender, language, and context.

Summary. Numerous studies resulted in confirmation of the Lombard Effect in speakers, and female speakers tended to display a greater change in amplitude. Researchers found speakers could be trained to overcome the Lombard Effect when told to concentrate on the feel of their vocal production, rather than on the sound. These results indicated the possibility for muscle memory to be a useful tool in overcoming the reflexive nature of the Lombard Effect.

Neurological Basis for the Lombard Effect

The neurological basis for the interpretation of sound by the singer may be linked to a process known as temporal integration or temporal summation. In this phenomenon, the ear integrates sound energy across a period of around 200 ms, during which time the brain analyzes the sound signal for perceived frequency, perceived amplitude or loudness, directional information, and environmental cues, such as ambient noise. Greater perceived energy in the ambient noise could result in an increase in amplitude from the singer, a principle known as the Lombard Effect.

Hage, Jürgens, and Ehret (2006) studied the neural response to vocalizations of squirrel monkeys in noise using surgically implanted electrodes on the brainstem of 3 three-year-old male squirrel monkeys. Recording sessions occurred daily during feeding time and lasted approximately 10-15 minutes. Auditory stimuli included white noise produced by the researchers and spontaneous vocalizations from the monkeys. Results showed several areas of audio-vocal neural integration including some not previously recorded. Using the electrical impulses from the electrodes, individual neurons were located in the superior olivary complex (195), the ventral nucleus of the lateral lenmiscus (19), the lateral lemniscus (16), and the pontine reticular formation (223). The researchers identified three groups of neurons: Group 1 (auditory neurons) responded to noise but showed no activity prior to onset of self-produced vocalizations; Group 2 (nonauditory neurons) reacted spontaneously but showed no reaction to auditory stimuli; Group 3 (audio-vocal neurons) reacted to self-produced vocalizations with a noticeable change in neuronal activity prior to vocal onset, as well as being active in response to auditory stimuli and vocalizations from peers. Group 3 neurons further divided into two subsets based on how they responded to self-produced vocalization: excitatory audio-vocal units located mostly in the lateral brainstem, and inhibitory audio-vocal units in the more medial portions of the brainstem. About one-third of audio-vocal neurons responded to external sounds. In addition, purely auditory neurons (Group 1) located near an audio-vocal neuron showed similar responses to external stimuli. The authors hypothesized these neurons play a role in the amplitude of vocal output in response to masking noise. Correlating these results with the data of a previous study (Hage & Jürgens, 2006) locating structures in the vocalization pathway, the close approximation of the audio-vocal units and the ventrolateral pontine vocalization area suggested a reciprocal relationship between the two.

The ventrolateral pontine vocalization area is connected to multiple neuron pools that control various aspects of vocalization, such as amplitude and duration. Any changes or reflexes affecting those characteristics could be influenced by signals received from the audio-vocal neurons (Hage, Jürgens, & Ehret, 2006). These neurons are situated in an area of transition between the pons and the midbrain which integrates auditory perception and vocal production. This transitional area shows evidence of phasic responses to auditory stimuli (Brumm & Zollinger, 2011). Jürgens (2009) also suggested the periaqueductal gray (PAG), gray matter surrounding the cerebral acquaduct in the midbrain, acted as a gating system that effects vocal initialization and intensity, though not vocal patterning. The PAG is not directly related to the phonatory motor neurons, but rather indirectly connected via other neurons that connect to the phonatory motor control, suggesting that intensity control is only indirectly related to the motor cortex and thus may be somewhat reflexive (Jürgens, 2002).

Electrical stimulation of the PAG produced species-specific vocalizations in several species, including cats, bats, squirrel monkeys, rhesus monkeys, chimpanzees, and humans, suggesting vocalization neurons not only travel through the PAG on the way to the motor cortex, but possibly also synapse in that area (Jürgens, 2002). The vocalizations produced were habitual sounds, such as hissing, yapping, or laughing. Simonyan and Horwitz (2011) noted involuntary or innate vocalizations in mammals appeared to be initiated in the sensory and motor nuclei located in the lower brainstem, while voluntary vocalizations initiated in the forebrain.

Nonaka, Takahashi, Enomoto, Katada, and Unno (1997) electrically stimulated the PAG of decerebrated cats ($N = 10$) in the presence of auditory stimuli from a loudspeaker at 105 dB SPL and a control scenario with no noise. The researchers used electromyograms (EMGs) to monitor the thyroarytenoid muscle (TA), the diaphragm, and the external oblique abdominal muscles. The cats produced species-specific vocalizations in both conditions, however, in the presence of the noise, the cats exhibited greater vocal intensity and greater adduction in the TA and external oblique abdominal muscles. Results suggested that neuronal control for the Lombard Effect is sufficient in the midbrain and can be exhibited without any voluntary motor cortex involvement. In other words, the change in amplitude due to the Lombard Effect may be largely reflexive. However, loose neuronal connections in the afferent auditory pathway where the PAG and the dorsal nucleus of the lateral lemniscus (LLD) converge suggest the possibility for some voluntary control over the Lombard Effect in higher cortical areas.

Eliades and Wang (2012) showed differences in auditory processing in the presence of masking noise in marmoset monkeys. During self-produced vocalizations in normal conditions with no masking noise, some neurons related to auditory feedback are suppressed. However, in the presence of masking noise, that suppression decreased, resulting in a greater sensitivity of the auditory cortex to sensory feedback during self-produced vocalization. The researchers hypothesized the change in suppression was a correction of the auditory cortex toward a normalization of sensory feedback, compensating for the distance between the current vocalization representation and a target representation.

Similar results in human neuroimaging studies showed a suppression of the auditory cortex during participants' self-speech (Numminen, Salmelin, & Hari, 1999; Curio, Neuloh, Numminen, Jousmäki & Hari, 2000; Houde, Nagarjan, Sekihara, & Merzenich, 2002; Ventura, Nagarajan & Houde, 2009), but a change in auditory feedback, such as masking noise or changes in vowel formants, decreased the extent of the suppression in the auditory cortex (Houde & Jordan, 2002; Heinks-Maldonado, Nagarajan, & Houde, 2006). Liu, Zhang, Xu, and Larson (2007) found participants ($N = 10$) compensated their vocal amplitude when auditory feedback was adjusted by ±3 dB for 200 ms durations. Vocal amplitude shifted by a mean of 0.86 dB with a mean latency of 142 ms. The rapid adaptation of participants' vocal amplitude suggested a reflex mechanism in place for controlling the amplitude of speech production.

Summary. The complete neural picture regarding the Lombard Effect is still somewhat unclear. However, neural research in multiple species suggests a complex arrangement of multiple levels of neural control of Lombard Effect, from automatic brainstem reflexes to higher cortical mechanisms.

Acoustics and Vocal Production

Recent studies have examined the effects of room acoustics on speech production. Pelegrin-Garcia and Brunskog (2012) put adult speakers (*N* = 13 and *N* =21 in two experimental groups) in an absorbent room with ten electronically-simulated acoustical conditions including differing reverberation times and decay rates. In each condition, speakers gave a three-minute lecture in their native language. Participants had a tendency to lower the intensity of their voices as the auditory feedback increased, though the extent of this effect was highly variable.

Reverberation time is often considered the most important acoustical parameter of a room. Pelegrin-Garcia, Fuentes-Mendizabal, Brunskog, and Jeong (2011) found changes in room acoustics, such as reverberation, room gain, reflections, and sidetone, produced changes in speech production similar to the Lombard Effect. The researchers instructed participants (*N* = 14) to match the loudness of their own voices to a reference sound kept at a constant amplitude. As the synthesized acoustical characteristics of the room changed, the researchers noted changes in the amplitude of the participants, which showed participants can use clues other than loudness to adjust their own speaking voices.

Husson (1962) reported subjective physiological conditions during vocalization in rooms for performance with known reverberation times. Rooms with less than 0.5 s of reverberation time led to “very laborious and rapidly fatiguing singing” (p. 9). Rooms with 0.5 to 1.0 s of reverberation time produced “laborious phonation.” Husson continued, “An experienced singer can, however, voluntarily modify his buccopharyngeal adaptation in order to reduce this distressing characteristic" (p. 9), suggesting that adequate training may help the singer to overcome reflexive phonation behaviors in various acoustical environments.

Foot (1965) measured the effect of auditory feedback on the intensity of singing. Participants ($N = 25$) sang the vowel [a] in an absorptive room giving low-intensity auditory feedback, and again in the same room modified with reflective panels placed in such a way as to give high-intensity feedback. In 44 out of 50 trials, vocal output evidenced significantly greater amplitude in the low-intensity feedback condition, but participants perceived no differences in their tone quality between low-intensity and high-intensity conditions.

Guyette (1996) compared the impressions of singers ($N = 5$) in multiple acoustical simulations with perceptions of expert listeners. Using a Lexicon CP1 effects processor, the researcher designed nine simulated acoustical environments in an anechoic chamber. Participants sang three songs in each of the different acoustical characteristics. Participants completed surveys after each singing repetition to determine perception of physiological changes in their singing technique as the environment changed. Singer perceptions of adjustments as acoustics changed did not match perceptions reported by a panel of expert listeners, which heard recordings of the participants in each acoustical environment. The researcher concluded that singers may adjust unconsciously or reflexively to an acoustical environment. The participants reported a preference for more reverberant spaces overall. Comparisons between survey results from participants and listeners revealed singers and listeners did not always agree on perceptions of aspects of singing including tone quality, amplitude, and diction.

A case study by Nelson (2014) measured singers' ($N = 8$) phonation behaviors in a room deemed the most preferred individual practice room by vocal majors in a music building at a large Midwestern university. The most preferred room had a longer reverberation rate when compared to the least preferred practice room. Participants wore an Ambulatory Phonation Monitor (APM) and performed a series of six vocalises and the melodies to two well-known Italian art songs in two rounds using two neutral syllables. Seven participants sang with greater amplitude in the most preferred room with the longer reverberation time. The lone participant with varying results reported on the survey a perceived a greater reverberation in the least preferred room and subsequently adjusted technique, however, the participant's perception did not match the acoustical findings and could explain the difference results from the other participants. In general, participants were inconsistently aware of the amplitude adjustments made between the two rooms. Participant preferences were evenly split between the two rooms.

Measures of Vocal Production. Recent studies of vocal production have attempted to quantify vocal loading, or the stress exerted on the vocal muscles during periods of use. Remacle, Finck, Roche and Morsomme (2012) analyzed acoustical data and subjective ratings acquired from participants ($N = 50$) who read aloud in two hour-long sessions at varying amplitudes (60-65 dB SPL and 70-75 dB SPL, respectively). Results indicated that prolonged reading at a higher amplitude significantly influenced shimmer percentage, average F_0, and frequency range, as well as participants' subjective ratings of phonation effort, vocal fatigue, mean F_0, and maximum phonation time. The authors concluded that vocal amplitude and duration can both affect vocal loading. Titze, Svec, and Popolo (2003) asked participants ($N = 6$) to read in normal, monotone, and exaggerated speech a passage from the "Goldilocks" passage (Svec, Popolo, & Titze, 2003). Increases in the variation of F_0 and SPL produced increases in distance dose (Dd).

Previous research measured vocal timbre using the long-term average spectrum (LTAS), the mean of all sound spectra taken over a relatively long sound sample (Baker and Orlikoff, 2000). Ferguson, Kenney, and Cabrera (2010) used LTAS to measure the energy ratio (ER) and mean sound pressure level (SPL) from nine male classical singers with differing levels of training. The researchers analyzed the spectral energy in the 2-4 kHz range, the area that most likely contained the singer's formant for the ER and the mean SPL for each recorded sample. Participants with more singing experience tended to show greater SPL overall and a more narrow distribution of spectral energy than singers with less experience.

Nacci, Fattori, Mancini, Panicucci, Ursino, Cartaino, and Berrettini (2013) examined clinical and research uses for the Ambulatory Phonation Monitor (APM; KayPENTAX) in voice assessment. Benefits noted in using the APM included the longitudinal possibilities in data collection, rather than collecting small samples of voicing from a microphone. The APM used transducers connected to the neck just above the sternal notch to measure vibratory patterns of the vocal folds, enabling measurement of vocal dosing, vocal amplitude in dB SPL, fundamental frequency, phonation density, and total phonation time over the entire recording period without the confounding factors of ambient noise or privacy issues associated with using microphones for recording. The researchers determined the function of the APM is valid for artistic uses in examining phonation behaviors.

Perception of Electronic Self Sound. Kaplan, Aziz-Zadeh, Uddin, and Iacoboni (2008) used fMRI to examine the brains of right-handed participants (N =12) in four conditions: seeing a picture of one's own face, seeing a picture of a friend's face, hearing a recording of one's own voice, and hearing a recording of a friend's voice. The fMRI results showed greater activity in the inferior frontal gyrus of participants when seeing his or her own face and his or her own voice when compared to that of a friend. These results could suggest that hearing an electronic version of one's own voice could be recognized as self-sound, however, fMRI results were not compared to hearing one's own voice as the participant was speaking and receiving acoustical feedback without electronic recording or manipulation.

Summary. Singers are often asked to perform in various spaces with widely varying acoustical properties. Universities provide rooms for student singers to use in rehearsal, but these rooms are often spare with little attention paid to acoustical concerns and can be vastly different from a performing environment. Prefabricated rooms with electronic virtual acoustics claim to mimic common performing environments using microphones, a computer-processing system, and well-placed speakers, somewhat similar to electronic active acoustics systems that have been in use in performing halls around the world for some time.

What the singer hears can affect phonation behaviors. The well-documented Lombard Effect contributes to changes in amplitude in speakers and singers. It is unknown at what point decaying sound in a space ceases to be perceived as self-sound and becomes ambient noise and thus could trigger the Lombard Effect in singers. Similarly, although there is evidence of higher frontal lobe activity when hearing one's own speaking voice, it is unclear if electronically-manipulated singings is perceived as self-sound or as ambient noise.

Lombard Effect, and thus the compensatory changes in amplitude, appear to be largely reflexive in nature with its neurological basis in the brainstem rather than in higher cortical areas. This would seem to indicate that singers and speakers may be largely unaware of their own changes in amplitude, and may be less able to consciously inhibit vocal amplitude increases. However, relying on muscle memory and proprioception, rather than auditory cues, has shown to be helpful in monitoring phonation behaviors by singers in various noise conditions.

Acoustical feedback can effect vocal production and vocal loading in singers and speakers. Results of previous studies varied on phonation behaviors in differing acoustical environments, with some finding a decrease in vocal amplitude when in the presence of higher intensity feedback while others found an increase. However, nearly all found singers to generally be unaware of changes in their own vocal production when introduced to different acoustical environments. Researchers have hypothesized that some changes in acoustical characteristics of an environment can produce a change in singing behaviors similar to the Lombard Effect.

Chapter Three

Methods

The purpose of this study was to assess selected phonation behaviors and perceptions of female collegiate vocal soloists ($N = 20$) performing in two rooms: (a) a university Recital Hall, and (b) an individual practice room with four digitally-adjustable simulations of reverberation and reflections (Practice Room, Large Auditorium, Large Recital Hall, and Arena). This chapter details the participants, procedures, equipment, and analyses needed to carry out that purpose.

Participants

Participants ($N = 20$) for this study constituted a convenience sample of female singers. Participants with at least two years of singing experience at the college or university level with no self-reported hearing or vocal inefficiencies were invited to participate. Participants were recruited by word of mouth and included current and former vocal music students from a local large Midwestern university, professional vocal musicians from the local metropolitan area, and local vocal music teachers.

Sung Examples

Participants sang the melodies of two Italian art songs (see Figures 6 and 7) in one recital hall condition and four virtual acoustics conditions The songs chosen were the melodies of “Lasciateme, morire” and “Nel cor piu non mi sento” from the G. Schirmer edition of *Twenty-Four Italian Songs and Arias* for medium low voice.

I selected these songs because of the difference in tempo between each melody, the similarity in range, the related key signatures (one in Eb major and one in c minor), and their likely familiarity to participants. I modified the melody of “Nel cor più non mi sento” slightly to remove written embellishments and any notes shorter in duration than a sixteenth note. I then timed “Lasciatemi, morire” at 55 s and “Nel cor più non mi sento” at 37 s at the designated tempo for each melody. When combined for LTAS analysis, the two sung melodies together totaled 92 s.

Figure 6. The melody of “Lasciateme, morire” as sung by the participants.

Figure 7. The melody of "Nel cor piu non mi sento" as sung by the participants.

Prior to data collection, participants had access to these scores and mp3 files via a Dropbox file. I instructed participants to learn the melodies to the songs on the neutral syllable [dɑ] at the designated tempi.

Equipment

Ambulatory Phonation Monitor. Each participant wore an Ambulatory Phonation Monitor (KayPENTAX Model 3200) for the duration of the testing. The APM consisted of a small transducer attached with medical adhesive to the outside of the neck just above the sternal notch. Before each data collection period, I visually examined the transducer's wires and connectors for damage.

Participants were instructed to thoroughly clean the skin above the sternal notch with an alcohol wipe to remove any residue on the skin that might hinder a complete adhesion. I then brushed a thin layer of medical adhesive over the skin-side surface of the transducer to ensure the entire surface of the transducer would attach thoroughly. I carefully placed the transducer on the participant's neck slightly above the sternal notch. The participant held the transducer firmly against the skin for about one minute while the adhesive dried. I then connected the transducer's cable into the battery-powered microprocessor and placed the microprocessor into a waist pack.

Each participant required calibration detailed in the manufacturer's instructions for the APM to accurately measure vocal fold vibration. The participant sat at a desk in front of a laptop loaded with APM software. A microphone positioned 15 cm from the participant's mouth measured by a metal spacer captured the participant's voice for calibration. The microphone connected via USB to the computer, which in turn was connected via cable to the microprocessor. A green status light on the microprocessor indicated the appropriate connections had been made and the unit was ready for calibration.

The participant executed a vocal slide beginning at a low pitch and low amplitude and gradually rising in pitch and amplitude. At least 20 frequency data points and an SPL range of at least 40 dB SPL constituted a successful calibration, confirmed by an onscreen dialog box. Participants repeated the calibration process as necessary to obtain a successful calibration. I clicked on the "Start Phonation Monitor" button in the dialog box at which time the APM unit began collecting phonation data, as indicated by the status light on the microprocessor which changed from green to flashing orange. The cable connecting the microprocessor to the computer was disconnected. The transducer measured vibrations produced by the movement of the vocal folds and calculated SPL based on the intensity of those vibrations. Raw data were collected 20 times per second and transferred via cable to the battery-powered microprocessor.

Head-Mounted Microphone. Participants also wore a battery-powered, head-mounted, omni-directional microphone (Countryman Model E6DW7) to record the vocal signal. The microphone end cap recorded the voice signal as a flat response without boosting higher frequency partials. The microphone frequency response ranged from 30 Hz to 15 kHz with an amplitude sensitivity of 0.60 mV/Pascal. Equivalent acoustic noise levels were 39 dBA SPL and the overload sound pressure level was 140 dB SPL.

I calibrated the microphone before each recording period by removing the end cap and placing the end of the boom into the calibrator set at 94 dB at 1 kHz. I installed two 9-volt batteries into the battery pack and connected the microphone to a Tascam mobile US-122 MKII USB 2.0 preamplifier and audio/MIDI interface which then connected via USB to a MacBook Pro loaded with Audacity 2.0.5 software. I turned on the power source to the microphone and the calibrator and selected “Record” in Audacity to record a waveform produced by the calibrator. I selected “Analyze” and then “Plot Spectrum” and set the algorithm to spectrum, the function to Hanning window, the size to 512, and the axis to linear frequency. The analysis window showed the frequency and amplitude of the 1 kHz. I adjusted the preamplifier control knobs and retested until the amplitude at 1 kHz read -39.2 dB for each recording session. I replaced the end cap on the boom of the microphone before placing the microphone on the participant.

A 5 cm spacer marked the distance between the microphone end cap and the right corner of the participant’s mouth. A small piece of medical tape adhered the boom of the microphone to the participant’s cheek to maintain the prescribed distance from the microphone end cap to the participant’s mouth during the recording period. A clip secured the wire from the earpiece to the participant’s lapel and the battery pack clipped to the participants waist band. The boom of the microphone was positioned near the right corner of the participant's mouth, out of the direct airstream. Each iteration was recorded into the laptop using Audacity at 44.1 kHz at a 16 bit sampling rate.

Individual Practice Room. The Wenger individual practice room with virtual acoustics utilized for this study consisted of prefabricated components installed in a small Midwestern university school of music. Walls were constructed of cold-rolled steel sheet compliant with ASTM A 1008/A, commercial steel, Type B. The walls contained sound attenuation materials compliant with ASTM C 665, Type I, 1.5-lb/cu. Ft (24 kg/cu. m). Wall frames were constructed of 14-gauge/0.075 in. (1.91 mm) steel channels and connected with customized gaskets that created a compression seal and locked each wall together. Wall panels measured 96' x 30' x 4', with an interior face 22-gauge/0.0299 in. (0.76 mm) perforated or solid steel panel and an exterior face of 16-gauge/0.0598 in. (1.52 mm) solid steel panel (Wenger, 2004). Perforated panels hid speakers along the walls and ceiling. Figure 8 shows corners of the individual practice room, showing both solid and perforated wall panels.

Figure 8. Corners of the individual practice room showing solid and perforated wall panels.

Each room contained a sound-isolating door with a double-paned glass panel and magnetic seals along three edges and a floor sweep seal. Each room utilized internally installed lighting, wiring, and ventilation. Two switches on the wall with the door turned on the lights and ventilation system and the active acoustical system. Ceiling panels contained lights, sprinkler connections, and speakers, and were constructed with the same steel material as the interior walls (Wenger, 2004). Short pile carpet tiles covered the floor. Figure 9 shows a portion of the magnetic seals along the edge of the door.

Figure 9. Magnetic door seal.

Microphones contained behind a small, perforated screen in perforated panel walls picked up user sounds. The manufacturer retained proprietary rights to the technical details of the microphones, and so are excluded from this document. Figure 10 shows the microphone screen in a portion of a perforated panel.

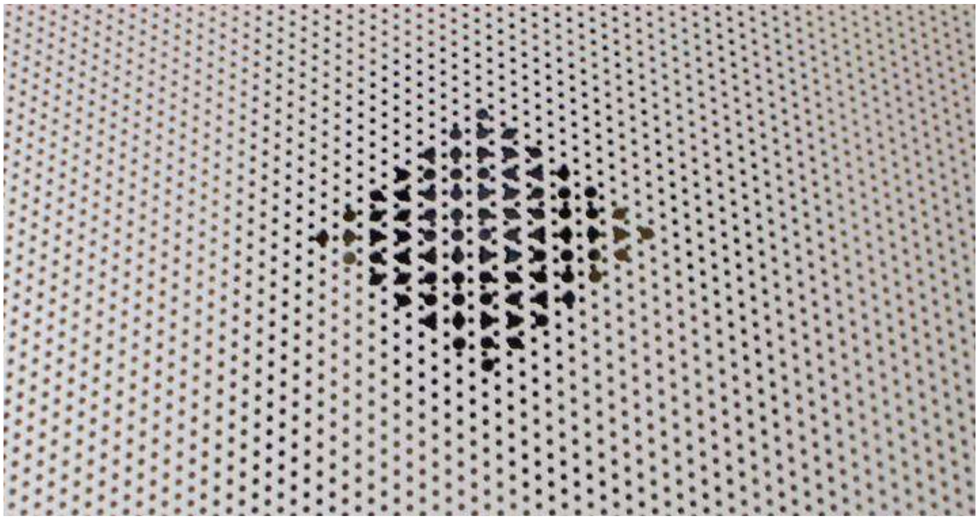


Figure 10. Microphone opening in a perforated wall panel.

Speakers were tiled in the room to reduce the likelihood a user could localize to any particular speaker location. Each channel in the processor corresponded to a speaker array. Figure 11 shows an example of the tiling of speakers in the ceiling of the individual practice room.

1	2	3	4
3	4	1	2
1	2	3	4

Figure 11. Schematic of speaker tiling in the ceiling.

Figures 12 and 13 show photos of the speakers installed in an individual practice room under construction.

Figure 12. Speakers tiled in a room under construction (Freiheit, 2010).

Figure 13. Speakers tiled in a room under construction (Freiheit, 2010).

The virtual acoustical system control panel had ten buttons for the nine active acoustical settings available and an “Off” button. Two volume control buttons allowed the user to set the volume from a minimum volume of 1 to a maximum of 30. For this study, the volume was set at

30 for each data collection period. Additional buttons and USB connections allowed users to record sessions onto a USB drive, but were not utilized during this study. Figure 14 shows a portion of the virtual acoustics control panel.

Figure 14. Control panel for the active acoustical system.

Manufacturer materials reported the ambient noise in the individual practice room to be less than NC 25. Once turned on, the ventilation system ran continuously. Total ventilation exchange averaged 35 times per hour, with some variability due to occupation. Ventilation panels in the ceiling measured 15 in. by 6 in. Sound-absorbing duct liners 1-1/2 in. thick lined ducts that connected to the main buildings HVAC system (Wenger, 2004).

Four active acoustical settings provided the variables for the acoustical and singing tests.

I chose the settings based on the manufacturer's descriptions as spaces that would typically be found on larger university campuses. The manufacturer described the settings as follows:

- Practice Room: Modeled after the acoustics of a typical 8' x 10' music practice room with minimal acoustic treatment on the walls.
- Large Recital Hall: A larger recital hall, ranging from 350 to 500 seats. Halls like these are typically found on college campuses and intended for performances of larger groups. The hall is modeled after spaces with hard walls and high ceilings with the addition of diffusing wood panels along the side and back walls. In the ceiling area are reflective clouds to provide enhanced early reflections. Characteristics of this space are a bright sound with a smooth, longer decay of sound.
- Large Auditorium: A large space with 1,200 to 1,500 seats. These types of auditoriums are common in larger high schools, college schools of music, larger churches, performing arts centers, and civic facilities. It's modeled with hard walls and ceilings, carpeted aisle ways, padded seating, and absorption on the back wall to prevent strong reflections back to the stage. The room has a large proscenium stage with sidewalls containing wood diffusing surfaces and additional reflective surfaces in the ceiling area near the stage. Characteristics of this space include a warm, enveloping sound yet still maintaining good clarity to the sound. There is a noticeably longer decay of sound.
- Arena: Very large space with seating for 10,000. The space is modeled after typical indoor sports facilities found on larger college campuses and in larger cities. The characteristic sound of these spaces is dominated by hard surfaces with

little absorption. Sidewalls are located some distance away, creating early reflections that are noticeably delayed. Sound decays very slowly in these types of spaces due to the size and larger area of hard reflecting surfaces (Wenger, 2006).

For the purposes of this study I used the manufacturer's labels for each of the corresponding virtual acoustic conditions.

Acoustical Testing. I conducted acoustical testing to determine if the different active acoustical settings yielded measurable acoustical results. Impulse response testing using a maximum length sequence (MLS) impulse measured reverberation times at T30, the time required for the source sound to decay by 30 dB, averaged across all octave bands and also separated into individual octave bands. Testing used both a dodecahedron speaker to equally distribute sound throughout the room and a small directional speaker to mimic the sound directionality from a singer's head and mouth. Speakers stood in the center of the room at approximately head height to an average female. During each test, I stood outside of the room with the door closed. Impulse response tests using the small directional speaker and pink MLS were repeated for each of the four active acoustical settings used for this study.

The "Practice Room" setting showed a reverberation time of 0.23 s averaged across all octave bands with pink MLS. Figure 15 graphs the reverberation time at T30.

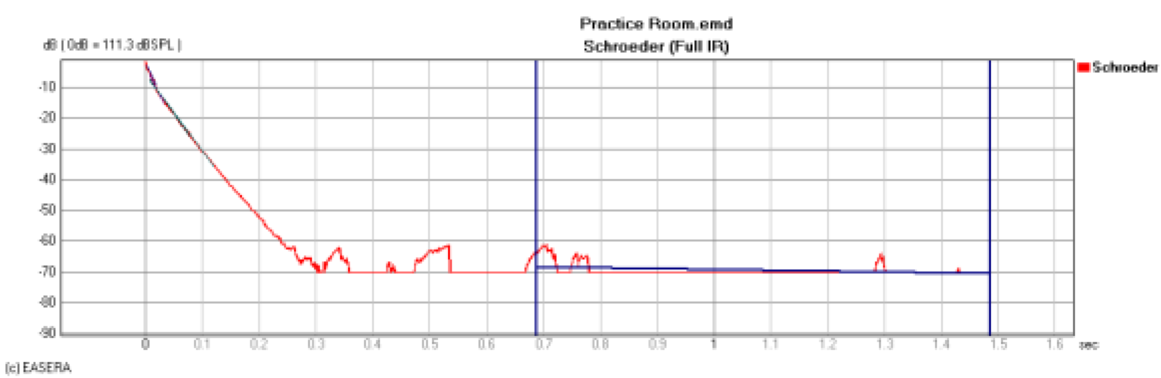


Figure 15. Reverberation time averaged across all octave bands in "Practice Room."

Table 2 displays reverberation times separated into individual octave bands at T10, T20, and T30.

Table 2

Reverberation Times in Seconds in Individual Octave Bands in "Practice Room"

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	250 Hz -2 kHz	500 Hz -4 kHz
EDT	0.09	0.08	0.16	0.19	0.23	0.20	0.17	0.16	0.19
T10	0.10	0.12	0.21	0.17	0.21	0.18	0.15	0.18	0.19
T20	0.20	0.12	0.14	0.22	0.25	0.22	0.21	0.18	0.21
T30	0.16	0.14	0.19	0.27	0.26	0.23	0.21	0.21	0.23

The "Large Recital Hall" setting showed similar results averaged across all octave bands. Figure 16 displays the reverberation time at T30.

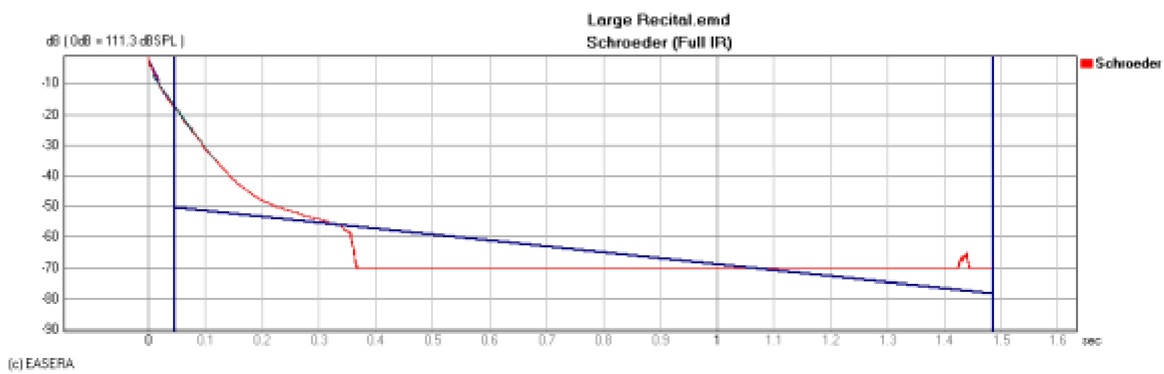


Figure 16. Reverberation time averaged across octave bands in "Large Recital Hall."

Individual octave bands showed a very small increase in reverberation time at T30, but likely not enough to be noticeable. Table 3 displays the variation in reverberation time at T10, T20, and T30 in the "Large Recital Hall" setting.

Table 3

Reverberation Time in Seconds in Individual Octave Bands in "Large Recital Hall"

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	250 Hz -2 kHz	500 Hz -4 kHz
EDT	0.09	0.08	0.17	0.19	0.22	0.19	0.17	0.16	0.19
T10	0.09	0.12	0.21	0.17	0.21	0.19	0.15	0.18	0.20
T20	0.19	0.13	0.14	0.22	0.25	0.22	0.20	0.19	0.21
T30	0.16	0.14	0.19	0.28	0.25	0.23	0.21	0.22	0.24

The "Large Auditorium" setting showed a slightly longer reverberation time with some noticeable reflections at 0.7 and 1.6 s. Figure 17 graphs the reverberation time at T30 averaged across all octave bands.

