THE EFFECT OF TWO DIFFERENT ROOMS ON ACOUSTICAL AND PERCEPTUAL MEASURES OF SATB CHOIR SOUND

By

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ABSTRACT

The purpose of this study was to explore the effect of two different rooms (choir rehearsal room, performance hall) on acoustical (LTAS, one-third octave bands) and perceptual (singer [$N = 11$] survey, listener [$N = 33$] survey, Pitch Analyzer 2.1) measures of soprano, alto, tenor, and bass (SATB) choir sound. Primary findings of this investigation indicated: (a) significant differences in spectral energy comparisons of choir sound between rooms, (b) choristers' perceptions of hearing and monitoring their own voices differed significantly depending on room, (c) most choristers (82%) perceived that the choir performed best within the Performance Hall, (d) perceived pitch of selected sung vowels within recordings differed significantly based on room conditions, (e) 97% of listeners perceived a difference in choir sound between room recordings, and (f) most listeners (91%) indicated preference for the Rehearsal Room recording.

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CHAPTER 1

Introduction

Choirs from around the world rehearse and perform in different rooms intended for various purposes. Often, the acoustical qualities of these rooms widely differ. From small, carpeted rehearsal spaces to large, stone cathedrals with high ceilings; choirs sing the same repertoire in rooms with divergent acoustic properties. Depending on the event or performance purpose, it is not uncommon for a choir to sing in large gymnasiums, outdoors, in small absorbent rooms, in large reverberant rooms, and even in noisy cafeterias or shopping malls. At times, choral directors may set up acoustical panels or intersperse microphones to try and help the audience to hear the choir, or they may even instruct students to sing differently for performances in different acoustical environments.

Rooms for Music: Views of Choral Conductors and Choral Conducting Texts

When investigating the potential impact of rehearsal and performance venues on singers, it is important to consider what choral conductors say about room acoustics for choirs. In performing a search within ChoralNet forums on the American Choral Directors Association (ACDA) website for statements by choral directors regarding room acoustics, one will find several personal anecdotes and opinions.

One such example (Chapman, 1995) expresses a conductor's concerns about performance spaces with low ceilings and carpet, which lead to poor performance experiences for his choir. He asserts that reverberant acoustics are advantageous for choirs; but in order to prepare to sing in performance spaces with bad acoustics, rehearsal conditions should be able to match those less desirable acoustical characteristics to help the choir acclimate. Less reverberant rehearsal acoustics, he contends, will lead to more exciting and rewarding performances in more reverberant rooms.

In an article addressing new music facility construction, Carter (1959) emphasizes the importance of room size, construction, and acoustical treatment. One simple suggestion he offers for sound treatment is the use of non-parallel walls and splayed ceilings. While he notes that choirs tend to prefer longer reverberation times (0.75-1.5 seconds for a large ensemble room), he admits not all conductors agree and that acoustical tiles can help to cut down reverberation times if so desired. Auditoriums, he says, "must provide for sound propagation, sound dispersion and sound absorption" (p. 40).

It is also important to consider what recognized choral textbooks say about acoustics for rehearsal and performance, as they are often the front line of information dissemination in the field of choral music. Few current choral conducting texts address the topic of room acoustics interacting with choirs head-on. Authors of choral methods or conducting texts often focus on conducting and rehearsal techniques and make no promises of the comprehensive nature of such writings.

Older choral conducting texts (Bodegraven & Wilson, 1942; Fuhr, 1944; Hertz, 1967; Stanton, 1971), however, offer room acoustic specifics and provide suggestions and cautions about effects on choristers and overall choir sound. The texts that include detailed information about rooms and their effects on choirs offer a variety of information and suggestions, although few texts include a scientific or research basis for their claims.

Literature selection. Decker and Kirk (1988) suggest that choral directors select literature based on its appropriateness for specific performance venues. Gordon (1977) states that performance venues with vaulted ceilings better suit motets. He also recommends gearing literature selections to match the facility acoustics. Garretson (1998) mentions that the overall effectiveness of choral literature relies greatly on the acoustical characteristics of the room in which it is performed.

Tempo. One of the most common recommendations for adjusting choral performances in response to room acoustics is that of tempo. Various texts (e.g. Bartle, 2003; Gordon, 1977; Garretson, 1998; and Stanton 1971) advise choral conductors to modify tempos based on acoustics. Garretson (1998) stresses the importance of taking faster tempos in rooms with low reverberation and slower tempos in live rooms.

Gordon (1977) advises the opposite, thus stating that slower tempos better suit rooms with slower reverberation times. Bartle (2003) warns against singing songs with fast tempos in live halls because it will be difficult for singers to hear each other. He recommends adjusting the song tempo or avoiding singing the song in that venue altogether.

Intonation. Fuhr (1944) notes several threats to choral intonation including (a) low ceilings, (b) poor acoustical properties, (c) an overheated auditorium, and (d) a large and echoing auditorium. While he does not indicate specific poor acoustical characteristics, he asserts that overheating causes flat intonation while the large and echoing room causes sharpness. Brinson (1996) proposes that intonation issues arise from singing environment difficulties including room temperature and singers not being able to hear themselves accurately.

Acclimation to acoustics. A common recommendation by choral conducting authors (e.g., Bartle, 2003; Bodegraven & Wilson, 1942; Brinson, 1996; Decker & Kirk, 1988; Fuhr, 1944; Hylton, 1995; Roe, 1970) suggests that choirs to rehearse in performance spaces prior to a concert to better acclimate to differing room acoustics. Hylton (1995) suggests that the final rehearsals leading up to a performance provide an opportunity for singers to adapt to the acoustics, which are likely different from the regular rehearsal environment.

Bodegraven and Wilson (1942), on the other hand, recommend frequent rehearsals in the venue. They also argue that while a performance hall's acoustics cannot be changed, the choir can alter their performance in the given acoustics to achieve the best results. Thus, one proposal includes moving the choir as far forward on the stage as possible.

Presumed effects of acoustics on singers. Decker and Kirk (1988) contend that singing in rooms that are intended for other purposes that music, such as speech, can be "hazardous to choral singing" (p. 157). Fuhr (1944) also provides a rather vague statement to never have a choir sing in "unfavorable physical surroundings which can be avoided" (p. 32).

Perhaps one reason for this is that choirs with less experience may be asked for more volume, which could result in forceful, unbalanced, and unblended choral sound. Regardless of what singers hear in different rooms, students should be cautioned to sing at the same volume level as in rehearsals (Bodegraven & Wilson, 1942).

Hylton (1995) explains that singers may hear themselves and others differently if the performance venue differs in reverberation from the rehearsal room. When changing between venue acoustics, he recommends singing in the same manner, even if the sound differs.

Rooms for Music: Views of Musical Acousticians

Musical acoustics textbooks (e.g., Carter, 1956; Hall, 1991) typically explain the basics of room acoustics. Carter (1956) addresses optimal decay time, and refers to the studies of Sabine, Watson, Knudsen and others and concludes "optimal reverberation time of an enclosed space depends upon the volume of the room and also upon the use to which the room is to be put" (p. 285). Other suggestions Carter offers include sound (a) isolation, (b) reinforcement, and (c) amplification.

According to Hall (1991), there are seven general criteria or standards for room acoustics: (a) clarity, (b) uniformity, (c) envelopment, (d) freedom from echo, (e) reverberation, (f) performer satisfaction, and (g) freedom from noise. Hall explains the context of these elements within an auditorium and provides suggestions for basic room construction in order to avoid undesirable effects. Reverberation time alone does not guarantee pleasing acoustics, he asserts. Hall suggests that "Auditorium design is still as much an art as a science, and even the best architects sometimes encounter difficulties" (p. 327).

Rooms for Music: Views of Architectural Acousticians

Sabine (1922), a physicist and mathematician, later earned his title as the first acoustician after investigating the architectural acoustics of a Harvard University lecture room. During this project, he examined relationships of room volume, reverberation time, and absorption. This combination of acoustics and architecture led Sabine to develop a formula for room absorption proportional to its area. His equation (Sabine equation) is still used in the field of architectural acoustics in order to use room volume and surface area to calculate reverberation time (Beranek, 2004).

Sabine widened the scope of his consulting experiences through planning the architectural acoustics of the Boston Symphony Hall. The acoustical properties of this hall are still considered the finest in the world. Now considered the father of modern day architectural acoustics, Sabine's investigations of performance halls, theatres, and musical pitch helped to merge architectural acoustics and music. These inquiries paved the way for later acoustical consultants and architects by providing common language and algebraic formulae.

Not until the mid to late twentieth century, however, does empirical research begin to address the effects of architectural characteristics on the resulting acoustical quality of musical sound and music performance. Leo Beranek (2004) is one of the greatest contributors to the study of concert hall architectural acoustics. He investigated and compiled information about the acoustics of hundreds of concert halls and music performance venues in order to compare objective measurements to subjective preferences in order to determine which characteristics of architectural design impacted listener preference.

Objective measures of room acoustics help quantify what listeners hear, and listener preferences help to contextualize the measurements. Husson (1962) argues that certain halls are labeled with "good acoustics" based on objective measurements and listener perceptions of music performances with very little consideration of the music makers (p. 8).

Overall acoustical quality of concert halls depends on architectural attributes, which include: (a) age, (b) shape, (c) music power, (d) audience absorption and type of seating, and (e) surface materials for walls, ceiling, and stage. These architectural characteristics then influence the acoustical quality, which is measured physically by: (a) reverberation time (RT), (b) early decay time (EDT), (c) binaural quality index (BQI), (d) loudness or sound strength (G), (e) warmth, bass ratio (BR), and bass strength (G_{low}), (f) intimacy and initial-time-delay gap (ITDG), (g) lateral fraction (LF_{E4}), (h) acoustical 'glare' and surface diffusivity index (SDI), (i) listener envelopment, (j) clarity, (k) texture, (l) brilliance, and (m) noise, vibration, and echo (Beranek, 2004).

Beranek (2004) argues that preferred values of acoustical parameters depend on repertoire, and he provides specified values for (a) symphonic music, (b) chamber music, and (c) opera. If rehearsal spaces are provided separately from performance halls, Beranek suggests that the reverberation time should be lower by about 0.2 to 0.4 seconds to allow the musicians to hear subtle nuances while rehearsing. This hearing would not be possible, he contends, in a concert setting with a reverberation time exceeding 1.7 seconds.

According to Ando (1985), optimal concert hall design objectives fall into three areas including (a) listening level, (b) early reflections following direct sound, and (c) subsequent reverberation time. Regarding reverberation time, Ando refers to research by Kuhl, which suggests reverberation times to coincide with specific music types: (a) 1.54 s for classical music, (b) 2.07 s for romantic music, and (c) 1.48 s for modern music.

Architects Schuette and Kirkegaard (2006) provide principles of shaping spaces for sound by considering (a) direct sound, (b) acoustic signature of a space, (c) room width, (d) side galleries and boxes, (e) room height, (f) reverberation time and volume, and (g) variable acoustics. All of these elements contribute to hall acoustics, and they suggest finer details of controlling sound anomalies such as echo, coupled spaces, and balance.

Schuette and Kirkegaard also suggest performers need strong and balanced feedback of their own sound. Ceiling shapes and fronts of balconies, for instance, can provide performer meaningful direct responses of their own sound. While architects may not know every intended use for a facility, good planning should provide optimal acoustics for a variety of conditions (Schuette & Kirkegaard, 2006).

Rooms for Music: Views from Singing Research

When talking about the life of a sound, it is useful to divide its life into three stages. These stages include sound production, transmission through technical media or a room, and listener perceptions (Ternström, 1991). In other words, sound can be studied by its production, propagation, and perception. While certain areas of architectural acoustics study focus primarily on the perspectives of listeners, few consider the musicians, especially singers. Not only is it important to analyze the efficiency of their singing, but also their perceptions of singing, hearing their own voices, and hearing other singers or instruments. These foci should pertain to rehearsal and performance settings alike.

Performers often carry the burden of adjusting to room acoustics, especially due to the signal-to-noise ratio, which is the relationship or competition between sounds singers try to hear and environmental noise. Some voice scientists suggest that attention be given to altering existing room acoustics to better suit performers and be aware of what about room design promotes vocal comfort and efficiency. Sataloff (2010), for example, contends that singing teachers must help to create singing environments “that will allow our students and audiences to enjoy the best possible auditory perception with the least possible phonatory effort” (p. 431). These environments can be achieved through effective room design and surface materials. Rather than modifying rooms after the fact or teaching students “how to survive acoustically challenging environments” (p. 429), Sataloff recommends advocating for involving engineers and architectural acousticians during the building design phase.

Ternström and Karna (2002) describe room acoustics fundamentals and the comparisons between physical and perceptual properties of sound. Sound loudness, pitch, and timbre, they suggest, correspond inexactly to the physical and measurable elements of sound. These include (a) sound pressure level, (b) fundamental frequency, and (c) energy distribution over frequency, which can all be measured by acousticians.

Ternström and Karna (2002) also provide four categories of concern regarding choir acoustics: (a) loudness or balance, (b) intonation, (c) timbre, and (d) multivoice issues. The categories provide a means for understanding and negotiating the acoustical problems that choirs often encounter.

These previously mentioned categories further divide to include: (a) choir size, formation, and spacing, (b) room absorption, (c) self-to-other ratio (SOR), (d) risers, shells, and reflectors, (e) effects of SOR on intonation, (f) effects of room response on singer voice use, (g) effects of different absorbing materials, (h) wall proximity to bass singers, (i) positioning of music folder, (j) relation of choir placement to audience, (k) comparison of room reverberation and choir size, and (l) ensemble timing (Ternström & Karna, 2002).

Ternström (1991) contends that choirs, to some extent, adapt their voice usage and sound level to the room acoustics. The chorusing effect, which occurs when phonation frequency fluctuations of three or more singers interact and interfere, causes "independent amplitude modulation of partial tones" (p. 128). This effect, according to Ternström, is also influenced by room reverberance. Depending on the reverberation time of the room, it can sometimes act as a chorus member through its feedback and reflections to singers blending with their direct sound.

If reference sound is too loud for singers to hear their own voices, an increase of room absorption or inter-singer spacing could assist choristers. Research in choir spacing (Daugherty 1996, 1999, 2003; Daugherty, Manternach, & Brunkan, 2011) indicates that 95% of singers thought that spacing affected their choral sound. Consistently, singers preferred greater space around them, which allowed them to (a) sing freely, (b) hear themselves, and (c) hear others. Choral spacing also contributed greatly to listener preferences of choral sound when listening to paired performances.

The acoustic properties of rooms influence choral sound. Rooms with high levels of absorption, for example, cause singers to compensate by singing with greater vocal effort (Ternström, 1989), which could lead to vocal strain. Therefore, it is of great importance to investigate rooms used for choral singing and their effect on acoustical data as well as singer and listener perceptions, which leads to the present study.

Need for the Study

Only two studies, to date, have addressed effects of different rooms on the long-term average spectra (LTAS) of choral sound. Ternström (1989) measured the LTAS of three different choirs performing the same repertoire in three different rooms. Daugherty, Grady and Coffeen (2013) measured the LTAS of one choir singing in six chorister spacing configurations in two different rooms. While Daugherty, et. al. solicited singer and listener perceptives as well, these perceptions focused largely on perceived differences according to inter-singer spacing in two performance halls.

No study to date has employed both LTAS and EASERA measures in conjunction with singer and listener perceptions of a choir performing the same literature in one chorister standing order in two different rooms, one of which was a designated rehearsal room and the other of which was a performance venue. Data from such a study could interest choir teacher-conductors about singer perceptions of different venues; and it could interest architects or acousticians in the development and treatment of choral rehearsal and performance rooms.

Purpose Statement

The purpose of this study is to explore the effect of two different rooms (choir rehearsal room, performance hall) on acoustical and perceptual measures of SATB choir sound.

Research Questions

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

(1) To what extent, if any, will acoustical (LTAS, one-third octave band) measurements vary based on performances of an SATB choir in two different rooms (choir rehearsal room, performance hall)?

(2) Will singer perceptions vary significantly according to different room acoustics?

(3) Will listener perceptions (pitch analysis, listening panel) vary significantly according to choir performances recorded in two different rooms?

Definitions

Early decay time (EDT). The initial sound decay phase, which computes "the exact amount of time it takes for a sound from a musical note to decay 10 decibels after it is cut off, multiplied by a factor of 6" (Beranek, 2004, p. 23).

EASERA. "Electronic and Acoustic System Evaluation and Response Analysis" (Retrieved from http://easera.afmg.eu/), is computer software that acquires, stimulates, computes, and analyzes acoustical data. From impulse response data, measurements made using EASERA may include (a) total sound pressure level (SPL), (b) strength (G), (c) reverberation time, (d) room frequency response, (e) reflection calculations, (f) early decay time, and (g) interaural cross-correlation coefficient (IACC). In addition, EASERA allows for frequency, amplitude, and SPL measurements over time in various researcher-selected octave band settings or divisions therein.

Long-term average spectrum (LTAS). A measurement tool used for voice analysis that retains long-term aspects of voice timbral characteristics by averaging amplitude and frequency over time (Ternström, 1989).

Pitch Analyzer 2.1. A computer software tool that produces a sinusoidal reference tone set to relate recorded pitch to score notated pitch for specific extracted vowels within a sung selection. The software then determines the difference between the notated frequency and the perceived frequency (presented in hertz) and converts the difference to cents.

Reverberation time (RT). An important component of room acoustical measurement that computes "the number of seconds it takes for a loud tone to decay 60 decibels after being stopped" (Beranek, 2004, p. 20-21).

Room impulse response (RIR). An acoustical measurement that measures "reverberation time, early decay time and clarity index" (Cabrera, 2010, p. 801). Using a swept sine wave or a Maximum Length Sequence, the acoustical response of a room can be determined across various frequencies. This is most importantly determined "independent of its gain," or listening level (Cabrera, 2010, p. 802).

Delimitations of the Study

Findings of this investigation are limited to its particular participants, venues, and procedures. Therefore, results are not necessarily inferable to other populations. It may be conjectured that different results might be obtained by varying such elements as microphone location, singing task, tempo, or measurement methods and equipment. However, this study is not concerned with such possible variables. Rather, its purpose is to assess the potential effect of contrasting room conditions on acoustical and perceptual measures as described above. Future research may seek to explore any number of other variables that may contribute to possible correlations between room conditions and singer behaviors, singer preferences, and listener preferences.

CHAPTER 2

Review of Literature

This chapter reviews empirical research literature related to architectural acoustics for music. This chapter begins by examining developments of architectural acoustics pertaining to general objective and subjective measurements of music performance spaces. Thereafter, this review examines studies on acoustical and perceptual characteristics of rooms and their effect on music and its performance, specifically considering instrumental and vocal musicians.

Acoustical Characteristics of Rooms for Music

Empirical studies to date have investigated various aspects of architectural acoustics. According to Beranek (2004), Wallace Clement Sabine was the first acoustician to design a concert hall based on scientific principles. Sabine was one of the first in the early twentieth-century to measure the physical conditions of a room and their effect on piano sound and musical taste. Since then, several studies have focused on specific acoustical characteristics of rooms and their implications on perception (e.g., Beranek, 2011; Gourévitch & Brette, 2012; Morimoto et al., 2007; Smitthakorn, 2006). A number of other studies have focused on objective and subjective measurements of multipurpose rooms and churches or synagogues (e.g., Cirillo & Martellotta, 2005; Farina, 2001; Kleiner & Klepper, 2007, Martellotta, 2009, Zamarreño et al., 2007). Further investigations have focused on specific architectural characteristics within rooms for music and their effects on objective measures and perceived acoustical quality (e.g., Chiang, 1994; Fujii et al., 2004; Torres et al., 2004).

In order to focus better on musical acoustics and the potential influence of architectural elements, other researchers focused on rooms intended solely for musical performances. Numerous studies have concentrated on objective and subjective measurements of listeners and performers in concert halls (e.g., Ando, 2007; Aretz & Orlowski, 2009; Barron, 2001; Barron, 2005; Barron & Lee, 1988; Jeon & Barron, 2005; Marshall & Barron, 2001; Nishihara & Hidaka, 2012; Pancharatnam & Ramachandraiah, 2005; Pirn, 1992; Semidor and Barlet, 2000; Skålevik, 2010; Witew, Behler, & Vorländer, 2005).

Jurkiewicz, Wulfrank and Kahle (2012) developed a solid angle theory by studying the acoustic efficiency of reflecting solid angle surfaces in a concert hall. They concluded that (a) acoustic reflectors differ in efficiency, (b) reflectors visible from stage provided the most efficient reflections, and (c) the greatest amount of acoustic efficiency resulted from shallow-angled early reflectors to create higher average sound strength for late reverberation within the hall.

Hawkes and Douglas (1971) examined subjective assessments of a concert hall with an Assisted Resonance System and found common factors for acoustical evaluation using terms from a list developed by Leo Beranek (1962). These factors were then used for rating different positions within the same hall and rating different concert halls during symphonic performances. The researchers discovered that the factor ratings depended on and varied with the state of the concert hall, musical content variation, and performance manner. Subjective responses positively correlated based on the following factors: (a) reverberance and reverberation time, (b) evenness and alignment with and distance from the orchestra, (c) intimacy and initial time delay gap, (d) brilliance and longer reverberation times at high frequencies.

Hojan and Pösselt (1990) measured impulse responses of European concert halls ($N = 6$) and compared them to subjective evaluations of recordings made in each hall. Randomly selected participants ($N = 10$) subjectively evaluated recorded speech and music signals based on four, ten-point scales: (a) clarity, or temporal sound structure, (b) localization sharpness, (c) spaciousness, and (d) overall impression. Results indicated high positive correlation between localization sharpness and clarity and a low positive correlation between spaciousness and overall impression, and the impressions of music signals showed a stronger response than those of speech signals.

Ellison and Schwenke (2010) measured acoustic preferences of multi-purpose rooms. They found a wide range of desired reverberation times depending on room use. As a result, Ellison and Schwenke recommended using variable acoustics for multi-purpose rooms and mentioned the potential benefit of varying acoustics within a single musical performance, depending on musical style.

Zha, Fuchs and Drotleff (2002) explored low-frequency absorption efficiency of small spaces intended for musical rehearsal and performance. The researchers increased acoustical absorption in tested spaces to (a) limit hearing damage, (b) improve communication, and (c) to help musicians hear themselves and other performers. The researchers determined that the additional absorption improved acoustics and mitigated the former acoustic hindrance placed on musicians working in the treated areas.

Pätynen (2007) investigated the use of electro-acoustics to improve practice rooms acoustic conditions. The researcher increased acoustical absorption of the tested rooms (*N* = 3; *n* = 2 practice rooms, *n* = 1 concert hall) and enhanced the reverberation using an electro-acoustic system without increasing sound pressure levels. Instrumental musicians (*N* = 30) evaluated the quiet and loud settings, each at reverberation times of around 1.5 s and 2.4 s. Results indicated that (a) electro-acoustic system modifications benefitted acoustic conditions of practice rooms, (b) users' ease of playing positively correlated with room responsiveness based on added reverberation, and (c) users preferred lower sound pressure levels in the practice rooms, which were reduced by about 6 dB.

Hidaka and Beranek (2000) surveyed opera conductors (*N* = 22) about the perceived quality of acoustic parameters in opera houses (*N* = 21) and compared responses to objective acoustical measurements. The most highly rated halls exhibited the following characteristics: (a) optimal reverberation times ranging from 1.2-1.6 s, (b) ideal clarity in the range of 1 to 3 dB, (c) averaged spaciousness factor greater than 0.6, (d) the initial-time-delay-gap of 20 ms or below, (e) sound strength of 1-4 dB with an additional 3dB for more absorbent halls, (f) bass ratio greater than 1.05, (g) substantial early reflections with uniform spacing, and (h) irregularities for sound diffusion and reflection on walls, ceilings, and balcony faces.

Galiana, Llinares, and Page (2012) collected questionnaires and analyzed subjective evaluations of acoustic properties in 17 music halls (*n* = 74 expert music users, *n* = 236 non-expert music users). Results of this study showed that participant groups perceived acoustic discrepancies differently. Non-expert responses indicated the following ranking order of hall sound attributes: (a) fidelity and quality, (b) intimacy, (c) power, and (d) lack of sound defects. The experts, on the other hand, indicated a different ranking: (a) balance and pitch quality, (b) intimacy and wide dynamic range, (c) absence of enhanced bass. The researchers concluded that intimacy and power are especially important factors common to both expert and non-expert perceptions of concert hall acoustical quality. Haan and Fricke (1997) compared calculated sound diffusion of 53 concert halls to acoustic perceptions of guest musicians (*N* = 32). Results indicated a very high positive correlation between surface diffusivity and perceived acoustic quality of concert halls.

Kahle and Jullien (1995) isolated perceptual listener data and subjective room acoustic evaluations under live music performance conditions with a structured questionnaire. Results indicated that responses depended on (a) acoustics of the hall, (b) musical repertoire, (c) performing ensemble, (d) listener, and (e) the interactions between musical works and hall acoustics. Results also indicated high positive correlation between subjective and objective evaluation measures.

Koskinen, Toppila, and Olkinuora (2010) examined music education facilities (*N* = 7) renovations and collected teachers' (*N* = 31) preferences of the facilities before and after renovations in light of the Finnish acoustic code recommendations for adequacy in noise exposure. Questionnaire results showed that teachers perceived sound level improvements in the renovated rooms, which was not confirmed by sound level measurements. One possible explanation for this perception was that low frequency sound decreased, thus not contributing to decibel measurements but decreasing teacher annoyance. Objective measurements showed that changes of room reverberation, while shortened in each renovated room, did not decrease noise level exposure of student or teacher users of the rooms.

Acoustics and Perceptions of Rooms for Instrumental Musicians

Room acoustics matter to musicians. Just as listeners in a hall depend on the quality of acoustic conditions for performances, so do performers. In addition to exploring the point-of-view of listeners, empirical research investigated the point-of-view of instrumentalists who rely on room acoustics to hear themselves and their ensembles.

Simulated room conditions for instrumentalists. Gunnlaugsdóttir (2008) investigated the effect of different simulated music practice room conditions ($N = 6$) on perceptions of instrumental musicians ($N = 10$) to determine optimal practice room acoustical conditions. Participants played individually in each simulated condition, surrounded by four loudspeakers, at three different strength levels. The researcher then completed a bipolar evaluation for each reverberation condition. Results indicated only weak correlations (positive or negative not specified), resulting in no specific conclusions about optimal music practice room acoustics.

Chiang and Huang (1999) examined subjective preferences of solo instrumental performances in auditoria ($N = 6$) based on the total acoustical environment. Participants ($N = 20$; $n = 10$ professional musicians and $n = 10$ members of the general public) listened to 66 paired-comparisons of dry recordings with applied hall impulse responses and responded whether they liked or disliked each sound field. Results indicated that the most important measures for evaluating solo performance acoustical quality were overall level and early level (energy combined up until 80 ms), especially at high frequencies. Results also indicated prominent listener preference of reverberation time, early decay time, and clarity.

Kato, Ueno and Kawai (2008) studied the effect of different simulated room acoustic conditions on sound signals produced by professional musicians (*N* = 5). They found that in the more reverberant room, the participants suppressed the higher harmonics of the tones and changed tone and interval length between staccato notes.

Ueno and Tachibana (2003) used a 6-channel directional sound simulation system to isolate three aspects of room response: (a) early reflections, (b) reverberation decay process, and (c) late reflections. The researchers investigated the effect of each aspect of room response on subjective judgments of professional instrumentalists (*N* = 12) who played in each condition on a stage. Results showed that while the responses of the musicians diverged and no categories were easily drawn from the data, three common conditions correlated positively with the instrumentalists' overall impressions and preferences: (a) moderate reverberation time, (b) weaker early reflection, and (c) stronger late reflection.

Ueno, Kanamori, and Tachibana (2005) investigated the effect of simulated sound fields on subjective impressions of instrumental ensemble playing. Participants (*N* = 14) included string and wind instrumental chamber musicians who each played in an anechoic room while a violinist co-player played along in another anechoic room. The musicians were able to see one another and various experimental adjustments were made to three acoustical conditions in both rooms: (a) early reflection magnitude, (b) reverberation time, and (c) reverberation magnitude. Results indicated that the most important factors necessary for the musicians included hearing each other, and making harmony. Results also indicated that the players (a) preferred moderate early reflections from the co-player, (b) showed no tendency for reverberation time preference, (c) moderate magnitude of reverberation time allowed for musicians to better hear one another and harmonize.

Gade (1989a) investigated preferred room support of solo (*N* = 9) and ensemble (*N* = 20) instrumentalists in concert hall simulations. For the studies of soloists, he changed the delay of the early reflection of the musician's own instrument sound and compared it with simulated early hall reflections to give the soloists an acoustic impression of the room. Results indicated that soloists (a) favored some reverberation, and (b) preferred audible levels of early reflected sound, or support, which in certain halls can be masked. For the ensemble studies, two symphonic instrumentalists played in two isolated anechoic rooms where the researcher mixed the signals of each musician to change the direct sound, reflections and reverberation. The participants (*n* = 5 violin/cello duos, *n* = 5 violin/flute duos) evaluated room condition preference by paired comparison after playing in each. Results showed that (a) the instrumentalists preferred direct sound from coplayers to have little delay and to be unmasked, (b) the level of direct sound and reflected energy in relation to emitted sound level is important for hearing each other, and (c) reverberance had a negative influence on ensemble playing.

Instrumental sound. Kato, Nagao, Yamanaka, Kawai and Sakakibara (2010a) investigated perceptions of the effect of simulated room reverberation on the timbral brightness of anechoically recorded clarinet tones. Participants (*N* = 15) listened to three clarinet tones at three different dynamic levels. Results indicated that (a) room conditions significantly affected perceived tone brightness (b) perceived brightness depended on amplification level, and (c) timbral brightness of the same note varied in different room conditions. In a related investigation, Kato, Nagao, Yamanaka, Kawai and Sakakibara

(2010b) developed a linear equation used to relate perception of clarinet tone brightness to room conditions and performing style.

Lokki, Pätynen, Kuusinen, Vertanen and Tervo (2011) evaluated listeners' (*N* = 20) perceptions and comparisons of recordings of an anechoic orchestra presented by a loudspeaker orchestra in three listening positions within three concert halls. Results indicated that (a) listeners identified five perceptual dimensions including reverberance associated with the size of the room, enveloping reverberance, sound width, distance or loudness, and definition, (b) perceived reverberation depended on enveloping reverberance or the size of the hall and (b) the use of sensory evaluation to assess acoustics of concert halls was valid.

Soulodre and Bradley (1995) recorded binaural impulses and anechoic music using a head and torso simulator. The participants (*N* = 10) listened to and judged the music as each pair of examples switched between two sound fields using the following areas of comparison: (a) loudness, (b) clarity, (c) reverberance, (d) bass, (e) treble, and (f) preference. Results indicated that early decay time (EDT) was important in predicting subjective reverberance, and that EDT within six octave bands (63 Hz – 40 kHz) should be considered in overall room measures rather than just the mid-range frequencies.

Lee, Cabrera, and Martens (2012) completed two experiments similar to the 1995 study of Soulodre and Bradley. For the first experiment, they used anechoic musical excerpts of an orchestra played back in three different size auditoria ranging from 700-2800 seats using modeled reverberance. Participants (*N* = 20) listened to the excerpts and increased or decreased the decay rate, affecting the energy of room impulse rate (RIR) until they matched the reverberance within the just-noticeable (JND) range. The second experiment was almost identical, but instead used an anechoic excerpt of an operatic tenor, which was played back in an audiometric booth. The researchers found that (a) listening to music with modeled reverberance was more effective than listening directly to RIRs, and (b) RIRs can be analyzed to predict music stimuli reverberance.

Instrumental soloists. Ueno and Tachibana (2005) surveyed instrumental musicians (*N* = 13) about concert hall awareness and found that (a) individual musicians perceived and adjusted to concert hall characteristics differently, and (b) musicians adjusted to acoustical spaces unconsciously without logical thinking.

Osman (2010) discussed reverberation times of various music rooms and reviewed design options and methods for varying reverberation time in rooms for instrumental musicians or multi-purpose use. He recommended that (a) the design of small music rooms depend on potential instrument loudness, (b) absorptive materials be applied to achieve desirable reverberation times, (c) varied absorption be used to allow for acoustic versatility based on different instruments, and (d) diffusion be incorporated into practice room walls to minimize flutter echo and specular reflections.

Blankenship, Fitzgerald and Lane (1955) compared physical and acoustical measurements of university music rooms with subjective responses of musicians who used the rooms to determine desirable characteristics of the rooms. Their experiment consisted of three parts. For the first part, instrumental musicians (*N* = 20) performed in practice rooms (*N* =2) before and after acoustical treatment, and then rated them on (a) tone quality, (b) dynamic range, and (c) reverberation. Results indicated that the instrumentalists preferred the addition of one panel for acoustical treatment of the practice rooms. The same participants were also used to investigate preferences of teaching studios ($N = 2$) with variable acoustics. The researchers found that participants preferred the studios to the practice rooms and better liked the larger of the two studios.

Instrumental ensembles. For the third segment of their 1955 study, Blankenship et al. asked university music instrumental and choral faculty participants ($N = 7$) to evaluate large university music rooms ($N = 3$) including an auditorium, a recital hall and a rehearsal room. Participants evaluated the rooms in regards to three music performance types: (1) solo, (2) chamber, and (3) large ensemble. Results showed that the faculty (a) disagreed regarding room reverberance, (b) provided consistent opinions of room suitability based on performance types, (c) agreed that the recital hall was less than ideal for large ensembles based on its size, and (d) rated the rehearsal room unsatisfactory without consensus as to the factors contributing to the poor acoustical conditions.

Marshall, Gottlob, and Alrutz (1978) conducted two experiments investigating the effect of spectral, spatial and temporal reflection variations on ease of instrumental ensemble playing. In the first study, they recorded a string trio playing in an anechoic room and experienced alterations of sound field reflections via loudspeakers. The participants responded with their preferences of directional and temporal reflection variations. Results showed that participants agreed and preferred the second and more moderate of the four conditions, indicating that in general ensembles prefer reflections within a very specific temporal window.

For the second study, the researchers tested high-frequency reflection components and sound delay to alter simulated stage size in order to measure their effect on ensemble playing. Results indicated that (a) participants preferred high-passed filtered reflection conditions, (b) high-pass filtered reflections were essential to performance, and (c) sounds below 0.5 kHz were somewhat disadvantageous for ease of ensemble.

Patrick and Boner (1966) surveyed band directors about acoustical characteristic preferences of instrumental rehearsal rooms (*N* = 6). Results showed that the common factors or preferences indicated by the directors differed considerably from the construction standards of music rooms including ensemble balance in specific registers, indistinct separation of sounds, and difficulty hearing certain instruments.

Chiang, Chen and Huang (2003) evaluated perceptions of the ratio of early-to-direct energy (*ED100)* of instrumental musicians (*N* = 9) playing solo and in small chamber ensembles (duet, trio, quintet) on different concert hall stages (*N* = 5). Results indicated that (a) optimum values of *ED100* ranged from -12 dB to -11 dB with an upper limit of -8 dB, (b) instrumentalists did not require strong early energy, (c) subjective evaluations positively correlated with late reflection acoustical measurements, and (d) listeners preferred performance conditions which provided higher lateral energy.

Betancourt (2011) analyzed the effects of acoustics of four different rooms (chorus chamber, organ hall, rehearsal room, recording room) on the perceptions and preferences of musicians (*N* = 5). The researcher collected acoustic measurements in each of the rooms prior to performances. The musicians included one guitarist/singer and a small instrumental ensemble (voice, guitar, cello, bass, and percussion). Participants played and recorded in each of the rooms and completed surveys about performing in each room.

Due to time constraints the participants listened to the recordings to refresh their memories before completing the surveys, which focused on measures of clarity, reverberance, envelopment, loudness, background noise, and balance. Results indicated that the participants thought (a) their sound was lost in the larger and more absorbent chorus chamber, (b) the organ chamber with higher reverberation time in mid-frequencies absorbed too much of the bass sound and lost overall sound intimacy and clarity, (c) the recording room offered greater intimacy and clarity but due to its dryness lacked envelopment, and (d) the rehearsal room, with the greatest reverberance, increased envelopment while also increasing loudness and sound isolation which some players found annoying.

Berndtsson (1995) evaluated the effect of acoustic walls (wooden loudspeaker system designed to enhance room reverberation) on acoustical measurements and perceptions of musical ensemble performances. Expert listeners ($N = 10$) rated live performances of choral singing and string ensemble playing. Results indicated that the acoustic walls greatly increased reverberation, echo, and ringing tones. Thus, the researcher considered acoustic walls a disadvantage due to the ringing tones they created in the room and recommended different acoustic wall box sizes to vary resonance frequencies as a possible solution.

Gade (1989b) completed a three-part study surveying orchestral musicians ($N = 71$) about the acoustical characteristic of different concert halls. The most important criterion by an orchestra for acoustical evaluation included timbre, reverberance, and ensemble factors, and support. Results indicated a significant difference between judgments of each hall, but also showed a wide spread in the evaluations including inconsistencies between orchestral sections. Results also indicated that evaluations of musicians hearing others reflected their judgments more clearly than hearing themselves.

Acoustics and Perceptions of Rooms for Vocal Musicians

Fewer studies have been conducted with vocal musicians than with instrumentalists in regard to the influence of room acoustics. Due to the nature of the acoustics of the singing voice, singers rely heavily on feedback, which can be influenced by room acoustics.

Simulated room conditions for vocalists. Sato and Prodi (2009) developed simulated sound fields from multiple receiver locations (*N* = 7) inside a group of theatres (*N* = 4) and adjusted acoustic parameters to match conditions of open-air Italian opera theatres. Anechoic recordings of a soprano singer and piano were separately channeled and mixed with binaural impulse responses in each of the sound fields from simulated stage and pit/orchestra source locations. Participants (*N* = 15) listened to paired-comparisons and judged which recording in each pair contained the best balance between the singer and piano. Results indicated a significant degree of agreement between listeners within four octave bands (500-4000 Hz) than other octave bands. Results also indicated that the acoustic characteristics from a stage source versus a pit or orchestra source allow for better judgment of balance.