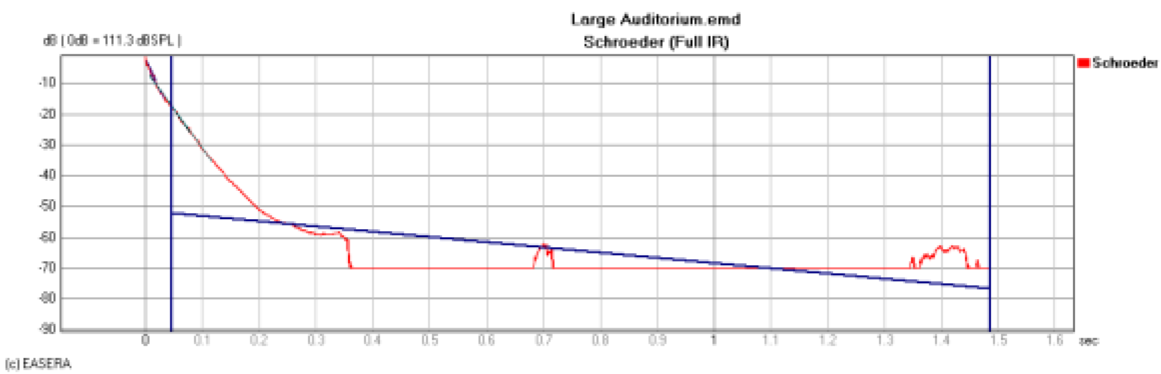


Figure 17. Reverberation time averaged across all octave bands in "Large Auditorium."

Only a negligible difference in individual octave bands appeared at T30 in "Large Auditorium" when compared to the two previous settings. Table 4 shows reverberation time in individual octave bands at T10, T20, and T30 in "Large Auditorium."

Table 4

Reverberation Times in Seconds in Individual Octave Bands in "Large Auditorium"

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	250 Hz -2 kHz	500 Hz -4 kHz
EDT	0.09	0.08	0.17	0.19	0.22	0.20	0.17	0.16	0.19
T10	0.09	0.12	0.20	0.17	0.22	0.18	0.15	0.18	0.19
T20	0.20	0.13	0.14	0.22	0.25	0.22	0.20	0.18	0.21
T30	0.16	0.14	0.19	0.27	0.25	0.22	0.20	0.21	0.23

The "Arena" setting did not display a longer reverberation time or any delayed reflections as was described by the manufacturer's materials. The reverberation time averaged across all octave bands was 0.23 s at T30, as displayed in Figure 18.

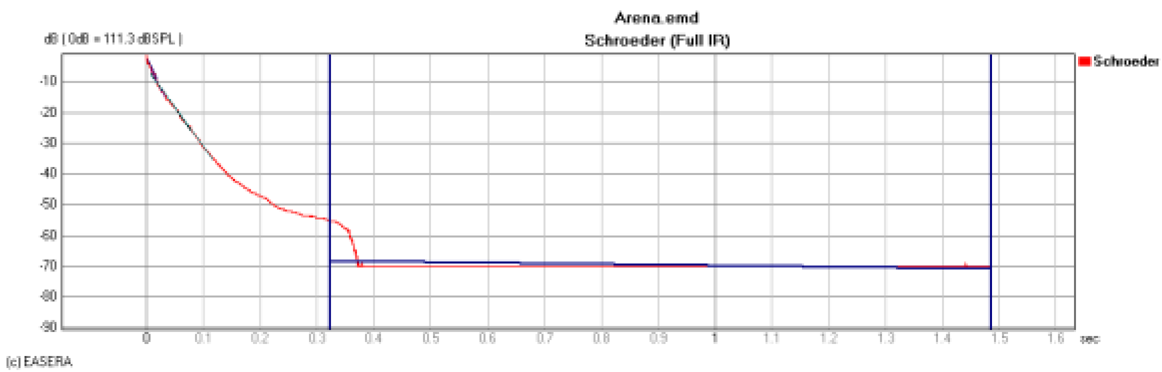


Figure 18. Reverberation time averaged across all octave bands in "Arena."

Table 5 showed some variation in the reverberation time in individual octave bands at T10, T20, and T30.

Table 5

Reverberation Time in Seconds in Individual Octave Bands in "Arena"

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	250 Hz -2 kHz	500 Hz -4 kHz
EDT	0.09	0.08	0.17	0.19	0.22	0.19	0.17	0.16	0.19
T10	0.09	0.12	0.20	0.17	0.21	0.19	0.15	0.18	0.19
T20	0.20	0.13	0.14	0.22	0.25	0.22	0.20	0.18	0.21
T30	0.17	0.14	0.19	0.27	0.25	0.22	0.21	0.21	0.23

Impulse response testing utilizing the dodecahedron speaker used a log sweep and pink MLS on the "Arena" setting at maximum volume for comparison to the settings obtained by the directional speaker. The log sweep averaged across all octave bands showed a reverberation time of 0.21 s at T30 using Schroeder Reverberation Time (RT). Figure 19 shows the log sweep graphed at T30.

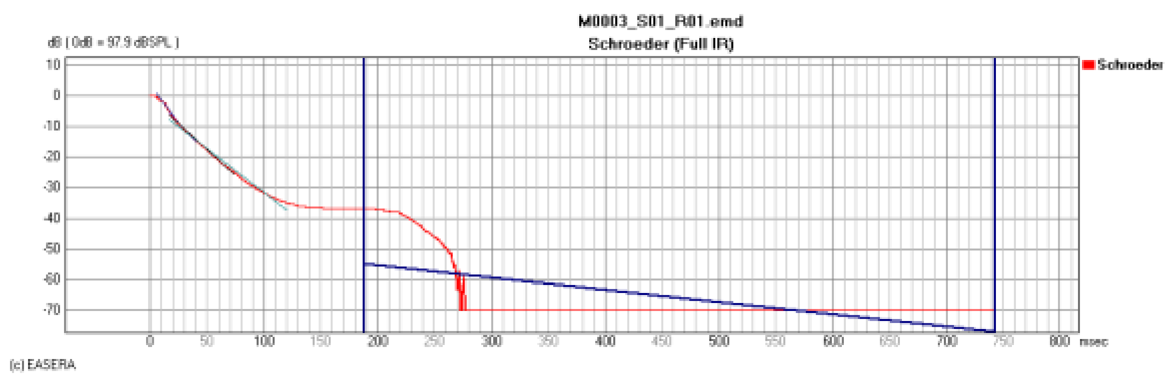


Figure 19. Reverberation time at T30 using a log sweep with Schroeder RT.

Analyzing the reverberation time across octave bands with the log sweep showed a nearly constant reverberation time across all octave bands. Table 6 shows the reverberation times using the log sweep at T10, T20, and T30.

Table 6

Reverberation Times in Seconds Using Log Sweep Across Octave Bands

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	250 Hz -2 kHz	500 Hz -4 kHz
EDT	0.26	0.18	0.13	0.14	0.15	0.13	0.12	0.15	0.13
T10	0.20	0.18	0.19	0.18	0.18	0.16	0.15	0.18	0.18
T20	0.18	0.12	0.17	0.19	0.20	0.18	0.18	0.17	0.19
T30	0.17	0.10	0.20	0.19	0.24	0.19	0.22	0.18	0.20

MLS tests showed similar results. Averaged across octave bands, the pink MLS impulse produced a reverberation time of 0.19 s at T30. Figure 20 shows the graph of the reverberation time across averaged octave bands.

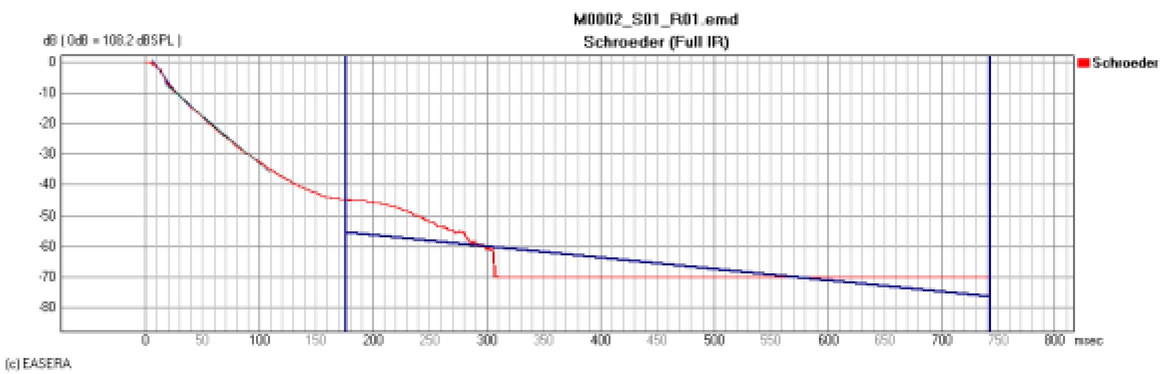


Figure 20. Reverberation time using pink MLS averaged across octave bands at T30.

Table 7 displays the reverberation time in individual octave bands at T10, T20, and T30 using the dodecahedron speaker.

Table 7

Reverberation Times in Seconds in Individual Octave Bands Using Pink MLS

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	250 Hz -2 kHz	500 Hz -4 kHz
EDT	0.27	0.22	0.13	0.14	0.15	0.13	0.12	0.16	0.13
T10	0.20	0.17	0.20	0.18	0.18	0.16	0.15	0.18	0.18
T20	0.20	0.19	0.17	0.20	0.20	0.18	0.17	0.19	0.19
T30	0.25	0.20	0.18	0.18	0.22	0.19	0.20	0.19	0.19

Real Recital Hall

Impulse response testing with a dodecahedron speaker placed on the stage area used a log sweep and pink maximum length sequence (MLS) averaged across all octave bands. Results showed a reverberation time of 1.62 s at T30. Figure 21 shows the pink MLS reverberation time in Schroeder RT analysis averaged over all octave bands.

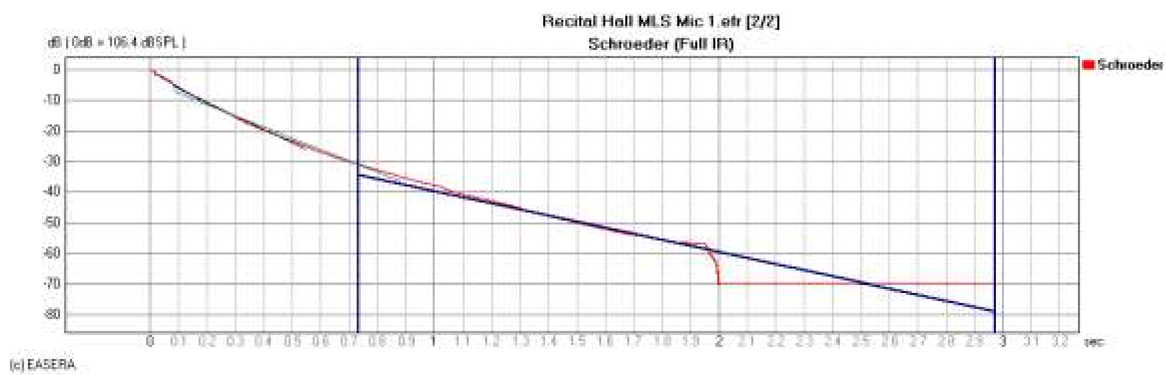


Figure 21. Pink MLS reverberation time in Schroeder analysis.

Reverberation in octave bands revealed variations in the reverberation time, peaking at 1 kHz. The reverberation time at 2 kHz in the area of the singer's formant reached 1.85 s. Figure 22 displays the reverberation time of the pink MLS impulse at T30.

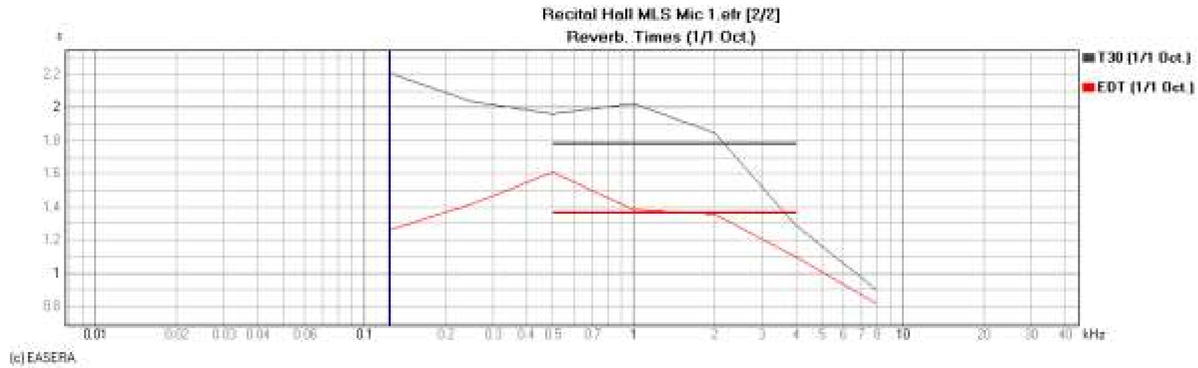


Figure 22. Pink MLS reverberation time at T30.

Table 8 displays reverberation times using pink MLS impulse across octave bands.

Table 8

Pink MLS Reverberation Times in Seconds in Octave Bands

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	250 Hz -2 kHz	500 Hz -4 kHz
EDT	1.26	1.41	1.61	1.38	1.35	1.10	0.82	1.44	1.36
T10	1.71	1.62	1.65	1.58	1.46	1.22	0.88	1.58	1.48
T20	2.09	1.92	1.82	1.73	1.60	1.19	0.88	1.77	1.59
T30	2.20	2.04	1.96	2.02	1.85	1.29	0.90	1.97	1.78

Repeated acoustic testing using a small directional speaker to mimic a singer's head and mouth similar reverberation results.

The log sweep averaged across all octave bands showed a reverberation time of 1.62 s at T30. Figure 23 graphs the reverberation time using the log sweep.

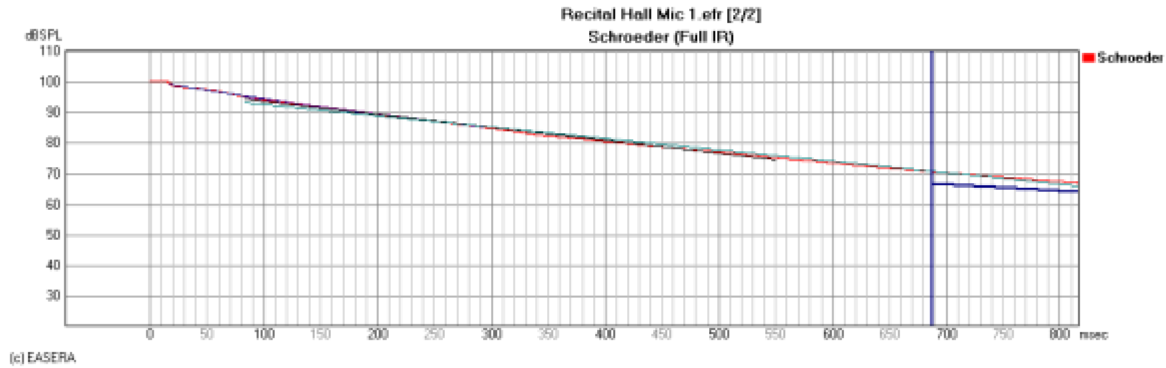


Figure 23. Reverberation time at T30 using the log sweep averaged across octave bands.

When separated into individual octave bands, the log sweep showed variation among the frequency regions. Figure 24 displays the reverberation time using the log sweep in individual octave bands.

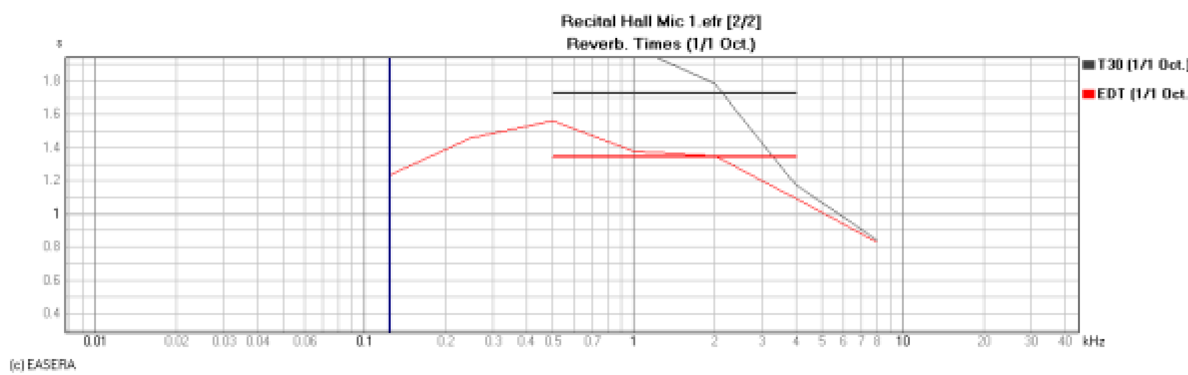


Figure 24. Reverberation time in individual octave bands using log sweep.

Table 9 shows the variation in reverberation time in individual octave bands at T10, T20, and T30.

Table 9

Reverberation Times in Seconds in Individual Octave Bands

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	250 Hz - 2 kHz	500 Hz - 4 kHz
EDT	1.24	1.46	1.56	1.38	1.35	1.10	0.83	1.44	1.35
T10	1.62	1.63	1.61	1.59	1.45	1.21	0.88	1.57	1.46
T20	2.07	1.96	1.83	1.74	1.60	1.17	0.86	1.78	1.58
T30	2.18	2.03	1.94	2.01	1.79	1.18	0.84	1.94	1.73

Maximum length sequence (MLS) testing with the small directional speaker showed a longer reverberation time at 1.42 s at T30. Figure 25 shows the MLS reverberation time in Schroeder RT analysis averaged over all octave bands.

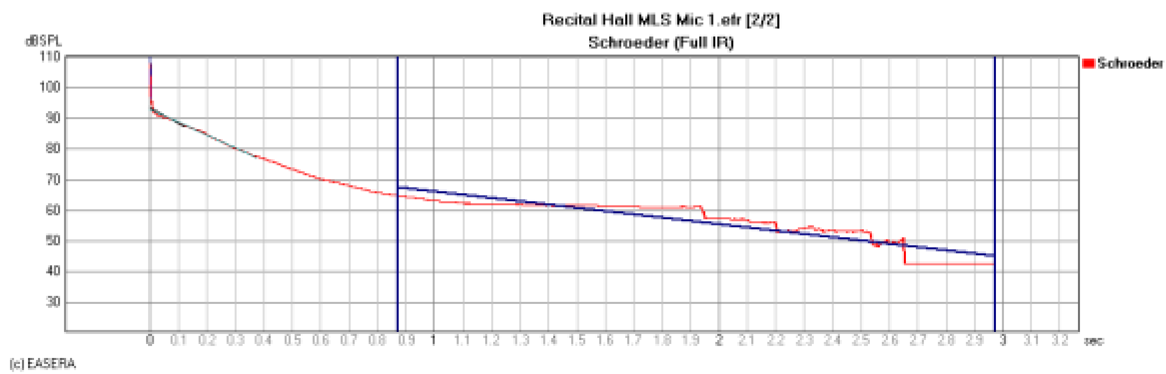


Figure 25. Reverberation time averaged across octave bands using MLS at T30.

Reverberation in octave bands revealed variations in the reverberation time, peaking at 1 kHz. The reverberation time at 2 kHz in the area of the singer's formant reached 1.63 s. Figure 26 displays the reverberation time of the MLS impulse at T30.

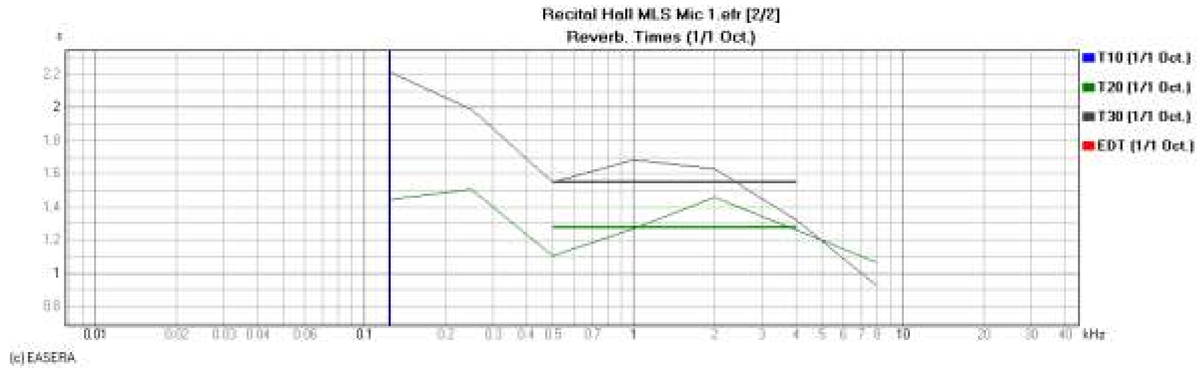


Figure 26. Reverberation time across octave bands using MLS at T30.

Table 10 shows reverberation times across octave bands using pink MLS at T10, T20, and T30.

Table 10

Reverberation times in Seconds Across Octave Bands Using Pink MLS

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	250 Hz - 2 kHz	500 Hz - 4 kHz
EDT	0.09	0.04	0.02	0.01	0.01	0.01	0.00	0.02	0.01
T10	0.06	0.03	0.03	0.08	0.01	0.01	0.00	0.04	0.03
T20	1.44	1.51	1.11	1.27	1.46	1.26	1.06	1.33	1.27
T30	2.21	1.99	1.54	1.68	1.63	1.32	0.92	1.71	1.55

Figures 27 and 28 show the placement of the participant in the Real Recital Hall and the view of the recital hall from where the participant stood.

Figure 27. Placement of the participant in the Real Recital Hall.

Figure 28. The real recital hall from the participant's viewpoint.

Figure 29 shows the Real Recital Hall from the back of the room toward the platform.

Figure 29. Real recital hall from the rear.

Procedures

I verbally briefed each participant on the data collection procedure and gave an opportunity for participants to ask questions. Written instructions were provided for reference (see Appendix A). Participants signed an informed consent form before the data collection began (see Appendix B). The entire data collection procedure for each participant took about 40 minutes.

Randomization. To control for potential order effect, I randomly selected one half of the participants to begin the data collection process in the recital hall, with the other one-half of participants beginning in the individual practice room. Thereafter, I randomized the order of the 4 practice room contexts among the participants.

Singing Tasks. The singing tasks consisted of performing the melody to two well-known Italian art songs sung on the neutral syllable [da] four times each in the individual practice room with four separate active acoustical settings randomized to reduce order effect, and once each in the university recital hall.

In the practice room, each participant stood behind a taped line 36 in from the wall, facing away from the control panel. I sat in a chair beside the control panel and adjusted the virtual acoustical settings. Each participant sang through the melody four times to four different virtual acoustical settings in random order: Practice Room, Large Recital Hall, Large Auditorium, and Arena.

Participants were given the opportunity to acclimate to each room by vocalizing and/or singing through the melody of the songs. While in the individual practice room the virtual acoustic setting was muted during the participants' warm up period.

A visual metronome sat on a stand in front of the participant and kept the beat at 80 beats per minute using a flashing light. I gave the starting pitch to "Lasciatemi, morire" from a pitch pipe with the virtual acoustic system muted. I then unmuted and set the acoustical setting for that individual run. I quietly tapped the floor four times in time with the metronome to indicate to the participant he or she could proceed, and the participant sang through the melody on the neutral syllable [da]. Immediately after the participant finished with the run I muted the system and instructed the participant to complete a portion of a short survey survey (see below). The sequence repeated for each four of the virtual acoustical settings, then repeated again for "Nel cor più non mi sento."

Participants repeated the singing task in the Real Recital Hall. Participants stood in the middle of the second step of the platform, 12 in. from the floor. A music stand with the visual metronome and a copy of the score was placed in front of the participant on the first step of the platform. I played a starting pitch from a pitch pipe, and then each participant sang "Lasciatemi, morire" and completed the appropriate portion of the survey. The participant then sang "Nel cor più non mi sento" after a starting pitch from a pitch pipe. The participant completed the final portion of the survey, including the opportunity to give open comments.

Survey

Each participant completed two questionnaires. The first (Appendix A) solicited demographic information and self-reports of any previous vocal or hearing inefficiencies. The second questionnaire (Appendix B) contained three modified visual analog scales inviting participants to share their perceptions of (a) ability to hear their own vocal sound, (b) singing efficiency, and their (c) degree of preference for the particular acoustic environment. This questionnaire also provided participants an opportunity to offer comments about their perceptions and preferences. Participants completed this second questionnaire 10 times, immediately after singing each singing task in each of the five environments assessed by this study.

Because the order of performance environments was randomized among participants, I notated on each participant's questionnaire the order of the four virtual acoustics environments in which they sang, and whether the participant began the study in the university recital hall or in the individual practice room. Using a ruler with millimeter increments, I then recorded each participant's responses as marked on the visual analog scales, measuring from the midpoint of each scale, prior to transferring these responses to a spreadsheet for subsequent analyses.

Ambulatory Phonation Monitor Data

After the data collection period ended, I removed the batteries from the microprocessor of the APM to end the unit’s operation. The participant gently removed the transducer from his or her neck and cleaned the skin with an alcohol pad to remove any adhesive residue. I then cleaned the transducer with another alcohol pad to sanitize the transducer in preparation for the next participant.

I connected the microprocessor to the computer previously used for calibration. A dialog window indicated the computer was ready to transfer data to the hard drive for analysis. When the transfer of data finished, two graphs displayed data. The Phonation Time Graph displayed amplitude in dB SPL over time. Cursors placed around a portion of the graph isolated individual repetitions of the singing tasks and provided phonation statistics for that individual repetition. The Sound Pressure Level Histogram displayed amplitude distribution.

Long Term Average Spectra

I used Computerized Speech Lab (CSL, KayPentax) software to calculate Long Term Average Spectra (LTAS) from the acquired direct sound field recordings. I employed a window size of 512 points with no pre-emphasis or smoothing, a bandwidth of 86.13 Hz, and a Hamming window.

Both melodies sung by the participants used the same key signature and had a similar range and tessitura. For analysis, I merged recordings of both songs in the same condition, for example both melodies sung in the “Arena” setting, into one file using Audacity software (2.1.1). Merging the two files created a longer sample totaling 92 s, which allowed for a more credible LTAS analysis of persisting spectral events in each environmental setting than would analysis of each melody separately.

Statistical Analysis

Statistical analysis utilized three repeated-measures analysis of variance (ANOVA) tests, the first using dosimeter-acquired amplitude measurements, the second dosimeter-acquired distance dose, and the third LTAS measurements as dependent variables. Each ANOVA used the five acoustical conditions as independent variables. In addition, two correlations examined the relationships between (a) perceived singing effort reported on the visual analog scale and dosimeter-acquired amplitude measurements, and (b) perceived hearing efficiency reported on the visual analog scale and dosimeter-acquired amplitude measurements. Because this study had 20 participants, a lack of significant differences could indicate a Type II error.

Chapter Four

Results

The purpose of this study was to assess selected phonation behaviors and perceptions of female collegiate vocal soloists (*N* = 20) performing in two rooms: (a) a university Recital Hall, and (b) an individual practice room with four digitally-adjustable simulations of reverberation and reflections (Practice Room, Large Auditorium, Large Recital Hall, and Arena). Because the manufacturer's description of the "Large Recital Hall" virtual acoustic condition most closely matches that of the Real Recital Hall used in this study, particular attention focused on comparing results of these two conditions. This chapter presents the results according to the research questions posed for this investigation. A predetermined alpha level of .05 indicated significance in statistical tests. A predetermined alpha level of .05 indicated significance in statistical tests. This alpha level balanced the opposing risks of Type I and Type II errors based on the particular sample and singing tasks in this study.

Research Question One: Dd, Dosimeter-Acquired Amplitude, and LTAS analyses

Distance dose. Distance dose (Dd) is a measure of the distance the vocal folds travel from the midline during phonatory vibration cycles. Distance dose can be affected by amplitude, frequency, and duration of phonation. Thus Dd is a useful measure when analyzing phonation behaviors among the various virtual and real acoustical conditions of this study.

Table 11 shows the grand mean cumulative Dd in meters for all participants in each of the simulated reverberation conditions and in the university Recital Hall.

Table 11

Distance Dose Grand Mean and Standard Deviation in Meters for All Five Room Conditions

	M	*SD*
Practice Room	102.03	45.63
Large Recital Hall	103.43	47.95
Large Auditorium	105.39	50.13
Arena	104.69	50.05
Real Recital Hall	123.59	60.25

Note: The frequency and duration components of the Dd readings are directly comparable across participants. However, because the APM calculates amplitude against the calibration file of each singer, rather than to a set common standard, the grand Dd means presented here serve to indicate relative tendencies rather than absolute values.

Participants on the whole exhibited lesser grand mean distance dose (range: 102.03 - 105.39 m) in the four virtual room conditions than in the Real Recital Hall (123.59 m). A one-way repeated measures ANOVA indicated a significant difference in means, Wilks' Lambda = .55, F (1, 19) = 3.308, $p < .05$. However, pairwise comparisons did not yield significant differences in two pairings: Large Auditorium vs. Real Recital Hall ($p = .060$) and Arena vs. Real Recital Hall ($p = .084$).

Table 12 presents culmulative Dd in meters for each participant in each acoustical condition.

Table 12

Cumulative Dd in Meters for Each Participant in Each Acoustical Condition

Participant	Practice Room	Large Recital Hall	Large Auditorium	Arena	Real Recital Hall
1	82.60	86.01	88.08	82.19	108.46
2	130.06	136.63	141.98	150.07	149.79
3	80.64	70.75	72.40	75.99	96.96
4	103.86	105.03	99.07	108.03	103.22
5	88.07	91.46	93.54	87.67	113.92
6	83.16	73.26	74.95	78.49	99.48
7	86.15	92.58	94.56	89.02	115.03
8	128.36	134.98	140.26	148.40	148.09
9	129.88	122.63	144.76	142.06	117.95
10	53.25	49.45	54.59	51.26	69.34
11	42.77	42.14	41.40	41.60	43.53
12	60.15	53.25	51.02	48.85	59.00
13	86.15	88.88	93.92	97.70	95.18
14	86.97	60.53	55.01	65.55	236.32
15	129.40	142.29	125.79	130.24	137.20
16	56.64	70.90	72.66	68.08	67.67
17	73.54	78.19	71.77	79.51	73.33
18	231.47	218.65	218.06	240.13	223.61
19	183.85	192.26	194.55	187.61	273.19
20	123.57	158.71	179.39	121.35	140.44

Table 13 shows comparisons per participant between the Large Recital Hall and Real Recital Hall Conditions.

Table 13

Dd in Meters for Each Participant in the Large Recital Hall and Real Recital Hall Conditions

Participant	Large Recital Hall Setting	Real Recital Hall
1	86.01	108.46
2	136.63	149.79
3	70.75	96.96
4	105.03	103.22
5	91.46	113.92
6	73.26	99.48
7	92.58	115.03
8	134.98	148.09
9	122.63	117.95
10	49.45	69.34
11	42.14	43.53
12	53.25	59.00
13	88.88	95.18
14	60.53	236.32
15	142.29	137.20
16	70.90	67.67
17	78.19	73.33
18	218.65	223.61
19	192.26	273.19
20	158.71	140.44

Fourteen participants (70%) exhibited greater mean distance dose in the Real Recital Hall, while 6 participants (30%) acquired greater mean distance dose in the simulated Large Recital Hall Condition. Among those with a greater Dd in the Real Recital Hall condition, Participant 14 displayed the greatest difference (175.79 m) and Participant 11 showed the least difference (1.39 m). Of those 6 participants exhibiting a greater Dd in the Large Recital Hall virtual condition, Participant 20 showed the greatest difference (18.27 m) and Participant 4 displayed the least difference (1.81 m).

Dosimeter-Acquired Amplitude. Amplitude can be variable among singers, as it can be a function of technique and may be more refined in singers with greater cumulative experience than those with less experience. For this study, I measured APM acquired amplitude, that is, sound pressure level as an estimate of the intensity created by the force of the contact of the vocal folds measured in decibels as calculated by the the APM accelerometer attached to the skin above the sternal notch.

Table 14 shows the grand mean amplitude in decibels displayed by each participant in each acoustical condition.

Table 14

Amplitude Grand Mean and Standard Deviation (dB SPL) for All Five Room Conditions

	M	*SD*
Practice Room	84.76	9.91
Large Recital Hall	85.80	10.97
Large Auditorium	86.02	10.64
Arena	85.52	10.46
Real Recital Hall	90.12	11.77

Note: Because the APM calculates amplitude against the calibration file of each singer, rather than to a set common standard, the grand means presented here serve to indicate relative tendencies rather than absolute values.

Participants displayed greater grand mean dosimeter-acquired amplitude in the Real Recital Hall condition (90.12 dB) than in any of the virtual acoustic conditions (range: 84.76 dB – 86.02 dB). A one-way repeated measures ANOVA measured for significance among room conditions and amplitude. The multivariate tests did not show overall significant differences according to mean amplitude, Wilk's Lambda = .65, $F\ (1, 19) = 2.133$, $p < .05$. Pairwise comparisons examined differences between individual pairs of conditions, and showed significance in differences between the Real Recital Hall and all virtual acoustic conditions. The finding of no overall significance coupled with the small sample size contributed to the possibility of a type II error.

Table 15 shows the mean amplitude (dB SPL) for each participant in each acoustical condition.

Table 15

Mean Amplitude (dB SPL) for Each Participant in Each Acoustical Condition

Participant	Practice Room	Large Recital Hall	Large Auditorium	Arena	Real Recital Hall
1	78.98	80.45	80.90	79.15	86.16
2	88.72	91.25	92.41	93.13	93.98
3	84.47	80.41	80.58	83.04	84.75
4	85.73	86.29	85.15	87.13	85.86
5	81.40	78.23	83.39	81.65	88.68
6	85.53	89.78	93.01	91.64	92.51
7	84.80	80.77	81.41	83.40	85.12
8	84.11	79.07	80.70	82.66	84.43
9	101.48	104.44	100.79	104.48	101.80
10	75.02	75.21	76.57	74.03	80.82
11	65.27	64.22	64.25	64.19	64.22
12	75.01	76.70	71.28	74.10	73.63
13	82.75	84.21	85.54	85.49	84.72
14	74.71	75.99	75.57	75.03	109.30
15	95.32	99.16	92.31	91.79	92.46
16	84.98	87.48	88.90	84.85	90.42
17	73.41	79.61	82.21	78.07	82.43
18	105.52	106.21	105.44	106.39	107.71
19	96.01	97.28	97.61	96.90	107.81
20	91.91	99.24	102.37	93.33	105.56

Table 16 shows the mean amplitude for all participants in the Large Recital Hall and Real Recital Hall conditions.

Table 16

Mean Amplitude (dB SPL) Comparisons for All Participants in the Large Recital Hall and Real Recital Hall Conditions

Participant	Large Recital Hall	Real Recital Hall
1	80.45	86.16
2	91.25	93.98
3	80.41	84.75
4	86.29	85.86
5	78.23	88.68
6	89.78	92.51
7	80.77	85.12
8	79.07	84.43
9	104.44	101.80
10	75.21	80.82
11	64.22	64.22
12	76.70	73.63
13	84.21	84.72
14	75.99	109.30
15	99.16	92.46
16	87.48	90.42
17	79.61	82.43
18	106.21	107.71
19	97.28	107.81
20	99.24	105.56

Sixteen participants (80%) displayed greater amplitude in the Real Recital Hall, 3 participants (15%) displayed greater amplitude in the virtual acoustic condition, and a single participant, Participant 11 (5%), displayed the same dosimeter-acquired amplitude in both conditions. Among those with greater amplitude in the Real Recital Hall, Participant 14 displayed the greatest difference (33.13 dB) and Participant 19 showed the least difference (1.50 dB). Among those participants with greater dosimeter-acquired amplitude in the virtual acoustic condition, Participant 13 showed the greatest difference (3.07 dB) and Participant 4 had the least difference (0.43 dB). Seventeen participants (85%) had at least 1 dB difference between the Large Recital Hall and Real Recital Hall conditions.

LTAS analysis. Human sound consists of multiple frequencies, including the fundamental frequency and a series of overtones that create timbre. Certain frequencies are amplified by the shape of the vocal tract, known as formants. One particular region between the 2 kHz and 4 kHz encompasses the area where human hearing is most sensitive (Fletcher & Munson, 1933). Listeners would tend to be more attune to energy differences in this region. This frequency range also occurs in and around the area known as the singer's formant, which is largely responsible for giving the solo voice ring and projection. Howard and Angus (2006) stated signal energy differences in complex sound of 1 dB can constitute a just noticeable difference in perceived loudness among listeners depending on the hearing acuity of listeners, and therefore can serve as a useful measurement in comparing the signal energy of acoustical conditions with one another. A 3 dB difference indicates a doubling of sound pressure.

Figure 30 displays grand mean LTAS countours (0-10 kHz) for all participants across all five acoustical conditions.

Figure 30. Grand mean LTAS in the 0-10 kHz spectrum for all participants in all five acoustical conditions.

A one-way repeated measures ANOVA measured for significance among room conditions and grand mean LTAS across the 0-10 kHz spectrum. Results were significant in both the overall ANOVA and in every pairwise comparison, Wilk's Lambda = .016 F (1, 117) = 1729.270, $p < .05$.

Participants in the Real Recital Hall showed a grand mean LTAS of 21.56 dB SPL across the 0-10 kHz spectrum. Among the virtual conditions, participants in the Large Auditorium setting showed the greatest grand mean spectral energy (18.88 dB SPL), differing from participants' spectral energy in the Real Recital Hall by 2.68 dB SPL. Participants exhibited the least grand mean spectral energy in the Practice Room setting (17.83 dB SPL), differing from participants' grand mean spectral energy in the Real Recital Hall by 3.73 dB SPL.

Figure 31 shows the grand mean LTAS in the 2-4 kHz spectrum for all participants in all acoustical conditions.

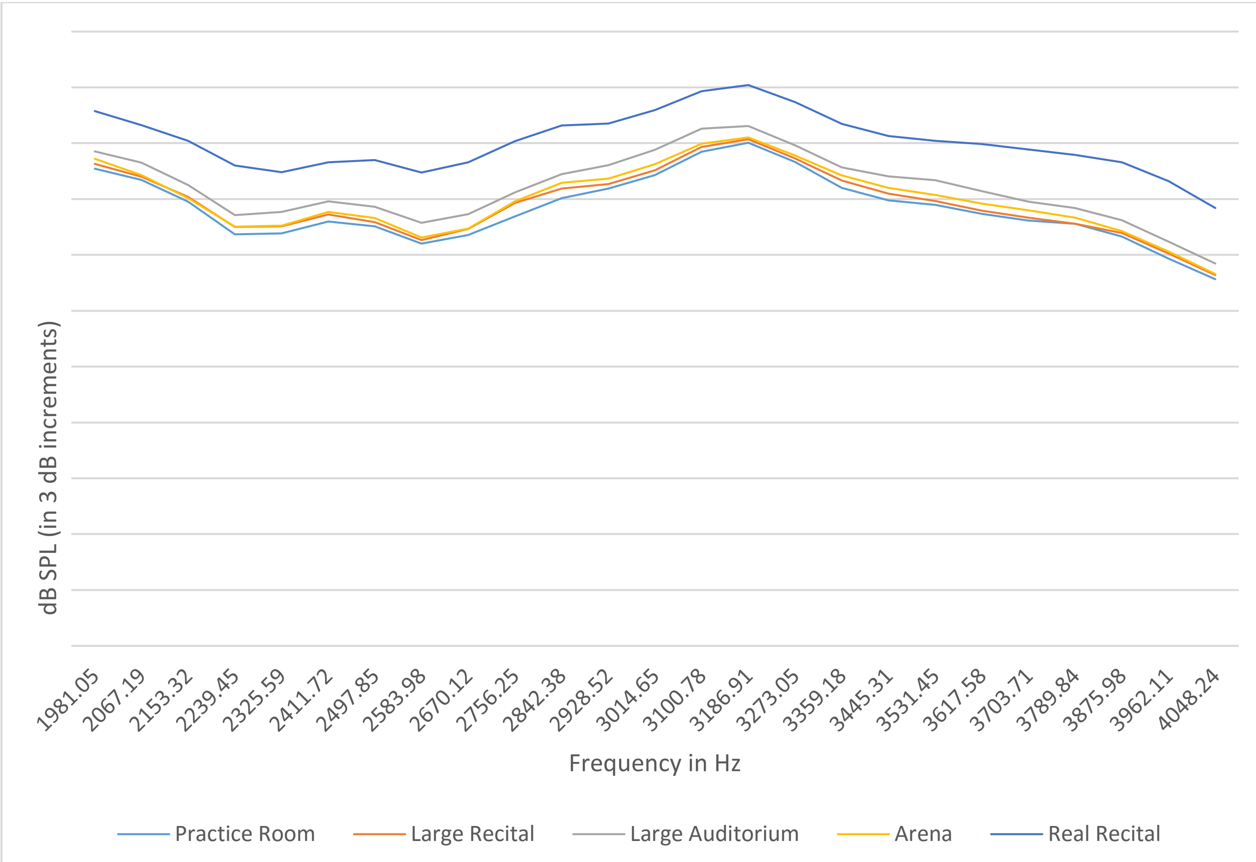


Figure 31. Grand mean LTAS in dB SPL in the 2-4 kHz spectrum for all participants in all acoustical conditions.

A one-way repeated measures ANOVA measured for significance among room conditions and grand mean LTAS in the 2-4 kHz spectrum. Results were significant in both the overall ANOVA and in every pairwise comparison, Wilk's Lambda = .006 $F\ (1, 24) = 946.290$, $p < .05$.

Participants in the Real Recital Hall showed a grand mean LTAS of 27.06 dB SPL across the 2-4 kHz spectrum. Among the virtual conditions, participants in the Large Auditorium setting showed the greatest grand mean spectral energy (24.59 dB SPL), differing from participants' grand mean spectral energy in the Real Recital Hall by 2.47 dB SPL. Participants exhibited the least grand mean spectral energy in the Practice Room setting (23.51 dB SPL), differing from participants' grand mean spectral energy the Real Recital Hall by 3.55 dB SPL.

Eleven participants (55%) showed the greatest mean spectral energy in the Real Recital Hall. Four participants (20%) had the greatest spectral energy in one of the virtual acoustic conditions (Participant 4 = Arena, Participant 15 = Large Recital Hall, Participant 19 = Large Auditorium, and Participant 20 = Practice Room). Five participants (25%) showed the least amount of spectral energy in the Real Recital Hall (Participants 6, 9, 13, 14, and 16).

Table 17 shows mean LTAS in dB SPL for all participants in all five acoustical conditions across the 0-10 kHz spectrum.

Table 17

Mean LTAS in dB SPL For All Participants in All Five Acoustical Conditions across the 0-10 kHz spectrum

Participant	Practice Room	Large Recital Hall	Large Auditorium	Arena	Real Recital Hall
1	15.74	16.29	16.10	15.15	16.83
2	14.09	14.44	15.60	14.73	17.43
3	13.87	14.52	14.30	14.24	16.05
4	14.25	13.40	14.05	15.00	14.71
5	25.65	27.63	27.62	27.08	32.42
6	23.54	22.52	22.19	24.11	17.99
7	13.88	14.14	14.99	15.08	16.77
8	25.65	27.63	27.62	27.08	48.83
9	16.00	16.48	16.98	16.96	15.74
10	21.99	21.07	21.49	20.46	47.73
11	15.78	16.24	30.04	15.74	48.34
12	15.41	15.41	15.10	15.45	18.30
13	17.85	19.41	18.71	19.25	13.48
14	22.98	21.87	21.72	22.53	9.54
15	11.87	12.25	11.93	11.25	11.86
16	29.74	31.94	31.44	31.36	16.20
17	11.97	11.99	12.43	12.65	18.18
18	12.67	13.59	12.68	13.93	17.15
19	17.18	16.71	17.47	17.43	17.19
20	16.45	14.93	14.87	15.15	16.43

Table 18 shows the mean LTAS in dB SPL for all participants in the Large Recital Hall virtual acoustic condition and the Real Recital Hall condition across the 0-10 kHz spectrum.

Table 18

Mean LTAS in dB SPL for All Participants in the Large Recital Hall and Real Recital Hall Conditions Across the 0-10 kHz spectrum

Participant	Large Recital Hall	Real Recital Hall
1	16.29	16.83
2	14.44	17.43
3	14.52	16.05
4	13.40	14.71
5	27.63	32.42
6	22.52	17.99
7	14.14	16.77
8	27.63	48.83
9	16.48	15.74
10	21.07	47.73
11	16.24	48.34
12	15.41	18.30
13	19.41	13.48
14	21.87	9.54
15	12.25	11.86
16	31.94	16.20
17	11.99	18.18
18	13.59	17.15
19	16.71	17.19
20	14.93	16.43

Table 19 shows the mean LTAS in dB SPL through the 2 kHz to 4 kHz region for all participants in all conditions.

Table 19

Mean LTAS in dB SPL for All Participants in All Conditions in the 2-4 kHz Region

	Practice Room	Large Recital Hall	Large Auditorium	Arena	Real Recital Hall
1	21.22	21.44	21.31	20.23	22.12
2	16.81	16.97	18.75	17.33	20.36
3	20.02	20.82	20.91	20.77	23.08
4	21.00	20.01	20.73	21.72	21.76
5	31.39	32.91	33.13	32.58	38.25
6	31.54	30.53	29.53	31.71	25.41
7	22.74	22.82	23.20	23.32	25.13
8	31.39	32.91	33.13	32.58	53.57
9	20.12	20.71	21.27	21.61	19.44
10	25.92	25.34	25.46	25.08	50.99
11	20.95	21.17	36.13	21.23	52.81
12	20.25	20.74	20.02	20.84	24.78
13	23.14	24.45	24.35	24.95	19.10
14	26.33	25.48	25.02	26.10	8.82
15	17.41	18.29	17.82	16.11	18.23
16	36.81	39.47	39.24	38.82	21.65
17	15.85	15.97	16.36	16.47	21.99
18	17.30	18.61	17.29	18.94	23.36
19	25.25	24.43	25.31	25.93	25.57
20	24.77	22.69	22.83	23.09	24.82

Table 20 shows the mean LTAS for all participants in the Large Recital Hall virtual condition and the Real Recital Hall condition in the 2-4 kHz range.

Table 20

Mean LTAS in dB SPL for All Participants in the Large Recital Hall and Real Recital Hall Conditions in the 2-4 kHz Region

Participant	Large Recital Hall	Real Recital Hall
1	21.44	22.12
2	16.97	20.36
3	20.82	23.08
4	20.01	21.76
5	32.91	38.25
6	30.53	25.41
7	22.82	25.13
8	32.91	53.57
9	20.71	19.44
10	25.34	50.99
11	21.17	52.81
12	20.74	24.78
13	24.45	19.10
14	25.48	8.82
15	18.29	18.23
16	39.47	21.65
17	15.97	21.99
18	18.61	23.36
19	24.43	25.57
20	22.69	24.82

LTAS in the range of 2 kHz to 4 kHz where human hearing is most sensitive showed 14 participants (70%) displayed the greater mean spectral energy through this region in the Real Recital Hall condition compared to the simulated conditions. Of the remaining six participants, five (25%) showed less spectral energy in the Real Recital Hall condition than in the simulated conditions, and one (5%) displayed greater spectral energy in the Large Recital Hall condition and the least spectral energy in the Arena virtual condition. Comparisons of the Large Recital Hall and Real Recital Hall conditions displayed similar results as those across all conditions. Fourteen participants (70%) showed the greatest spectral energy in the Real Recital Hall condition, with Participant 11 showing the greatest difference (31.64 dB SPL) and Participant 1 showing the least difference (0.68 dB SPL). Of the six participants (30%) who showed greater spectral energy in the Large Recital Hall virtual acoustic condition, Participant 16 had the greatest difference (17.62 dB SPL), and Participant 16 had the least difference (0.06 dB SPL).

LTAS can be variable between singers depending on factors such as development of technique. LTAS measurements for each participant show comparisons of timbre in each of the virtual acoustic conditions and the Real Recital Hall. All participants (100%) showed differences of at least 1 dB SPL at the point of greatest difference both in the 0-10 kHz range and the highlighted 2-4 kHz range when comparing the Large Recital Hall virtual acoustic condition and the Real Recital Hall condition, indicating listeners would likely be able to perceive a difference in amplitude between the two conditions.

Figure 32 shows the LTAS contours for Participant 1 in all five acoustic conditions across the 0-10 kHz spectrum.

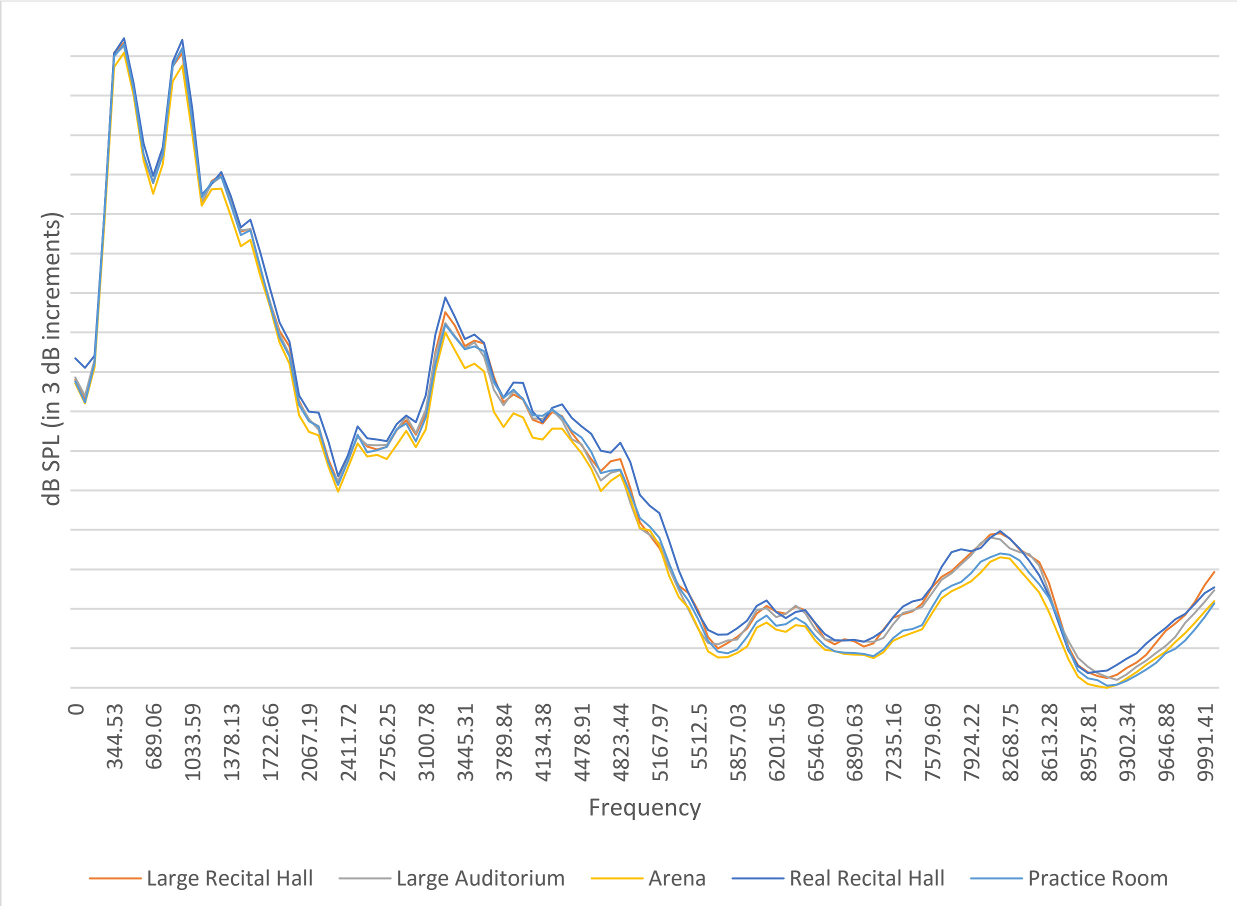


Figure 32. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 1.

Participant 1 was a 36-year-old with 18 years of singing experience and no reported vocal or hearing inefficiencies. The greatest difference in spectral energy is shown between Arena and the Real Recital Hall, ranging from 0.43 dB SPL at the point of the smallest measured difference (1.21 kHz) to 3.05 dB SPL at the point of the greatest measured difference (4.61 kHz).

Figure 33 shows the LTAS contours for Participant 1 in all five acoustic conditions across the 2-4 kHz spectrum.

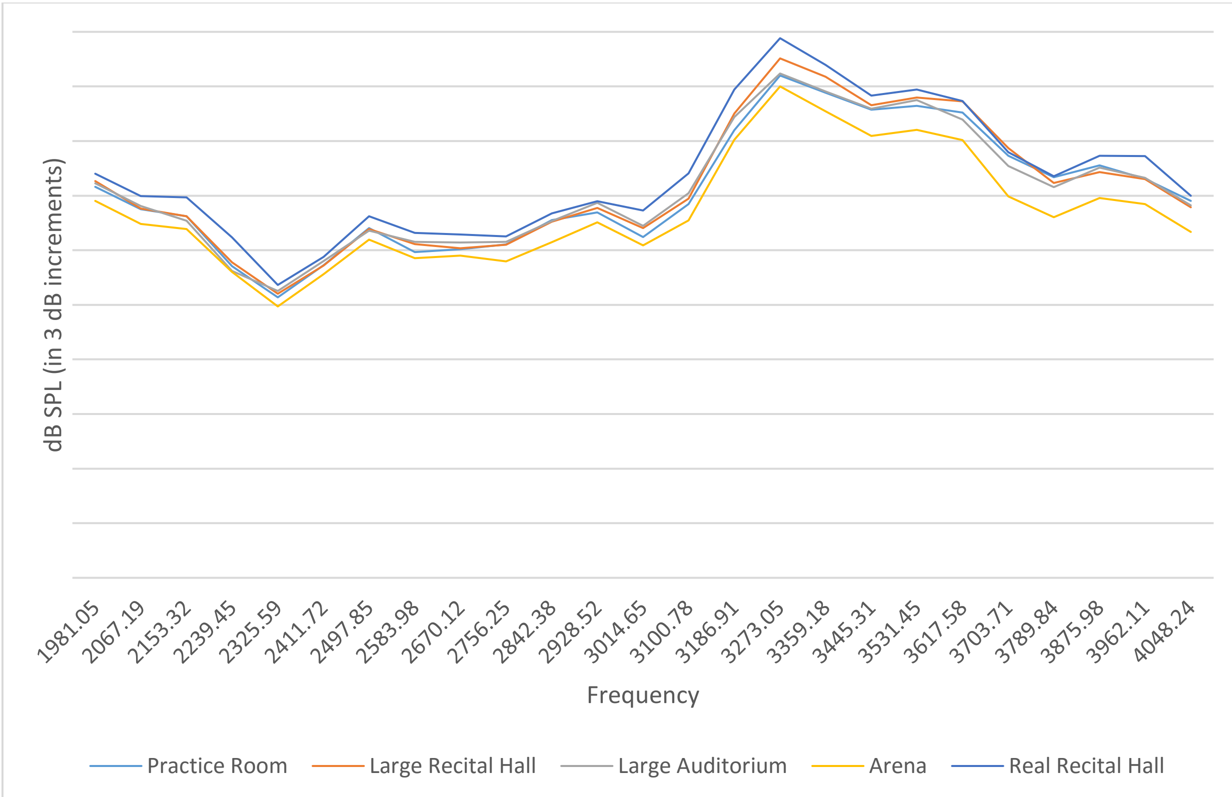


Figure 33. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 1.

The difference in spectral energy for Participant 1 between Arena and the Real Recital Hall within the 2-4 kHz region ranged from 0.95 dB SPL at the point of the smallest measured difference (2.41 kHz) to 2.77 dB SPL at the point of the greatest measured difference (3.19 kHz).

Figure 34 gives LTAS contour for Participant 2 in all five acoustical conditions in the 0-10 kHz range.

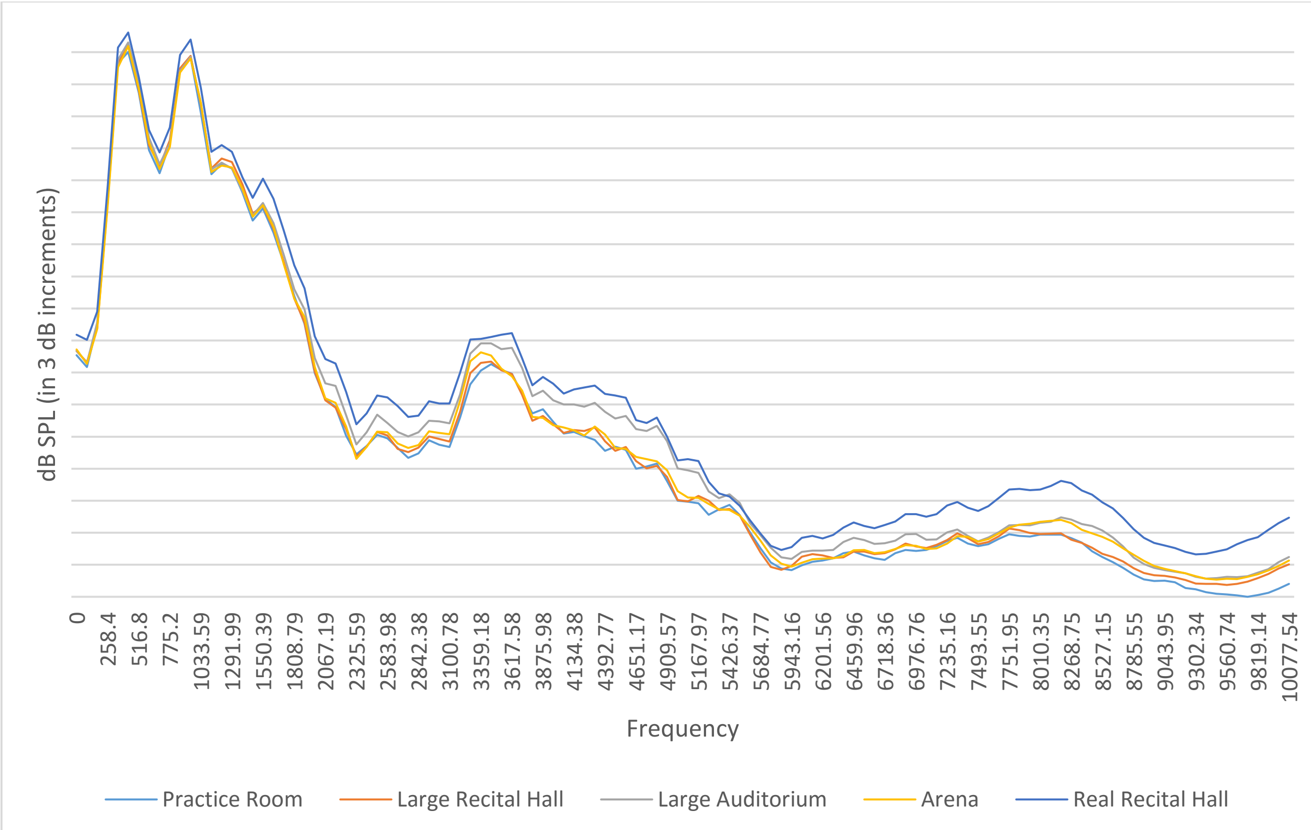


Figure 34. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 2.

Participant 2 was 19 years old with 3 years of singing experience and no reported vocal or hearing inefficiencies. The greatest difference in spectral energy was between the Real Recital Hall and Practice Room conditions, with a range of 0.77 dB SPL at the point of the smallest measured difference (5.42 kHz) to 6.21 dB SPL at the point of the greatest measured difference (10.08 kHz).

Figure 35 shows the LTAS contours for Participant 2 in all five acoustic conditions across the 0-10 kHz spectrum.

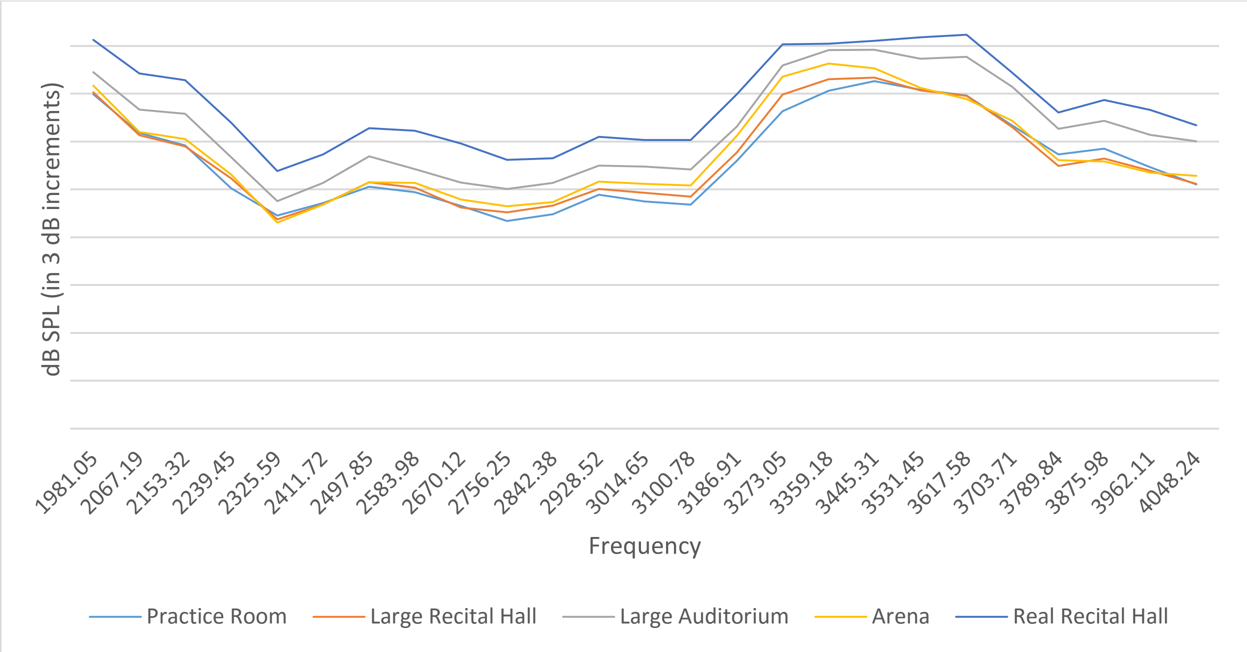


Figure 35. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 2.

Participant 2 showed the greatest difference in spectral energy between the Real Recital Hall and Practice Room conditions in the 2-4 kHz region, as well, with a range of 2.54 dB SPL at the point of the smallest measured difference (3.4 kHz) to 4.19 dB SPL at the point of the greatest measured difference (3.27 kHz) between the two conditions.

Figure 36 shows the LTAS contours for Participant 1 in all five acoustic conditions across the 0-10 kHz spectrum.