Sakai, Ando and Setoguchi (2000) evaluated the effect of different reverberation times in simulated sound fields (*N* = 5) on listeners' (*N* = 8) perceptions of vocal music. Participants listened to an anechoic recording of a soprano through two loudspeakers; one speaker provided the direct sound and the early reflection, and the other speaker provided reverberation and initial reflections. Paired-comparison evaluations indicated that listeners preferred reverberation times between 0:55 s and 1:22 s.

Robinson, Xiang, and Braasch (2010) investigated the effect of concert hall acoustic simulations (*N* = 8) on listener (*N* = 23) perceptions of auralizations of operatic instrumental and singer performance. They found that participants might have used different evaluation criteria when ranking on a sliding scale, which resulted in a wide range of perceptions. Results showed high positive correlations between perceptions and stage to pit ratios of (a) clarity, (b) spaciousness, (c) envelopment, and (d) balance.

Guyette (1996) investigated the effects of different concert hall conditions (*N* = 10) on physical and psychological singer adjustment and on the perceptions of performances by experienced singers (*N* = 5). The participants recorded familiar vocal repertoire within an anechoic chamber and evaluated their perception of the characteristics and their own performance in each simulated acoustic condition. Listeners (*N* = 3) evaluated each of the recordings, and these results were compared to singer responses. Results indicated that singers perceived that the room conditions as unnatural, but preferred the fan-shaped setting to the rectangular-shaped setting. Listening data from this study were incomplete as listeners only evaluated performances by two of the singers. Listener results indicated that the impressions of the performances in different conditions by listeners positively correlated with singer impressions with too few participants to indicate statistical significance.

Noson, Sato, Sakai, and Ando (2000) examined the preferred time delays of simulated reflections for solo singers. Participants (*N* = 4) sang at both slow and fast tempos within an anechoic chamber and experienced single simulated reflections at varied delayed times (5, 10, 20 or 40 ms). Results indicated that tempo caused no changes and the singers preferred delay times within a range of 13-21 ms with a mean of 17.5 ms.

In a later study, Noson et al. (2002) investigated singers' ($N = 6$) preferences of simulated acoustical conditions ($N = 4$) depending on lyric or melisma singing styles (with and without lyrics). Participants sang in a semi-anechoic chamber with time-delayed reflections simulated by a loudspeaker behind them. In each condition, singers were allowed to repeat performances to overcome some drawbacks of singing in a simulated environment. The participants experienced randomly presented reflection delays (10, 20, 40 or 80 ms), which they then evaluated for preference. Results showed that for melisma singing the maximum range of delayed reflection preference ranged from 20 to 40 ms, with an average of 23 ms for preferred delay time. The lyric singing preferences ranged from 10-18 ms, with an average of 14 ms. These results indicated that reflection time preferences for the singers decreased by 60% with the addition of text.

Marshall and Meyer (1985) recorded solo singers ($N = 3$; $n = 2$ females, $n = 1$ male), a vocal quartet, and a 14-member choir in a hemi-anechoic room. They then simulated different stage conditions by varying reverberation time, reflection level, reflection delay, and reverberation onset time. Results indicated that (a) early reflections assisted singers, but they disliked reflections delayed about 40 ms, (b) in conditions without early reflections, changes in reverberation time did not affect chorister preference, and (c) ease of ensemble for solo singers related directly to singing comfort and was controlled by reverberant conditions.

Cabrera, Davis, and Connolly (2011) investigated the effect of projection and acoustic environment on the vocal directivity of professional opera singers ($N = 8$, $n = 6$ females, $n = 2$ males). They asked the participants to sing the same song in four ways: (a) focused on intonation, (b) performance singing, (c) imagined a large auditorium, and (d) imagined a small theatre. Results indicated that the directivity of singers' sound varied considerably and the singer's formant frequencies, 2- to 4-kHz, showed greater directivity than lower frequencies. Results also showed that singers adjusted formants when singing in different conditions, including an increase in projection in the singer's formant region from the small-hall to large-hall conditions.

Vocal soloists. Skirlis, Cabrera and Connolly (2005) studied singer vocal effort variation based on imagined room size. Professional opera singers ($N = 8$) sang in an anechoic chamber and were asked to imagine performing in a small hall for one recording set and a large hall for the second recording set. Results indicated that for the imagined large hall renditions, singers employed greater amplitude and faster tempos than for the small hall renditions.

Nelson (2011) used impulse responses to measure reverberation time and early decay time of two highly preferred and two lesser-preferred university vocal practice rooms. Results indicated that the most preferred practice room ($N = 1$) showed (a) stronger reflections in the 2 kHz octave band center frequency than other rooms tested, (b) a longer reverberation time, and (c) a longer decay time of the lateral reflections in the first 50 ms.

Husson (1962) examined the effect of increasing room reverberation on physiological singing conditions. The subjective conditions ranged from "very easy phonation" to "very laborious and rapidly fatiguing phonation" (p. 9) and were matched with approximate reverberation times that matched the various singing perceptions. Results indicated that singers found the greatest singing ease with a reverberation time near 4 s (between 3-6 s), which showed incompatibility between Sabinian calculations of hall acoustics, ideal listening conditions, and optimal singing conditions.

Foot (1965) investigated the effect of two conditions of acoustical feedback (absorbent room, reflecting panels) on the (a) tonal wave form, (b) intensity, and (c) intelligibility, of singers (*N* = 25) with experience in individual voice and choral ensembles. Auditors (*N* = 10) Results indicated that (a) changes in intensity of feedback did not cause changes in tone quality or wave form, (b) singer intensity increased significantly in the absorbent conditions, (c) auditors perceived the increase of singer intensity, (d) singer vocal intensity decreased with a 20% increase of auditory feedback, and (e) changes in contrasting feedback did not affect singer intelligibility.

Self-to-other ratio. Ternström (1994) established a method to determine a sound ratio of Self-to-Other (SOR) experienced by individual choristers. Binaural microphones placed at the singer's ears measured in dB a singer's "Self" feedback of airborne sound. "Other" feedback includes direct sound from other singers or from reflections or reverberations provided by the acoustics of the room or venue. Self-to-Other ratios of singers (*N* = 12) were measured while (a) singing with a choir, (b) singing alone, and (c) remaining silent as the choir sang. Ternström concluded that room acoustics were the determining factor for a balance between feedback and reference sounds.

Ternström (1999) investigated SOR preferences of choir singers (*N* = 23) while singing sustained vowels at two different frequencies. A synthesized choir accompanied and tracked the loudness of the individual singers. Participants were able to adjust the relative sound pressure of the choir by adjusting their distance from the microphone.

Results indicated that (a) participant SOR preferences varied individually by about 2 dB, and (b) individual preferences of participants varied greatly, ranging from -1 to +15 dB.

Ternström, Cabrera, and Davis (2005) recorded opera chorus members ($N = 4$) with binaural condenser microphones to estimate SOR values based primarily on sound pressure level (SPL) measurements. The researchers measured stage support according to impulse response measurements within the stage area and found that acoustical conditions were consistent with normal unoccupied conditions of the auditorium, including a 1.0 s reverberation time. Results indicated that (a) SOR increased with greater singer SPL, (b) if all singers in a chorus increase SPL by the same dB level, SOR values remain consistent, (c) SOR values were considerably high ranging from +10 to +15 dB, and (d) results paralleled other studies of choruses in more reverberant rooms, suggesting that in this acoustical condition the physical spacing and SPL of highly trained singers offset the high room absorption.

Choral ensembles. Tonkinson (1990) assessed the ability of singers ($N = 27$) to resist the Lombard effect while singing in a choir. Participants sang along with a choir heard through headphones. The researcher instructed singers to resist increasing vocal intensity as the choir sound levels increased. Results indicated that (a) as auditory feedback increased, most of the choral singers succumbed to the Lombard effect by increasing their vocal intensity, (b) experience level of singers was not significant, and (c) instructions to control vocal intensity significantly affected vocal intensity. These results further suggested that instructions to raise awareness of vocal intensity regulation benefitted choral ensemble performers by preventing vocal misuse or abuse.

Dupere (1993) sought to ascertain and classify acoustical characteristics preferred by choral directors for choral performance venues. The researcher asked four recognized Midwest college and university choral conductors to each identify two preferred rooms for choral music performance, and then examined each of the venues with the help of an acoustician to classify the architectural features and resulting acoustical characteristics of each room. Results indicated that choral conductors preferred rooms with: (a) reverberation times of over 2.0 s, (b) greater length than width, and (c) ceiling heights of over 43 ft.

Manternach (2010) surveyed choral conductors ($N = 33$) about their acoustical preferences or perceptions of room layout, reverberation, and general comments identifying likes or dislikes of their choral rehearsal rooms. Case studies of each of the rooms noted room characteristics, absorption, and acoustical measurements and compared them with conductor surveys to investigate possible reasons for survey responses. Results showed little consensus between conductor preferences. Manternach suggested adding variable acoustics options to the rooms to allow for acoustical alterations based on the preferences and needs of each conductor or ensemble.

Ford (2003) assessed auditor ($N = 139$; $n = 49$ undergraduate choral or vocal majors with choral training, $n = 47$ undergraduate instrumental majors with no choral training, $n = 43$ undergraduates with no musical training) preference of singer's formant strength in the tone of an ensemble comprised of graduate voice students ($N = 8$). Singer participants recorded four choral excerpts twice in an anechoic chamber: once with a more soloistic tone (greater singer's formant) and once with a less soloistic tone (lesser singer's formant). Auditors then listened to six paired trials and indicated which excerpt of each pair exhibited the tone quality they best preferred. Ford found significant differences for auditor preference between resonant and non-resonant tone, which showed that most auditors preferred non-resonant choral tone. Results also indicated that auditor musical training resulted in significant preference differences, revealing a high positive correlation between choral training and preference for lower singer's formant resonance in conglomerate choral tone.

Wheatcroft (2001) interviewed participants ($N = 15$) before and after listening to choral performances recorded in two acoustically contrasting worship spaces to investigate the effect of acoustical conditions on listener perceptions. Results indicated that reverberation played an important role in listener impressions of performances.

Noson, Sato, Sakai, and Ando (2000) studied a choir's response to changes in reflective surfaces within an existing performance room. They measured the room reverberation time before and after the choir was in place and discovered that it dropped by 20% with the choir present. The singers performed two passages in duets by unison voice part (soprano, alto, tenor, bass). They performed one selection with staccato style at a fast tempo, and one with legato style at a slow tempo. After singing in the room with different simulated reflections, several singers ($N = 9$) evaluated the sound fields based on preference by paired comparison. Singer preference correlated negatively with increased decay times; and their preference increased with short-delay simulated reflections, the most preferred was 10 ms. Results also suggested that adding new reflectors in the studied room could noticeably improve the choir acoustics.

Marshall (1993) evaluated the problem of balance between a chamber choir and orchestra by adding reflective panels to add more early reflected sound to the performance. Subjective impressions of the choir and orchestra members indicated that the reflectors (a) increased ease of ensemble, (b) improved lateral communication within the choir and with the conductor, and (c) enhanced the projection of the male singers' voices. Results also indicated that the audience perceived substantial improvements in loudness and clarity of the choir in addition to balance between the choir and orchestra.

Burd and Haslam (1994) investigated the architectural acoustics of two concert halls in relation to combined orchestra and choir performances. The researchers recorded architectural elements of each hall, such as stage area, reflective surfaces, choir seating, space between choir and orchestra, and ceiling heights. Within each hall, the researchers used impulse response to determine useful early and late reflections and reverberation times. Burd and Haslam asked several choristers (number of participants not specified) who perform regularly with orchestras to complete a questionnaire. Results of this investigation indicated that (a) reflective surfaces over the orchestra within their line of view inhibited the choristers' ease of singing and ability to project, (b) stage enclosures provided advantageous early reflections for the instrumentalists, and (c) choristers preferred close proximity to the conductor. These results suggested that concert seating should allow space for choirs while maintaining a close relationship with the conductor and orchestra.

Daugherty, Grady and Coffeen (2013) measured the effects of: (a) two different choral riser heights (traditional riser height, 8 in. additional height), (b) three choral spacing conditions (close, lateral, circumambient), and (c) two venues, on conglomerate choral sound. LTAS and one-third octave band analyses showed significant differences between the choral spacing conditions. Results showed only minor differences between riser heights, but a 3 dB singer vocal output increase within the more absorbent of the two rooms.

In a study closely related to the present investigation, Ternström (1989) investigated the effects of (a) acoustics of three different rooms, (b) vocal effort, (c) different musical material, and (d) type of choir, on long-time average spectra (LTAS) measurements. Three different choirs participated in this study including a boy's choir (*N* =16, mean age 12 years), a youth choir (*N* = 30, mean age 18 years), and an adult choir (*N* = 27, mean age 30 years). Each group contained only small age scatter. The three rooms used for this study included (a) a large, reverberant church hall, (b) a choir rehearsal room, and (c) an absorbent basement room. In each room the choirs performed two different musical selections at three levels of vocal effort ranging from very soft to very strong (*pianissimo, mezzo forte, fortissimo*). The youth and adult choirs sang mixed-voice versions of the songs, while the boys' choir sang the melody in unison.

LTAS measurements indicated negligible differences between musical selections and between *pianissimo* and *fortissimo* vocal effort conditions. In contrast, large effects on LTAS levels were detected based on the room conditions and absorption.

The reverberation times for the three rooms included: (a) church hall, 3.90 s; (b) choir rehearsal room, 0.85 s; and (c) basement room, 0.34 s. In addition, results regarding room acoustics indicated that the church hall and choir rehearsal room were considered well behaved because they showed a power loss of only 1 dB. As a result, low frequencies decayed much slower, and the power loss was considered quite large at 5-6 dB. The basement room, due to its high absorption and small volume, did not allow for much reverberance or for a proper diffuse field to be achieved.

Overall, spectral differences of the choirs' reference noise source differed by up to 13 dB between different rooms, depending on frequency. Results showed that the youth and adult choirs used less power in the more reverberant rooms. In contrast, within the basement room two of the choirs appeared to compensate for the high absorption by using an increased vocal output level. The choirs increased their power while singing in the basement room by approximately 2 dB. The boys' choir did not show this same effect, but did use pressed phonation while singing in the more absorbent basement room.

Ternström found that singers changed toward pressed phonation in room conditions with an increased spectral slope, which included decreased low frequencies and increased high frequencies. While singing in the basement room, all choirs showed a 5 – 10% increase of higher formant frequencies, which could be caused by increased subglottal pressure and resulting in raised larynges.

CHAPTER 3

Method

The purpose of this study was to explore the effect of two different rooms (rehearsal room, performance hall) on acoustical (LTAS, EASERA) and perceptual (singer [*N* =11] survey, listener [*N* = 31] survey, Pitch Analyzer 2.1) measures of an SATB choir performance of a homophonic motet. This chapter addresses the method and procedure employed in this investigation.

Participants

Choir. The choir for this study was a convenience choir comprised of university undergraduate and graduate music students. Choristers (*N* = 11) in this study ranged in age from 18-32 years, with a median age of 21 years (*M* = 23.73, *SD* = 7.001). There were seven females (four soprano, three alto) and four males (two tenor, two bass) in the ensemble. All participants had previously participated in choirs with an average of approximately four years of collegiate choir experience. Most participants had choral experience in (a) elementary school (*N* = 9, 82%), (b) middle school (*N* = 10, 91%), and (c) high school (*N* = 8, 82%).

The choral selection sung and heard for this study was "Laudate nomen domini," an unaccompanied Renaissance composition by Christopher Tye (available from the Choral Public Domain Library, www.CPDL.org) for SATB voices. For each trial, the choir sang the entire excerpt (duration = 1 m 25 s) observing repeats while using the Latin text.

This composition was selected due to its simple harmonies, the limited presence of voiceless fricatives, and the predominantly homophonic textures at the beginning of each section. The sung excerpt lasted approximately 83 seconds allowing a long enough sample to provide adequate LTAS measurements, according to Fant's 1959 study as referenced by Sergeant and Welch (2008).

Auditors. A convenience sample of auditors (*N* = 33) participated in this study. A majority of the listeners (*n* = 24) were between the ages of 18 years and 25 years, several others (n = 5) were between the ages of 26 years and 39 years and the remaining participants (n = 4) were aged 40 years or above. Among them were individuals with varying degrees of musical experience and included undergraduate students (*n* = 18) and graduate students (*n* = 13). No listeners reported that they were experiencing any difficulty hearing.

The primary purpose of soliciting auditor responses was in order to learn whether human listeners representing an audience member could perceive any acoustical differences between the binaural choral recordings captured within each of the two rooms. Therefore, listeners were selected irrespective of major or performing instrument, and according to their availability and willingness to participate in the study.

Controls

Random assignment of chorister positions. To control for potential effects of such potential inter-singer variables as singer height, voice compatibility, inclinations, and individual singing experiences that were not concerns of this study, choristers were assigned in random positions in a 3-row block sectional formation. Within the block sectional formation, choristers stood with a consistent 24 in. lateral spacing between singers.

According to Daugherty (1999), different choir formations do not significantly impact choral sound, while inter-singer spacing does have an effect. The choir stood on Wenger Tourmaster three-step risers with 8-inch step heights and 18-inch step width using a sectional block formation with consistent lateral inter-singer spacing (Daugherty, 1999), with 18 inches between each row of singers and 24 inches between each singer in each row. Lateral shoulder-to-shoulder distances were measured by placing 24-inch wooden dowels between the upper arms of neighboring singers. The researcher collected the dowels before the choir began to sing.

Conducting. During recording sessions, the choir observed a video recorded conductor. The projection screen was centrally located in front of the choir where the conductor appeared life-size, which was determined by the conductor standing next to the projection prior to recording. Video recorded conducting ensured consistency of conductor behaviors and tempo in each performance.

The choir followed the conductor on a projector screen following a digital recording created using a Flip UltraHD Video Camera. The ensemble conductor was recorded on video several times while actually conducting the choral excerpt for this study in a rehearsal prior to the recordings sessions. Prior to the recording sessions, choristers practiced with the recorded conducting. All choristers agreed they could follow the video recorded conductor.

Risers were positioned 30 feet from the projected videos to allow space for recording equipment. A research assistant controlled playback of the video by queuing the mp4 formatted video file in Windows Media Player on a Toshiba Portégé R705 laptop connected via VGA to an NEC MT-1075 LCD projector. The projector was covered with a thick material during recording sessions to reduce equipment noise or sound leakage that might have been picked up by the recording instruments.

Rehearsals. The choir rehearsed the musical excerpt used for this study with random placement assignments and lateral spacing. The choir rehearsed in both the rehearsal room and the performance hall prior to the recording sessions in order to allow singers to acclimate to both acoustical environments (Bartle, 2003; Bodegraven and Wilson, 1942; Brinson, 1996; Fuhr, 1944; Hylton, 1995; Pfautsch, 1973; Roe, 1970).

Recording Procedures & Equipment

Recording sessions. Two recording sessions occurred on the same day, one directly after the other. Each session lasted approximately 30 minutes. Prior to each recorded trial, singers heard the tonic pitch of the excerpt sounded by a Master-Key pitch pipe (C – C range).

Microphones. Microphones used included (a) two Earthworks precision instrumentation omni-directional condenser microphones (model M30) calibrated with a Cirrus CRL 551E microphone calibrator at 94 dB, 1000 Hz, and (b) one Crown International SASS-P stereo PZM microphone system (model MKII).

Based on choir location, room area, room volume, and acoustician recommendations, the microphones were placed in the following locations:

1. Earthworks microphone, conductor position: placed 2.74 m (9’) from the center front row of choir at a height of 1.6 m (5’ 3”) or approximate conductor ear height in both rooms.