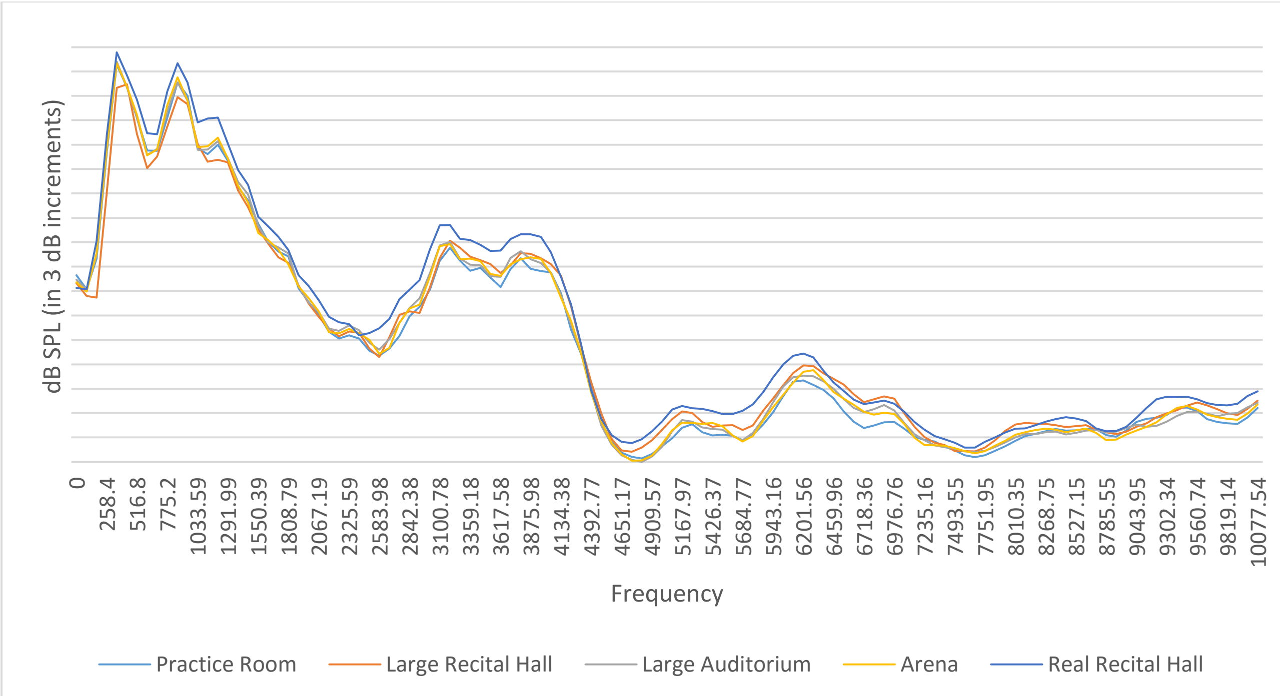


Figure 36. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 3.

Participant 3 was a 36-year-old with 8 years of vocal training with no reported hearing inefficiencies but one past diagnosis of vocal nodules that had completely resolved. The Practice Room and Real Recital Hall conditions showed the greatest differences in spectral energy, ranging from 0 dB SPL (86.13 Hz) to 4.95 dB SPL at the point of the greatest measured difference (3.01 kHz). However, there is a noticeable grouping of the virtual acoustic conditions apart from the Real Recital Hall condition.

Figure 37 shows the LTAS contours for Participant 3 in all five acoustic conditions across the 2-4 kHz spectrum, showing a noticeable bunching of the measurements made in the virtual acoustic environments compared to the Real Recital Hall.

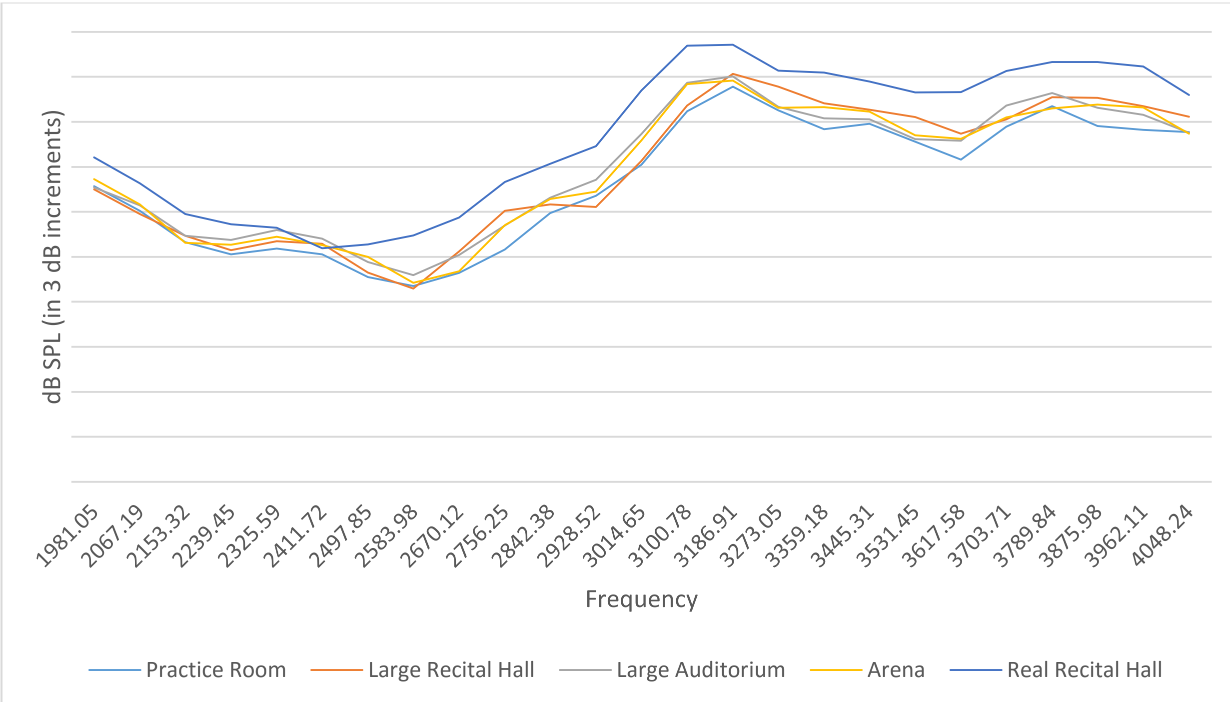


Figure 37. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 3.

The difference in spectral energy through the 2-4 kHz region in the Practice Room and Real Recital Hall conditions ranged from 0.40 dB SPL at the point of the smallest measured difference (2.41 kHz) to 4.95 dB SPL at the point of the greatest measured difference (3.01 kHz).

Figure 38 shows the LTAS contours for Participant 4 in all five acoustic conditions across the 0-10 kHz spectrum.

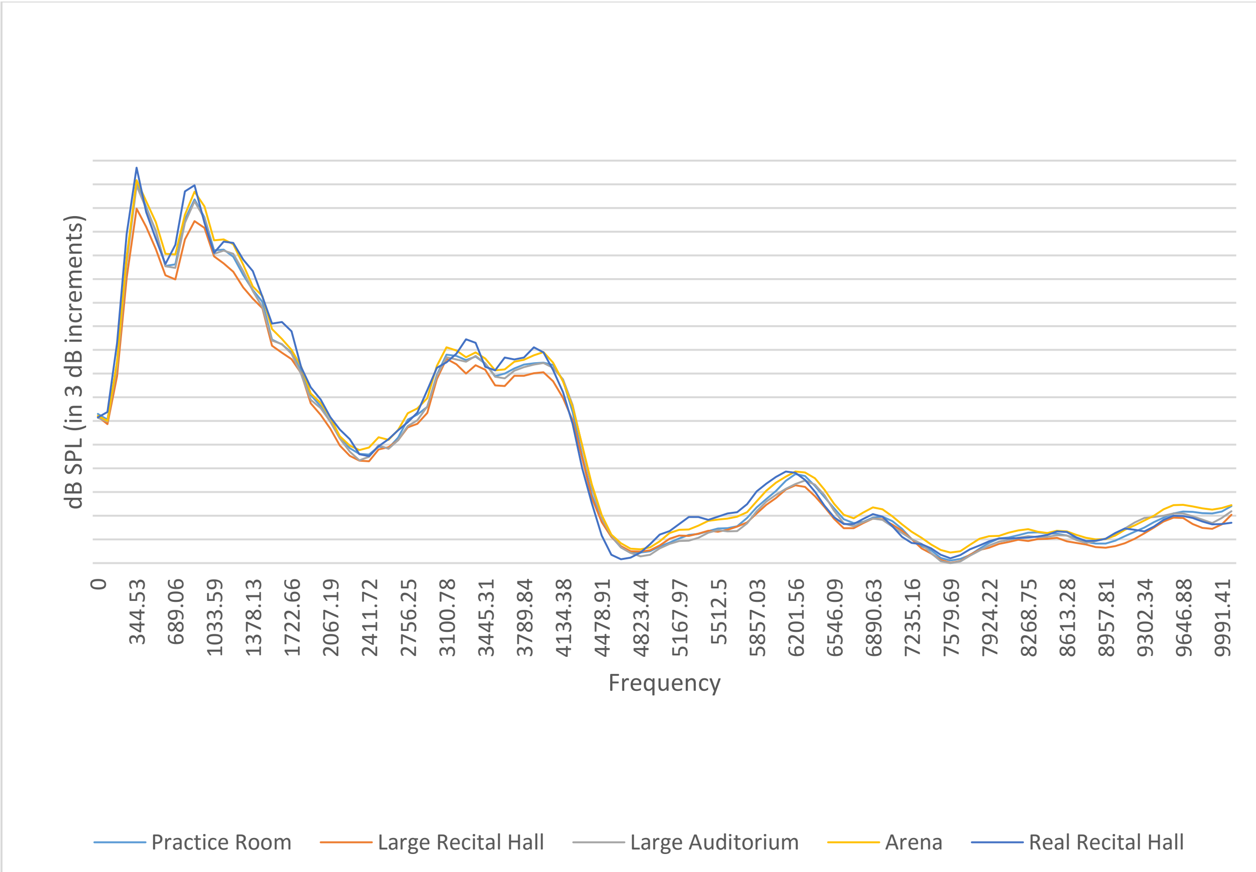


Figure 38. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 4.

Participant 4 was 22 years old and had 6 years of singing experience with no prior reported vocal or hearing inefficiencies. Overall measurements of spectral energy were variable between conditions and showed no consistent pattern. The Arena condition showed the highest mean spectral energy, just 0.03 dB SPL greater than the mean spectral energy in the Real Recital Hall. Comparing the difference between the Large Recital Hall and Real Recital Hall conditions yielded a range of 0.12 dB SPL at the point of the smallest measured difference (0.00 Hz) to 6.09 dB SPL at the point of the greatest measured difference (775.20 Hz).

Figure 39 shows the LTAS contours for Participant 4 in all five acoustic conditions across the 2-4 kHz spectrum.

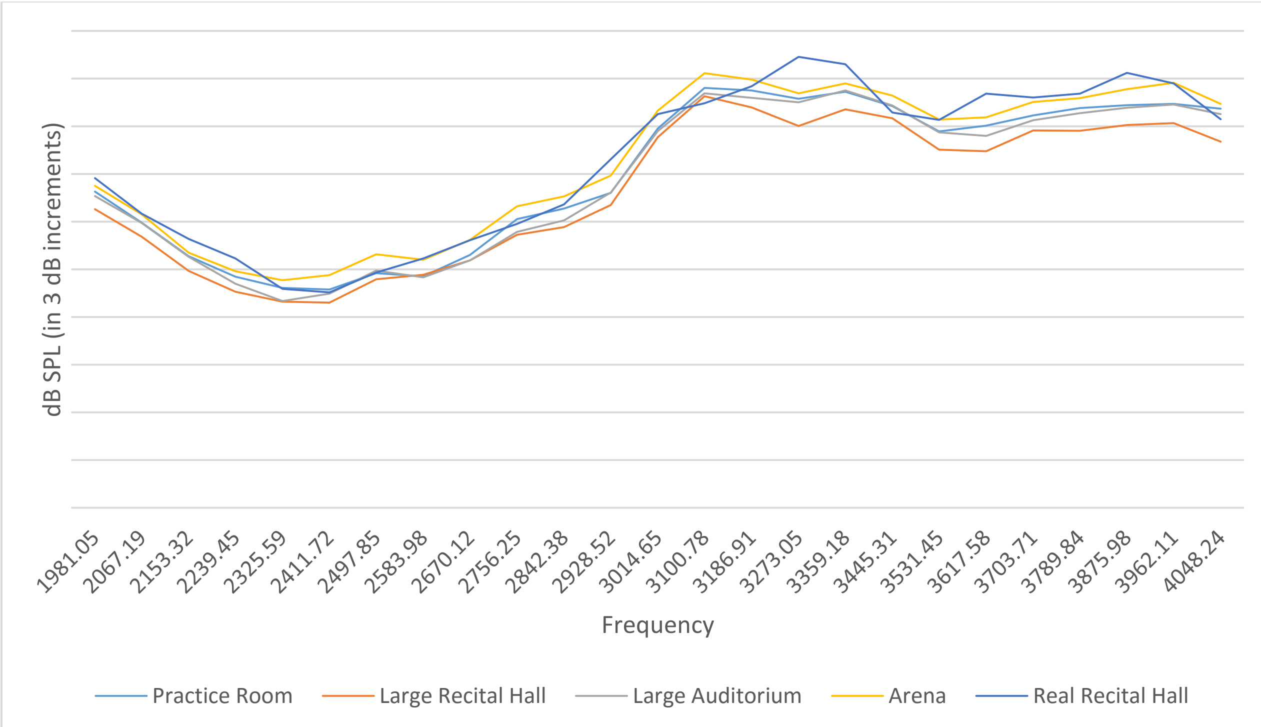


Figure 39. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 4.

In the region of 2-4 kHz the difference between the Large Recital Hall and the Real Recital Hall conditions ranged between 0.43 dB SPL at the point of the smallest measured difference (3.10 kHz) to 4.35 dB SPL at the point of the greatest measured difference (3.27 kHz).

Figure 40 shows the LTAS contours for Participant 5 in all five acoustic conditions across the 0-10 kHz spectrum.

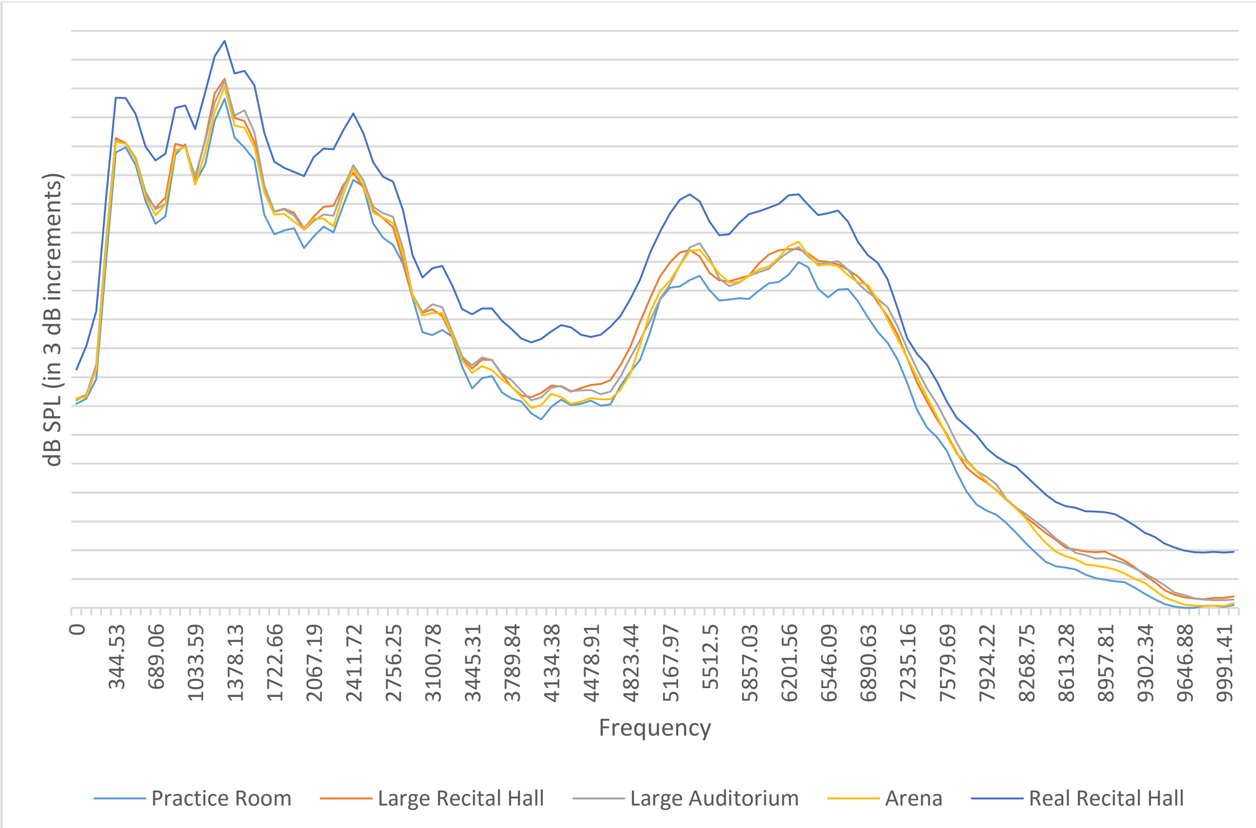


Figure 40. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 5.

Participant 5 was a 34-year-old with 12 years of prior singing experience and no reported vocal or hearing inefficiencies. LTAS showed a marked difference in spectral energy between the Real Recital Hall and all virtual acoustical conditions. Between the Large Recital Hall and Real Recital Hall conditions differences in spectral energy ranged from 2.08 dB SPL at the point of the smallest measured difference (7.24 kHz) to 6.68 dB SPL at the point of the greatest measured difference 4.31 kHz).

Figure 41 shows the LTAS contours for Participant 5 in all five acoustic conditions across the 2-4 kHz spectrum.

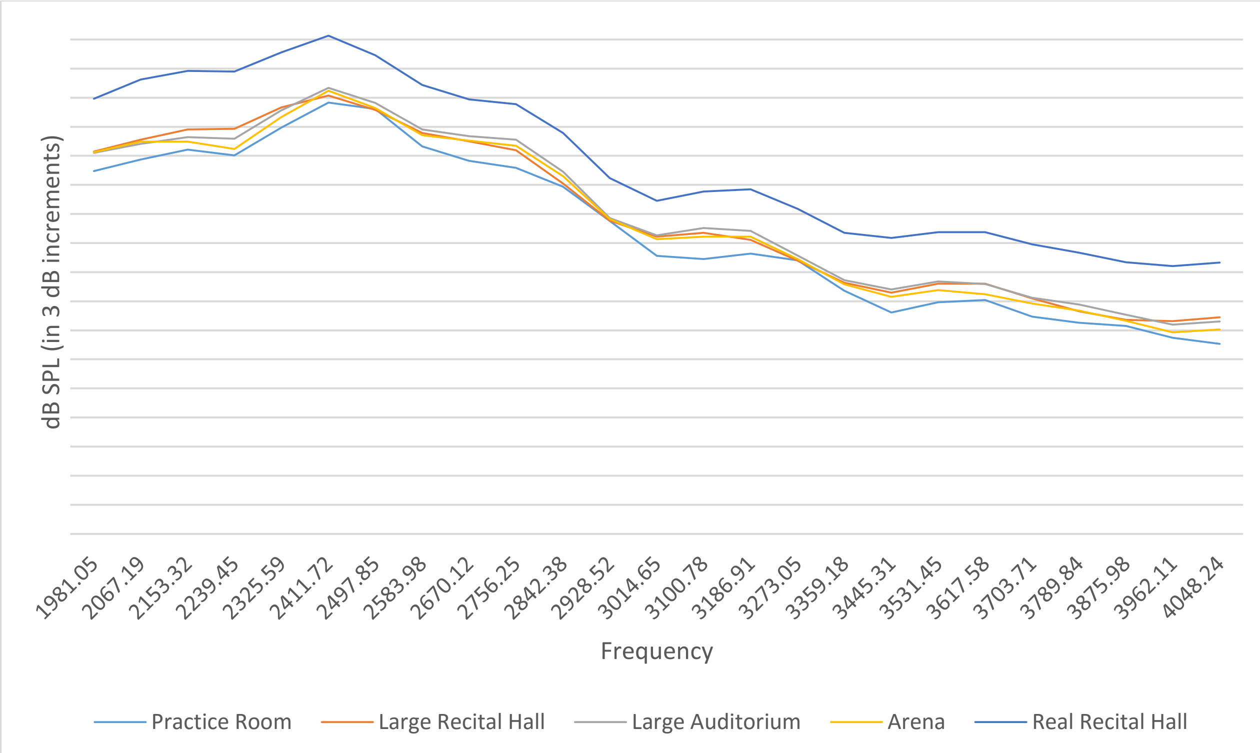


Figure 41. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 5.

Further scrutiny of the region of 2-4 kHz further illustrates the stark difference in spectral energy between the Real Recital Hall and all the virtual acoustical conditions, which are bunched together with similar measurements between Large Recital Hall, Large Auditorium, and Arena, and Practice Room generally slightly lower in strength. Isolating the differences between the Large Recital Hall and Real Recital Hall conditions yielded a range of 3.70 dB SPL at the point of the smallest measured difference (3.01 kHz) to 6.21 dB SPL at the point of the greatest measured difference (2.07 kHz).

Figure 42 shows the LTAS contours for Participant 6 in all five acoustic conditions across the 0-10 kHz spectrum.

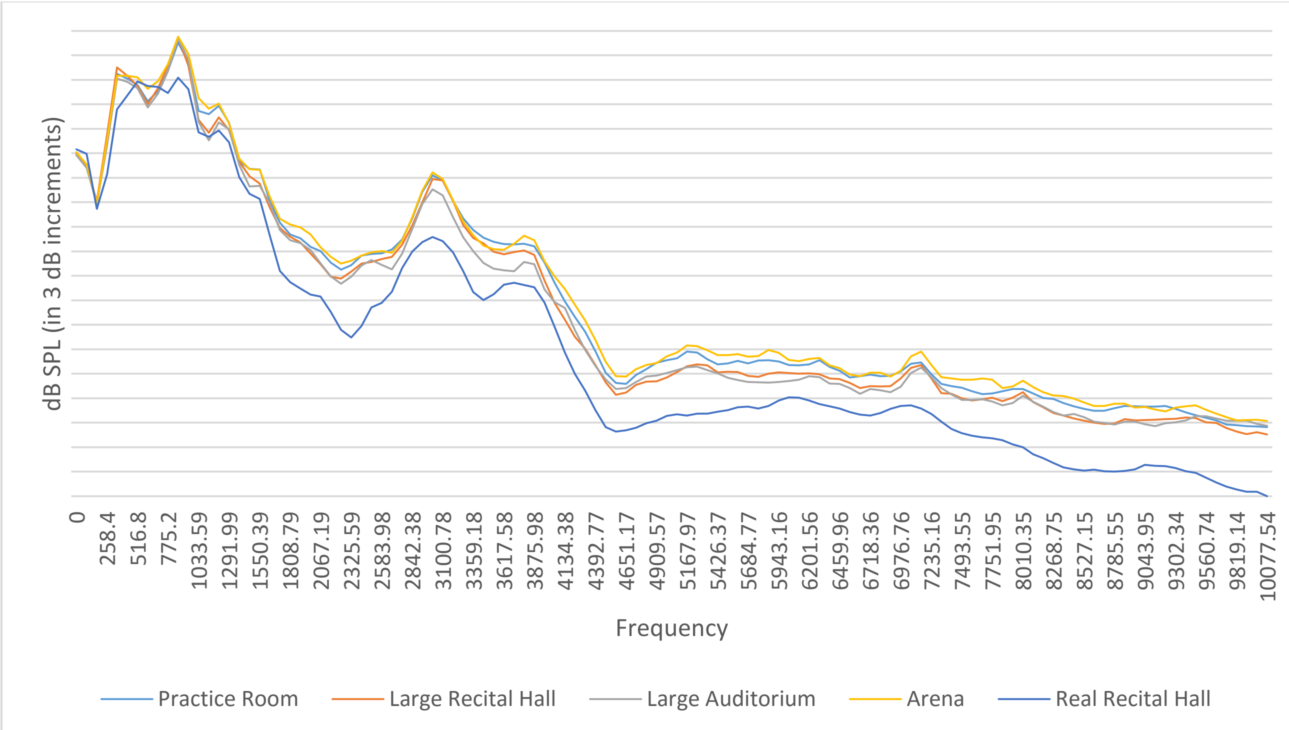


Figure 42. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 6.

Participant 6 was 33 years old with 6 years of singing experience and no prior reported vocal or hearing inefficiencies. Interestingly, all virtual acoustical settings were grouped together and the Real Recital Hall measured discernibly lower in spectral energy across the bulk of the spectrum. The difference between the Large Recital Hall and Real Recital Hall condition ranged from 0.15 dB SPL at the point of the smallest measured difference (689.06 Hz) to 8.07 dB SPL at the point of the greatest measured difference (2.32 kHz).

Figure 43 shows the LTAS contours for Participant 6 in all five acoustic conditions across the 2-4 kHz spectrum.

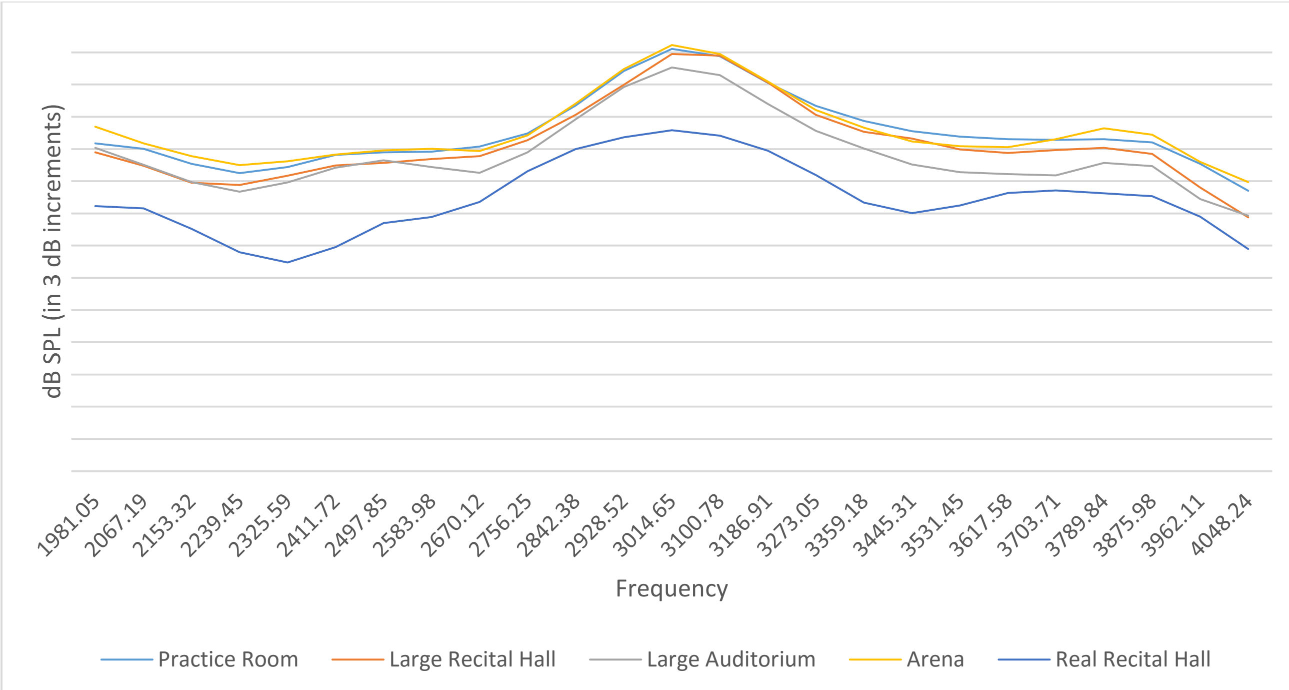


Figure 43. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 6.

The range between the Large Recital Hall and Real Recital Hall conditions in the 2-4 kHz regions measured between 2.70 dB SPL at the point of the smallest measured difference (3.96 kHz) and 8.07 dB SPL at the point of the greatest measured difference (2.32 kHz).

Figure 44 shows the LTAS contours for Participant 7 in all five acoustic conditions across the 0-10 kHz spectrum.

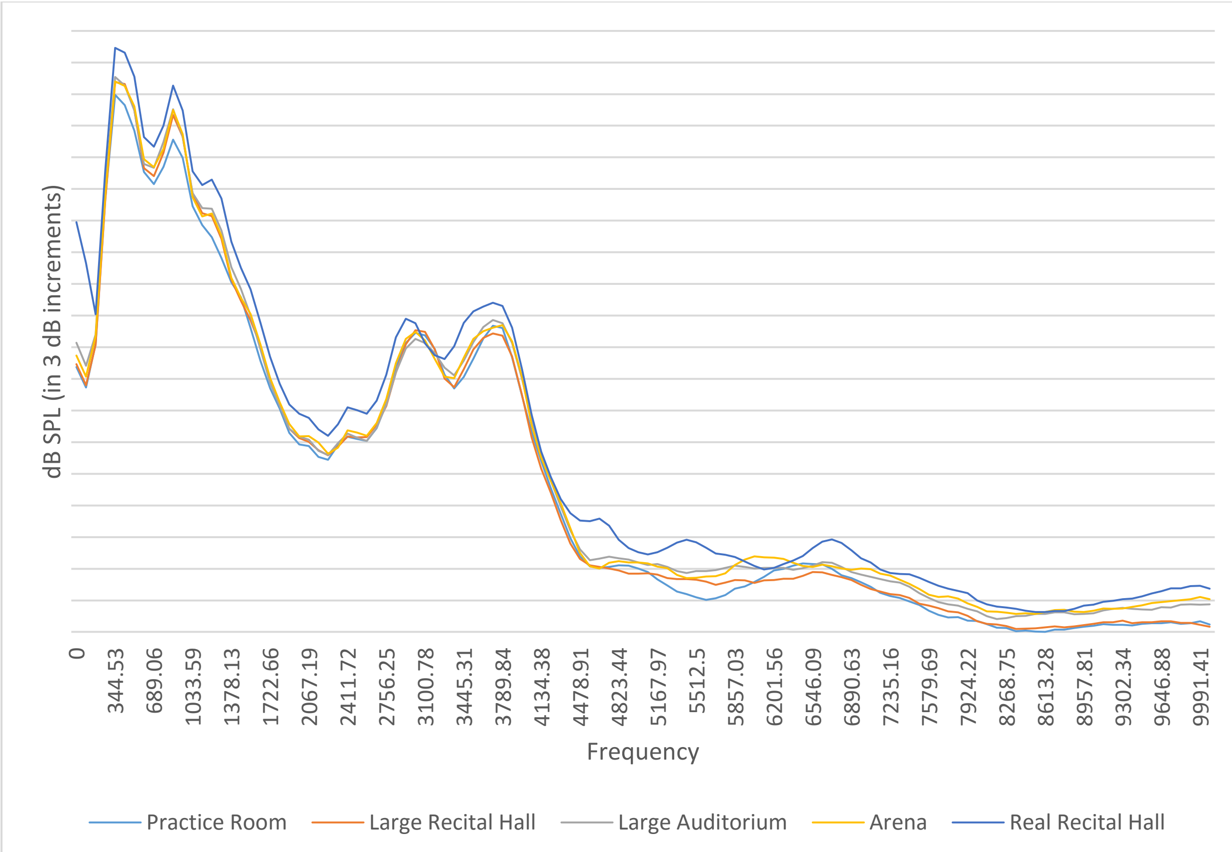


Figure 44. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 7.

Participant 7 was a 41-year-old with 15 years of singing experience and no prior history or vocal or hearing inefficiencies. LTAS generally shows a higher spectral energy of approximately 3 dB SPL between the Real Recital Hall and the virtual acoustic conditions. Between the Large Recital Hall and Real Recital Hall conditions, spectral energy differences ranged from 0.59 dB SPL at the point of the smallest measured difference (3.19 kHz) to 13.47 dB SPL at the point of the greatest measured difference (0.00 Hz).

Figure 45 shows the LTAS contours for Participant 7 in all five acoustic conditions across the 2-4 kHz spectrum.

Figure 45. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 7.

LTAS contours showed similarities in spectral energy in the virtual acoustic conditions and higher energy in the Real Recital Hall. Between the Large Recital Hall and Real Recital Hall conditions differences ranged between 0.59 dB SPL at the point of the smallest measured difference (3.19 kHz) and 4.4 dB SPL at the point of the greatest measured difference (3.45 kHz).

Figure 46 shows the LTAS contours for Participant 8 in all five acoustic conditions across the 0-10 kHz spectrum.

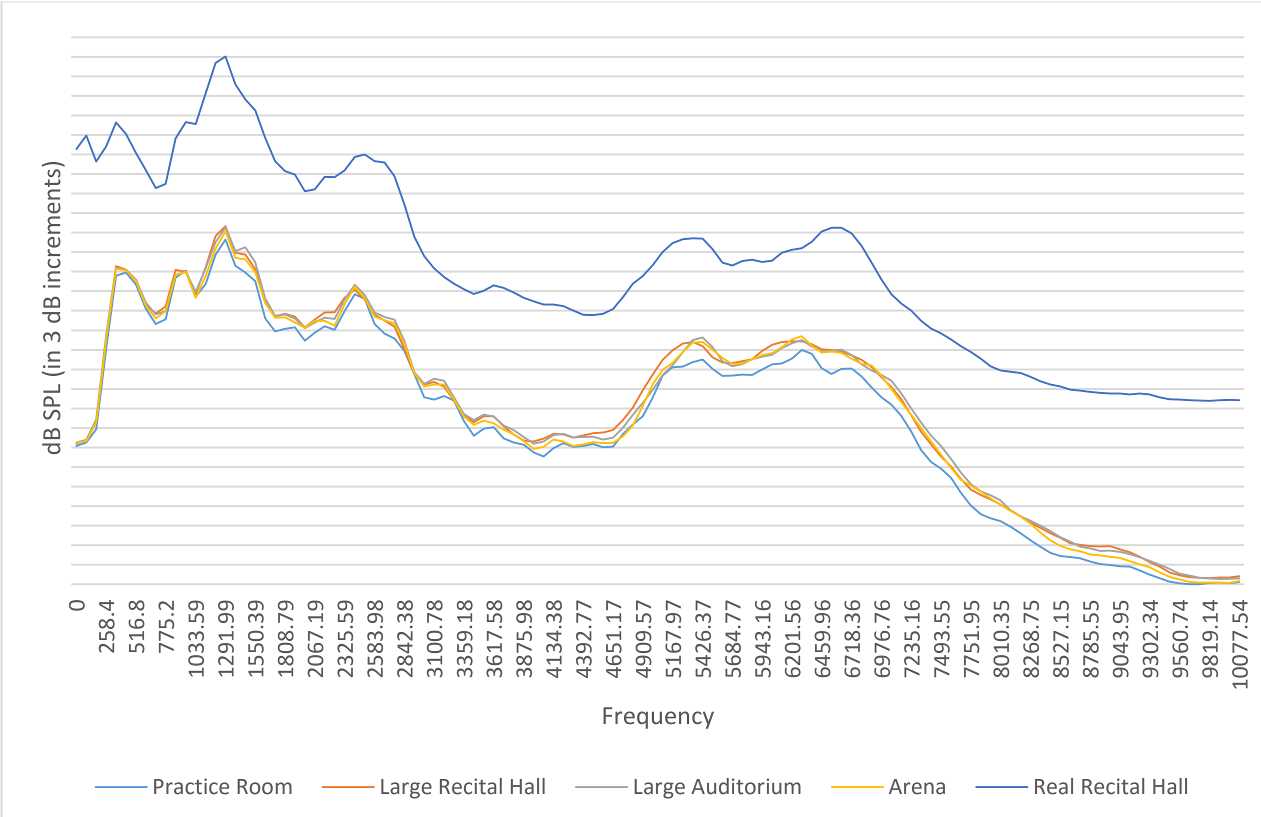


Figure 46. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 8.

Participant 8 was 34 years old with 10 years of singing experience, no reported prior vocal inefficiencies, and a reported temporary loss of high frequency hearing related to an ear infection that had completely resolved. Participant 8 demonstrated a vast difference in spectral energy between the Real Recital Hall and all the virtual acoustic conditions. Between the virtual acoustical conditions, the Practice Room condition had a generally lower spectral energy than the other three virtual acoustical conditions. Isolating the Large Recital Hall and Real Recital Hall conditions showed a range of difference between 12.96 dB SPL at the point of the smallest measured difference (6.03 kHz) and 46.78 dB SPL at the point of the greatest measured difference (86.13 Hz).

Figure 47 shows the LTAS contours for Participant 8 in all five acoustic conditions across the 2-4 kHz spectrum.

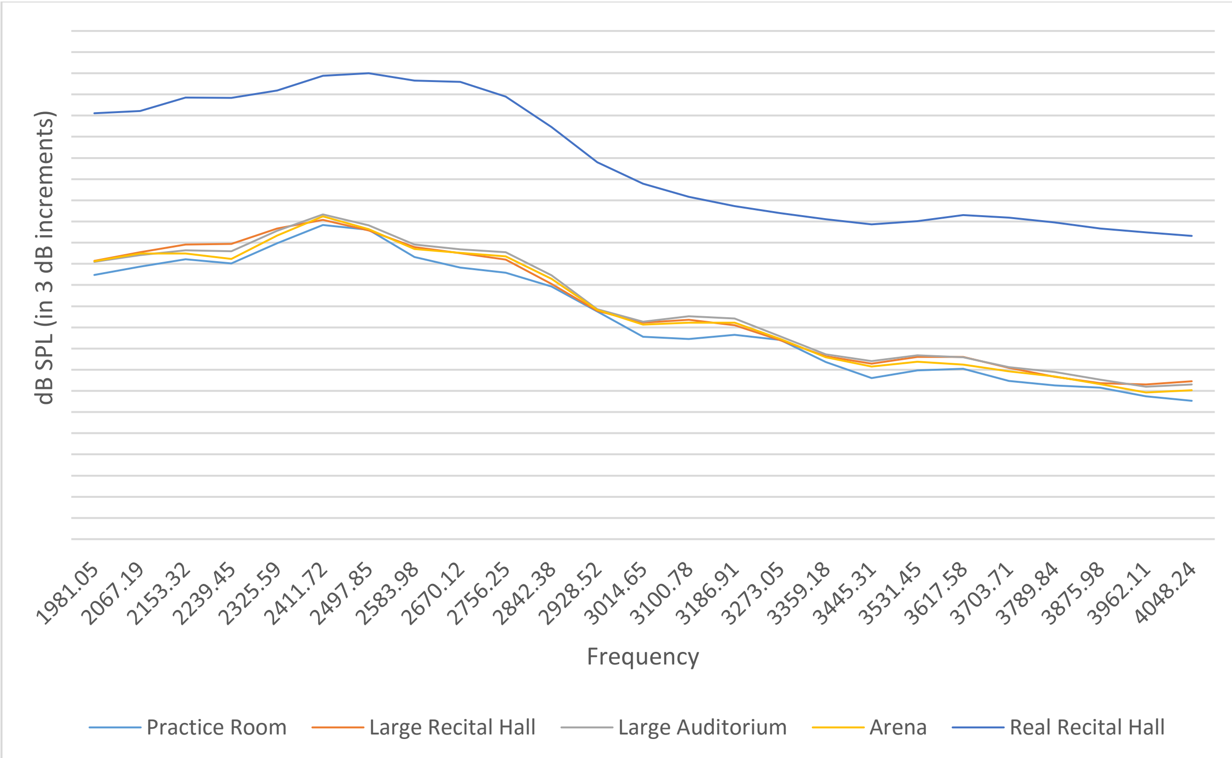


Figure 47. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 8.

In the 2-4 kHz region, the range of differences in spectral energy was 16.85 dB SPL at the point of the smallest measured difference (3.19 kHz) to 24.26 dB SPL at the point of the greatest measured difference (2.67 kHz).

Figure 48 shows the LTAS contours for Participant 9 in all five acoustic conditions across the 0-10 kHz spectrum.

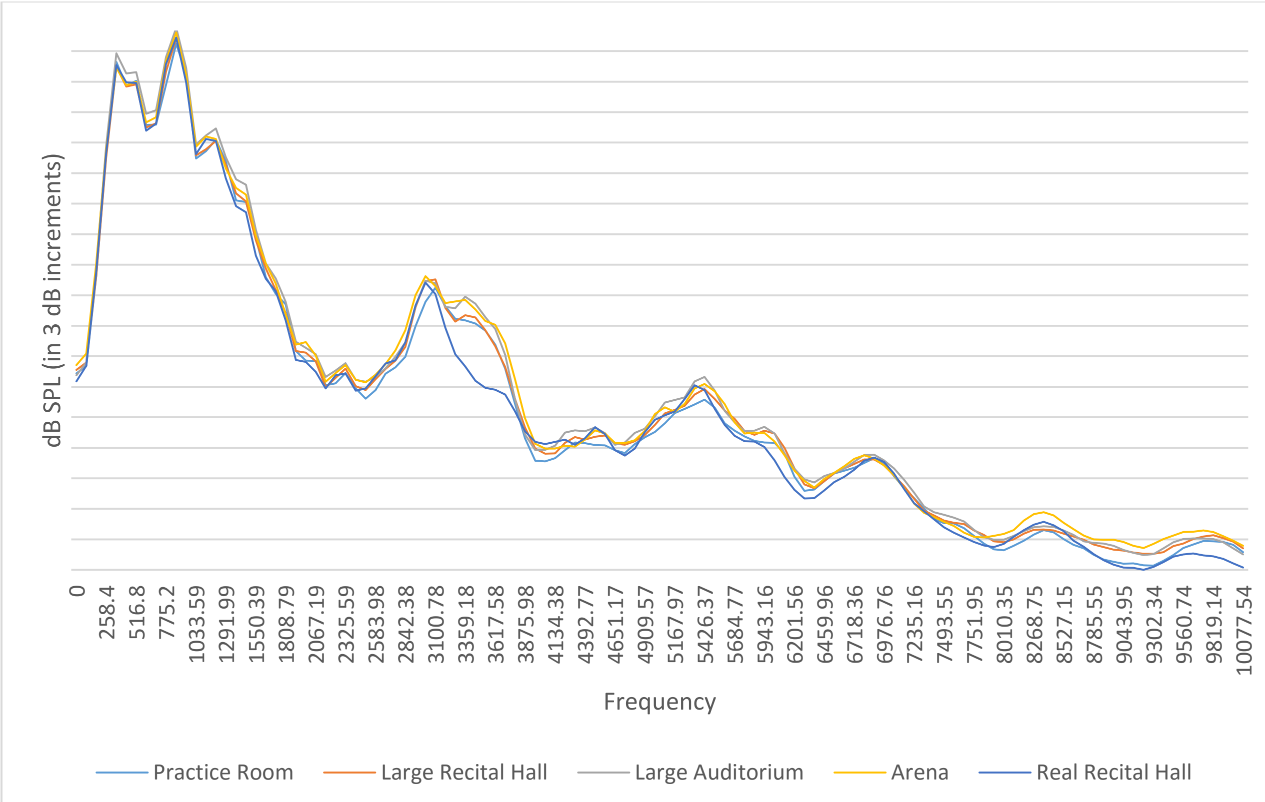


Figure 48. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 9.

Participant 9 was a 47-year-old with 5 years of singing experience, no history of vocal inefficiencies, and mild reported tinnitus. LTAS showed a similar pattern of spectral energy across all five acoustical conditions with one area of lower spectral energy in the Real Recital Hall in the 2-4 kHz region. Spectral energy in the Real Recital Hall condition generally measured lower than the Large Recital Hall virtual acoustic condition, ranging between 0.03 dB SPL at the point of the smallest measured difference (2.76 kHz) and 6.23 dB SPL at the point of the greatest measured difference (3.45 kHz).

Figure 49 shows the LTAS contours for Participant 9 in all five acoustic conditions across the 2-4 kHz spectrum.

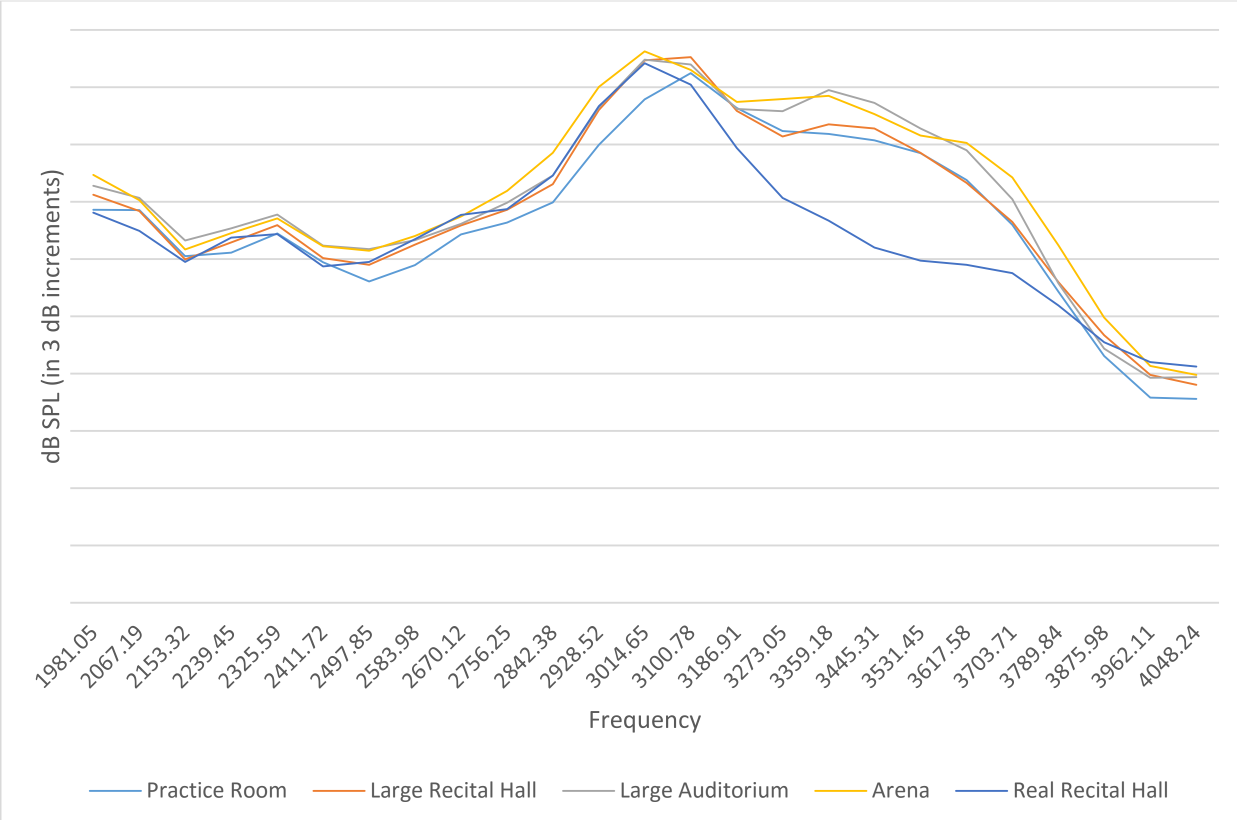


Figure 49. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 9.

Isolating the Large Recital Hall and Real Recital Hall conditions shows a generally higher spectral energy in the virtual acoustical condition, ranging between 0.03 at the point of the smallest measured difference (2.76 kHz) and 6.23 dB SPL at the point of the greatest measured difference (3.45 kHz).

Figure 50 shows the LTAS contours for Participant 10 in all five acoustic conditions across the 0-10 kHz spectrum.

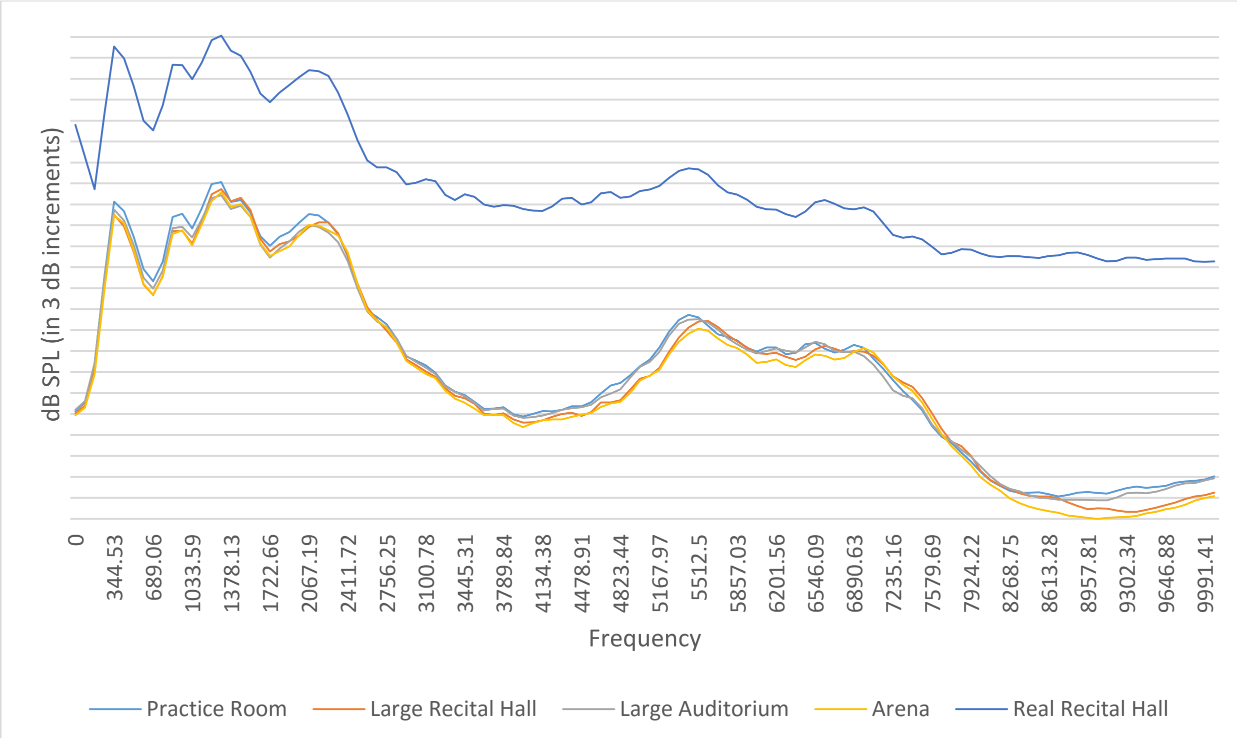


Figure 50. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 10.

Participant 10 was a 43-year-old with 20 years of singing experience, no history of hearing inefficiencies, and a history of vocal nodules early in her career that had resolved completely. Throughout the entire spectral region the Real Recital Hall measurements were much higher than the virtual acoustic conditions. The virtual acoustic conditions were grouped together across the spectrum. The difference in spectral energy between the Large Recital Hall and Real Recital Hall conditions ranged between 19.76 at the point of the smallest measured difference (1.55 kHz) and 41.27 dB SPL at the point of the greatest measured difference (0.00 Hz).

Figure 51 shows the LTAS contours for Participant 10 in all five acoustic conditions across the 2-4 kHz spectrum.

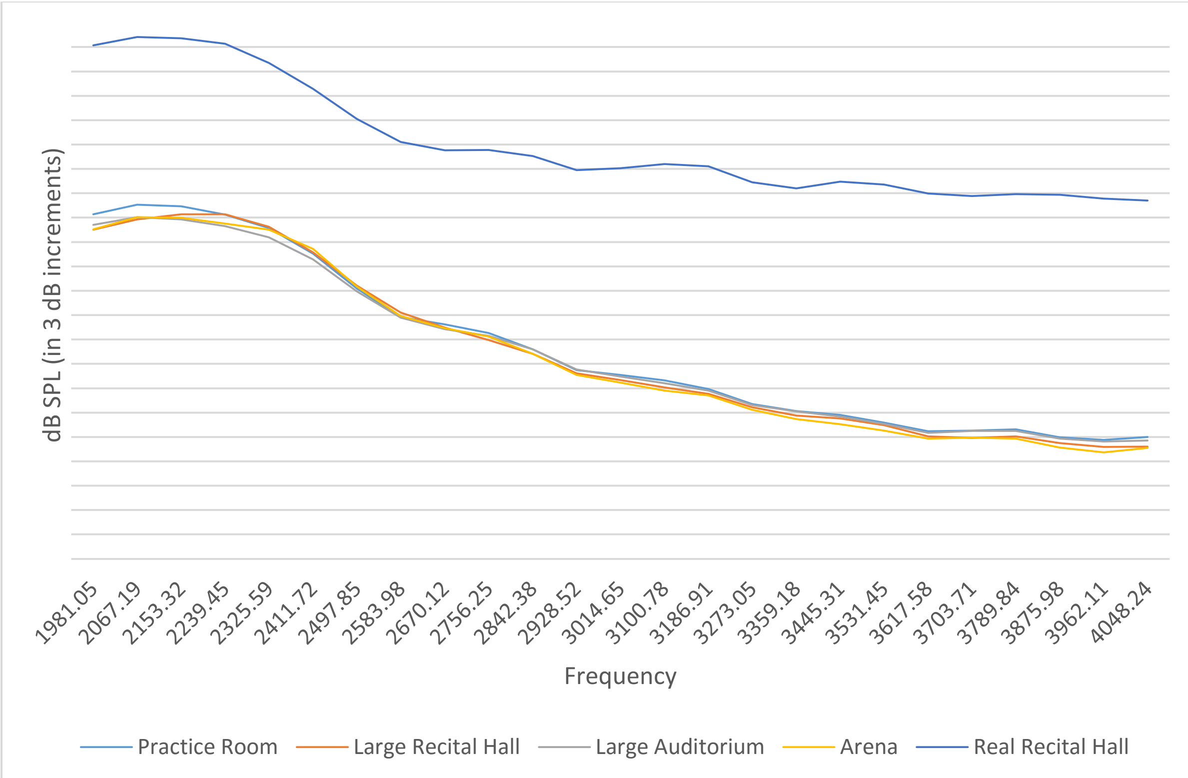


Figure 51. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 10.

The difference in spectral energy between the Large Recital Hall and Real Recital Hall conditions ranged between 20.13 dB SPL at the point of the smallest measured difference (2.41 kHz) and 30.59 dB SPL at the point of the smallest measured difference (3.88 kHz).

Figure 52 shows the LTAS contours for Participant 11 in all five acoustic conditions across the 0-10 kHz spectrum.

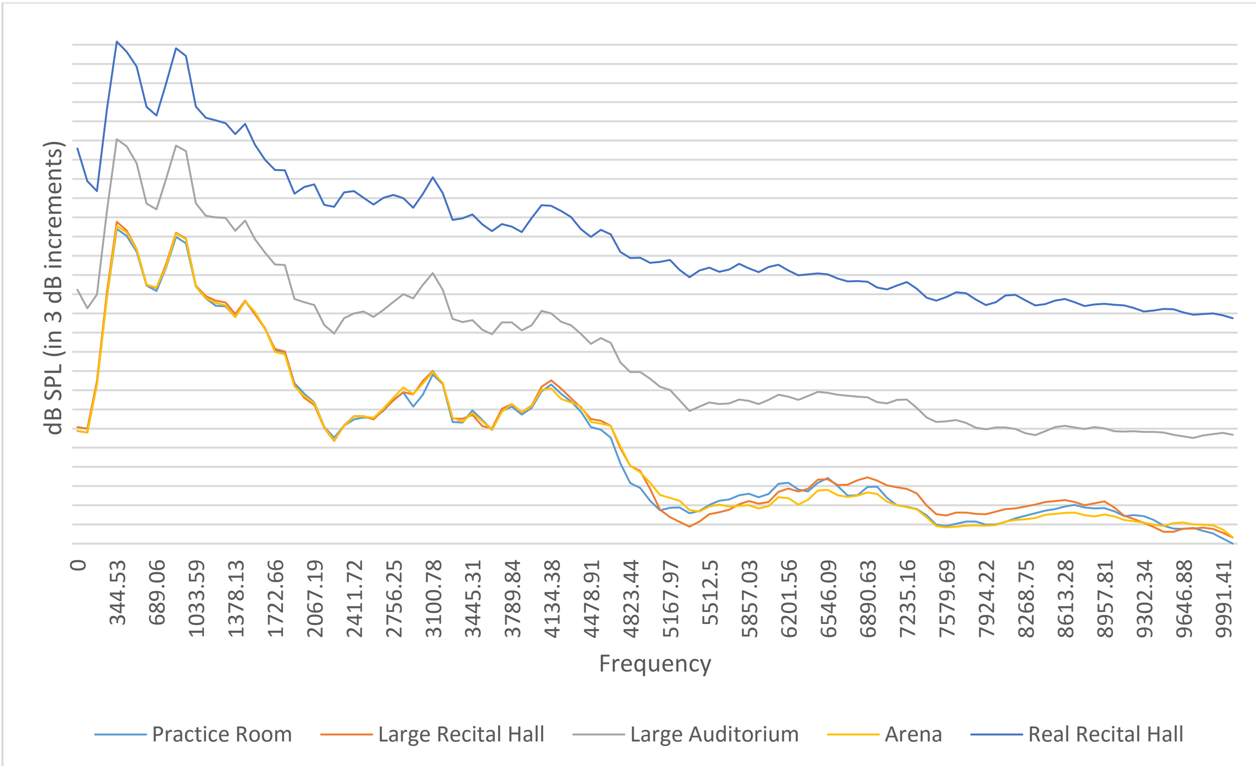


Figure 52. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 11.

Participant 11 was 20 years old with 2 years of singing experience and no reported hearing or vocal inefficiencies. LTAS shows large differences in spectral energy of nearly 30 dB between the highest readings in the Real Recital Hall and the Practice Room, Large Recital Hall, and Arena virtual acoustic settings. The Large Auditorium setting stood out in the spectrum, approximately 15 dB SPL less in spectral energy than the Real Recital Hall. Isolating the Large Recital Hall and Real Recital Hall conditions yielded differences in spectral energy ranging between 26.45 dB SPL at the point of the smallest measured difference (1.64 kHz) and 43.57 dB SPL at the point of the greatest measured difference (0.00 Hz).

Figure 53 shows the LTAS contours for Participant 11 in all five acoustic conditions across the 2-4 kHz spectrum.

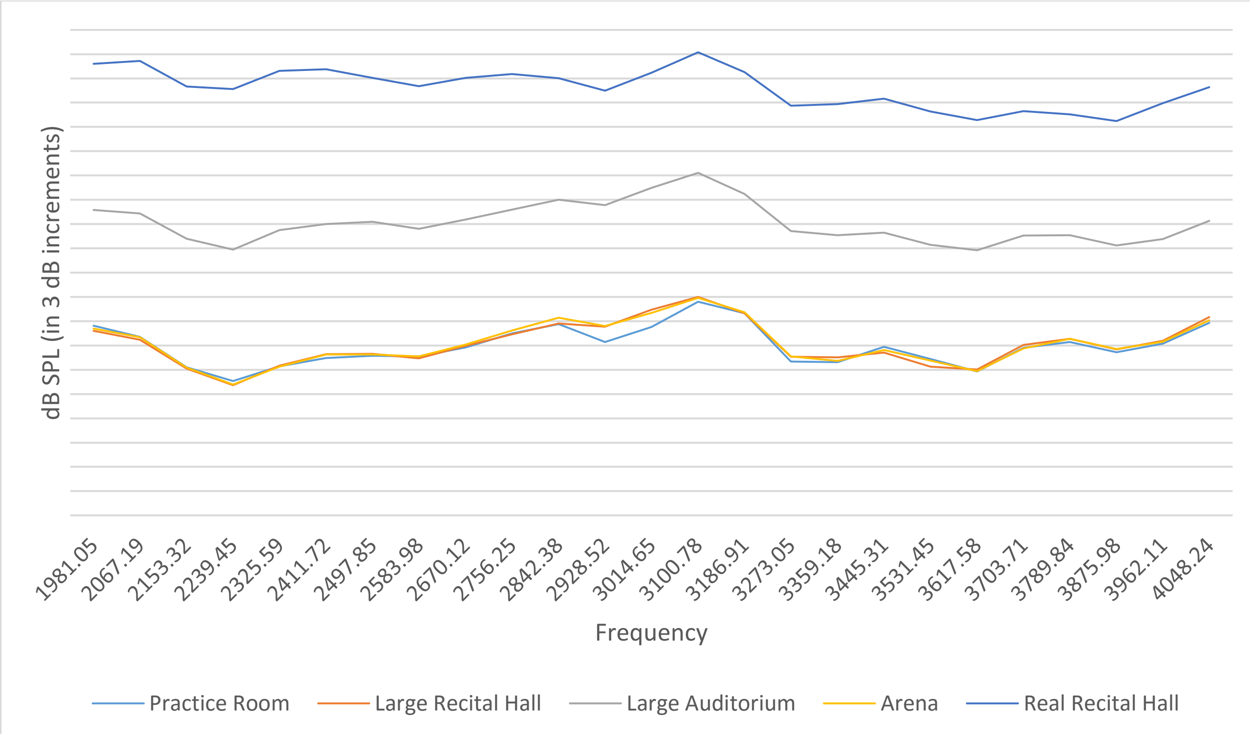


Figure 53. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 11

The range of difference in spectral energy between the Large Recital Hall and Real Recital Hall conditions was 27.29 dB SPL at the point of the smallest measured difference (4.13 kHz) and 36.59 dB SPL at the point of the greatest measured difference (2.24 kHz).

Figure 54 shows the LTAS contours for Participant 12 in all five acoustic conditions across the 0-10 kHz spectrum.

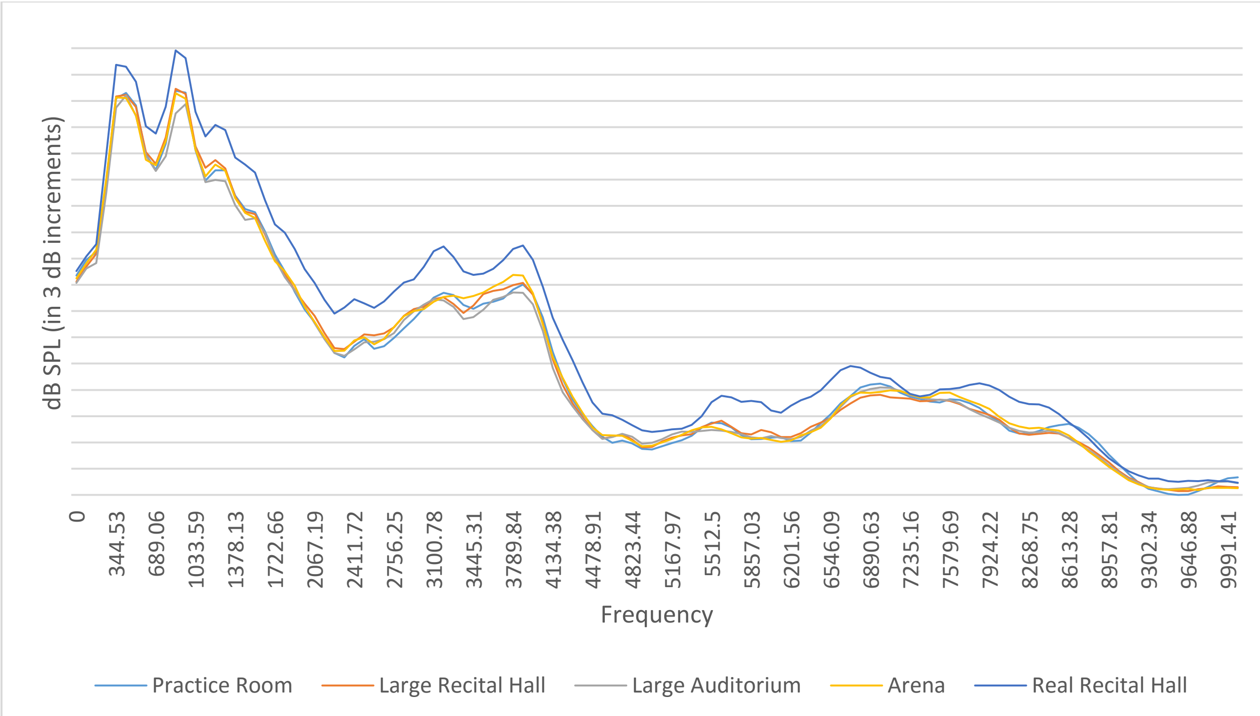


Figure 54. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 12.

Participant 12 was 20 years old with 7 years of singing experience and no reported history of vocal or hearing inefficiencies. LTAS shows a greater spectral energy in the Real Recital Hall compared to the virtual acoustical conditions across most of the spectrum. The difference between the Large Recital Hall and the Real Recital Hall measured 0.49 dB SPL at the point of the smallest measured difference (8.96 kHz) and 5.81 dB SPL at the point of the greatest measured difference at (3.19 kHz).

Figure 55 shows the LTAS contours for Participant 12 in all five acoustic conditions across the 2-4 kHz spectrum.