2. Earthworks microphone, second row audience position: placed 7.49 m (24’ 7”) from front row of choir near a center audience area seat at a height of 1.02 m (40”) or approximate seated audience member ear height in both rooms.
3. PZM microphone assembly, second row audience position: placed 7.49 m (24’ 7”) from front row of choir near a center audience area seat at a height of 1.02 m (40”) or approximate seated audience member ear height in both rooms.

The microphones input to an Aubion X.8 audio interface device following the same arrangement as later employed for gathering impulse response data. Adobe Audition software (version 5.0) captured the audio of each recording. (See Figure 1.)

Figure 1. Binaural and omnidirectional microphones. PZM binaural assembly (top) and Earthworks omnidirectional (bottom).

Dependent Measures

Venue acoustics. Prior to recordings, the researcher noted room surface area, volume, construction materials and other characteristics that could potentially affect acoustics. In order to determine room acoustical characteristics, the researcher used room impulse response (RIR) of a swept sine wave stimulus and maximum length sequence (MLS) that energized a custom dodecahedron loudspeaker using Renkus-Heinz drivers (see Figure 2). Set at approximate head height near the center choir position in each room, the loudspeaker acted as a transducer.

Figure 2. Dodecahedron loudspeaker.

The researcher gathered the measurements at the listener position using an Earthworks M30 omni-directional condenser microphone calibrated to 94 dB at 1000 Hz and also input to the Aubion interface device. The interface device connected via Ethernet to a Dell 1557 notebook computer using an Intel Core i7 processor and Windows 7 operating system. Adobe Audition software captured the audio of each impulse response.

In order to compare acoustics within both rooms with and without the choir in place (Ternström, 1989), the researcher analyzed the obtained RIR data and calculated the RT (T20) and EDT for each room using EASERA software. Mid-frequencies averages (measured in seconds) are illustrated below in Table 1. Soulodre and Bradley

(1995) recommended averaging EDT from 63 – 4000 Hz, whereas acousticians typically measure EDT by averaging mid-frequency bands (500 – 1000 Hz). In the table below, mid-frequency and an average of multiple octave bands (125 – 4000 Hz) are reported.

Table 1.

RT and EDT Comparisons at Mid-frequencies With and Without Choir

		No Choir			With Choir		
Measure	Signal	Reh. Room	Perf. Hall	Diff.	Reh. Room	Perf. Hall	Diff.
RT (*T20*)	Swept Sine	2.13	1.50	0.63	1.98	1.40	0.58
	MLS	2.11	1.57	0.54	1.96	1.40	0.56
EDT	Swept Sine	2.01	1.38	0.63	1.76	1.20	0.56
	MLS	2.01	1.40	0.61	1.79	1.25	0.54
EDT (Avg.)	Swept Sine	1.90	1.26	0.64	1.70	1.15	0.55
	MLS	1.91	1.26	0.65	1.72	1.18	0.54

Note. RT (T20) = reverberation time at 20 ms, *EDT* = early decay time, *RR* = Rehearsal Room, *PH* = Performance Hall. All values (in seconds) reflect average octave band calculations either in mid-frequencies (500 – 1000 Hz) unless denoted as specific band averages (EDT [Avg.], 125 – 4000 Hz).

The researcher measured the fixed sound source data at a later date within both rooms using the same omnidirectional listener microphone placed at the same position as the original recording sessions. Pink noise was fed into a Renkus-Heinz Rhaon PF1-200R loudspeaker that was placed in the same location as the center of the choir from the recording sessions. The sound was produced and measured using the same setup as earlier described.

The Rehearsal Room used for this investigation is a large university choral room (see Figure 3) with an area of approximately 26,964 cubic feet. Room dimensions were 44’ 5” by 35’ 5” with a ceiling height of 17’. The room contains three splayed walls, gypsum wallboard ceiling parallel to the floor, and very little absorption. From an acoustical standpoint, the splayed walls of the Rehearsal Room provide sound dispersion, the heavily painted block walls cause primarily sound reflection, and the parallel ceiling and floor surfaces likely create flutter echo.

The Performance Hall used for this study is a small, 350-seat university auditorium with a raked tile floor, stage, upholstered seats, and an approximate area of 67,155 cubic feet (see Figure 3). Within the seating area, average room width is 49’ with an average ceiling height of 20’. Distance from the upstage wall to the back of the auditorium is 80’. The hall contains splayed sound diffusion panels on the ceiling, splayed walls, an absorbent back wall, and upholstered auditorium seats. The splayed design of the ceiling panels located over the audience seats may deliver some sound dispersion; but due to the design and placement of the panels, their function was unknown.

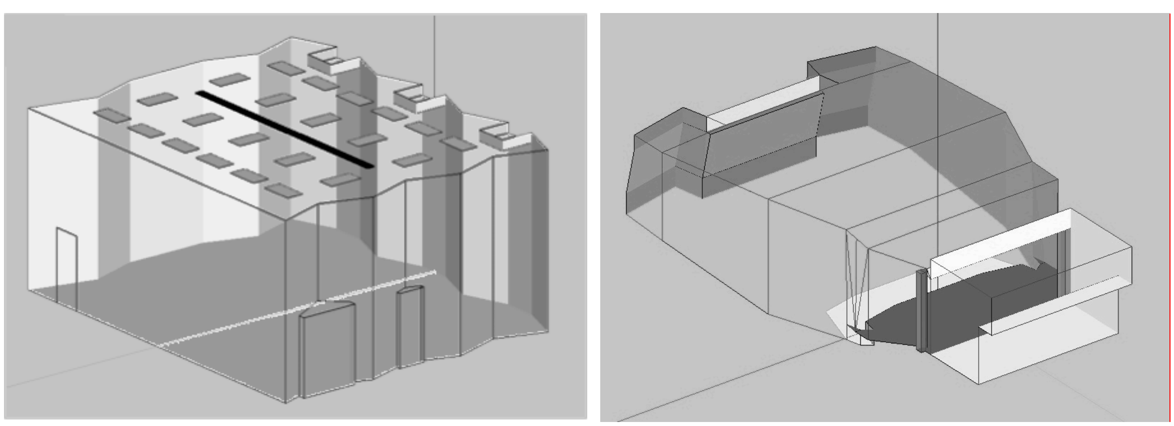

Figure 3. EASE computerized room models of the two rooms. Rehearsal Room (left) and the Performance Hall (right).

Indoor noise criteria. Indoor Noise Criterion (NC) ratings measure ambient indoor noise and vibration, which are then plotted along criteria curves falling between

63 Hz and 8 kHz. In order to provide very good listening conditions, recommended ranges for noise criteria are NC-20 for recital halls and between NC-20 and NC-30 for music practice rooms (Egan, 2007).

According to Figure 4 below, the Rehearsal Room measured at approximately NC-39, while the Performance Hall measured at around NC-23. Both rooms exceeded recommended room ratings, most likely due to heating, ventilation, and air conditioning (HVAC) noise.

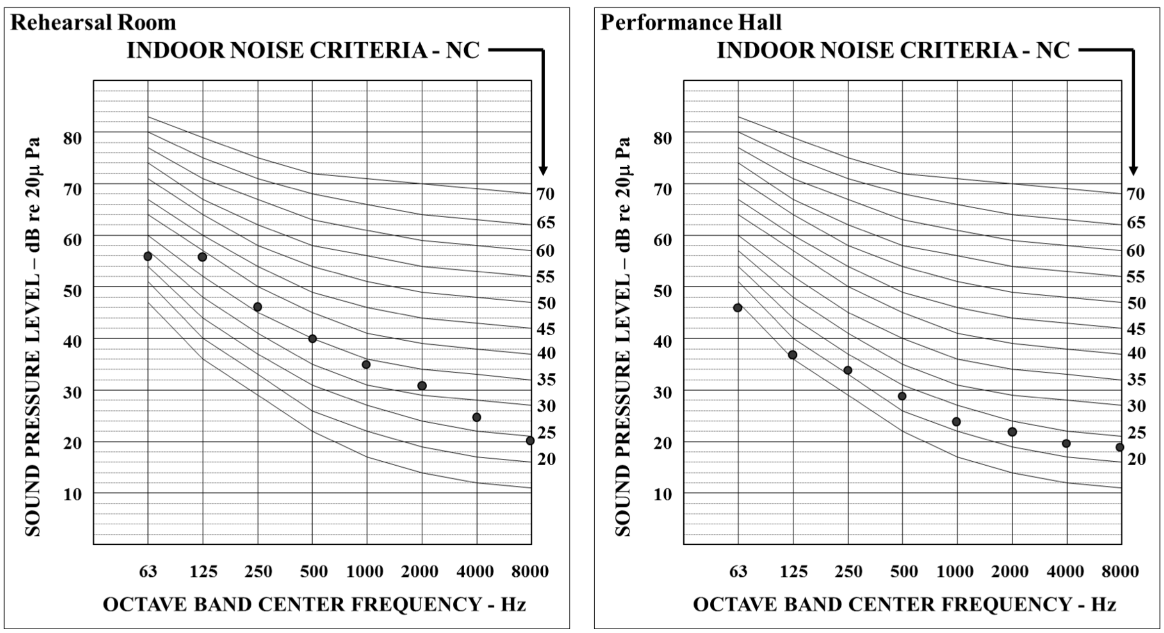

Figure 4. Indoor Noise Criteria (NC) rating charts. These NC rating charts show octave band measurements of the ambient room noise in dB SPL of both the Rehearsal Room (left, NC-39) and the Performance Hall (right, NC-23).

Long-term average spectra data. Long-term average spectra (LTAS) data were acquired from the .wav recordings through KayPentax Computerized Speech Lab (CSL) Model 4500 software using a window size of 512 points with no pre-emphasis or smoothing, a bandwidth of 86.13 Hz, and a Hamming window. Data were then transferred to an Excel spreadsheet and Statistical Package for the Social Sciences (SPSS) for subsequent statistical analyses.

One-third octave band measurements. One-third octave band data were acquired using EASERA software, which averaged frequency and amplitude measurements across one-third octave frequency bands. While one-third octave bands provided fewer data points than LTAS, they related closer to hearing acuity, commonly measured by critical intervals (Goupell and Hartmann, 2006).

Choir intonation. For analysis of pitch, the researcher extracted sustained vowels from recordings of the choir in each room. Analyses of one-second excerpts from the midpoint of each sustained vowel provided intonation comparisons among the sung trials.

Because choral sound constitutes a complex interactive acoustic phenomenon, use of computerized extractions of fundamental frequency (F_o) is problematic. Therefore, following procedures used by Howard (2004) the researcher evaluated perceptual "pitch" using Pitch Analyzer 2.1 software and a MacBook Pro laptop computer.

Excerpted vowels were selected and cut using Audacity audio editing software. The selections were opened within Pitch Analyzer individually and the midpoint of the vowel was selected. The Pitch Analyzer configuration produces a sinusoidal reference tone set to the score-notated pitch. The frequency of the reference tone was then adjusted to match the perceived pitch of the sung excerpt. Within an Excel spreadsheet the researcher recorded (a) score notated frequency, (b) perceived frequency, and (c) the provided conversion to cents. A second listener repeated the same procedures for reliability. The average of difference in cents from target pitches within analyzed excerpts was then compared between rooms using a *t*-test to determine statistical significance.

Singer survey. Immediately following the completion of each recording session, singers completed a brief perceptual survey (see Appendices A and B) formatted after one used by Daugherty (1996) to indicate ease of singing, ability to hear themselves and other singers, and to indicate any outside influences that they think affected their singing.

The choir was aware that this study dealt with choral sound in different rooms and that the ensemble would be asked to sing in different venues. The choir was also informed that singer preferences and opinions would be solicited at some point. The choir members were asked to not discuss or share nonverbally their perceptions until after completing the recording sessions and surveys.

Auditor survey. Auditors ($N = 33$) listened to four pairs of the sung excerpts, and responded to each pair by indicating: (a) whether a difference between the two excerpts was perceived, and, if so, the description of that difference, and (b) any preference for one excerpt in each pair over another. If auditors perceived a difference between the paired excerpts, they were asked to select one word best explaining the factor most influencing the difference they heard (Daugherty, 1996). They were also given an option to complete an open-ended question to further explain the factor that influenced their perception.

All listeners marked their responses on the Listener Response Form (Appendix C). Listeners were not informed of the specific variable (differing room acoustics) of interest; thus they were unaware which recordings pertained to which room condition.

The researcher manually transferred acquired .wav file recordings to a compact disc that was accessed by a Sony CDP-497 compact disc player connected to a Denon DRA-685 stereo receiver and a PreSonus HP4 distribution amplifier. At no time were electronic signals compressed.

Auditors listened to recorded excerpts in a listening room with a low reverberation time. Recordings were played using consistent sound pressure levels from SONY MDR-7506 Professional circumaural headphones.

Statistical tests. Statistics used for singer and auditor perceptual data included descriptive statistics and paired *t*-tests. Tests used for LTAS and one-third octave band measurements included paired *t*-tests and independent sample *t*-tests to determine specific differences between room trials. All tests utilized a predetermined .05 *alpha* level.

CHAPTER 4

Results

This chapter presents results according to the research questions posed for this investigation. Reported results include statistical measurements and visual interpretation using graphs, as appropriate to the research question and type of obtained data.

Preliminary Considerations

Ambient room noise. The researcher measured and evaluated ambient noise within each of the two rooms using LTAS and one-third octave band analysis. Recording levels shown below 80 Hz likely reflect ambient room noise in the recording rather than choral sound. Both analyses showed high levels of lower frequency noise (0-125 Hz), especially in the Rehearsal Room (see Figures 5 and 6). The data were considered reliable with at least a 10 dB difference between the recording and ambient noise measurements.

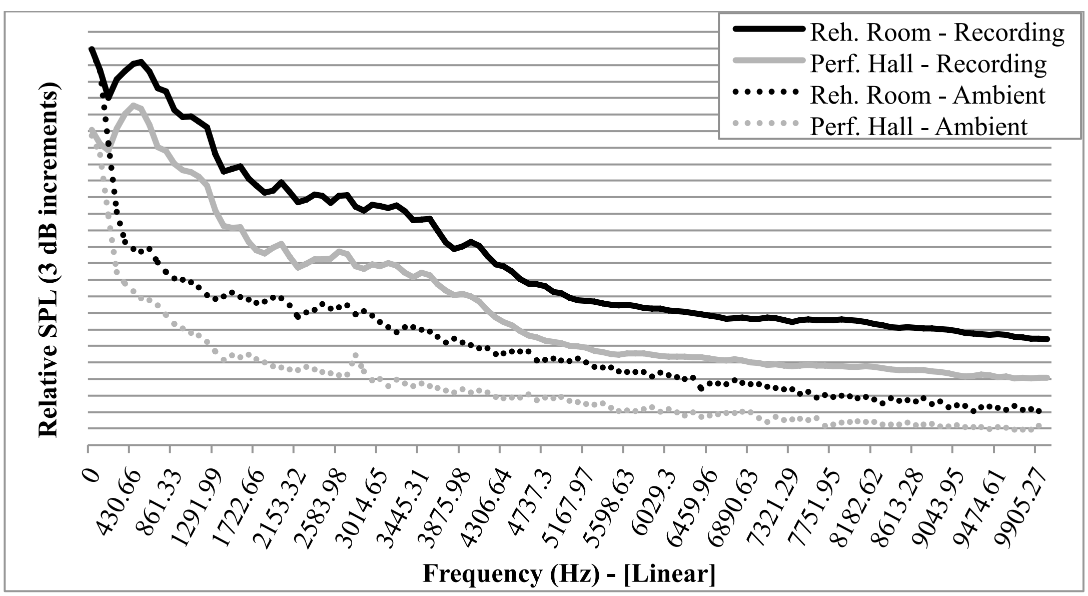

Figure 5. LTAS spectral energy comparisons of recordings and ambient noise within both rooms.

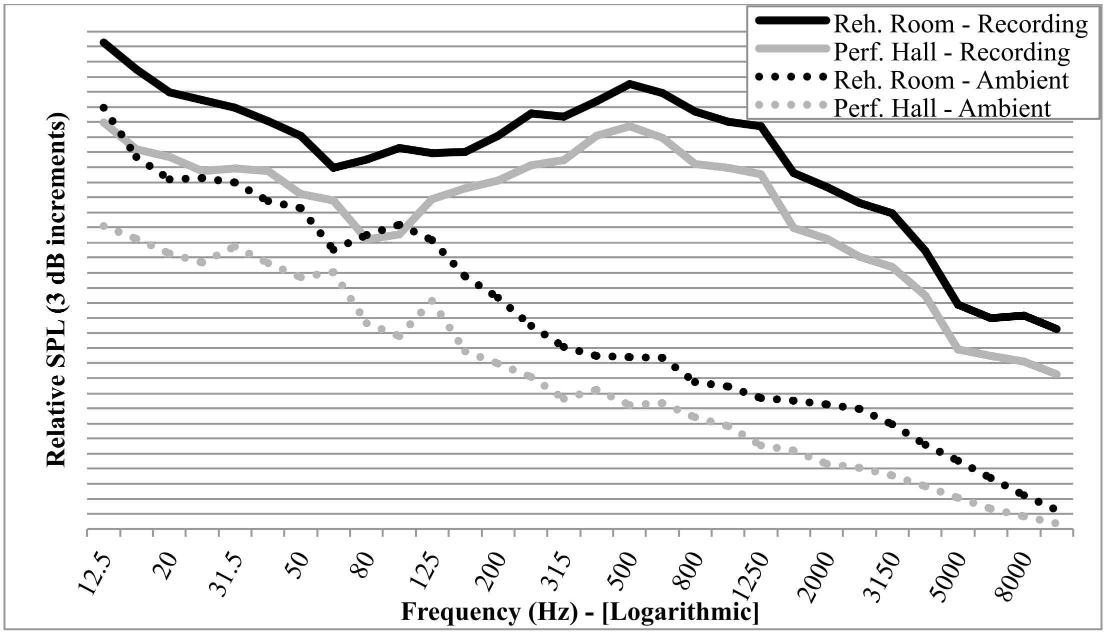

Figure 6. One-third octave band comparisons of recordings and ambient noise within both rooms.

Research Question One: Acoustical Measurements

The first research question asked to what extent, if any, acoustical measurements would differ based on performances of an SATB choir in two different rooms. The researcher employed two forms of acoustical measurement (LTAS, one-third octave bands) to analyze acoustical data and determine any differences between recordings. Statistical tests were performed to report effects within both sets of data due to their different scales of measurement (linear, logarithmic), and the varying degrees of freedom, using 117 points and 22 points from each, respectively.

LTAS. Long-term average spectra (LTAS) measurements use the Fast Fourier Transform (FFT) algorithm to display the resulting power spectrum of waveform data within a specified range. LTAS graphs present sound pressure as a function of frequency averaged over time. Sound pressure level (SPL) is presented according to a continuous decibel (dB) scale. Frequency is presented in vibrations per second, or hertz (Hz); and kilohertz (kHz) serves as a shorthand expression for higher frequencies that entail thousands of cycles per second. LTAS data provide a quantifiable index of persistent spectral events and sound quality over a specified period of time. The LTAS measurements used in this study follow a linear scale representing 0 Hz – 10 kHz, resulting in 117 data points. Measurements above 10 kHz were omitted for overall recording analyses as these frequencies may represent sound other than choral sound.