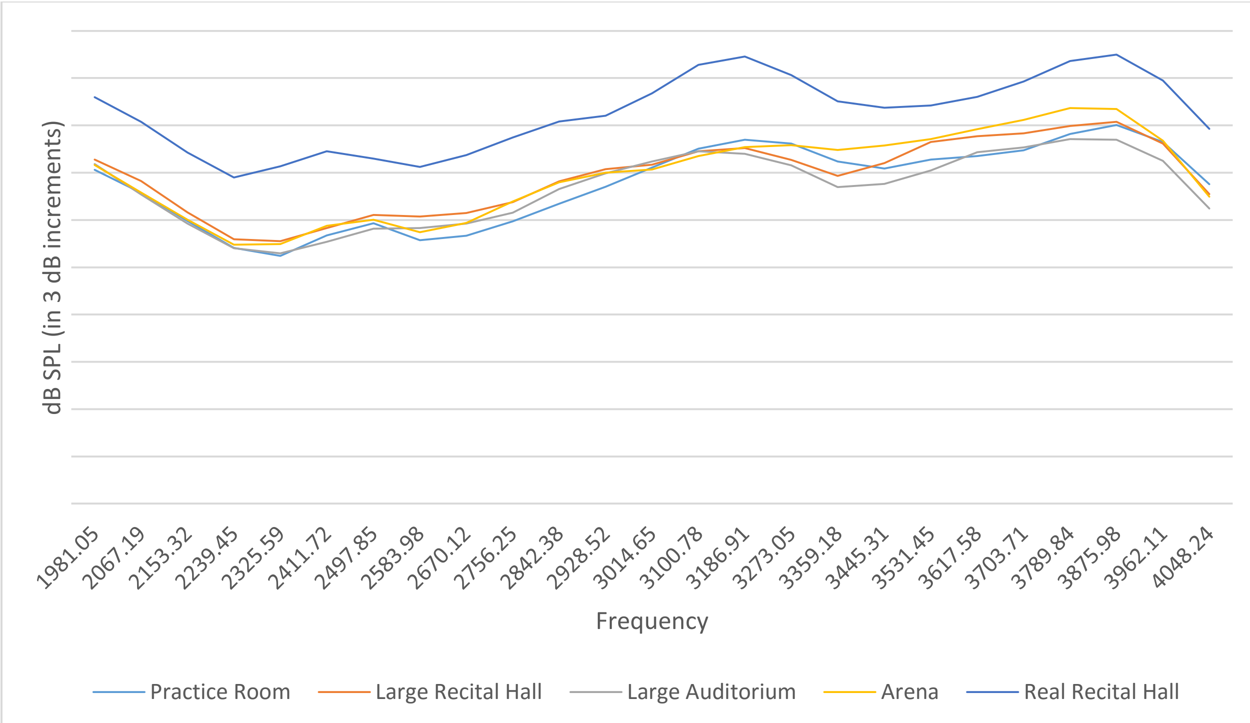


Figure 55. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 12.

Isolating the Large Recital Hall and Real Recital Hall conditions showed a difference in spectral energy of 2.33 dB SPL at the point of the smallest measured difference (3.53 kHz) and 5.81 dB SPL at the point of the largest measured difference (3.19 kHz).

Figure 56 shows the LTAS contours for Participant 13 in all five acoustic conditions across the 0-10 kHz spectrum.

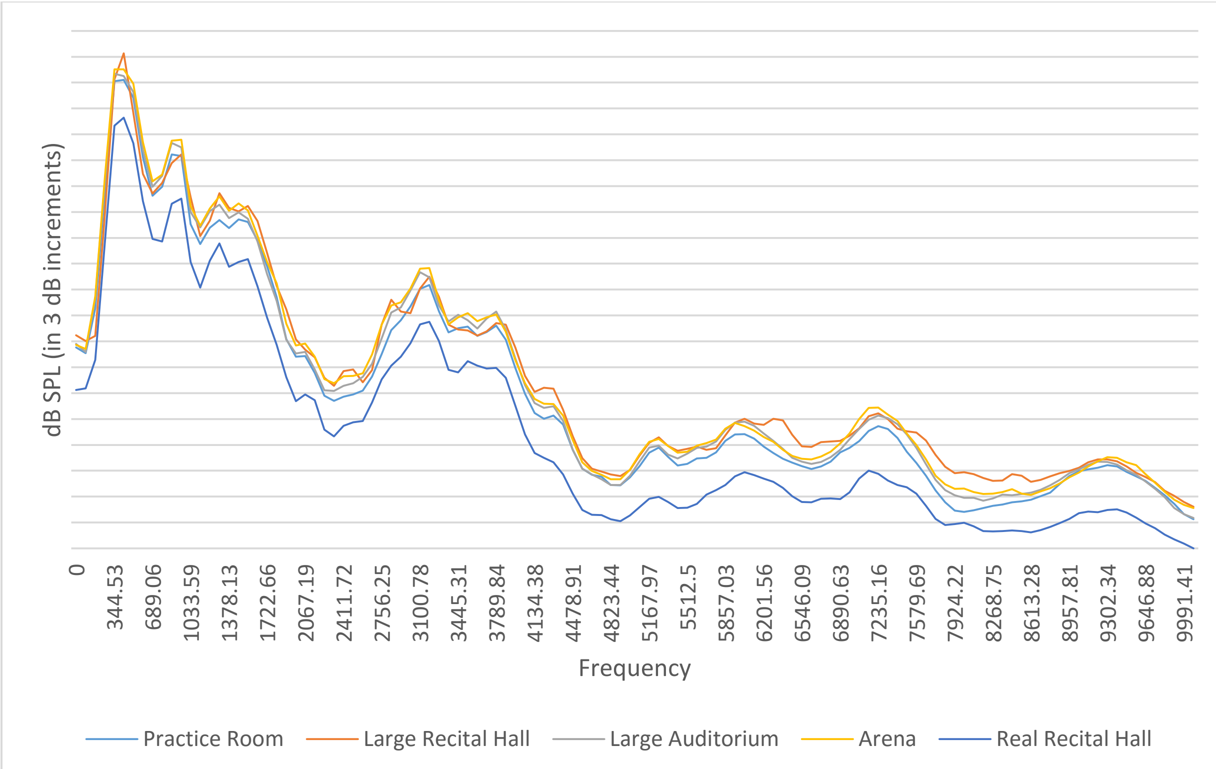


Figure 56. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 13.

Participant 13 was a 37-year-old with 6 years of singing experience and no reported prior history of vocal or hearing inefficiencies. Similar to Participant 6, the spectral energy of the Real Recital Hall was lower overall than the virtual acoustical conditions. The difference between the Large Recital Hall and the Real Recital Hall conditions was 2.78 dB SPL at the point of the smallest measured difference (172.27 Hz) and 8.51 dB SPL at the point of the largest measured difference (4.31 kHz).

Figure 57 shows the LTAS contours for Participant 13 in all five acoustic conditions across the 2-4 kHz spectrum.

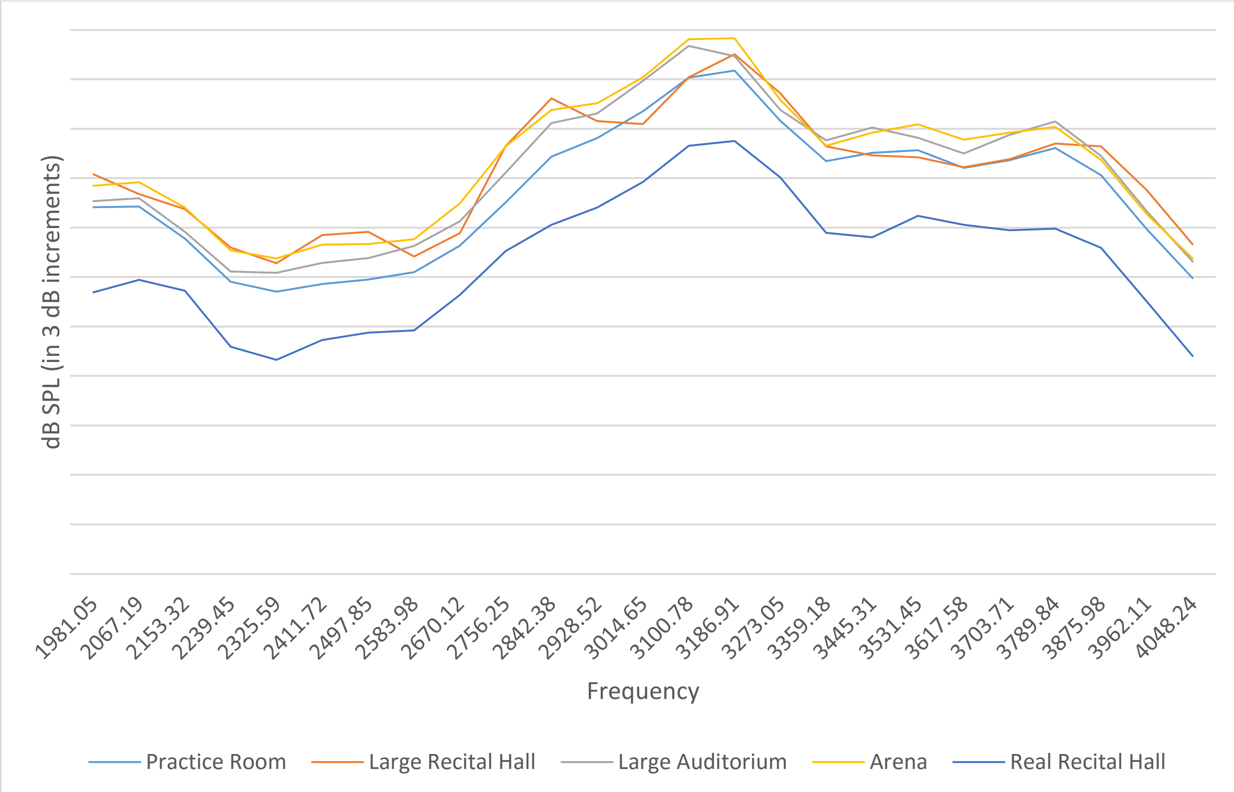


Figure 57. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 13.

The Large Recital Hall and Real Recital Hall conditions differed in spectral energy by 3.50 dB SPL at the point of the smallest measured difference (3.62 kHz) and 7.66 dB SPL at the point of the largest measured difference (2.84 kHz).

Figure 58 shows the LTAS contours for Participant 14 in all five acoustic conditions across the 0-10 kHz spectrum.

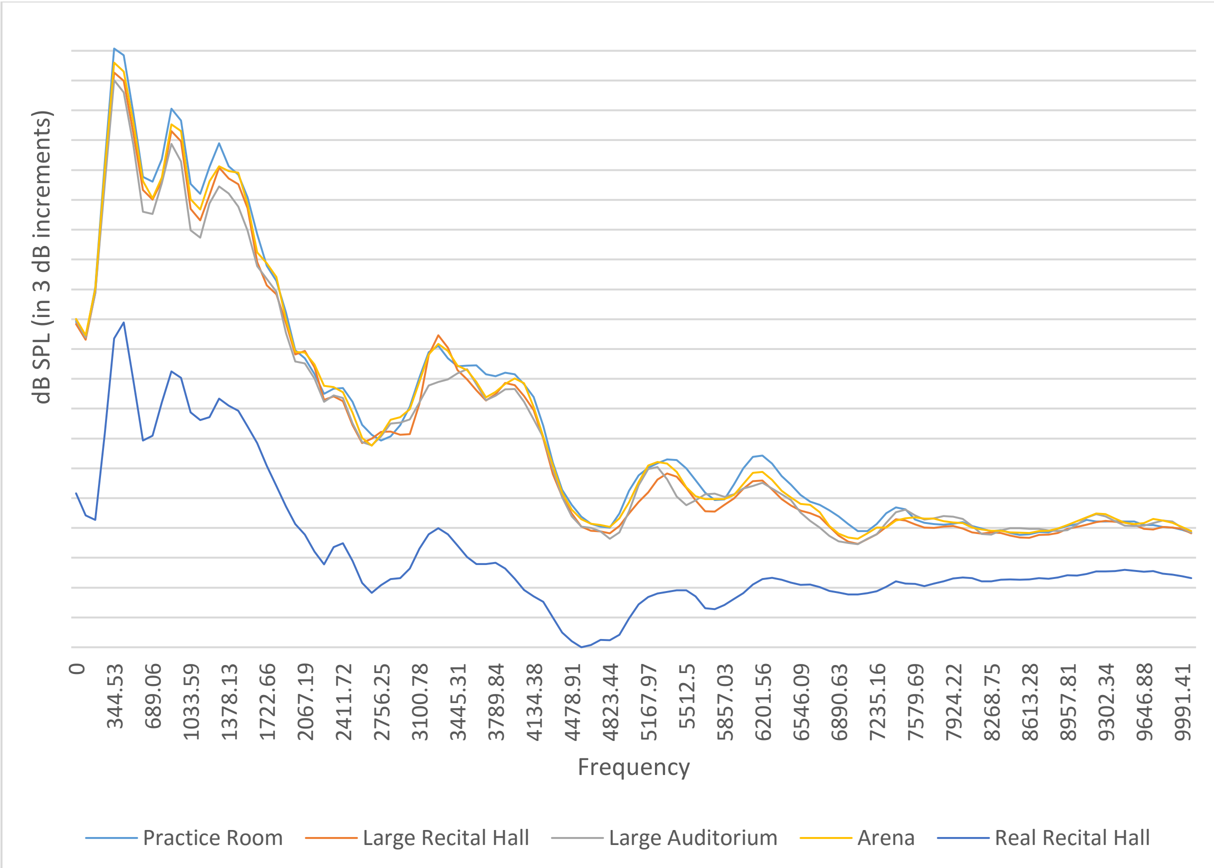


Figure 58. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 14.

Participant 14 was a 31-year-old with 6 years of singing experience and no prior history of hearing or vocal efficiencies. LTAS shows the Real Recital Hall measurements were lower than the virtual acoustical conditions. The Large Recital Hall and Recital Hall conditions measured a difference of 4.18 dB SPL at the point of the point of the smallest measured difference (8.61 kHz) and 26.76 at the point of the largest measured difference (344.53 Hz), with the virtual acoustic condition having greater spectral energy at both points.

Figure 59 shows the LTAS contours for Participant 14 in all five acoustic conditions across the 2-4 kHz spectrum, and shows the virtual acoustical conditions following a similar pattern of spectral energy, except for a decrease in spectral energy in the Large Auditorium setting between 3.2-3.5 kHz, while the Real Recital Hall condition is considerably lower in spectral energy than the virtual acoustic conditions.

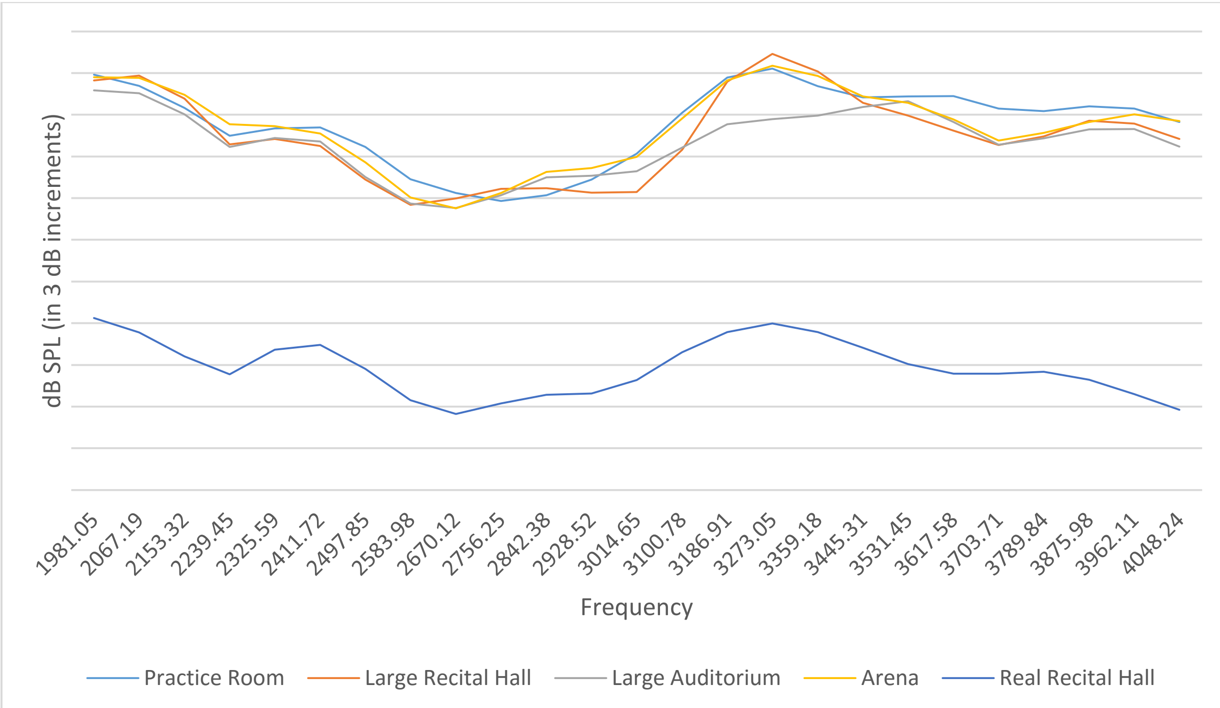


Figure 59. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 14.

The difference between the Large Recital Hall and Real Recital Hall conditions in the region of 2-4 kHz measured 13.52 dB SPL at the point of the smallest measured difference (3.01 kHz), and 19.49 dB SPL at the point of the largest measured difference (4.05 kHz), with the virtual acoustic condition showing greater spectral energy at both points.

Figure 60 shows the LTAS contours for Participant 15 in all five acoustic conditions across the 0-10 kHz spectrum.

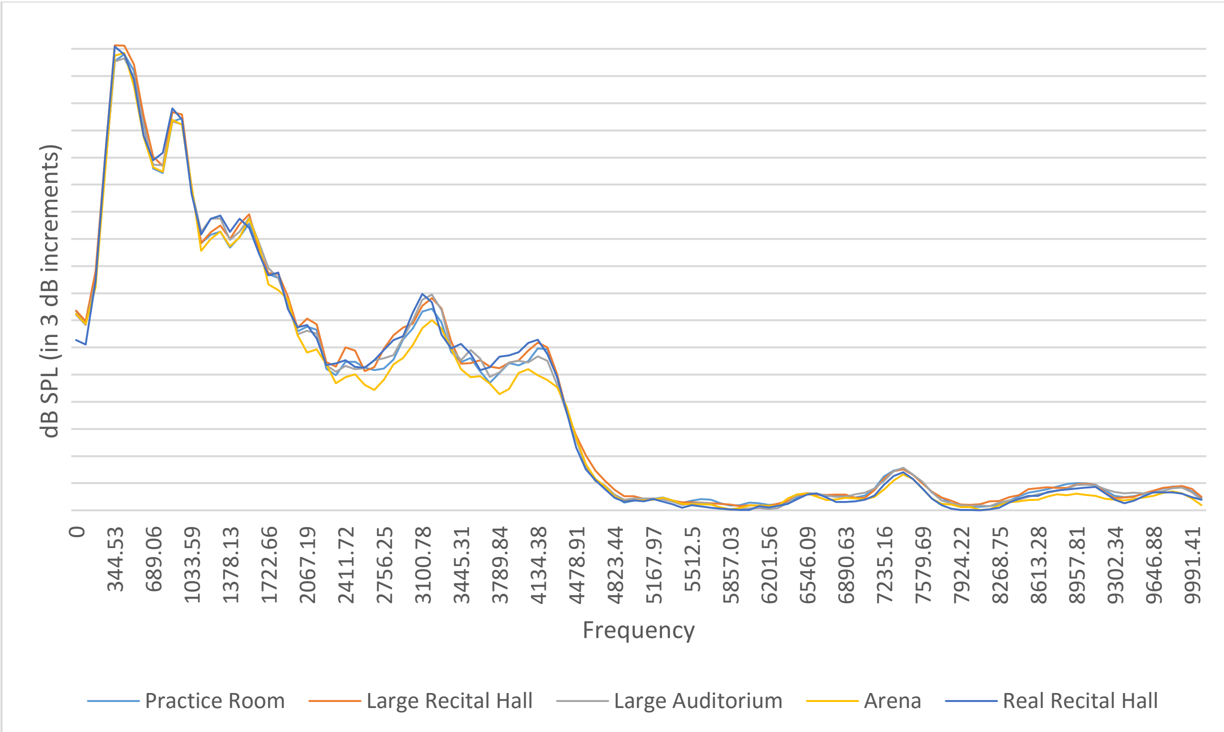


Figure 60. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 15.

Participant 15 was a 29-year-old with 12 years of singing experience and no reported inefficiencies in voice or hearing. Her LTAS measurements lacked distinguishing differences in spectral energy among the five acoustical conditions. Comparing the Large Recital Hall and Real Recital Hall conditions showed differences in spectral energy ranging from 0.01 dB SPL at the smallest point of measured difference (6.55 kHz) and 3.24 dB SPL at the greatest point of measured difference (0.00 Hz).

Figure 61 shows the LTAS contours for Participant 15 in all five acoustic conditions across the 2-4 kHz spectrum.

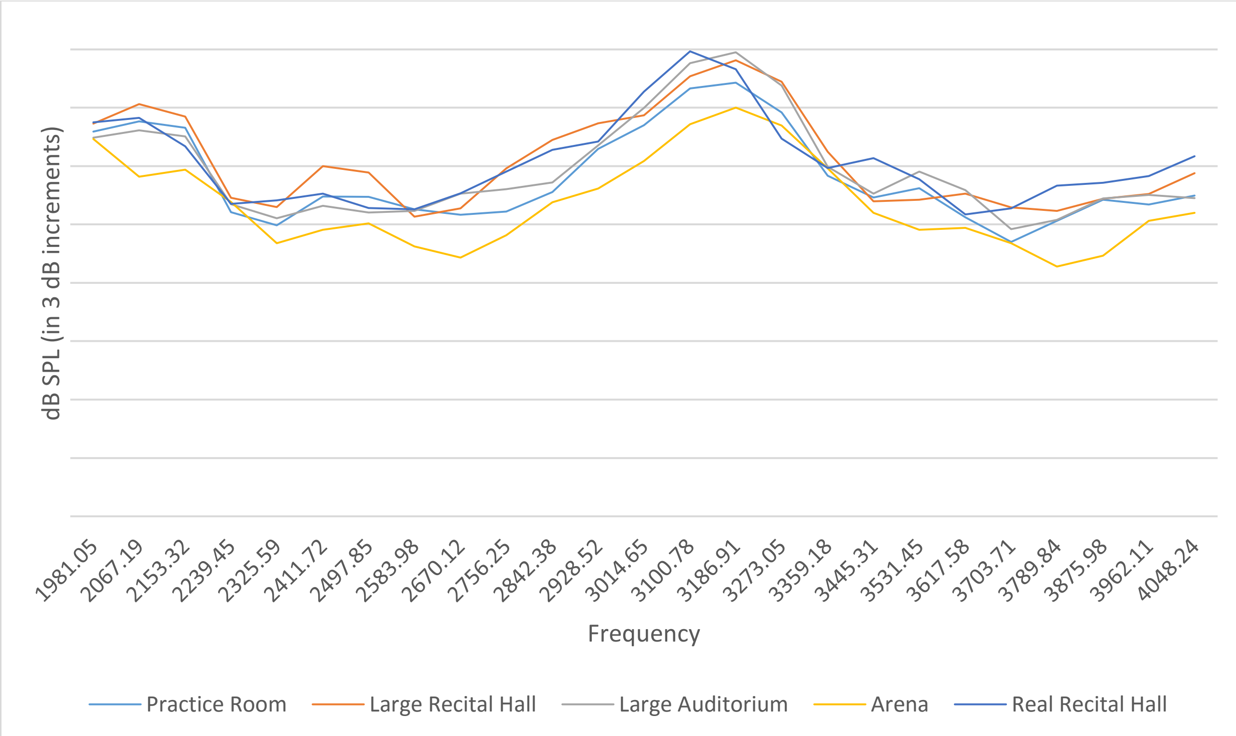


Figure 61. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 15.

In the region of 2-4 kHz, the individual acoustical conditions lacked uniformity and showed no discernible pattern of different in spectral energy. Isolating the Large Recital Hall and Real Recital Hall conditions measured differences of 0.05 dB SPL at the smallest measured point of difference (3.70 kHz) and 2.93 dB SPL at the greatest measured point of difference (3.27 kHz) in the 2-4 kHz region.

Figure 62 shows the LTAS contours for Participant 16 in all five acoustic conditions across the 0-10 kHz spectrum.

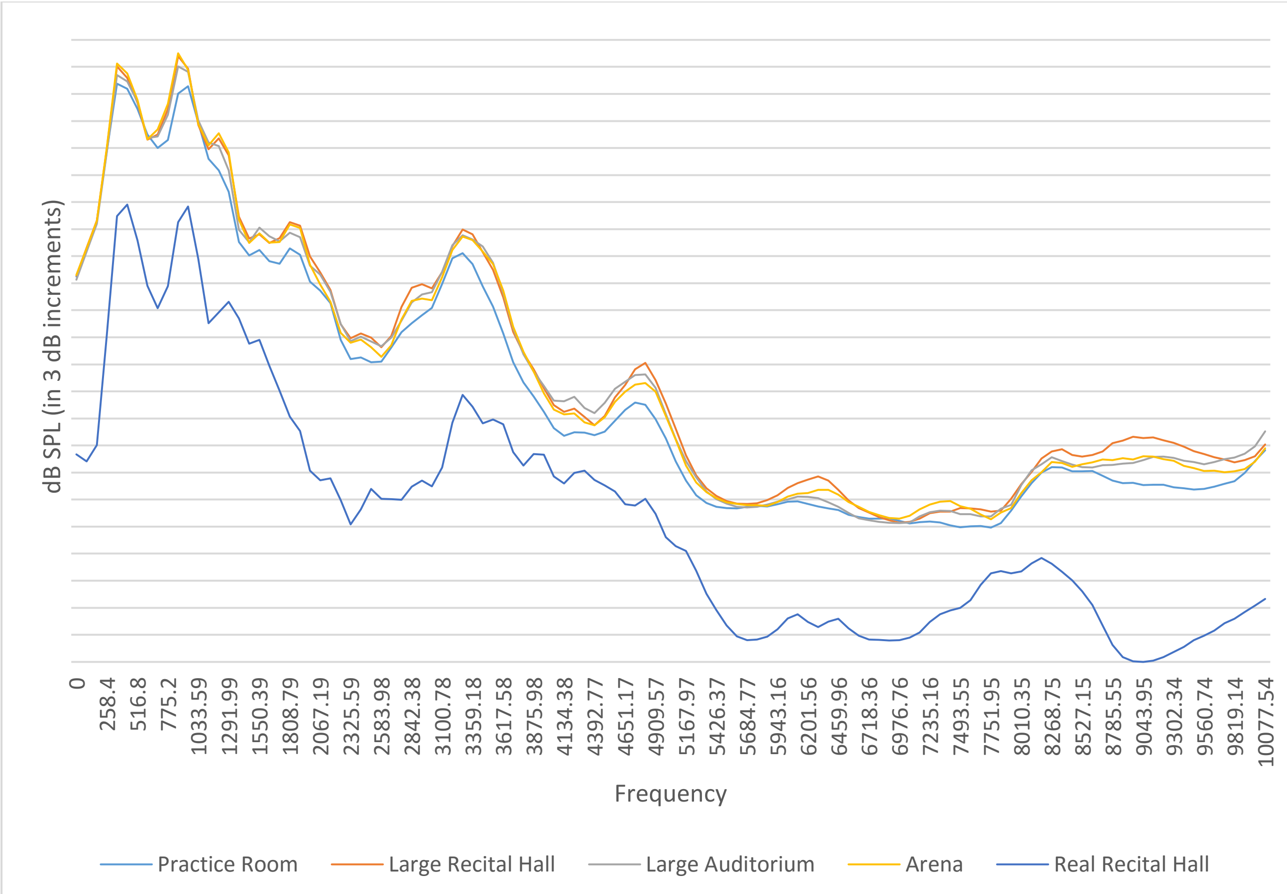


Figure 62. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 16.

Participant 16 was 26 years old with 3 years of singing experience and no prior history of vocal or hearing inefficiencies. She also displayed a dampening of spectral energy in the Real Recital Hall in comparison with the virtual acoustic conditions, differing nearly 20 dB SPL in the region of 2-4-kHz. Between the Large Recital Hall and Real Recital Hall conditions differences ranged from 5.93 dB SPL at the point of the smallest measured difference (4.31 kHz) and 24.92 dB SPL at the point of the largest measured difference at (8.96 kHz).

Figure 63 shows the LTAS contours for Participant 16 in all five acoustic conditions across the 2-4 kHz spectrum, which includes the largest measured difference in spectral energy between the Real Recital Hall and the virtual acoustic environments.

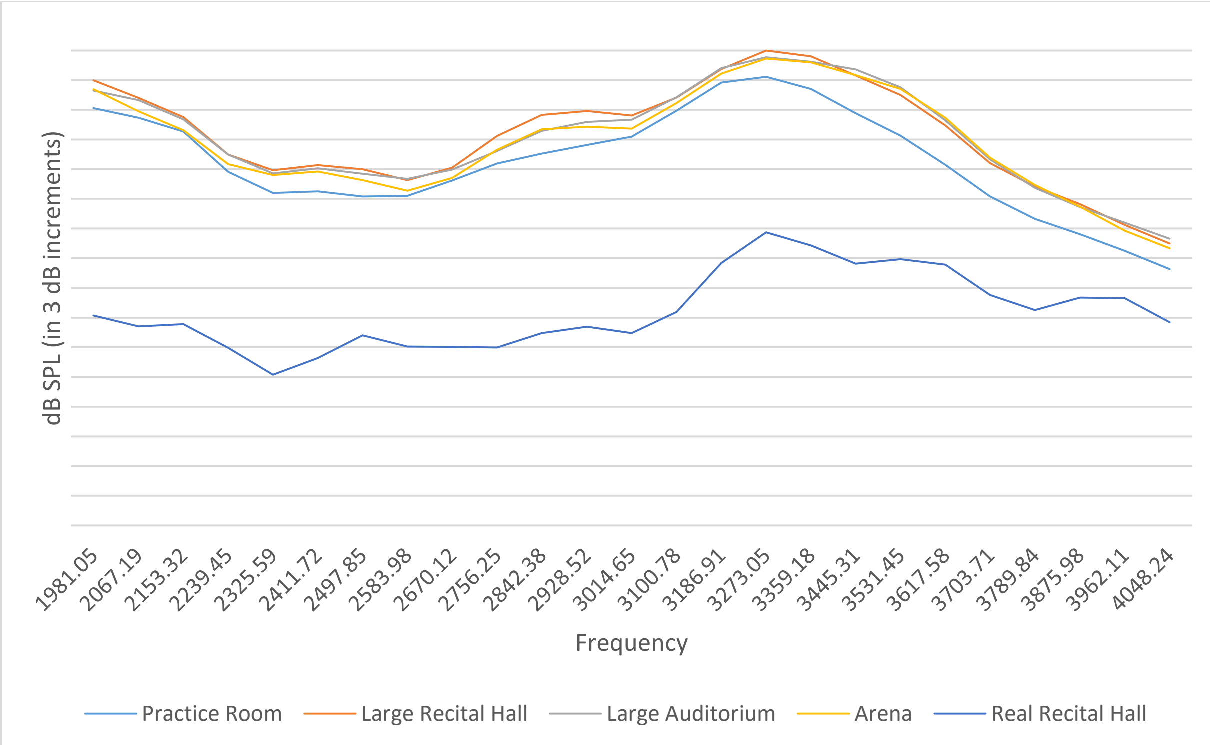


Figure 63. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 16.

The Large Recital Hall and Real Recital Hall conditions yielded differences of 7.40 dB SPL at the point of the smallest measured difference (3.96 kHz) and 23.06 dB SPL at the point of the largest measured difference (2.06 kHz), with the virtual acoustic condition showing greater spectral energy at both points.

Figure 64 shows the LTAS contours for Participant 17 in all five acoustic conditions across the 0-10 kHz spectrum.

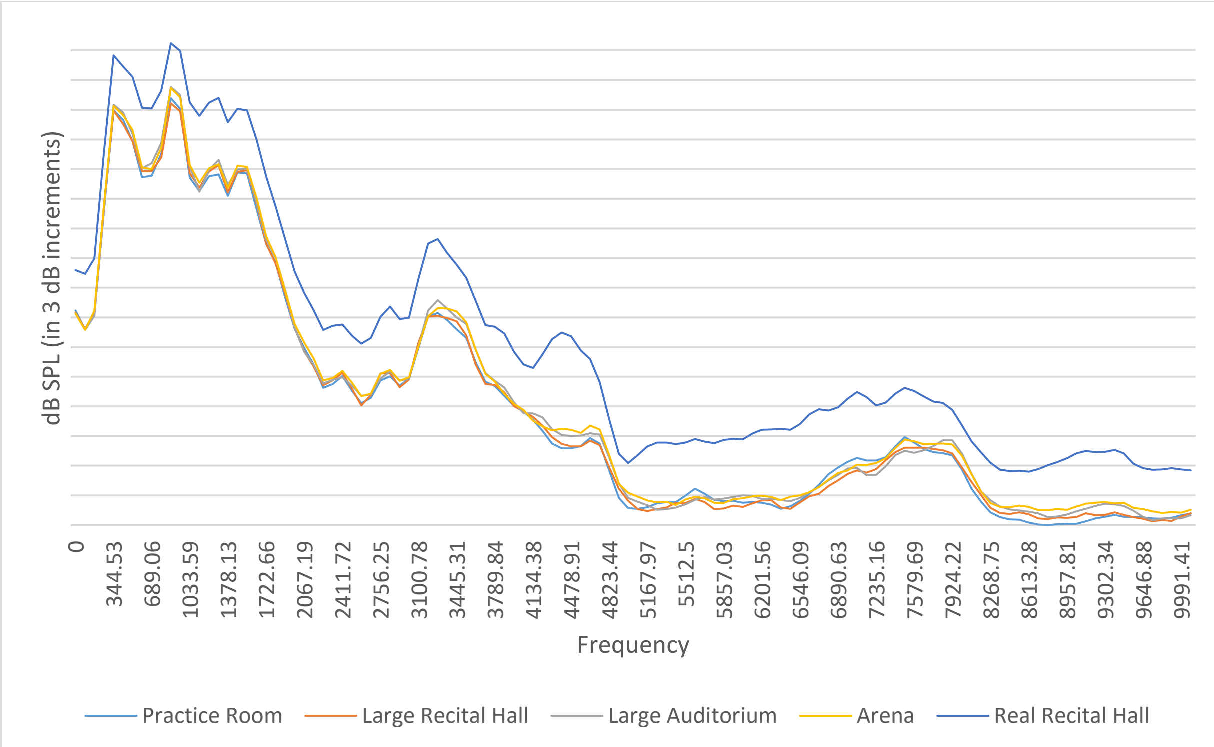


Figure 64. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 17.

Participant 17 was 35 years old with 2 years of singing experiences and no prior history of vocal or hearing inefficiencies. LTAS shows a consistent difference in spectral energy between the Real Recital Hall and the virtual acoustical conditions of approximately 5 dB SPL. The Large Recital Hall and Real Recital Hall measured a 3.53 dB SPL difference at the point of the smallest measured difference (4.91 kHz) and 11.24 dB SPL difference at the point of the largest measured difference (4.39 kHz).

Figure 65 shows the LTAS contours for Participant 17 in all five acoustic conditions across the 2-4 kHz spectrum.

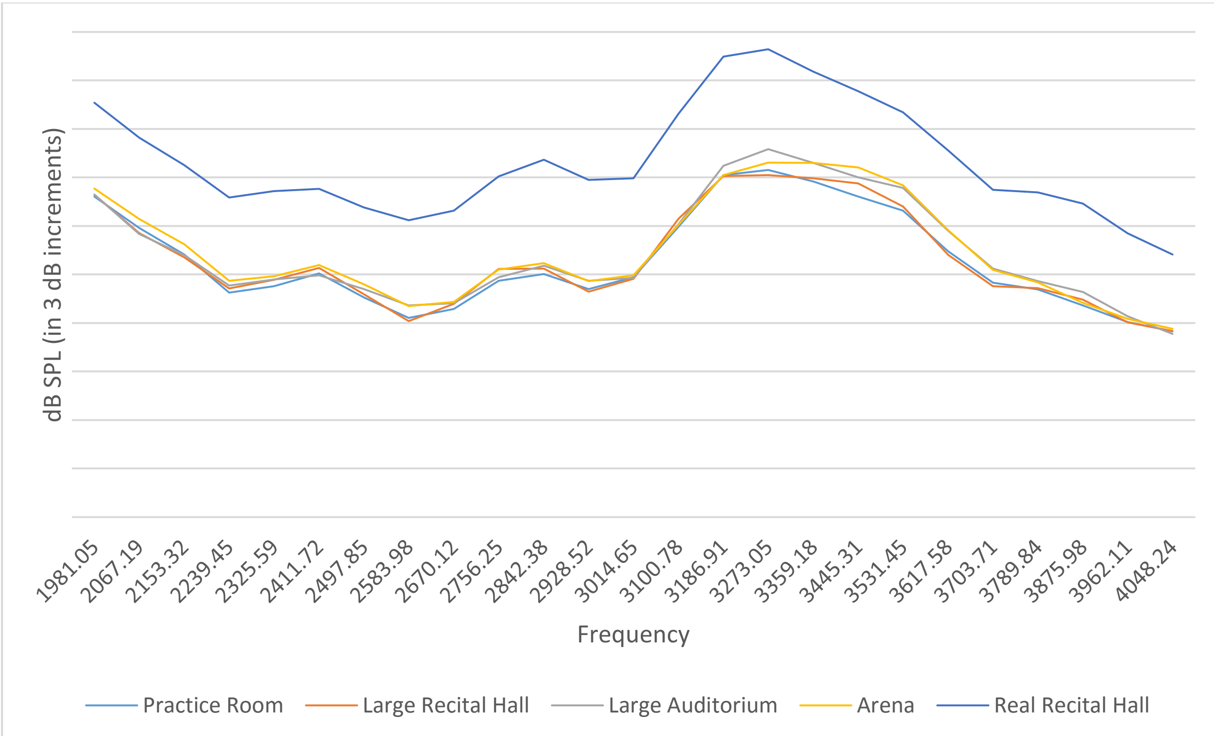


Figure 65. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 17.

The smallest measured difference between the Large Recital Hall and the Real Recital Hall conditions was 4.73 dB SPL (4.05 kHz), and 7.77 dB SPL at the point of the largest measured difference (3.27 kHz).

Figure 66 shows the LTAS contours for Participant 18 in all five acoustic conditions across the 0-10 kHz spectrum.

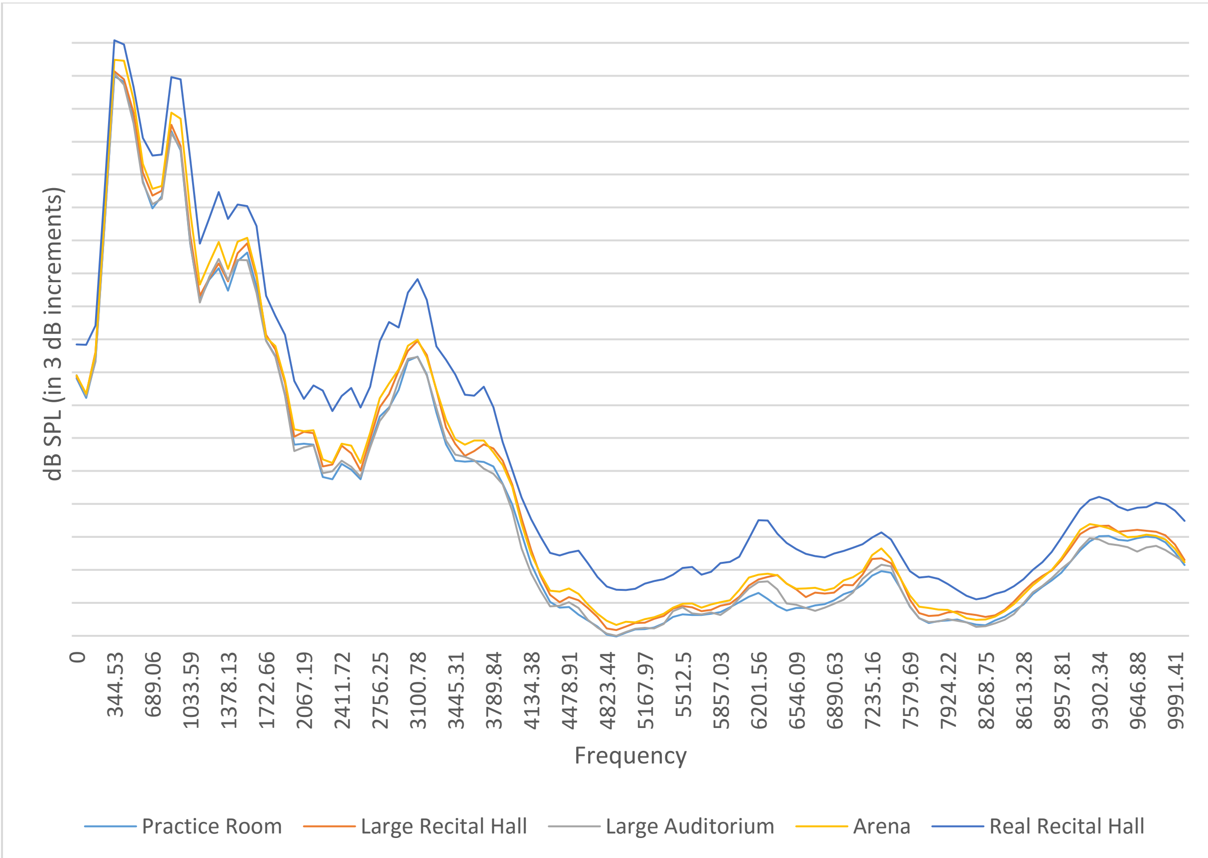


Figure 66. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 18.

Participant 18 was a 23-year-old with 4 years of singing experience and no reported history of vocal or hearing inefficiencies. LTAS shows a general increase in spectral energy in the Real Recital Hall of over 5 dB SPL through most of the spectrum from 0-10 kHz. The Large Recital Hall and Real Recital Hall conditions differ by 1.1 dB SPL at the point of the smallest measured difference (8.61 kHz) and 6.94 dB SPL at the point of the greatest measured difference (1.03 kHz).

Figure 67 shows the LTAS contours for Participant 18 in all five acoustic conditions across the 2-4 kHz spectrum.

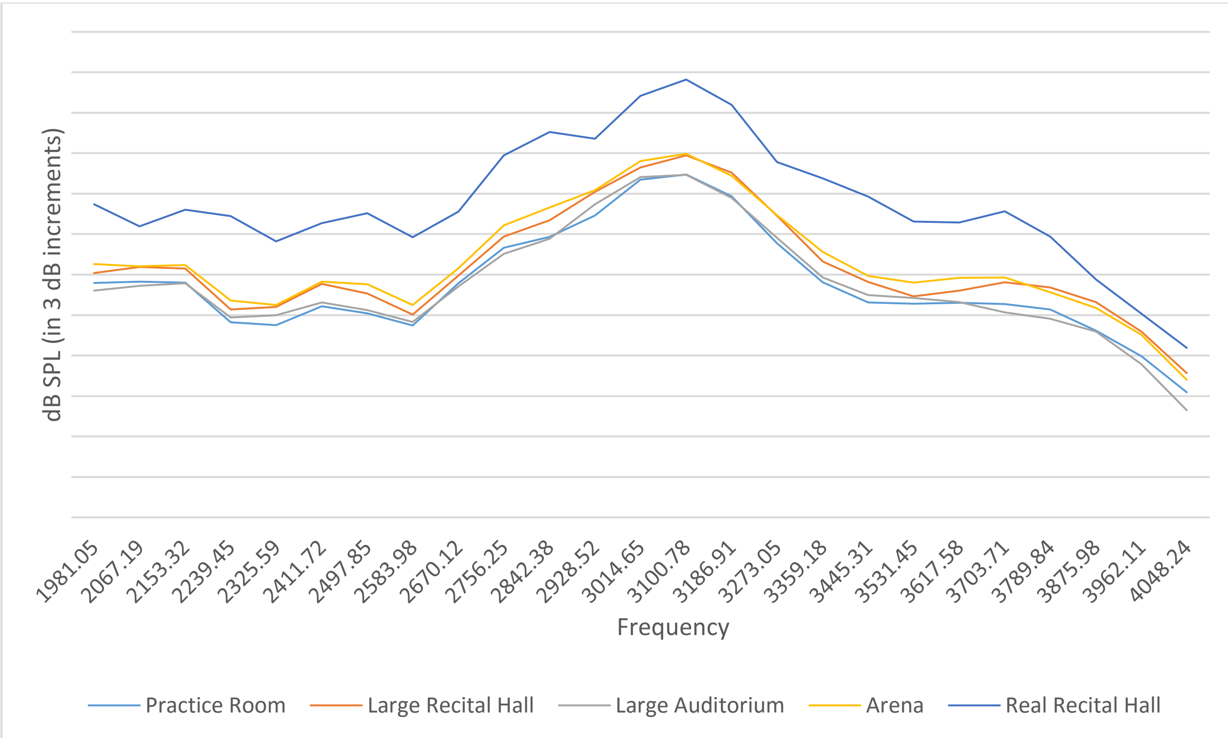


Figure 67. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 18.

Among the virtual acoustic conditions, spectral energy was similar but did show a slightly higher energy in the Large Recital Hall and Arena settings when compared to the Practice Room and Large Auditorium settings. The Large Recital Hall and Real Recital Hall conditions measured differences of 1.34 dB SPL at the point of the smallest measured difference (3.96 kHz) and 6.92 dB SPL at the point of the greatest measured difference (2.24 kHz).

Figure 68 shows the LTAS contours for Participant 19 in all five acoustic conditions across the 0-10 kHz spectrum.

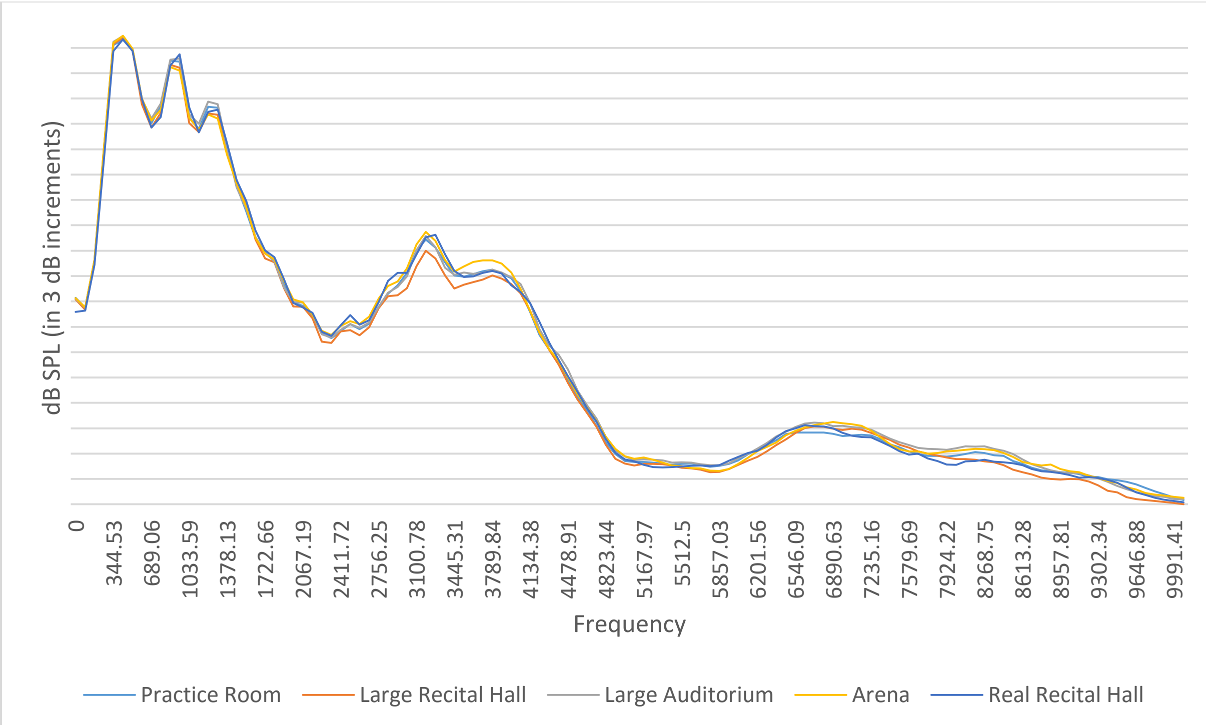


Figure 68. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 19.

Participant 19 was a 41-year-old with 23 years of singing experience, a history of swollen vocal folds that had resolved, and a history of mild tinnitus. LTAS shows a general similarity among all five acoustical conditions. The Large Recital Hall and Real Recital Hall conditions yielded differences ranging from 0.03 dB SPL at the point of the smallest measured difference (516.80 Hz) and 2.80 dB SPL at the point of the greatest measured difference (3.27 kHz).

Figure 69 shows the LTAS contours for Participant 19 in all five acoustic conditions across the 2-4 kHz spectrum.

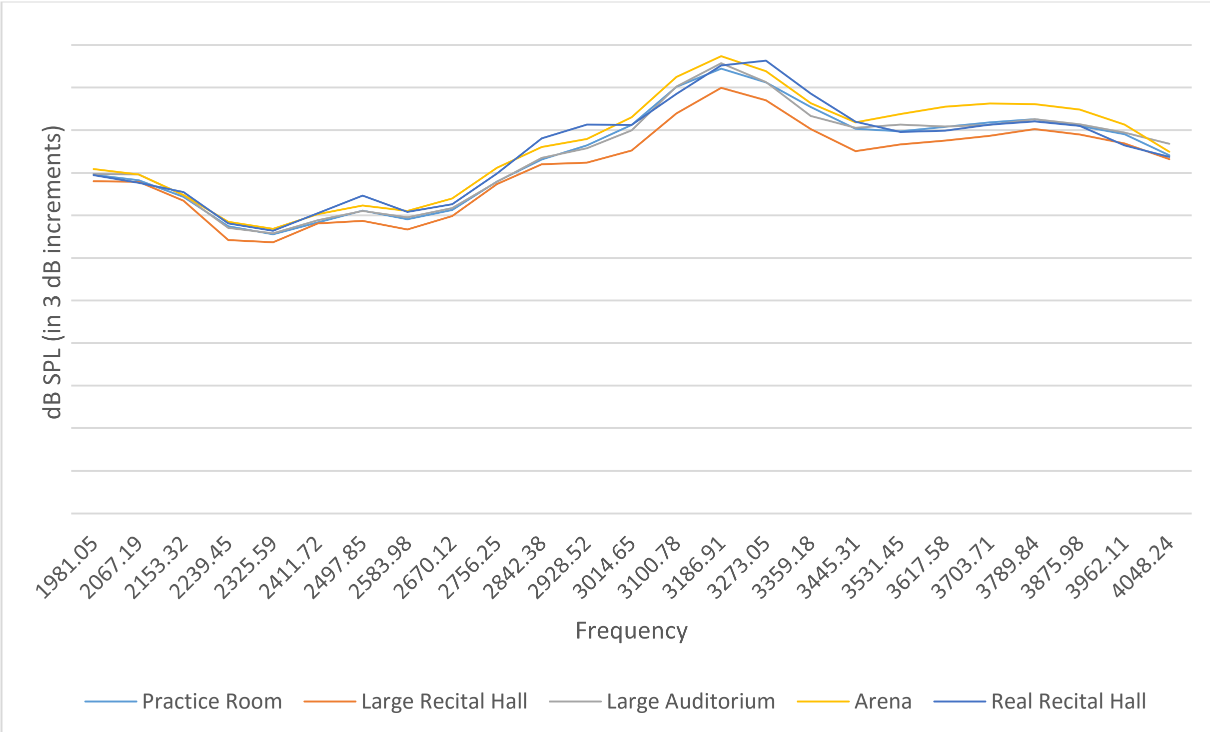


Figure 69. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 19.

In the 2-4 kHz range, the Large Recital Hall and Real Recital Hall conditions trended similarly, with the smallest measured difference between the two conditions measuring 0.07 dB SPL (2.07 kHz) and the largest measured difference measuring 2.80 dB SPL (3.27 kHz).

Figure 70 shows the LTAS contours for Participant 20 in all five acoustic conditions across the 0-10 kHz spectrum.

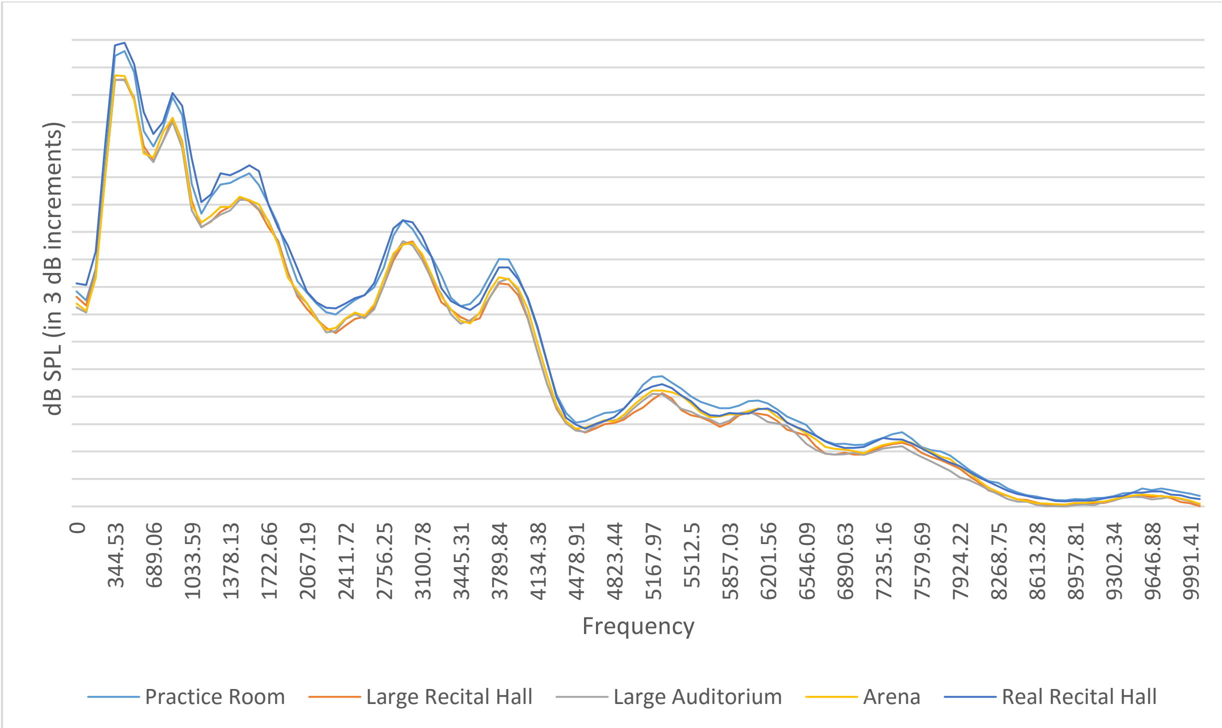


Figure 70. LTAS of all five acoustical conditions in the 0-10 kHz range for Participant 20.

Participant 20 was a 24-year-old with 9 years of singing experience and a history of swelling in the vocal tract related to GERD, but no history of hearing inefficiencies. LTAS shows two groupings among the five acoustical conditions. The Practice Room and Real Recital Hall settings showed similar energy levels, and the Large Recital Hall, Large Auditorium, and Arena settings tracked together. The Large Recital Hall and Real Recital Hall conditions yielded differences of 0.11 dB SPL at the smallest measured point of difference (9.39 kHz) and 4.59 dB SPL at the greatest measured point of difference (1.03 kHz).

Figure 71 shows the LTAS contours for Participant 20 in all five acoustic conditions across the 2-4 kHz spectrum.

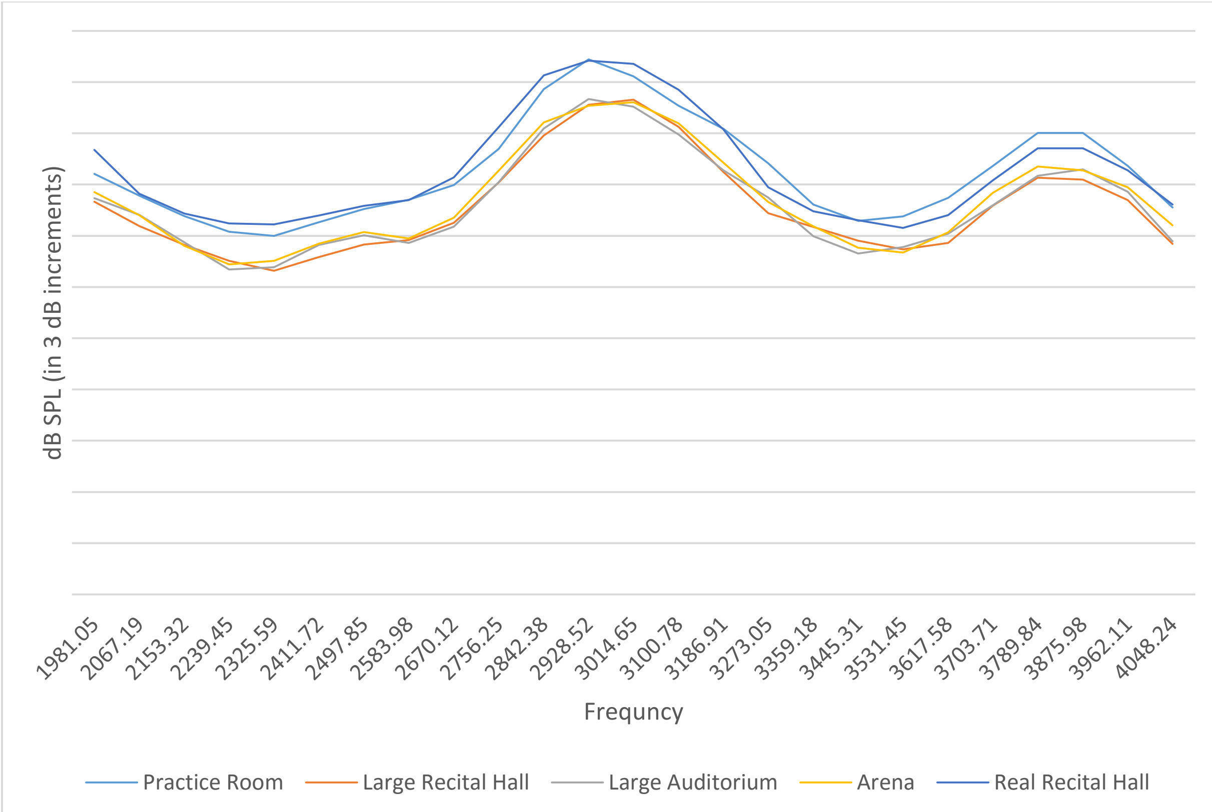


Figure 71. LTAS of the region between 2-4 kHz in all acoustical conditions for Participant 20.

The Large Recital Hall and Real Recital Hall conditions measured differently by 0.93 dB SPL at the point of the smallest measured difference (3.36 kHz) and 3.52 dB SPL at the point of the greatest measured difference (2.84 kHz).

Research Question Two: Perceptions of Hearing and Singing Efficiency

Immediately following their performance in each condition, participants completed a visual analog survey indicating their perceptions of hearing and singing efficiency in each of the five acoustical conditions.

Hearing efficiency. Table 21 shows mean participant responses of perceptions of hearing efficiency.

Table 21

Mean Participant Responses of Perceptions of Hearing Efficiency

	M	*SD*
Practice Room	16.43	16.48
Large Recital Hall	21.00	15.19
Large Auditorium	22.03	19.56
Arena	17.53	21.94
Real Recital Hall	29.65	17.46

A one-way repeated measures ANOVA showed overall significant differences in participants' perceptions of hearing efficiency among the five room conditions, Wilk's Lambda = .408, F (1, 19) = 5.808, $p < .05$. However, pairwise comparisons found significant differences only when the virtual acoustic conditions were compared with the Real Recital Hall. No significant differences were found when comparing any of the virtual acoustical conditions with another virtual acoustical condition. Eleven participants (55%) reported the greatest positive perception of hearing efficiency in the Real Recital Hall. However, when comparing the Large Recital Hall virtual acoustic condition and the Real Recital Hall, fifteen participants (75%) reported a greater perception of hearing efficiency in the Real Recital Hall.

Singing efficiency. Table 22 shows mean participant responses of perceptions of singing efficiency.

Table 22

Mean Participant Responses of Perceptions of Singing Efficiency

	M	*SD*
Practice Room	21.85	18.88
Large Recital Hall	27.26	11.46
Large Auditorium	29.23	19.61
Arena	23.90	18.30
Real Recital Hall	38.93	16.76

A one-way repeated measures ANOVA found overall significant differences in participants' perceptions of singing efficiency among the five room conditions, Wilk's Lambda = .488, F (1, 19) = 4.193, $p < .05$. As in the perceived hearing efficiency results, no significant differences in pairwise comparisons were found between any of the virtual acoustical settings when compared with other virtual settings, but significant differences were found when comparing the Real Recital Hall to Practice Room, Large Recital Hall, and Arena. The difference between the Real Recital Hall and Large Auditorium was not significant. Twelve participants (60%) reported the greatest positive perception of singing efficiency in the Real Recital Hall. When comparing the Large Recital Hall virtual acoustic condition and the Real Recital Hall, sixteen participants (80%) reported a greater positive perception of singing effort in the Real Recital Hall.

Additionally, fourteen participants (70%) reported a greater preference for the Real Recital Hall over all other conditions. When comparing the Large Recital Hall virtual acoustic condition with the Real Recital Hall, nineteen participants (95%) reported a greater preference for the Real Recital Hall, while the one remaining participant (5%) gave the same perceptual rating to both conditions.

Research Question Three: Correlations Between Amplitude and Participant Perceptions

Hearing efficiency and dosimeter-acquired amplitude. Five Pearson product moment correlation tests identified the strength of the relationship between dosimeter-acquired amplitude and participants' perceptions of hearing efficiency as recorded on the visual analog scale in each of the acoustical conditions. All five acoustical pairings lacked statistical significance, indicating no significant link between dosimeter-acquired amplitude and participant perceptions of hearing efficiency. Two pairings yielded weak negative associations indicating participants perceived slightly less hearing efficiency as amplitude increased: Practice Room $r = -.157$, $n = 20$, $p < .05$; and the Real Recital Hall $r = -.224$, $n = 20$, $p < .05$. Three pairings yielded weak positive associations, indicating participants perceived slightly greater hearing efficiency as amplitude increased: Large Recital Hall $r = .136$, $n = 20$, $p < .05$; Large Auditorium $r = .312$, $n = 20$, $p < .05$; and the Arena $r = .144$, $n = 20$, $p < .05$.

Singing efficiency and dosimeter-acquired amplitude. Five Pearson product moment correlation tests measured the strength of the relationship between amplitude and participants' perceptions of singing efficiency as reported on a visual analog scale. All five acoustical conditions lacked statistical significance, indicating no significant link between amplitude and participant perceptions of singing efficiency. Three pairings yielded weak negative associations, indicating participants perceived slightly less singing efficiency as dosimeter-acquired amplitude increased: Practice Room $r = -.257$, $n = 20$, $p < .05$; Arena $r = -.262$, $n = 20$, $p < .05$; and the Real Recital Hall $r = -.143$, $n = 20$, $p < .05$. Two pairings yielded a weak positive associations, indicating participants perceived a slight increase in singing efficiency as dosimeter-acquired amplitude increased: Large Recital Hall $r = .051$, $n = 20$, $p < .05$; and the Large Auditorium $r =$

.262, n =20, $p < .05$.

Research Question Four: Participant Comments

Participants were given the opportunity to comment freely about any aspect of the study. Participants recorded comments at the end of the participant survey. Twelve participants offered 35 discrete comments.

One participant gave an overall preference for the Real Recital Hall, stating, "The recital hall is by far the most preferred." Another commented that the Real Recital Hall had "nice acoustics." A third stated that she enjoyed singing in both rooms, but preferred the Real Recital Hall because of a "cleaner" sound.