Entire spectrum results. Figure 7 below presents LTAS data obtained according to the two different room conditions. Comparisons ($N = 2$) of overall (0 – 10 kHz) mean signal relative dB SPL differences indicated greater signal energy within the Rehearsal Room ($M = 34.65$, $SD = 14.98$) than in the Performance Hall ($M = 25.50$, $SD = 14.01$). *T*-test results indicated a significant difference ($M = 9.14$, $SD = 1.44$) between LTAS spectral data acquired from Rehearsal Room and Performance Hall recordings, $t(116) = 68.45$, $p < .001$, $d = 6.33$. Although the recording data from the two rooms differed significantly, the LTAS measurements showed high positive correlation, $r(115) = .997$, $p < .001$.

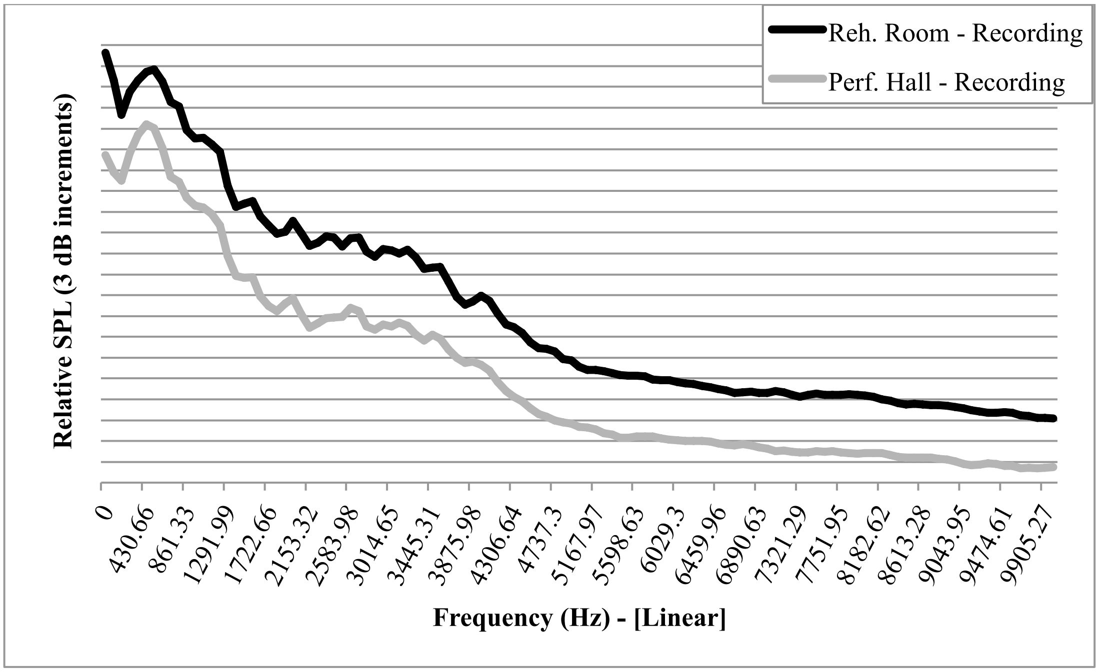

Figure 7. LTAS comparisons of choral recordings between rooms.

One-third octave bands. Octave bands are constant percentage (approx. 70.7%) bandwidths across the audio spectrum. The bands represent frequencies doubling from one octave to the next following a continuous logarithmic scale. One-third octave band measurements represent constant percentage (approx. 23.2%) fractional frequency ranges within each octave band. The smoothed 1/3 octave band measurements used in this study follow the logarithmic scale representing 80 Hz – 10 kHz, resulting in 22 data points. The researcher omitted measurements from 12.5 Hz – 63 Hz and 12.5 kHz – 20 kHz for overall recording analyses as these frequencies may represent sound other than choral singing.

Entire spectrum results. The researcher log-transformed all 1/3 octave band data to obtain a linear scale of measurement prior to statistical analysis. Due to potential calculation discrepancies caused by back-transforming data, the log-transformed values were maintained. Below, Figure 8 presents 1/3 octave band data acquired according to the two different rooms. Overall (80-10 kHz) mean signal relative dB SPL comparisons ($N = 2$) indicated greater signal energy within the rehearsal room ($M = 1.83$, $SD = 0.11$) than in the performance hall ($M = 1.76$, $SD = 0.13$). Results of *t*-test analysis indicated a significant difference between the log-transformed 1/3 octave band data ($M = .07$, $SD = 0.02$) of the two rooms, $t(21) = 13.796$, $p < .001$, $d = 3.5$. While the data showed significant differences, 1/3 octave band measurements also showed high positive correlation between the two recordings, $r(20) = .992$, $p < .001$.

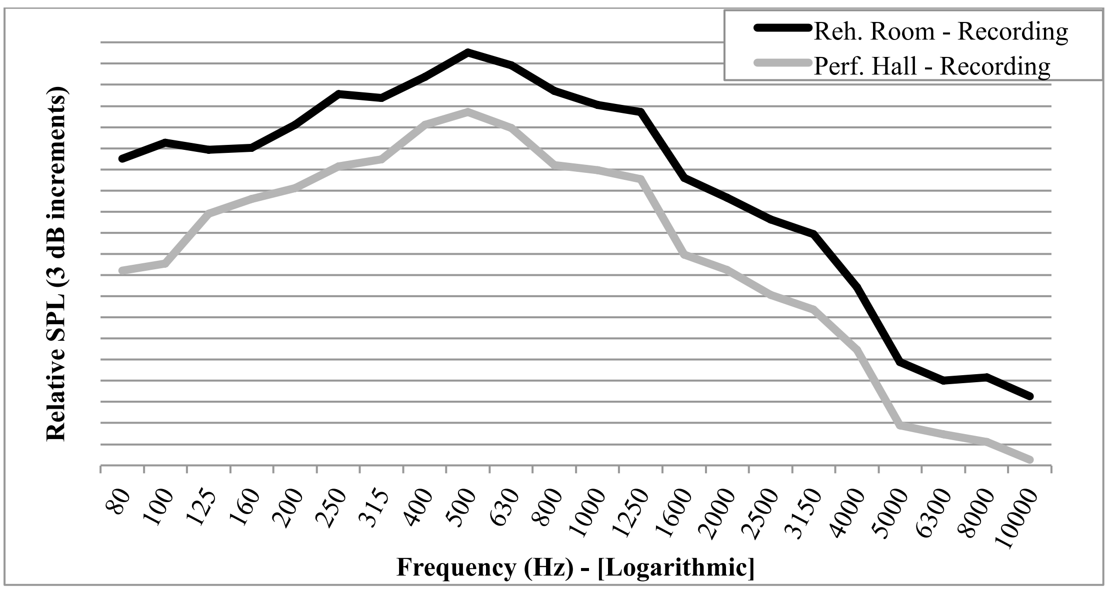

Figure 8. One-third octave band comparisons of choral recordings.

Fixed sound source. In order to further determine possible causes of the approximately 9.1 dB SPL mean difference (according to LTAS) between the two room recordings, it was necessary to isolate room response using a fixed sound source within each of the two rooms. This procedure helped to better determine if changes were due solely to the change in room, a change in vocal output by the singers, or a combination of the two.

The researcher placed the loudspeaker used for the fixed sound source at the position of the center of the choir location, and fed it pink noise. The receiving microphone and its location for the fixed sound recordings remained consistent with the choral recording sessions. It was placed in the same location in each of the two rooms as in the recording sessions. LTAS and one-third octave band analyses provided spectral data measurements of fixed sound recordings (see Figures 9 and 10).

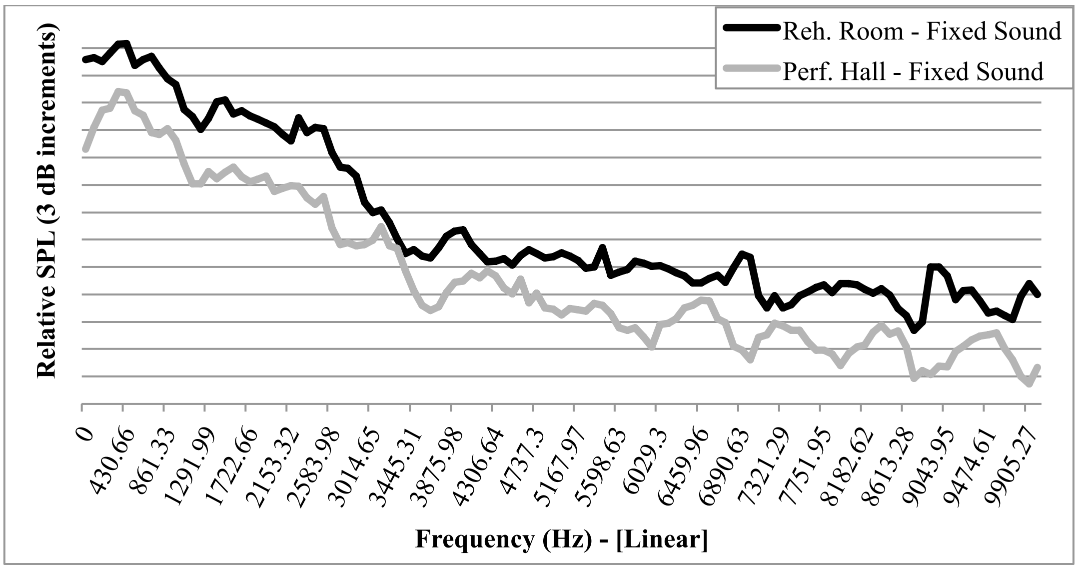

Figure 9. LTAS comparisons of fixed sound source recordings.

LTAS measurements of the fixed sound source spectra indicated frequent fluctuation in the source signal readings across the linear data points. This fluctuation may have resulted from the spectral characteristics of the pink noise signal used for the recording. The mean of the overall spectral data acquired from the fixed signal in the Rehearsal Room ($M = 49.68$, $SD = 9.02$) in comparison to that of the Performance Hall ($M = 43.99$, $SD = 8.64$) was significantly higher ($M = 5.69$, $SD = 2.31$), $t(116) = 26.634$, $p < .001$, $d = 2.46$.

One-third octave band analysis of the fixed sound source recording likewise indicated that the log-transformed mean SPL of the Rehearsal Room recording (*M* = 1.83, *SD* = 0.07) when compared to the log-transformed mean of the recording in the Performance Hall (*M* = 1.79, *SD* = 0.07) was again significantly higher (*M* = 0.04, *SD* = 0.01), $t(21) = 20.734$, $p < .001$, $d = 4$.

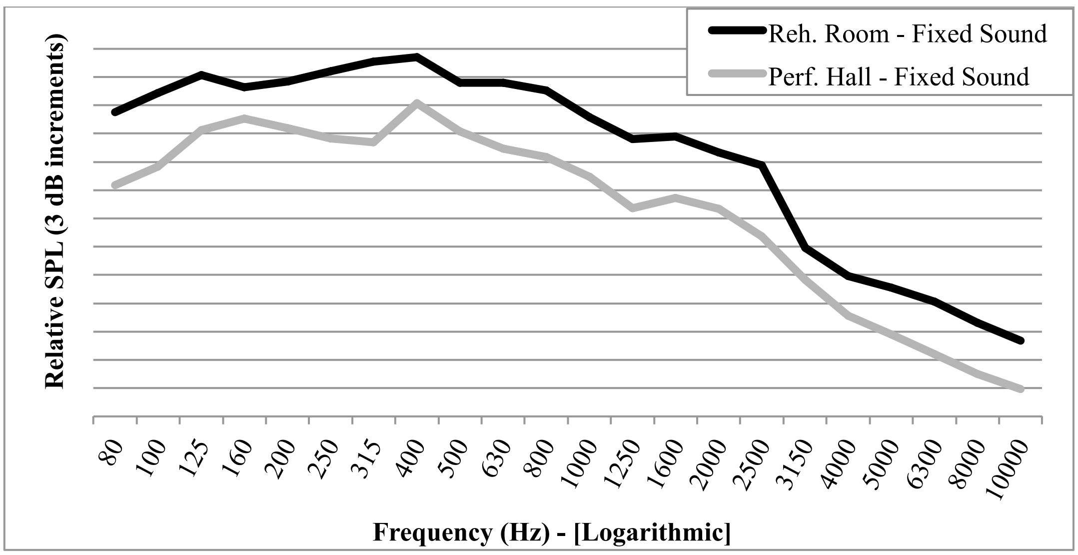

Figure 10. One-third octave band comparisons of fixed sound source recordings.

The mean of differences between LTAS measurements of the choral recording was ~9.1 dB SPL while the mean of differences for the fixed sound recording was ~5.7 dB SPL. Although the means more generally communicate potential differences caused by the choir, the researcher decided to take a more precise look at the specific spectral differences to gain better insight about the sound characteristics. Some spectral differences shown may reflect characteristics of the types of sound (choral singing, pink noise) recorded within each room; therefore the researcher only directly compared differences between the same types of sounds. Thus, the following calculations (see

Figure 11) helped to determine the overall spectral differences between data measured from the two sound sources.

RR choral recording – PH choral recording = *Recording spectral differences*

RR fixed sound recording – PH fixed sound recording = *Fixed sound spectral differences*

Recording spectral differences – Fixed sound spectral differences = ***Overall differences***

Figure 11. Calculations used to determine overall differences between choral recordings and fixed sound.

Overall LTAS differences illustrated in Figure 12 pinpointed particular areas of interest to the current investigation, including spectral peaks in the region of 2 – 4 kHz. Differences were particularly robust (7 – 10 dB SPL) in the 2.1 – 4.3 region; frequencies in and around what is called the "singer's formant" region. This could likely suggest that the difference in sound could be attributed to the singers who might have sung more efficiently within the Rehearsal Room, contributing somewhat to the SPL difference between the two rooms.

Other peaks of 5 – 6 dB SPL in the upper frequencies of the LTAS differences suggest that while the overall the choral sound was stronger within the Rehearsal Room than in the Performance Hall in addition to room reflections. Also of interest from the LTAS results are the negative values that might suggest that at certain higher frequencies particular sounds (such as consonants) may have been dampened more in the Rehearsal Room than in the Performance Hall.

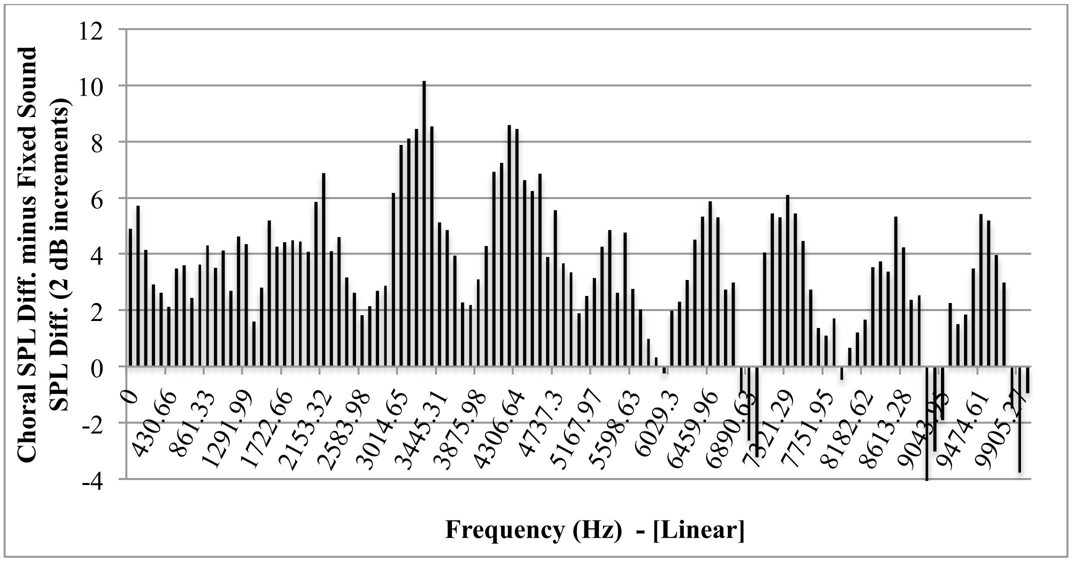

Figure 12. Overall LTAS differences between choral and fixed sound source recordings.

Overall one-third octave band differences also showed particular areas of interest, especially from 80 – 100 Hz and at 3.15 kHz. As Figure 13 below illustrates, the peak at 3.15 kHz shows a robust difference (approx. 7 dB SPL) between the choral recording and fixed sound within an area of the "singer's formant" region. Other frequencies within the same region (2 – 4 kHz) show less robust differences with only 2 – 4 dB SPL.

The comparison of calculations within the 80 – 100 Hz frequency bands in particular showed large 8 – 9 dB SPL overall differences. Usually lower frequency bands (12.5 – 63 Hz) showing high SPLs indicate increased room noise. Ambient noise measurements within the rooms did not show large noise level differences between the recordings of the choir the fixed sound. Sung notes by the choir included frequencies as low as 86 Hz, which may suggest that the fundamental frequencies (F_o) sung by the choir were much stronger within the Rehearsal Room than in the Performance Hall.

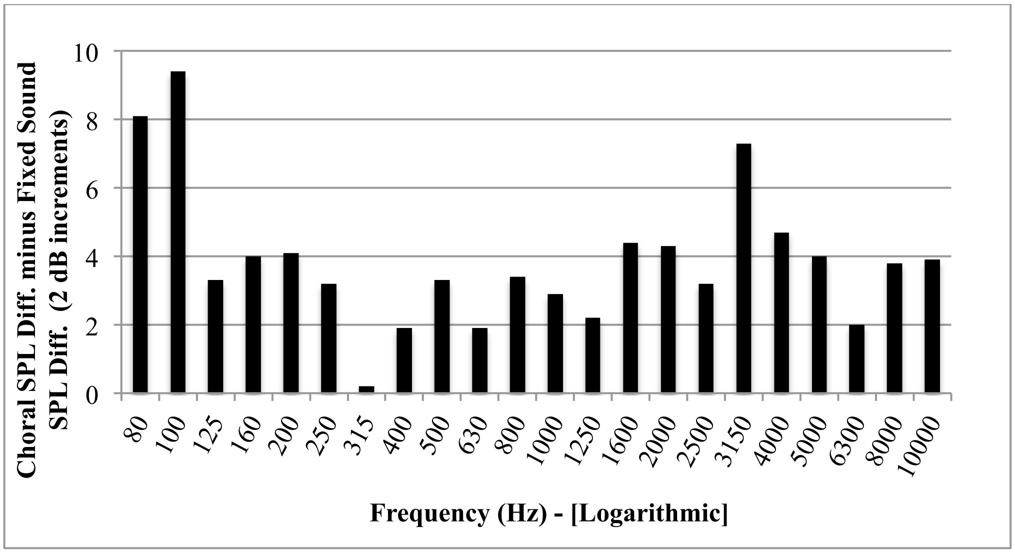

Figure 13. Overall one-third octave band differences between choral and fixed source recordings.

Summary. LTAS measurements of choral sound (0 – 10 kHz, 117 data points) differed significantly between rooms with an overall spectral mean of 9.1 dB SPL higher within the Rehearsal Room. One-third octave band measurements of choral sound (80 Hz – 10 kHz, 22 data points) also differed significantly between rooms. Fixed sound source differences between rooms showed an overall mean difference of 5.7 dB SPL. Comparisons of the differences of choral sound and fixed sound recordings suggested that the rooms contributed to the overall difference, but that singers also adjusted vocal output between room conditions.

Research Question Two: Singer Perceptions of Choral Singing

Singer perceptions. The second research question asked about singer perceptions gathered using two surveys after recording sessions in each of the two different rooms. All choristers completed surveys with a return rate of 100%. Statistical comparison of responses included paired *t*-tests using an alpha level of .05.

Singer survey item one: Perceptions of individual singing effort. The first and second items on each survey offered the following responses along a Likert-type scale: (a) 1 = *with much less effort than normal*, (b) 2 = *with moderately less effort than normal*, (c) 3 = *with slightly less effort than normal*, (d) 4 = *with normal effort*, (e) 5 = *with slightly more effort than normal*, (f) 6 = *with moderately more effort than normal*, and (g) 7 = *with much more effort than normal*.

Survey question one from the Rehearsal Room indicated that nearly half of the singers (45%) perceived using normal singing effort, while other responses indicated a wider range of perceptions. Responses from the Performance Hall indicated that a majority of choristers (64%) described their singing effort as normal while the remaining singers indicated using slightly or moderately more effort than normal (see Table 2).

Table 2.

Singer Survey Item One: Perceptions of Individual Singing Effort

Q 1. During today's recordings in the [Rehearsal Room/Performance Hall] **I** was singing _____________ (Circle one number):							
	1 With much less effort than normal	2	3	4 With normal effort	5	6	7 With much more effort than normal
Rehearsal Room							
f	0	0	2	5	2	2	0
%*f*	0%	0%	18%	45%	18%	18%	0%
Performance Hall							
f	0	0	0	7	3	1	0
%*f*	0%	0%	0%	64%	27%	9%	0%

Note. Responses shown correspond with Likert-type responses for each room. *f* = frequency, %*f* = frequency percentage.

Participant responses showed a slightly higher mean score within the Performance Hall (N = 11, M = 4.45, SD = 0.688) than in the Rehearsal Room (N = 11, M = 4.36, SD

= 1.027), however *t*-test comparisons showed no significant difference between the two rooms, $t(10) = .430$, $p > .05$.

Singer survey item two: Perceptions of choir singing effort. Similar to the first item, survey item two addresses perceptions of the overall choir's singing effort. Within the Rehearsal Room, the majority of singers indicated that they thought choir used normal effort or slightly more than normal effort with one respondent indicating less effort and one indicating moderately more effort. In the Performance Hall, participants indicated that the choir used normal, slightly more than normal, and moderately more effort when singing (see Table 3).

Table 3.

Singer Survey Item Two: Perceptions of Choir Singing Effort

Q 2. During today's recordings in the [Rehearsal Room/Performance Hall] **the choir** was singing __________ (Circle one number):							
	1 With much less effort than normal	2	3	4 With normal effort	5	6	7 With much more effort than normal
Rehearsal Room							
f	0	0	1	5	4	1	0
%*f*	0%	0%	9%	45%	36%	9%	0%
Performance Hall							
f	0	0	0	6	3	2	0
%*f*	0%	0%	0%	55%	27%	18%	0%

Note. Responses shown correspond with Likert-type responses for each room. *f* = frequency, %*f* = frequency percentage.

Although singers perceived slightly higher overall choir singing effort within the Performance Hall ($N = 11$, $M = 4.64$, $SD = 0.809$) than in the Rehearsal Room ($N = 11$, $M = 4.45$, $SD = 0.820$), no significant difference was found between responses from the two rooms according to paired comparison *t*-tests, $t(10) = 0.803$, $p > .05$.

Singer survey item three: Perceptions of hearing self. The third and fourth questions on each survey offered the following responses along a Likert-type scale: (a) 1 = *strongly disagree*, (b) 2 = *moderately disagree*, (c) 3 = *slightly disagree*, (d) 4 = *neutral*, (e) 5 = *slightly agree*, (f) 6 = *moderately agree*, (g) 7 = *strongly agree*.

Survey item three responses showed a majority of singers (64%, *n* = 7) indicating slight to moderate agreement with being able to hear their own voices while singing in the Rehearsal Room. As illustrated in Table 4, three choristers indicated slight disagreement (27%), while one singer (9%) indicated moderate disagreement with this statement. All respondents (100%) answered survey question three with some amount of agreement indicating that singers experienced no difficulty hearing their own voices in the Performance Hall.

Table 4.

Singer Survey Item Three: Perceptions of Hearing Self

Q 3. During today's recordings in the [Rehearsal Room/Performance Hall] I could hear/monitor the sound of **my own voice.** (Circle one number):							
	1	2	3	4	5	6	7
	With much less effort than normal			With normal effort			With much more effort than normal
Rehearsal Room							
f	0	1	3	0	2	5	0
%*f*	0%	9%	27%	0%	18%	45%	0%
Performance Hall							
f	0	0	0	0	5	3	3
%*f*	0%	0%	0%	0%	45%	27%	27%

Note. Responses shown correspond with Likert-type responses for each room. *f* = frequency, %*f* = frequency percentage.

The mean of singer responses concerning ability to hear and monitor their own voices was significantly higher within the Performance Hall (*N* = 11, *M* = 5.82, *SD* =

0.874) than in the Rehearsal Room (N = 11, M =4.64, SD = 1.567), t(10) = 2.797, p = .019.

Singer survey item four: Perceptions of hearing others. Regarding responses to the fourth survey item in the Rehearsal Room, a majority of respondents indicated varying degrees of ability to hear others while singing. Three choristers indicated neutrality in ability to hear the rest of the choir in the Rehearsal Room. Alternatively, within the Performance Hall, choristers most frequently answered *"with normal effort"* while other respondents indicated a much wider spread of perceptions (see Table 5).

Table 5.

Singer Survey Item Four: Perceptions of Hearing Others

Q 4. During today's recordings in the [Rehearsal Room/Performance Hall] I could hear/monitor the sound of **the rest of the choir.** (Circle one number):							
	1 With much less effort than normal	2	3	4 With normal effort	5	6	7 With much more effort than normal
Rehearsal Room							
f	0	0	0	3	2	5	1
%*f*	0%	0%	0%	27%	18%	45%	9%
Performance Hall							
f	0	0	2	4	1	2	2
%*f*	0%	0%	18%	36%	9%	18%	18%

Note. Responses shown correspond with Likert-type responses for each room. f = frequency, %f = frequency percentage.

Responses to survey item three concerning ability to hear the rest of the choir showed a greater mean within the Rehearsal Room (N = 11, M = 5.36, SD = 1.027) than in the Performance Hall (N = 11, M = 5.09, SD = 1.375) with no significant difference between the two rooms, t(10) = -0.498, $p > .05$.

Open-ended singer survey items. In addition to the Likert-type scale ratings, the singer survey contained two open-ended items. A majority of respondents (91%) wrote answers to these survey items (Appendix B).

The first item stated, "Please describe what influences, if any, you think the [Rehearsal Room/Performance Hall] had on your personal singing." Several singers (n = 4) responded about the Rehearsal Room indicating that they perceived an increase in overall sound level. One singer reported, "It makes me hear more of others' voices and less mine." Some singers indicated that they could not hear themselves and as a result sang louder or "with more confidence." In contrast, another singer reported, "It is [a] very loud room so I think I compensated by singing softer."

Other singers (n = 2) mentioned that they sang easier or with less effort.

Regarding singing within the Performance Hall, some singers (n = 3) commented about the ability to hear themselves and other singers, while other singers (n = 4) reported difficulty in hearing specific sections or across the choir. One singer in particular commented that the "lack of 'ring back' made it feel as if I was singing basically alone…[the] choir as a whole seemed 'distant' in my ear."

The second question stated, "Please describe what influences, if any, you think the [Rehearsal Room/Performance Hall] had on the singing of the whole choir." Within the Rehearsal Room, singers commented on the choir's increased volume and suggested an increase of confidence. Several comments (n = 5) indicated that choristers perceived greater ease of the choir's ability to hearing each other within the Rehearsal Room. Conversely, one singer stated, "The wetter acoustics made it harder to hear the whole group in some ways." Another chorister commented, "The room makes the voice[s] louder but less clear."

Multiple singers (*n* = 2) commented that the Performance Hall primarily influenced the choir's intonation. They perceived that the intonation suffered due to their inability to hear other sections and find an adequate blend and balance between sections. Most comments to this question referenced the singers' ability to hear and respond to the rest of the choir. One singer in particular stated, "The acoustics are poor for choral singing, so it's hard to match the volume and vowels of other parts."

Subsequent questions on the survey following the second recording session asked singers to indicate their perceptions and preferences of their own singing and the singing of the choir between the two rooms. Question seven asked, "In the performances recorded for this study, in which room do you feel you personally sang best?" The majority of singers (64%, *n* = 7) perceived that they sang best in the Performance Hall, while the remaining singers (36%, *n* = 4) perceived that they sang best in the Rehearsal Room.

Question eight inquired, "In the performances recorded for this study, in which rooms do you feel the whole choir sounded best?" Singers responded similarly as in question seven with 64% (*n* = 7) perceiving the overall best choir sound as being in the Performance Hall and 36% (*n* = 4) indicating that they thought the choir sounded best in the Rehearsal Room.

The next two questions focused on the choir's rehearsals within each of the two rooms. "During rehearsals for this study, in which room did you feel you personally sang best with this choir?" 82% (n = 9) of choristers thought that during rehearsals that they sang best in the Rehearsal room while 18% (*n* = 2) thought that they sang best in the

Performance Hall. In response to the second question referencing rehearsals ("During rehearsals for this study, in which room did you feel the whole choir sang best?"), 64% (n = 7) of participants thought the choir sang best in the Rehearsal Room, while 36% (n = 4) thought that the choir sang best during rehearsals in the Performance Hall.

The final survey item asked singers, "How much effect do you think different rooms have on the sound of a choir?" Most choristers (73%, n = 8) thought that rooms have a moderate to significant effect on choir sound, while two respondents (18%) thought rooms have a slight effect and one respondent (9%) was unsure of the influence of rooms on choirs.

Summary. Singer perceptions indicated that choristers' ability to hear themselves was significantly higher in the Performance Hall than the Rehearsal Room. Singers also indicated they perceived using slightly more singing effort both individually and as a choir in the Performance hall, but were better able to hear the rest of the choir in the Rehearsal Room.

Research Question Three: Listener Perceptions of Choral Sound

The third research question inquired about differences in listener perceptions based on pitch analysis and listener panel preference of choral recordings based on performances within two different rooms.

Pitch analysis. For pitch analysis, sustained vowels (N = 3) were selected from each recording including (a) /o/ vowel from "domini" within the second measure; (b) the /ɛ/ vowel from "et" in the repeated portion of the second half of the song; and (c) the /i/ vowel from "populi" in the final chord of the piece. The latter two excerpts were chosen within the portion of the recording cut for listener perceptions in order to provide a comparison to listener panel responses or preferences related to intonation.

The researcher evaluated and recorded pitch analysis data for all excerpted vowels. In order to obtain reliability for this perceptual measurement, another listener evaluated the same excerpts following the same procedure. Listener agreement included any amount within ±1 Hz difference; and disagreements included any difference greater than 1 Hz between like trials. The acquired reliability ratio – agreements divided by the sum of agreements and disagreements – was .92 (see Tables 6 and 7).

According to Sundberg (1982), deviations within ± 7 cents of a target fundamental frequency are usually considered in tune. Pitch analysis for this investigation showed the Rehearsal Room recording as the only example containing pitches perceived higher than the target frequencies. Within the Rehearsal Room, data showed the following mean perceived pitch deviations from target frequencies: (a) sopranos, 4.48 cents; (b) altos, -8.88 cents; (c) tenors, -5.27 cents; and (d) basses, -1.5 cents. Both listeners perceived the basses as only choral section not deviating from the fundamental frequency.

Table 6.

Rehearsal Room Pitch Analysis and Listener Reliability Comparisons

			Listener 1		Listener 2		Comparison	
Vowel	Part	Notated (Hz)	Perceived (Hz)	Diff. (c)	Perceived (Hz)	Diff. (c)	Diff. (Hz)	A/D
/o/	Sop.	523.00	524.35	3.31	525.20	6.61	-0.85	A
	Alt.	391.00	389.00	-8.88	389.36	-8.88	-0.36	A
	Ten.	329.00	328.20	-5.27	328.00	-5.27	0.20	A
	Bas.	130.00	130.00	0.00	130.90	0.00	-0.90	A
/ɛ/	Sop.	523.00	525.13	6.61	524.88	3.31	0.25	A
	Alt.	391.00	399.91	35.06	399.40	35.06	0.51	A
	Ten.	329.00	327.98	-10.56	328.21	-5.27	-0.23	A

	Bas.	130.00	129.89	-13.37	131.14	13.27	**-1.25**	**D**
/i/	Sop.	493.00	494.00	3.51	494.00	3.51	0.00	A
	Alt.	391.00	390.19	-4.43	390.16	-4.43	0.03	A
	Ten.	293.00	291.75	-11.86	291.81	-11.86	-0.06	A
	Bas.	195.00	195.00	0.00	194.83	-8.90	0.17	A

Note. Disagreements are in boldface. Sop. = soprano; Alt. = alto; Ten. = tenor; Bas. = bass; A = agree; D = disagree.

Table 7.

Performance Hall Pitch Analysis and Listener Reliability Comparisons

			Listener 1		Listener 2		Comparison	
Vowel	Part	Notated (Hz)	Perceived (Hz)	Diff. (c)	Perceived (Hz)	Diff. (c)	Diff. (Hz)	A/D
/o/	Sop.	523.00	520.96	-9.96	520.07	-9.96	0.89	A
	Alt.	391.00	390.00	-4.43	390.39	-4.43	-0.39	A
	Ten.	329.00	327.95	-10.56	328.65	-5.27	-0.70	A
	Bas.	130.00	129.97	-13.37	129.12	-13.37	0.85	A
/ɛ/	Sop.	523.00	519.44	-13.29	520.01	-9.96	-0.57	A
	Alt.	391.00	390.93	-4.43	390.47	-4.43	0.46	A
	Ten.	329.00	327.10	-10.56	328.34	-5.27	**-1.24**	**D**
	Bas.	130.00	129.82	-13.37	129.05	-13.37	0.77	A
/i/	Sop.	493.00	487.25	-21.20	488.10	-17.65	-0.85	A
	Alt.	391.00	385.96	-26.77	385.06	-26.77	0.90	A
	Ten.	293.00	290.47	-17.82	290.46	-17.82	0.01	A
	Bas.	195.00	193.27	-17.85	192.78	-26.84	0.49	A

Note. Disagreements are in boldface. Sop. = soprano; Alt. = alto; Ten. = tenor; Bas. = bass; A = agree; D = disagree.

Mean perceived pitch deviations by choir section from target frequencies within the Performance Hall included: (a) sopranos, -13.67 cents; (b) altos, -11.88 cents; (c) tenors, -11.22 cents; and (d) basses, -16.36 cents. Listener perceptions indicated that within the Performance Hall the altos sang the /o/ and /ɛ/ vowels more in tune than other sections (- 4.43 cents); but they sang the /i/ vowel the most out of tune (-26.77 cents) compared to the rest of the choir. As illustrated in Figure 14, listeners perceived that the recording within the Rehearsal Room was more in tune (< ± 7 cents) than the Performance Hall recording (> ± 7 cents).

Statistical comparisons of mean pitch deviations from target frequencies between the Rehearsal Room (*M* = -1.39 cents, *SD* = 13.87) and the Performance Hall (*M* = -13.28, *SD* = 7.07) showed significant differences (*M* = 11.89, *SD* = 12.45) based on room condition, $t(11) = 3.309$, $p < .05$, $d = 0.96$.

Within both recordings, the final vowel (/i/) showed the greatest deviation from the target frequency. The larger mean deviation of -21.59 cents of the ending /i/ vowel occurred in the Performance Hall recording. This indicated that even though the choir started the song below the notated pitch in the Performance Hall (/o/), they likely maintained that deviation consistently (/ɛ/) and deviated most from the fundamental frequency at the end of the recording (/i/).

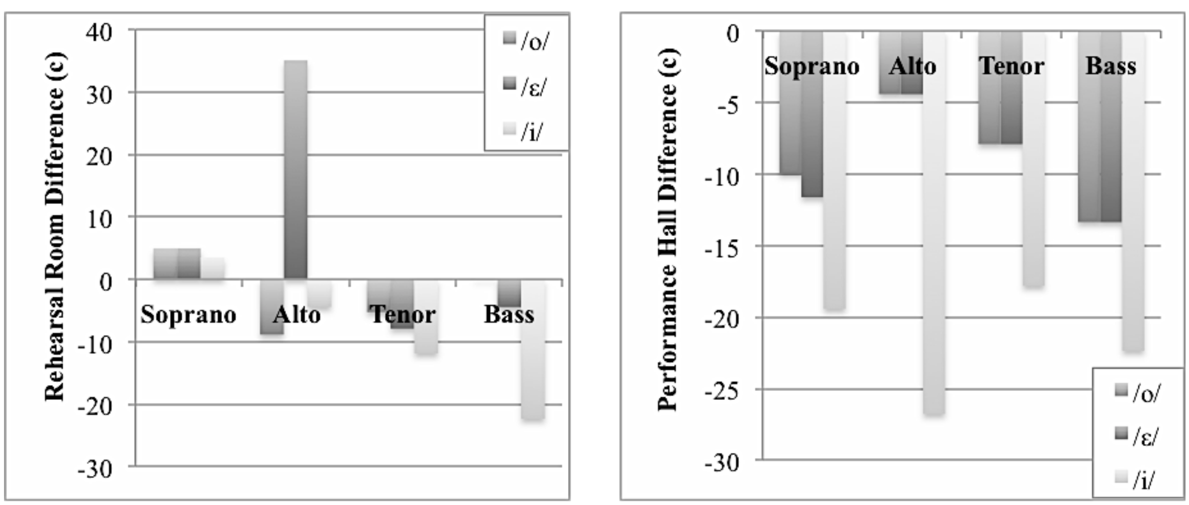

Figure 14. Mean perceived pitch differences in cents from target frequencies. Differences are disaggregated by vowel and voice part within the Rehearsal Room (left) and Performance Hall (right).

Listener perceptions. In order to determine whether particular listeners (N = 33) would indicate hearing differences in the overall choral sound recorded in two different rooms, a convenience sample of participants listened to four pairs of randomly ordered recordings: (a) rehearsal room vs. rehearsal room, (b) performance hall vs. rehearsal room, (c) rehearsal room vs. performance hall, and (d) performance hall vs. performance hall. Survey items prompted listeners to (a) indicate whether they heard a difference between performances and if so, how much of a difference, (b) indicate their preference within each pair of recordings, (c) mark the musical item that most influenced their decision, and (d) to write any comments describing their choices (see Figure 15). Descriptive statistical analysis of listener survey data allowed for the comparison of overall listener preferences between recordings from the two rooms. All listeners completed surveys with a 100% return rate.