Nine discrete comments focused on the adjustment of hearing a simulation of a larger room in a small room. One commenter said she was "surprised by the sound" and thought it had perhaps affected her overall performance in the virtual acoustic room. Another said, "They [the virtual settings] threw me off." Another commented that the "phony acoustic sound in the practice room was startling and didn't feel right."

Four discrete comments focused on the perceived lack of a realistic sound in the virtual acoustic conditions. "I found the electronic acoustic settings...to be less than helpful. Somehow they do not imitate the natural resonance of a concert hall in a helpful way. It sounded fake." Another said, "The reverb sounded artificial and threw off my sense of pitch." One commenter described the virtual settings as "eery [sic], like wind. It didn't feel natural."

One commenter related the acoustical settings to her singing efficiency, stating, "I find the live 'real' acoustics to be much better for my technique," and described the virtual acoustic settings as "extremely off-putting."

Three participants gave positive reviews of the virtual acoustic settings. One said," The fact that a person can make the practice rooms sound more like a concert hall would make practicing for a recital more efficient." The second stated, "I liked the practice room when it allowed me to hear myself without reverberating too much back at me." Another comment said, "The idea of controlled reverb in a practice room is fascinating. It's a really nice change from the dark, small, closed-off rooms typical of music departments. I'd like this kind of practice space regularly."

There were no clear demographic differences among participants who offered comments about the Real Recital Hall. There were no negative comments included about the Real Recital Hall. Comments regarding the virtual acoustical conditions tended to skew more positively for younger singers with less experience, and negative comments came mostly from singers with at least five years of singing experience.

Summary of Overall Results

Here follows a summary of primary results according to the research questions posed.

Distance dose. Grand mean Dd yielded significant differences overall, but pairwise comparisons indicated no significant mean differences in two pairings: Large Auditorium and Real Recital Hall, and Arena and Real Recital Hall. Grand mean values for Dd were greater in the Real Recital Hall than in any of the virtual acoustics conditions. Fourteen participants (70%) acquired greater mean Dd in the Real Recital Hall than in the Large Recital Hall virtual acoustic setting.

Dosimeter-acquired amplitude. Overall mean differences were not significant; however, pairwise comparisons yielded significant differences between all virtual acoustic conditions and the Real Recital Hall. Grand mean values for amplitude were greater in the Real Recital Hall than in any of the virtual acoustics conditions. Sixteen participants (80%) displayed greater amplitude in the Real Recital Hall, 3 participants (15%) displayed greater amplitude in the Large Recital hall virtual condition, one participant (5%) displayed the same amplitude in both conditions.

LTAS. Grand mean LTAS were significant overall and in every pairwise comparison in both the 0-10 kHz spectrum and across the spectrum that is most sensitive in human hearing between 2-4 kHz. LTAS also showed that grand mean spectral energy in the Real Recital Hall exceeded by over 2 dB the mean spectral energy of performances in all virtual acoustic conditions across the 0-10 kHz spectrum. In the 2-4 kHz spectrum, LTAS displayed greater grand mean energy by over 2 dB in the Real Recital Hall compared to all virtual acoustic conditions. Individual LTAS contours revealed variability among participants. Eleven participants (55%) displayed greater spectral energy in the Real Recital Hall compared to the Large Recital Hall virtual acoustic setting.

Singer perceptions of hearing and singing efficiency. Participants' responses to visual analog scales indicated significant differences in perceptions of both hearing and singing efficiency. However, pairwise comparisons yielded significant results only when virtual acoustic conditions were compared to the Real Recital Hall. Pairwise comparisons between any of the virtual acoustic conditions with another virtual acoustic condition yielded no significant results.

Correlations of participant's perceptions of hearing and singing efficiency with amplitude. Correlations of participants' perceptions of hearing and singing efficiency and acquired amplitude readings found no significant associations, although there were some weak correlations, both positive and negative.

Participant comments. Participant comments generally favored the Real Recital Hall. Some participants described the virtual acoustic conditions as "fake," "off-putting," and “surprising.”

Chapter Five

Discussion

This investigation looks at the intriguing notion of individual practice rooms designed to mimic larger performing spaces. In so doing, it employs phonatory (APM), acoustical (LTAS), and perceptual (survey) measures to assess the performances of experienced female singers (N = 20) in a Real University Recital Hall and in a practice room manufactured with four digitally-adjustable simulations of reverberation and reflections (Practice Room, Large Recital Hall, Large Auditorium, and Arena).

Primary results of this study, the first to examine the effects of virtual acoustics on singer phonation behaviors, indicate that participants on the whole (a) exhibit significantly greater mean distance dose and timbral spectral energy in the Real Recital Hall than they do in the virtual acoustic conditions and (b) perceive significantly greater hearing efficiency and singing efficiency in the Real Recital Hall compared to the four simulated conditions. Although (c) there appear to be no significant relationships between participants' exhibited amplitude and their perceptions of hearing and singing efficiency, (d) participant comments favor singing in the Real Recital Hall over singing with the practice room simulations.

These results are limited to the particular participants, protocols, dependent measures, and environments of this study. Findings should not be generalized to other singers or acoustical environments. Nonetheless, these results raise issues that merit attention among researchers and vocal music educators. The following discussion addresses such matters in light of the data from this study, and in so doing, addresses as well the limitations of the study, suggestions for future research, and implications of vocal music education.

Two previous studies (Nelson, 2012; Nelson, 2014) suggest that vocalists sing with greater distance dose and amplitude in an individual practice room with a longer reverberation time and decay time than in another individual practice room with less reverberation and a shorter decay time. If singers exhibit greater amplitude as reverberation increases, it would stand to reason that singers would sing with greater amplitude in a larger venue with a longer reverberation time. The present study appears to confirm that reasoning to the extent that participants exhibit greater mean amplitude in the Real Recital Hall than in any of the four virtual acoustic conditions. Moreover, although results of this study do not find significant differences in overall amplitude among the five singing environments explored, pairwise comparisons show significant differences between the Real Recital Hall and every virtual acoustic condition. There are no significant differences when comparing any of the virtual acoustic conditions with each another.

This latter finding may suggest that the virtual acoustic conditions are not differentiated enough from each another to prompt these singers, on the whole, to exhibit significant changes in source or APM-acquired amplitude when switching from one virtual environment to another virtual environment. It could be that the simulated reverberation and decay time do not sound real enough. Participant comments describing the simulated acoustics as “eery,” “fake,” and “off-putting” point to perceived deficiencies in the digitally-processed sound. Simply put, while the digital processing changes what the singer hears, it may not be sufficiently sophisticated to create simulated sound that would pass for the real thing.

Future research might explore specifically potential refinements in the digital processing of sung sound. As presently designed and marketed, virtual practice rooms appear not to distinguish between sound produced by a manufactured instrument and sound produced by a human voice.

An unspoken assumption in designing simulated reverberation for individual practice rooms to be used by singers is that digitally reproduced sung sound is perceived by the brain in the same way sung sound would be perceived without digital manipulation. To date, neuroimaging studies examining the auditory pathways that process self-sound have focused primarily on speech (Numminen, Salmelin, & Hari, 1999; Curio, Neuloh, Numminen, Jousmäki & Hari, 2000; Houde, Nagarjan, Sekihara, & Merzenich, 2002; Ventura, Nagarajan & Houde, 2009). Future neuroimaging studies could prove very helpful in further defining the neurological auditory pathways that process sung sound, and determine if digitally-processed sung sound is interpreted in a similar way by the brain as sung sound in a real acoustical environment.

Furthermore, it is not known if or at what point reverberated sung sound becomes ambient noise, which could lead to increased amplitude due to the Lombard Effect. Numerous studies examining the Lombard Effect in speakers (Siegel & Pick, 1974; Egan, 1975; Junqua, 1996; and Castellanos, Benedi, & Casacuberta, 1996) demonstrate changes in vocal amplitude in the presence of ambient noise. Neuroimaging and behavioral studies in animals and humans show that multiple areas in the brain become involved in processing both self-vocalizations and external auditory stimuli in the auditory cortex (Houde & Jordan, 2002; Heinks-Maldonado, Nagarajan, & Houde, 2006; Hage, Jürgens, & Ehret, 2006; Jürgens, 2009; and Brumm & Zollinger, 2011). Some studies (e.g., Nonaka, Takahashi, Enomoto, Katada, & Unno, 1997) focusing on neural pathways active during the Lombard Effect show evidence of reflexive changes in amplitude initiated in the midbrain. Further neuroimaging studies would be helpful in determining if the same areas of the brain process sung sound as in speech, and if so, if these similar pathways also suggest reflexive adjustments to singing amplitude in response to ambient noise. Additionally, neuroimaging studies that examine both neuronal activity in a real reverberant space and neuronal activity during processing of digitally-manipulated sung sound could determine if simulated reverberation is interpreted in the same way as reverberation in a real performing venue.

Another consideration is the phenomenon known as sidetone amplification (Lane & Tranel, 1971), in which speakers tend to decrease vocal amplitude in the presence of increased auditory feedback, and conversely increase vocal amplitude when auditory feedback decreases. Increased amplitude in more reverberant spaces, particularly in larger spaces, could be the result of the increased time it takes for reflections from nearby walls to reach the singer. The perception of sound occurs in a process known as temporal integration or temporal summation, by which the ear integrates sound energy during a period of time measuring approximately 200 ms. If reflections from nearby walls in a performing space take longer than 0.2 s to reach the singer, the brain could incorrectly interpret auditory feedback and reflexively increase vocal amplitude to compensate.

Sidetone amplification would be very difficult to simulate in an individual practice room due to the close proximity of the walls and the inability to lower auditory feedback through any of the virtual acoustic settings. However, this factor could explain the lesser mean amplitude in the smaller room, if in fact the brain was responding to increased auditory feedback in comparison to the Real Recital Hall. Unlike the Lombard Effect that remains fairly constant in the presence of continued ambient noise, sidetone amplification tends to normalize over time. In that regard, a possible limitation of the current study is the use of relatively short sung examples in a limited pitch range that allow for adequate data collection according to the study parameters, but do not allow for the observation of any changes in amplitude that might occur over the course of a longer sung example. Future research could examine longer singing examples using greater pitch ranges in both the Real Recital Hall and the virtual acoustics conditions to determine if amplitude remains consistent or changes over longer periods of time. If changes do occur, those changes could help to determine if singer amplitude could be influenced by sidetone amplification rather than the Lombard Effect.

Acoustic reflections in the individual practice room are another consideration. In a real performing space, natural reflections are governed by the physical proximity of the walls, ceiling, floor, and other surfaces. Noson, Sato, Sakai, and Ando (2000) note reflections in a performing space can occur from up to twelve locations, and singers tended to show a preference for side reflections. Late reflections contribute to a feeling of spaciousness (Wakuda, Furuya, Fujimoto, Isogai, and Anai, 2003). The nature of these natural reflections in a performing space would be vastly different than those in a practice room with close walls. The manufacturers of the virtual acoustic system do take reflections into account in the design of the sound system and digital processing software. For example, the description of the Large Recital Hall virtual acoustic setting includes, "The hall is modeled after spaces with hard walls and high ceilings with the addition of diffusing wood panels along the side and back walls. In the ceiling area are reflective clouds to provide enhanced early reflections. Characteristics of this space are a bright sound with a smooth, longer decay of sound" (Wenger 2006). However, the simulated reflections do not appear to be directional.

Instead, through speaker placement and careful assignment of the audio channels to the various speakers (see Figures 11, 12, and 13), the manufacturer has designed the virtual practice room to allow the user to feel enveloped by sound without being able to localize to any one speaker (Freiheit, 2003). The result of this design perhaps creates an inherently artificial acoustical environment that cannot realistically simulate the real thing. Future research could work toward designing a virtual acoustic system that would include directional reflections that might more closely mimic the reflections found in a real environment. Additionally, designs that include side reflections preferred by singers in contrast to other directional reflections preferred by instrumentalists might help to create simulated environments that singers would find useful. Future research comparing and contrasting singer perceptions to those of instrumentalists in both real and virtual acoustic environments could guide the design of virtual acoustics systems that best meet the needs of both groups of users.

Of course, all the sound design and digital processing would be for naught if the users respond to the natural acoustics of the room instead of the simulated ones. Results of impulse response testing in the individual practice room show the reverberation time and decay times remain essentially unchanged, regardless of whether the virtual acoustic system is turned on or off, or what virtual acoustic setting is engaged, The reverberation and decay times are very similar to a dry individual practice room, such as those tested by Nelson (2012). The walls do not contain enough absorption to negate the natural reflections and decay, and the steel parallel walls in the room may also produce a slight flutter echo in the center of the room. Participants therefore may hear both the actual reverberation and decay time of the room and also the electronically mimicked reverberation and decay time produced by the virtual acoustics system. It would be of great interest if future research could determine whether participants responded neurologically to the actual reverberation and decay time in the room, the simulated virtual reverberation and decay time, or a combination of both.

Dd grand means display significant differences overall, though pairwise comparisons do not indicate a significant difference between the Real Recital Hall vs. Large Auditorium virtual setting, and the Real Recital Hall vs. Arena virtual setting. Participant 14 stands out in particular for the large difference in both Dd and amplitude between the Real Recital Hall and all virtual acoustic conditions. It is possible her readings are an aberration that reflect a malfunction or miscalculation by the APM. However, LTAS results recorded from the head mic also show a large reduction in spectral energy between the Real Recital Hall and the virtual acoustic conditions as recorded, and seem to corroborate the large difference in the APM results. It must be noted that LTAS is not directly related to either Dd or source amplitude. The APM calibrates to each individual participant and measures amplitude directly from the source, while LTAS is measured from a head-mounted microphone, which captures sound after modification by the vocal tract. As such the two measurements cannot be compared directly but may reveal trends between the two metrics.

Participant 14 goes against the majority results with less spectral energy in the Real Recital Hall. That the increase in Dd and amplitude are reflected in a decrease in spectral energy is a curious finding. To wit, Participant 19 shows the next greatest difference in Dd and amplitude, but spectral energy is largely similar across the spectrum in all five acoustical conditions. Still, the very large differences between the Real Recital Hall and the virtual conditions for Participant 14 are worth examining more closely. She reports six years of singing experience, with some of that in solo contexts but mostly in choral settings. It is possible that her lesser experience with solo singing in a large performing venue such as the Real Recital Hall in the present study could explains the difference in measurements. Participant 14 is one of the few participants who offer positive comments about the virtual acoustics in the practice room. It is possible that her APM and acoustical data reflect her generally positive perceptions of the virtual acoustics. The present study design did not include more discrete or in depth exploration of voice training beyond the number of years of voice study. Future research designs could look more closely at nuances in the training or demographics of participants that could affect acoustical measures.

The current study focuses on a convenience sample of female singers with at least two years of singing experience. Research examining the Lombard Effect suggests female speakers may be more susceptible to greater changes in amplitude in the presence of ambient noise (Junqua, 1996). Future research could examine a male population or a mixed sex population to determine if sex may play a role in determining the degree of change between acoustic conditions. Solo singing is usually the main focus of university voice training; however, most vocal music students will also participate in vocal ensembles. Future research comparing phonation behaviors of small vocal groups in both real and virtual acoustic environments would be of great interest.

While Dd and amplitude are useful measures, LTAS is arguably the most important metric in the present study for exploring quantitatively whether virtual acoustics may be an acceptable substitute for a real performance venue. LTAS relates to vocal quality, and refining vocal quality is essentially the aim of vocal training. Grand mean LTAS show significant differences overall and in every pairwise comparison, further suggesting that participants may not sing comparably in the virtual acoustic conditions and in the Real Recital Hall. Full spectrum (0 - 10 kHz) grand mean differences between the Real Recital hall and all virtual acoustic conditions exceed the 1 dB just noticeable difference. In the 2-4 kHz range, important because it is the area most sensitive in human hearing, the grand mean difference is at least 2 dB between the Real Recital Hall and the virtual acoustics conditions.

Dosimeter-acquired amplitude and LTAS vary greatly among participants. These results are perhaps not surprising, considering amplitude and LTAS can be affected by numerous factors, including vocal training, individual anatomy, general health, and emotion. Neither amplitude nor timbre are aspects of phonation that have been adequately normalized in the literature. In other words, as far as amplitude and LTAS are concerned, there are no average singers. For this reason, it is useful to look at individual results and trends in data, in addition to means. One contribution of the current study is the examination of the individual results in each selected phonation measure. Both amplitude and LTAS show variability among participants in the different acoustic conditions that could be perceived by a listening audience. Future research using a panel of auditors to listen to recordings of individual singers in both real acoustic environments and virtual acoustics could be very informative.

This study closely compares the Real Recital Hall to the Large Recital Hall virtual acoustic setting because the manufacturer's description of the virtual acoustic setting most closely resembles that of the real environment (Wenger, 2006). Pairwise comparisons of mean LTAS show significant differences between these two conditions. Fifteen participants (75%) display marked differences in spectral energy between the two conditions. Eleven of those participants (55%) show greater spectral energy in the Real Recital Hall, while 4 (20%) show greater spectral energy in the virtual acoustic condition. Whether the spectral energy increased or decreased between the two conditions, the salient point is that the spectral energy changes between the two conditions for most participants. Indeed, for most participants the four virtual acoustic conditions display similar spectral energy patterns.

The second major thrust of the current study examines participant perceptions of hearing and singing effort in the five acoustical conditions. Participant responses yield significant differences in means in both hearing and singing efficiency. However, as with amplitude, pairwise comparisons yield significance only when comparing the virtual acoustics conditions to the Real Recital Hall, and not when comparing the virtual acoustics conditions to each other.

Additionally, fourteen participants (70%) prefer the Real Recital Hall over all virtual acoustic conditions. Directly comparing the Large Recital Hall virtual acoustic condition and the Real Recital Hall, 95% of participants report a preference for the Real Recital Hall, and the one remaining participant gives both conditions the same rating. Such results appear to suggest that most participants in this study do not perceive similarity between the real and virtual acoustic conditions. These findings seem to suggest again that the virtual acoustic conditions are not similar enough to the real environment to convince users to substitute the virtual acoustics for a real recital hall.

A limitation in the overall survey design weakens the perceptual results with respect to participant preference among acoustical conditions in this study. The wording of Question 3 on the current survey asks participants to report a preference on a visual analog scale, but the wording is such that it excludes a comparison to any other condition and thus cannot truly indicate a preference. Ranking conditions rather than using a visual analog scale would give a more accurate picture of participant preferences. Alternatively, a questionnaire design asking for a simple “Yes” or “No” response from participants about their preference for an acoustical condition could offer a clearer picture of participants’ perceptions. Future research utilizing a different survey design might find clearer relationships between acoustical and perceptual data. Future study designs using fewer virtual acoustic conditions could also simplify perceptual data, perhaps making perceptual comparisons between conditions more easily discernible for participants.

The demographic questionnaire asks basic information about each participant. A limitation of the current study is the exclusion of participants' height from demographic information. Participants' height could be a factor in phonation behaviors and possibly in the perception of the virtual acoustics, as all of the speakers in the individual practice room are located in the ceiling. Future research that includes participants' height as a possible influencing factor in both phonation behaviors and perceptions of the virtual acoustics could be helpful.

The individual practice rooms with virtual acoustics are modular in construction and can be built in different sizes and configurations, while still using the same digital processing and similar speaker configuration. Future research could also look at whether participants' perceptions and acoustic measures change based on the size of the individual practice room using virtual acoustics. If it is found that what participants see, namely the size of the room they must fill with their own singing sound, does impact the singing technique whether consciously or unconsciously, perhaps a visual element akin to visual virtual reality simulations may be a useful addition to practice rooms already utilizing virtual acoustics.

The visual differences between a real recital hall and an individual recital hall could contribute to singer perceptions. In most venues, recital halls are designed not only for auditory aesthetics but also visual aesthetics. Individual practice rooms are often drab, uninteresting spaces built for utility instead of beauty. In the current study, the individual practice room is constructed of walls generally of one color, uninteresting carpet, and florescent lighting with very little natural light. The Real Recital Hall, by contrast, is colorful, spacious, and uses a variety of lighting. The visual appeal of the Real Recital Hall over the individual practice room could enhance positive responses among participants asked to state a preference between the two spaces. Future research that utilizes virtual reality goggles or another similar type of visual simulation in conjunction with virtual acoustics could help to determine how much of what the participant sees contributes to participant perceptions of hearing and singing efficiency and preferences among acoustic conditions.

Considering participant responses and acoustical data, it is surprising that there is not a significant or even strong correlation between perceptions of singing and hearing efficiency and measures of amplitude. Of course, participant perception does not always equal acoustical reality, and it is possible that participants were simply not paying close enough attention to their own technique to accurately measure their own efficiency. It is also possible that using four different virtual acoustic conditions in addition to the Real Recital Hall detracts from participants' ability to accurately gauge their efficiency. Future research that limits the number of virtual acoustics conditions might allow for a better comparison between the real performing venue and the corresponding virtual acoustic condition.

Singing efficiency is difficult to quantify, and has never been adequately defined in the literature. Thus, participants could interpret efficiency differently. Strengthening perceptual data could require strengthening the definition of efficiency in singing. Rather than a single question on singing efficiency, future research could examine perceptions of multiple factors that contribute to perceived singing efficiency, such as perceptions of loudness, tension, or ease. Parsing out the various aspects of efficient singing technique could guide the singer to examine more closely the individual qualities of singing and give a fuller picture to the researcher about the perceptions of singer efficiency.

Some possible limitations to the current study could explain some differences in measurements between the Real Recital Hall and the virtual acoustic individual practice room. The lack of an adjustment period with each of the virtual acoustic settings and in the Real Recital Hall may be a limitation. Even singers who are used to performing in large spaces generally desire a rehearsal period to acclimate to the particular nuances of a space before singing for an audience. None of the participants in the current study had ever sung in a space using virtual acoustics before. This factor could have contributed to some of the perceptions of participants as reflected in comments that describe the virtual acoustics as “surprising,” “eery,” or “off-putting.” Although participants were given the opportunity to acclimate to the individual practice room with the system muted, and the virtual acoustic conditions were randomized during the data collection period to negate order effect, future researchers might consider allowing more time for participants to acclimate to each virtual acoustic condition.

The virtual acoustics system used in the current study includes nine settings intended to mimic various common performing venues. For the purposes of this study, only four settings that represent performing venues most commonly found on university campuses are examined. Future research that includes the remaining five settings could be warranted to determine if perhaps singers respond differently to other settings, or if the current findings hold true with respect to similar acoustical measures among the virtual acoustic conditions.

The current study, moreover, focuses on one particular performing venue and one individual practice room using multiple virtual acoustics settings. The settings included in the virtual acoustic system are not currently customizable, and so it is possible that no setting would exactly match the performing venue. As it is, the current study used the setting that most closely matches the characteristics of the Real Recital Hall, but not one specifically designed to mimic that space. It is possible that a virtual acoustic setting designed especially for a particular performing space could encourage more similar acoustical measures in singers between the real environment and the virtual environment. Future developments that would allow for a fully customizable virtual acoustic setting may show more promise in producing a truly virtual rehearsal space.

This study provides a snapshot of participants' singing in the five acoustical conditions, rather than focusing on long term singing behaviors. Indeed, most singers train for weeks or months before performing for an audience. The intent of the virtual acoustic system is to provide a place for rehearsal that sounds like a performing venue without actually being in the performing venue. Most singers are not afforded the luxury of regular rehearsals over a long period of time in performing venues, and so do the bulk of the preparatory work in small rooms. Singers then must adjust to the larger space before the performance. Pedagogically, it could be interesting to study acoustical measures of singers who regularly rehearse in a performing venue, and then compare results to singers who rehearse in small rooms to determine if significant differences exist between the two.

Likewise, the short nature of the current study does not adequately speak to how singers might adjust to the virtual acoustics over time. It is possible that as singers become more accustomed to the virtual acoustics system, acoustical measures gathered from virtual environments would converge with acoustical measures from real performance venues. Future research with a longitudinal design may be able to pinpoint if and at what point phonation behaviors in a virtual environment more closely match those measured in a real performing venue.

The acoustical environment of rehearsal space is an important, although insufficiently recognized, component of vocal music education. Because hearing and singing are so intimately related, the environment in which one hears one's voice reflected can impact phonation and hence development of efficient vocal technique. The small, individual practice rooms in university schools of music are an imperfect solution to the problem of providing rehearsal space for voice students. Additionally, these small rooms, often featuring hard floors and cement walls, have almost nothing in common with the larger performing spaces singers will utilize in recitals and concerts. Thus, the attempt to provide a variable, virtual acoustic environment in a smaller room holds great appeal. On the whole, however, the acoustic and perceptual results of the present study, the first investigation to look at phonatory behaviors in a virtual acoustics practice room, indicate its participants do not phonate similarly in the virtual acoustic conditions as in a real performing venue. Perhaps subsequent studies with different participants, venues, and protocols will yield different results. That is certainly possible. At present, however, it would seem that perhaps design limitations in the virtual acoustic practice rooms may be too great to overcome with present technology. Instead we are left with the reality that a small practice room is simply a small practice room, and at least at present cannot be anything other.

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Appendix A
Demographic Questionnaire

Participant Number: ____________________________________ Date: ______________________

Age: _________ Sex (circle one): Male Female Other

Voice Part (circle one): Soprano Alto Tenor Bass

Class (circle one): Freshman Sophomore Junior Senior Graduate

Years of vocal training: ____________

Have you experienced vocal inefficiency in the past? If yes, please describe: ________________

____

Have you experienced hearing inefficiency in the past? If yes, please describe: ______________

____

Appendix B
Participant Questionnaire

Participant Number: ___________________________________ Date: ______________________

Individual Practice Room Song 1 Repetition 1:

1. I could hear my own sound:

Not well at all |-----------------------------------|-------------------------------------| Very well

2. I was singing:

Not efficiently |-----------------------------------|-------------------------------------| Efficiently

3. This active acoustical setting is:

Not preferred |------------------------------------|------------------------------------| Preferred

Comments:

Individual Practice Room Song 1 Repetition 2:

1. I could hear my own sound:

Not well at all |-----------------------------------|-------------------------------------| Very well

2. I was singing:

Not efficiently |-----------------------------------|-------------------------------------| Efficiently

3. This active acoustical setting is:

Not preferred |------------------------------------|------------------------------------| Preferred

Comments:

Individual Practice Room Song 1 Repetition 3:

1. I could hear my own sound:

Not well at all |-----------------------------------|-------------------------------------| Very well

2. I was singing:

Not efficiently |-----------------------------------|-------------------------------------| Efficiently

3. This active acoustical setting is:

Not preferred |------------------------------------|------------------------------------| Preferred

Comments:

Individual Practice Room Song 1 Repetition 4:

1. I could hear my own sound:

Not well at all |-----------------------------------|-------------------------------------| Very well

2. I was singing:

Not efficiently |-----------------------------------|-------------------------------------| Efficiently

3. This active acoustical setting is:

Not preferred |------------------------------------|------------------------------------| Preferred

Comments:

Individual Practice Room Song 2 Repetition 1:

1. I could hear my own sound:

Not well at all |-----------------------------------|-------------------------------------| Very well

2. I was singing:

Not efficiently |-----------------------------------|-------------------------------------| Efficiently

3. This active acoustical setting is:

Not preferred |------------------------------------|------------------------------------| Preferred

Comments:

Individual Practice Room Song 2 Repetition 2:

1. I could hear my own sound:

Not well at all |-----------------------------------|-------------------------------------| Very well

2. I was singing:

Not efficiently |-----------------------------------|-------------------------------------| Efficiently

3. This active acoustical setting is:

Not preferred |------------------------------------|------------------------------------| Preferred

Comments:

Individual Practice Room Song 2 Repetition 3:

1. I could hear my own sound:

Not well at all |-----------------------------------|-------------------------------------| Very well

2. I was singing:

Not efficiently |-----------------------------------|-------------------------------------| Efficiently

3. This active acoustical setting is:

Not preferred |------------------------------------|------------------------------------| Preferred

Comments:

Individual Practice Room Song 2 Repetition 4:

1. I could hear my own sound:

Not well at all |-----------------------------------|-------------------------------------| Very well

2. I was singing:

Not efficiently |-----------------------------------|-------------------------------------| Efficiently

3. This active acoustical setting is:

Not preferred |-----------------------------------|-----------------------------------| Preferred

Comments:

Recital Hall Song 1:

1. I could hear my own sound:

Not well at all |-----------------------------------|-----------------------------------| Very well

2. I was singing:

Not efficiently |-----------------------------------|-----------------------------------| Efficiently

3. This active acoustical setting is:

Not preferred |-----------------------------------|-----------------------------------| Preferred

Comments:

Recital Hall Song 2:

1. I could hear my own sound:

Not well at all |-----------------------------------|-----------------------------------| Very well

2. I was singing:

Not efficiently |-----------------------------------|-----------------------------------| Efficiently

3. This active acoustical setting is:

Not preferred |-----------------------------------|-----------------------------------| Preferred

Comments:

Appendix C

Informed Consent Statement
HSCL #00001270

The Effect of Virtual Acoustics on Phonation Behaviors in Singers in Individual Practice Rooms for Voice

INTRODUCTION

The Department of Music Education and Music Therapy at the University of Kansas supports the practice of protection for human subjects participating in research. The following information is provided for you to decide whether you wish to participate in the present study. You may refuse to sign this form and not participate in this study. You should be aware that even if you agree to participate, you are free to withdraw at any time. If you do withdraw from this study, it will not affect your relationship with this unit, the services it may provide to you, or the University of Kansas.

PURPOSE OF THE STUDY

The purpose of this study is to investigate changes in vocal fold activity based on environment.

PROCEDURES

You will be asked to wear a vocal dosimeter (KayPentax Ambulatory Phonation Monitor) attached using medical adhesive to the sternal notch at the front of the neck and a head microphone that rests on your ear. You will then be asked to sing two songs in differing acoustical environments. Total singing time will be approximately 20 minutes. You will be recorded using the head microphone. Audio recordings will be used by the researchers only and will be stored in a locked office. You will be asked to complete a survey at the completion of each singing repetition taking approximately 5 minutes total. Your estimated time commitment will be approximately 30 minutes.

RISKS

Temporary minor redness or irritation at the site of adhesion may be possible.

BENEFITS

Benefits of this study include the development of future pedagogical practices to better prepare university vocal students to sing efficiently in active acoustics environments. There are no direct benefits to the participants.

PAYMENT TO PARTICIPANTS

Participants will not be paid for participation in this study.

PARTICIPANT CONFIDENTIALITY

Your name will not be associated in any publication or presentation with the information collected about you or with the research findings from this study. Instead, the researcher(s) will use a study number or a pseudonym rather than your name. Your identifiable information will not be shared unless (a) it is required by law or university policy, or (b) you give written permission.

Permission granted on this date to use and disclose your information remains in effect indefinitely. By signing this form you give permission for the use and disclosure of your information for purposes of this study at any time in the future.

REFUSAL TO SIGN CONSENT AND AUTHORIZATION

You are not required to sign this Consent and Authorization form and you may refuse to do so without affecting your right to any services you are receiving or may receive from the University of Kansas or to participate in any programs or events of the University of Kansas. However, if you refuse to sign, you cannot participate in this study.

CANCELLING THIS CONSENT AND AUTHORIZATION

You may withdraw your consent to participate in this study at any time. You also have the right to cancel your permission to use and disclose further information collected about you, in writing, at any time, by sending your written request to: Heather Nelson, Department of Music Education and Music Therapy, 1530 Naismith Drive, Lawrence KS 66045.

If you cancel permission to use your information, the researchers will stop collecting additional information about you. However, the research team may use and disclose information that was gathered before they received your cancellation, as described above.

QUESTIONS ABOUT PARTICIPATION

Questions about procedures should be directed to the researcher(s) listed at the end of this consent form.

PARTICIPANT CERTIFICATION:

I have read this Consent and Authorization form. I have had the opportunity to ask, and I have received answers to, any questions I had regarding the study. I understand that if I have any additional questions about my rights as a research participant, I may call (785) 864-7429 or (785) 864-7385, write the Human Subjects Committee Lawrence Campus (HSCL), University of Kansas, 2385 Irving Hill Road, Lawrence, Kansas 66045-7568, or email irb@ku.edu.

I agree to take part in this study as a research participant. By my signature I affirm that I am at least 18 years old and that I have received a copy of this Consent and Authorization form.

__________________________________ ________________________

Type/Print Participant's Name Date

____

Participant's Signature

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