First Pair

1. Comparing the overall sound of the choir in these two performances, I heard:

(A) No difference (B) A little difference (C) Much difference (D) Very much difference (E) Not sure

2. I preferred the overall choral sound of the:

(A) First performance (B) Second performance (C) Both sounded the same

3. If you heard a difference between the overall sound of these two performances, which one, if any, of the elements below MOST influenced your perception:

(A) Tempo (B) Volume (C) Blend/balance (D) Pitch/intonation (E) Tone quality (F) Other: ________

Comments:

Figure 15. Excerpt from listener survey.

Listener survey item one: Perception of difference. Almost all listeners (97%, N = 32) reported hearing a difference when presented with the two pairs containing different recordings: one from each of the two rooms. Responses differed based on which of the two performances was first. When the performance hall recording played first, listeners indicated hearing a larger magnitude of difference: (a) *a little difference, n* = 2; (b) *much difference, n* = 18; and (c) *very much difference, n* = 13. However, when the rehearsal room recording played first followed by the performance hall, listener responses indicated a wider range of perceived differences: (a) *no difference, n* = 1; (b) *a little difference, n* = 7; (c) *much difference, n* = 21; and (d) *very much difference, n* = 4. (See Figure 16.)

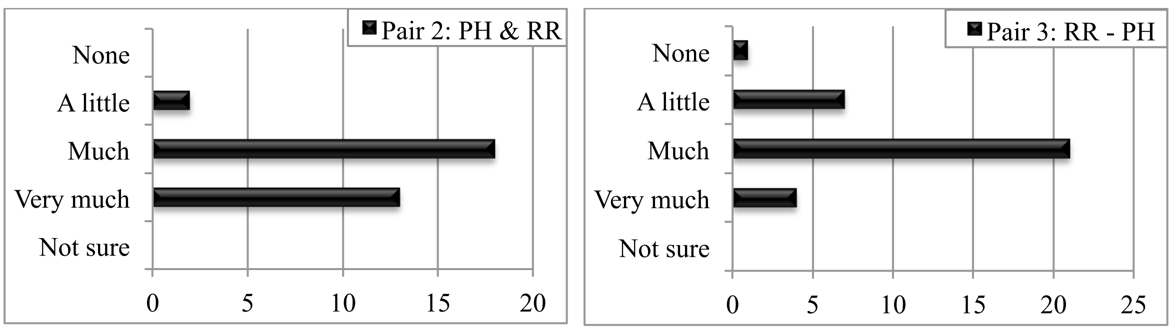

Figure 16. Listener Perceptions of recording differences. PH = Performance Hall; RR = Rehearsal Room.

Listener survey item two: Indication of recording preference. The majority of listeners (*n* = 30, 91%) preferred the recording within the Rehearsal Room whereas only a few listeners (*n* = 3, 9%) preferred the Performance Hall recording. (See Figure 17.) Although listener perception changed between the pairs of different recordings, listener preferences remained consistent between the same pairs. This indicated that although listeners perceived different magnitudes of change, the differences did not affect their preference for either recording.

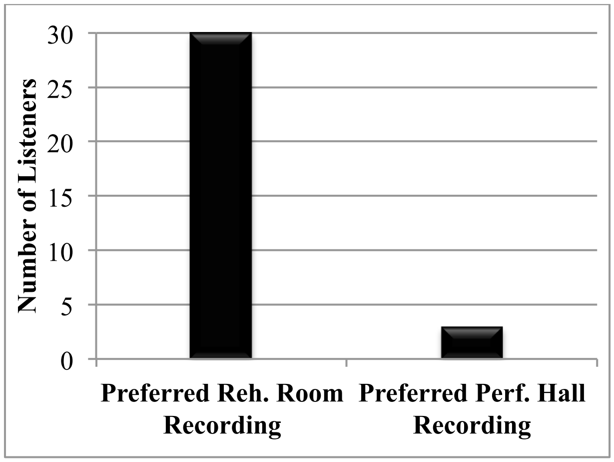

Figure 17. Listener recording preferences between Pair 2 recordings.

Listener survey item three: Element most influencing perception. Although listeners were asked to indicate one performance aspect that most influenced their decision, several listeners commented difficult in deciding on just one element in some cases. Due to this discrepancy between listener responses, the frequency of terms mentioned was included in Figure 18 below. The researcher performed no statistical analyses on these data.

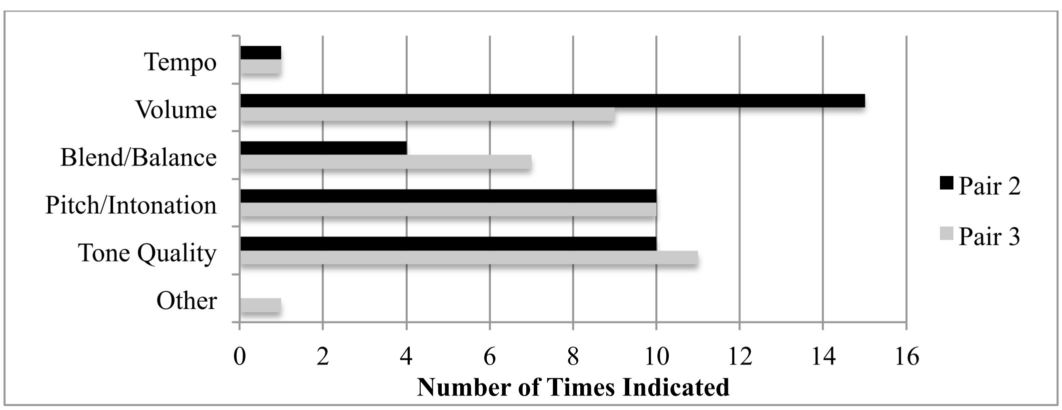

Figure 18. Terms listeners indicated as most influencing perceptions of recording differences disaggregated by pair.

Open-ended listener survey items. Several open-ended comments from listeners provided further information as to specific differences they perceived or indications for specific recording preference. Listeners perceived the sound within the Rehearsal Room as being "fuller," "louder," and "more energized." Some listeners commented that the recording from the Rehearsal Room had better sound quality due to intonation and blend. Listener comments referencing the less-preferred Performance Hall recording indicated that listeners perceived there being fewer singers or a "smaller" group with a more shallow and flat sound. One comment in particular noted that the Performance Hall recording sounded "listless and unsupported" while another said it sounded "tinny and thin."

The listeners who preferred the Performance Hall recording perceived it as being "more in tune" or having "more artistic overall affect." Another listener perceived that the Rehearsal Room recording "sounded slightly pressed." Listener comments are listed in Appendix F.

Identical listening pairs. Two listening pairs featured the same recording to check for accurate listener identification. In response to Pair 1, 19% of listeners correctly identified the recordings as the same; whereas for Pair 4, 52% of listeners correctly identified the identical paired recordings.

Summary. Pitch analysis of deviation from target frequencies on selected vowels within each recording indicated that the perceived intonation within the Performance Hall was considered out of tune and was found to be significantly lower than that of the Rehearsal Room. Almost all listeners (97%) perceived a difference between different room recordings, however perceived magnitude of difference changed based on the order of paired excerpts. The three most common factors for listeners most influencing their perceptions were: (a) volume, (b) pitch/intonation, and (c) tone quality. The majority of listeners (91%) preferred the Rehearsal Room recording.

CHAPTER 5

Discussion

The primary finding of this investigation is that choral sound differed according to the two room environments. The two environments contributed to changes in overall spectral energy, pitch, chorister perceptions of hearing self and others, and listener perceptions.

Due to the unique participants and varying room properties in this study, results should not be generalized to other choirs or rooms. Findings are limited to the venues, equipment, participants, and procedures of this particular investigation. Nevertheless, they present matters that deserve further reflection.

Singer vocal output differed significantly according to room environment, which indicates that rooms make a difference. For instance, singers modified their voice usage in the more reverberant Rehearsal Room (mid-frequency RT = 1.97 s) with a mean spectral energy increase of 9.1 dB SPL. Choristers may have compensated for the room reverberance by singing with greater power, which confirms Ternström's 1989 findings. In contrast, Ternström found that singer vocal output increased within the most absorbent room (RT = 0.38 s). Daugherty, Grady and Coffeen (2013) also found that choristers might have compensated for absorption between two different rooms by singing with 3 dB SPL greater power in the more absorbent room.

It may be that there is a 'point of no return' for extreme room reverberance or extreme absorption in consideration of their effects on choral singing. Future research could explore the possible existence of specific thresholds or limits of room absorption or reverberance levels before singers alter vocal output.

Much literature regarding perceptions of architectural acoustics focuses on audience preferences (e.g. Beranek, 2011; Gourévitch & Brette, 2012; Morimoto et al., 2007; Smitthakorn, 2006; Cirillo & Martellotta, 2005; Farina, 2001; Kleiner & Klepper, 2007, Martellotta, 2009, Zamarreño et al., 2007; Chiang, 1994; Fujii et al., 2004; Torres et al., 2004), however, this study shows that within the same room listeners and performers perceive different things. A majority of singers (63%) thought they performed best in the Performance Hall, though most listeners (91%) preferred the Rehearsal Room recording. Often, performance venues cater to listeners without considering the needs of singers. This study also shows that the rooms that singers most prefer can negatively affect listener perceptions; and the same environments that listeners most prefer may negatively influence singer performance or perceptions. More research is needed to determine specific architectural differences that benefit singers without detracting from listener overall impressions. Future research might also consider measuring choristers' perceptions within different rooms in correspondence with further acoustical measures such as strength (G) and clarity (C80). Future studies might also explore acoustic solutions that benefit both singers and audience members.

It is widely accepted by architectural acousticians (e.g. Sabine, 1922; Ando, 1998; Beranek, 2004; Egan, 2007) that different room construction and surfaces affect sound dispersion, propagation, or attenuation. Multipurpose halls and rooms differ greatly not just based on reverberation time, early decay time or other acoustical measures; rooms also differ based on reflective surfaces. While all room surfaces absorb sound to some extent with different response between frequency bands, certain materials – such as the painted concrete block within the Rehearsal Room – absorb less sound than others including glass or heavy drapery.

Sound reflections and a lack of absorption within the Rehearsal Room likely contributed to the increase of overall sound level within the Rehearsal Room. Usually, as sound encounters surfaces and reflects it loses energy with each reflection (Beranek, 2004). Due to the low absorption rates of the walls in conjunction with probable flutter echo caused by the parallel ceiling and floor in the Rehearsal Room, the choir's sound was reflected with little attenuation. Egan (2007) stated that repeated reflections of sound within a room could cause buildup in sound levels increasing the overall sound level.

According to Beranek (2004), reverberation is a component of rooms that is available to composers and performers for producing musical effects. He states that reverberation is what helps to provide musicians "fullness of tone" that they can restrain or employ (p. 21). As this study shows, however, there could be such a thing as too much reverberation.

Although rooms used for multiple purposes are usually suited for the most common use, they may be too reverberant for speech and not reverberant for choral music (Ellison & Schwenke, 2010). In the present investigation, the Performance Hall is most commonly used for student recitals and small ensemble performances. One could surmise that its acoustical response was possibly designed around this primary purpose.

Rooms whose structure and surfaces differ will also differ acoustically, even if the differences are slight. Decker and Kirk (1988) argued that rooms intended for purposes other than music could be hazardous to singers and unfavorable environments should be avoided. However, as this study and others point out, acoustics within rooms whose only purpose is music could differ greatly. Therefore a room's intended purpose for music does not necessitate its favorability for singers.

This investigation exhibited results consistent with previous studies that used different rooms and choristers (Ternström, 1989; Daugherty, Grady, and Coffeen, 2013). Thus, different rooms with varied acoustical properties will affect musicians differently. It may even be possible that different rooms affect diverse musicians in distinct ways.

Much literature addresses the needs and perceptions of instrumentalists within different rooms or acoustical conditions (e.g. Blankenship, Fitzgerald & Lane, 1955; Marshall, Gottlob, & Alrutz, 1978; Gade, 1989b; Chiang, Chen, & Huang, 2003; Ueno & Tachibana, 2005; Osman, 2010; Betancourt, 2011). Other research focuses on perceptions of conductors (e.g. Dupere, 1993; Hidaka & Beranek, 2000; Manternach, 2010). The effects of rooms on singers and choral singing merits further research.

Often choirs rehearse in rooms designated for music rehearsals and later perform in larger auditoria or performance venues that accommodate audiences. The rooms used in this study are realistic venues where choirs rehearse and perform. Future research might consider comparing choral sound within two rooms with similar purposes such as two rehearsal rooms or two performance halls. Future studies could also investigate acoustics and perceptions of intact choirs within their usual rooms commonly used for rehearsals and performances.

Given overall findings from this investigation, one might reasonably speculate that room acoustics – although apparently contributing to results of acoustical and perceptual measures – do not operate in isolation from other factors. Other factors to consider may include chorister ability to compensate for insufficient acoustics, chorister preferences for feedback while singing, and singer vocal production habits.

A change in venues – and essentially a change in acoustic conditions – could affect singers in a multitude of ways including singing effort, ability to hear their own voices, and ability to hear others. Furthermore, singers might change their voice usage to compensate for shortcomings of room absorption and inefficient acoustics (Ternström, 1991; Ternström, Cabrera, & Davis, 2005)

With respect to singing effort, it is widely accepted by voice experts that any increase in singer SPL could contribute to some sort of compensation in vocal production. According to Fant (1982), a singer's doubling of subglottal pressure raises the sound level by ~ 9 dB. In the present study, sound levels differed between rooms by around 10 dB within lower one-third octave frequency bands. This factor might indicate that singers increased subglottal pressure based on different room conditions. Within the context of choral performances in different rooms, more research is warranted to determine potential effects of different rooms on individual vocal production and possible changes in vocal tract or laryngeal positioning. Future studies could examine individual amplitude within a choral singing context using phonation monitors or measure glottal closure using an electroglottograph between different room conditions.

Considering that some singers ($n = 5$) indicated using less effort within the Rehearsal Room, these responses align with Husson's (1962) conclusion that singers sang with greater ease within rooms with a higher reverberation time. Due to differences between individual perceptions, singer effort presumably varies from person to person as indicated.

In relation to choral singing, room acoustics may also determine factors for singers to balance self-feedback and reference sounds (Ternström, 1994). One reason for fluctuations in singing effort could result from extreme absorptive and reverberant acoustical environments positively or negatively affecting the singers' ability to hear their own voice in relationship to feedback. Changes in hearing likely prompted singers to adjust their vocal effort to better balance out the ratio of hearing themselves compared to hearing others (Ternström, 1994). Tonkinson (1990) also indicated that as auditory feedback increases, so does singer vocal intensity. Future research could measure individual singer output and self-to-other ratio within a choir singing in different rooms to evaluate whether or not singers do increase or decrease intensity based on the Lombard Effect or a decrease in overall sound based on changes in room acoustics. Subsequent research might also want to investigate the most beneficial conditions for singer feedback in a choral setting.

Choristers reported they were better able to hear and monitor their own voices in the Performance Hall than in the Rehearsal Room. As indicated above, the different rooms contain divergent reflective and acoustical characteristics, which affected the feedback singers heard, which in turn may have contributed to their overall SPL. The high RT and EDT within the Rehearsal Room might have caused choristers to receive too much airborne feedback from others or from room reflections.

The choir sang with the greatest pitch deviations within the Performance Hall, where the singers reported significantly higher ability to hear their own voices. The singer-reported lack of feedback from others within the Performance Hall may have contributed to the issues with ability to tune across the choir and also intonation as noted in perceptual pitch analysis and listener perceptions. In accordance with research by Noson, Sato, Sakai, and Ando (2000), added reflectors within the Performance Hall could possibly improve choir acoustics.

Another possible reason for intonation discrepancies could be that because the Rehearsal Room was the second of the two recording venues, perhaps the pitches were slightly more solidified by the latter recording session. Future studies could test choir intonation consistency prior to recordings to account for room influence. Future research might also investigate whether extremely absorptive or reverberant conditions effect choral intonation.

According to Egan (2007), changes in sound level include: (a) 1 dB = "imperceptible", (b) 3 dB = "just barely noticeable", (c) 6 dB = "clearly noticeable" and (d) 10 dB = "about twice (or half) as loud" (p. 21). Howard and Angus (2006), however, suggest that 1 dB amplitude differences of complex sound may also constitute 'just noticeable differences' depending on listener hearing acuity and the nature of the sound. The fact that there was a 9.1 dB SPL mean difference between room spectral energy is likely the reason that 97% of listeners perceived a difference between the recordings, including "much difference" or "very much difference" difference between the recordings from the two rooms.

According to Ternstrom and Karna (2002), the chorusing effect occurs when three or more singers perform the same part. In this study, the convenience sample only included two tenors and two basses. Although this discrepancy could have contributed to a less blended choral sound or other changes in perception, choral programs often deal with the reality of not having three or more singers – especially males – on a particular voice part. Future research could investigate whether similar changes in room acoustics similarly affect acoustical measurements and perceptions of established choirs with balanced sections meeting the minimum of three singers in each section. Future studies may also want to incorporate same sex or like-voiced ensembles to determine whether similar results are found within divergent room conditions. Subsequent research may also want to consider larger choral ensembles or choirs with different size choral ensembles (with similar experience levels) to see how much combined increased singer intensity affects overall SPL within a reverberant room.

Although listeners may be biased toward or more accustomed to the sound of larger choral ensembles, several comments reported poor intonation within the Performance Hall as a large influence on perceptual differences and preference between recordings. Listeners might have preferred the Rehearsal Room because it was louder. A study by Marshall (1993) indicated that reflections increase audience perception of "loudness." Future research might consider listener preference of choral recordings based on listening volume or singer vocal output of consistent performances.

Listener preference for recordings within the more reverberant room may also have been because of the style, original purpose and time in which the composition "Laudate nomen domini" used in this study was written. Based on its sacred text and composition within the Renaissance, it was most likely written for a reverberant church setting. Other possible reasons for perceived differences could be that listeners listened for smaller details and found identifiable inconsistencies rather than focusing on overall choral sound. Future studies could control for listener preferences of room acoustics qualities by playing a consistent choral recording in different room environments.

Also of note, listeners showed little accuracy in identical pair identification, especially with the first listening pair (19%). Perhaps the prompt to listen for differences could be why 70% of listeners marked “a little difference” as they may have been expecting even slight differences between the first pair. After hearing the fourth pair, 52% of listeners correctly identified the recordings as the same, whereas the remaining 48% perceived hearing “a little difference.”

Due to the different metric scales of LTAS and one-third octave bands, LTAS measurements showed greater and more precise differences within the 2 – 4 kHz (singer’s formant) region and one-third octave bands showed greater and more precise differences within the 80 – 125 Hz (fundamental frequency) region. The two analyses in combination showed a more complete picture of the acoustical results, including frequencies of particular interest. This bigger picture then allowed for a more detailed look at room acoustic characteristics and resultant choral singing simultaneously for evaluation of differences.

Overall differences of fixed sound recording differences subtracted from choral recordings differences indicate that the singers likely sang with greater intensity in the more reverberant Rehearsal Room. One-third octave band analysis of these differences show that within specific frequencies coinciding with the male singing range (80 – 100 Hz) the SPL was around 9 – 10 dB higher in the Rehearsal Room. This coincides with a study by Marshall (1993) who found that an increase in reflections enhanced the projection of male singers’ voices. Marshall also found that reflectors increased singer-perceived ease of ensemble, and this concurs with the present investigation as some singers reported singing “easier” and with “more confidence.”

Choristers are routinely asked to rehearse and perform in a multitude of acoustical settings. Based on the results of this study, some environments may better allow singers to hear themselves and others, while other environments cater more to audience listening. Scientific research of different room acoustics, including differences between rehearsal and performance venues, can inform music educators and assist in making decisions within different acoustical contexts to meet the needs of singers.

Sataloff (2010) asserts that although music teachers make great efforts to educate students about survival within divergent room acoustics conditions, teachers should further consider understanding and even altering room acoustics to better suit singers. He also recommends communicating with architects and advocating for expert architectural acoustics consultation in the designing and building phases of music performance and rehearsal rooms.

Perhaps music instructors could follow the recommendation by Hylton (1995) to tell singers to use the same manner of singing if acoustics differ between rehearsal and performance venues. Tonkinson (1990), for instance, instructed singers not to sing louder in the presence of masking noise from other singers within one room environment. Choral directors could consider following Tonkinson's suggestion as a temporary solution within a particularly troubling acoustical environment. Although simply instructing singers might be possible within one room, future research could investigate whether this potential solution holds true in different rooms. Future studies might also consider whether its effects are long lasting or dependent on constant reminders to singers.

Ternström (1989) found that when singers raised their larynges when increasing sub-glottal air pressure, which may have been the case here. According to Daugherty, Grady and Coffeen (2013), singing with a raised larynx could produce pressed and less efficient phonation, especially by singers with less training. From a choral pedagogy standpoint, inefficient phonation should always be avoided. Therefore, choral directors should be cognizant of singer hearing issues in order to make any modifications within a performance venue. Such changes would improve singer feedback and avoid increasing vocal effort based on room absorption or reverberance. These modifications may include the addition of room absorption, sound diffusors and reflective panels. Other changes within the choral ensemble may include adjusting singer directionality or location. Based on studies of choir spacing (Daugherty, 1996, 1999, 2003; Daugherty, Manternach, & Brunkan; Daugherty, Grady, & Coffeen, 2013), increasing the inter-singer spacing may influence and improve singer feedback.

Options for architects and music teachers to consider that improve room acoustics for music include restructuring rooms include splayed walls to avoid flutter echo. In addition, Pätynen (2007) suggests adding materials that increase absorption or diffusion can control sound reflections if a building structure cannot be altered. Increased acoustical absorption, Pätynen states, may help improve communication and help musicians to hear themselves and others.

Long-term solutions for choral directors in improving rooms for singers might include assisting with room design or requesting acoustical consulting for areas where students report difficulties hearing or increased vocal effort. Variable acoustics within Rehearsal Rooms and Performance Halls would also provide opportunities for changing room characteristics to suit different types of musical styles and preferences (Manternach, 2010).

One potentially confounding variable of this study is that prior to the recording sessions these particular choristers may have had substantial experience singing in one or both of the rooms. Future investigations could control for this potentially confounding variable by having singers perform in venues with varying acoustics toward which the choristers have no previous bias.

The fact that the choir was a convenience sample of singers with varying degrees of choral experience constitutes a limitation of this study. Moreover, the limited number of choristers ($N = 11$) also meant fewer than three singers in the tenor and bass sections. More singers might also have increased statistical power for significance in perceptual responses. Future studies may consider using intact choirs. As possibly indicated by intonation results from the second recording session that occurred in the Rehearsal Room, it may be possible that some choristers became increasingly secure as recordings went on.

In conclusion, this study showed that room acoustics can affect choral sound and contribute to the perceptions of singers and listeners. These changes were to varying degrees depending on individual differences; and even insignificant changes could be later investigated with larger and more established choirs in different acoustical conditions for further information about their effects. Because few studies to date combine acoustical and multiple perceptual measures of choral sound and choirs continue to sing in rooms with widely differing acoustics, these results merit further reflection and research.

The architects Schuette and Kirkegaard (2006) stated, “What performers hear is as important as sound for the audience” (p. 102). Architects and choral directors alike should be knowledgeable about room characteristics that positively and negatively influence musical performances – especially from the perspectives of singers.

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APPENDIX A

Singer Response Form: First Recording Session

Singer Response Form 1 – First Recording Session

1. During today's recordings in Swarthout Performance Hall, **I** was singing _____________ (Circle one number):

1	2	3	4	5	6	7
With much less effort than normal			With normal effort			With much more effort than normal

2. During today's recordings in Swarthout Performance Hall, **the choir** was singing _____________ (Circle one number):

1	2	3	4	5	6	7
With much less effort than normal			With normal effort			With much more effort than normal

3. During today's recordings in Swarthout Performance Hall, I could hear/monitor the sound of **my own voice**. (Circle one number):

1	2	3	4	5	6	7
Strongly Disagree			Neutral			Strongly Agree

4. During today's recordings in Swarthout, I could hear/monitor the sound of **the rest of the choir**. (Circle one number):

1	2	3	4	5	6	7
Strongly Disagree			Neutral			Strongly Agree

5. Please describe what influences, if any, you think Swarthout Performance Hall had on <u>your</u> personal singing?

6. Please describe what influences, if any, you think Swarthout Performance Hall had on the singing of <u>the whole choir</u>?

YOUR AGE: ______	SEX (Circle one): M F		VOICE PART: _________________		
YEAR IN SCHOOL (Circle one):	Freshman	Sophomore	Junior	Senior	Graduate
YEARS OF CHORAL EXPERIENCE (Please write):	Elementary (K-5) _______	High School (9-12) _______	Middle School (6-8) _______	College (or beyond HS)_______	

APPENDIX B

Singer Response Form: Second Recording Session

1. During today's recordings in the Rehearsal Room, **I** was singing __________ (Circle one number):

1	2	3	4	5	6	7
With much less effort than normal			With normal effort			With much more effort than normal

2. During today's recordings in the Rehearsal Room, **the choir** was singing _____________ (Circle one number):

1	2	3	4	5	6	7
With much less effort than normal			With normal effort			With much more effort than normal

3. During today's recordings in the Rehearsal Room, I could hear/monitor the sound of **my own voice**. (Circle one number):

1	2	3	4	5	6	7
Strongly Disagree			Neutral			Strongly Agree

4. During today's recordings in the Rehearsal Room, I could hear/monitor the sound of **the rest of the choir**. (Circle one number):

1	2	3	4	5	6	7
Strongly Disagree			Neutral			Strongly Agree

5. Please describe what influences, if any, you think the Rehearsal Room had on <u>your</u> personal singing?

6. Please describe what influences, if any, you think the Rehearsal Room had on the singing of <u>the whole choir</u>?

7. In the performances recorded for this study, in which room do you feel <u>you</u> personally sang best?

(Circle one): Performance Hall Rehearsal Room

Why?

8. In the performances recorded for this study, in which rooms do you feel the whole choir sounded best?

(Circle one): Performance Hall Rehearsal Room

Why?

9. During rehearsals for this study, in which room did you feel you personally sang best with this choir?

(Circle one): Performance Hall Rehearsal Room

Why?

10. During rehearsals for this study, in which rooms did you feel the whole choir sang best?

(Circle one): Performance Hall Rehearsal Room

Why?

11. How much effect do you think different rooms have on the sound of a choir? (Circle one):

1	2	3	4	5	6	7
No effect			Not sure			Very much ef

Why/Why not?

THANK YOU FOR YOUR PARTICIPATION!

APPENDIX C

Listener Response Form

***Please circle your answers below, and make sure that answers correspond with the appropriate questions.**

1. Your present age range:

(A) 18 – 25 years (B) 26 – 39 years (C) 40+

2. Your sex:

(A) Male (B) Female

3. Do you have a degree in music? If yes, indicate the level of your last degree.

(A) No (B) Bachelor's (C) Master's (D) Doctorate

4. Do you have a degree in choral conducting or choral music education? If yes, indicate the level of your last degree.

(A) No (B) Bachelor's (C) Master's (D) Doctorate

5. Are you currently working on a degree in either choral conducting or choral music education?

(A) No (B) Yes

6. Have you ever been a member of any choir, band or orchestra at any time from your first year in high school to the present day?

(A) No (B) Yes

7. Have you sung in a choir for <u>two</u> or more years at any time from your first year in high school to the present day?

(A) No (B) Yes

8. Have you ever taken private lessons on the same musical instrument for a year or more?

(A) No (B) Yes

9. Are you experiencing any difficulty hearing today?

(A) No (B) Yes

10. How would you evaluate your hearing?

(A) Better than normal (B) Normal (C) Slight hearing loss (D) Moderate hearing loss (E) Severe hearing loss

When the administrator gives the direction to do so, please put on your headphones and continue on to the next page of this guide.

First Pair

11. Comparing the overall sound of the choir in these two performances, I heard:

(A) No difference (B) A little difference (C) Much difference (D) Very much difference (E) Not sure

12. I preferred the overall choral sound of the:

(A) First performance (B) Second performance (C) Both sounded the same

13. If you heard a difference between the overall sound of these two performances, which one, if any, of the elements below MOST influenced your perception:

(A) Tempo (B) Volume (C) Blend/balance (D) Pitch/intonation (E) Tone quality (F) Other: ________________

Comments:

Second Pair

14. Comparing the overall sound of the choir in these two performances, I heard:

(A) No difference (B) A little difference (C) Much difference (D) Very much difference (E) Not sure

15. I preferred the overall choral sound of the:

(A) First performance (B) Second performance (C) Both sounded the same

16. If you heard a difference between the overall sound of these two performances, which one, if any, of the elements below MOST influenced your perception:

(A) Tempo (B) Volume (C) Blend/balance (D) Pitch/intonation (E) Tone quality (F) Other: ________________

Comments:

Third Pair

17. Comparing the overall sound of the choir in these two performances, I heard:

(A) No difference (B) A little difference (C) Much difference (D) Very much difference (E) Not sure

18. I preferred the overall choral sound of the:

(A) First performance (B) Second performance (C) Both sounded the same

19. If you heard a difference between the overall sound of these two performances, which one, if any, of the elements below MOST influenced your perception:

(A) Tempo (B) Volume (C) Blend/balance (D) Pitch/intonation (E) Tone quality (F) Other: ________________

Comments:

Fourth Pair

20. Comparing the overall sound of the choir in these two performances, I heard:

(A) No difference (B) A little difference (C) Much difference (D) Very much difference (E) Not sure

21. I preferred the overall choral sound of the:

(A) First performance (B) Second performance (C) Both sounded the same

22. If you heard a difference between the overall sound of these two performances, which one, if any, of the elements below MOST influenced your perception:

(A) Tempo (B) Volume (C) Blend/balance (D) Pitch/intonation (E) Tone quality (F) Other: ________________

Comments:

THANK YOU FOR YOUR PARTICIPATION!

APPENDIX D

Singer Perception Comments

Rehearsal Room.

Influences of Rehearsal Room on personal singing.

"It is [a] very loud room so I think I compensated by singing softer."

"It made me sing quieter because I felt louder."

"I'm used to it! It's very open and loud."

"The sound was very echoed it distracted from the singing."

"It makes me hear more of others' voices and less mine."

"I sang easier."

"The [rehearsal room] allows you to hear the full sound of the choir; I sang with more confidence."

"The acoustics are more wet than [the performance hall], and it seemed like more effort was needed to generate sound."

"I couldn't hear myself due to the activity of sound waves in the choral room."

"I couldn't monitor it as much – made me want to sing louder to hear myself."

Influences of Rehearsal Room on choir singing.

"LOUD; we could hear each other."

"I'm not sure of any effect."

"It's very open and loud; I could hear more alto."

"All parts echoed and so we could at least balance."

"The room made us try a little less."

"I believe the choir sounded fuller and more confident."

"The wetter acoustics made it harder to hear the whole group in some ways."

“It was a lot easier to hear all parts of the choir in this room.”

Room singers perceived they individually sounded best: Rehearsal Room.

“I’m used to it and know how to adjust.”

“Better acoustics.”

Room singers perceived the choir sounded best: Rehearsal Room.

“We could hear all of the parts and match vowels and volume.”

“Partly because we had a few practices by the time we sang in this room.”

“We could listen to all parts.”

“The acoustics are easier to perceive.”

“It is the room we are used to singing in.”

Performance Hall.

Influences of Performance Hall on personal singing.

“The spacing I thought was really nice because I could hear good sound from the other sections and also a good sound from myself and try to balance it.”

“I had trouble blending with the rest of my section due to spacing.”

“I don’t think it had any effect on my singing.”

“Dry sound (more so than where I normally sing); proximity of singers (good!); I wish we were closer or more turned towards altos.”

“I could hear the other singers well and it helped me to better blend.”

“It is a bigger room, so it feels like you have to use more effort to fill it up, but you can hear what is going on pretty well.”

“I could vaguely hear the other voices singing my part (alto), but I couldn’t hear any other part but the basses.”

“It helps my voice spread further.”

“It made it a little easier to sing.”

"Lack of 'ring back' made it feel as if I was singing basically alone…choir as a whole seemed 'distant' in my ear."

Influences of Performance Hall on choir singing.

"None that I could think of – other than being able to hear other parts fairly well."

"Not good across choir intonation."

"I think, as a whole, we sang a bit louder than normally."

"Not good across choir singing (tuning)."

"It helped us to remain together."

"The hall made it easier to hear those closest to us, but it was maybe a little more difficult to hear down the row."

"The acoustics are poor for choral singing, so it's hard to match the volume and vowels of the other parts."

"Spreads the voice further, the voice seems louder."

"None."

"I felt it was difficult to discern balance and blend among the ensemble."

Room singers perceived they individually sounded best: Performance Hall.

"I felt I could sing out and use my full voice."

"I could hear my own voice better."

"It allowed me to hear myself and my choir better."

"The voice[s] there were clearer [sic.] than the choral room."

"The sound of the room was better."

"I could hear myself better."

"Probably because I could hear myself better."

Room singers perceived the choir sounded best: Performance Hall.

"Less loud of a room, better acoustics."

“It caused us to sing louder and gave us a fuller sound.”

“Less reverberant, provided a cleaner sound.”

“We were better together.”
“More clear sound in this room [sic.].”

“The sound of the room was better.”

“I think that’s hard to tell because in the Performance Hall [sic.] we’re able to hear each other more meaning we could monitor better, but in the Rehearsal Room [sic.] it blends better meaning if there are imperfections meaning they’re not as scary so more freedom of voice use.”

Perceptions of effects of rooms on choir sound.

“The acoustics make a difference.”

“I think it has a bit of an effect based on how we hear ourselves. It changes how we sing.”

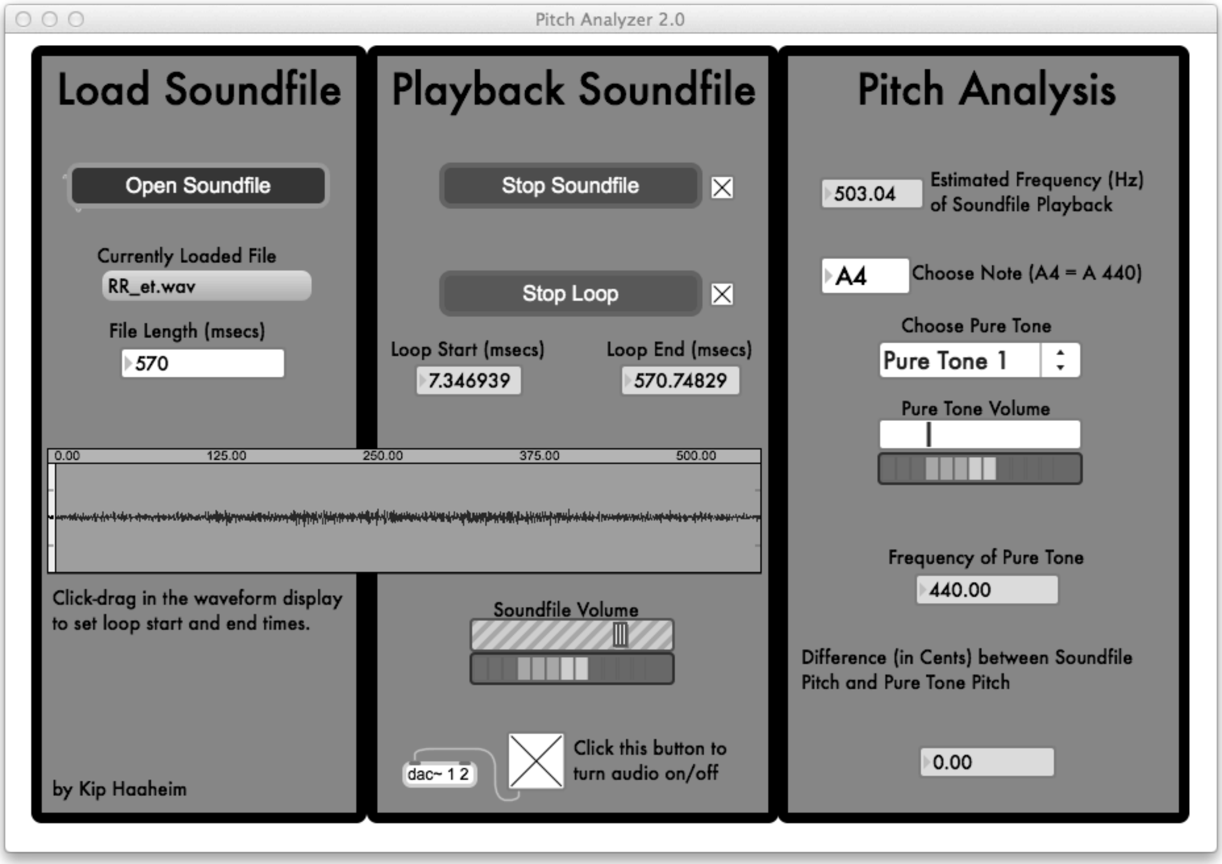
“Singers sing with more confidence when they can hear the sound of the ensemble as a whole.”

“There is a big difference in activity of sound waves that affects the way we hear each other.”

“Because of the liveliness of the [Rehearsal Room] vs. [Performance Hall].”

APPENDIX E

Pitch Analyzer 2.1 User Interface



APPENDIX F

Listener Perception Open-Ended Comments

Pair two: Performance Hall (PH) and Rehearsal Room (RR).

Comments from listeners who preferred the Performance Hall.

“Though both sound nice, the quieter one had a more artistic overall effect.”

“You could hear everything a lot better in the first one.”

“Second performance sounded slightly pressed.”

Comments from listeners who preferred the Rehearsal Room.

“First performance choir having problems of intonation; second performance – choir sounded more prepared musically and technically. Second performance recording volume louder.”

“Vowel shape was [sic.] drastically different.”

“Brighter sound. Second one tone quality sound better and blend better.”

“More musical.”

“The second was much more reverberant. The intonation in the first example was pretty sketchy.”

“First no depth to sound and seemed flat.”

“The volume for the second example gave off a ‘fuller’ sound quality. Slightly pitchy with the middle voices, but overall vocal balance seemed good.”

“Richer sound. Higher volume in second performance.”

“Much fuller sound (translate ‘louder’). They sang with a better quality which made them sound louder.”

“Second was much louder and had better blend/balance.”

“First performance a lot of individual voices within each section – the blend was not sufficient across the entire choir the balance was quite off.”

“Fuller sound the second time. Sound wrapped around listener.”

“Second performance was more in tune, as well as the rhythmic accuracy and unity throughout the whole choir.”

“There were cutoffs in both performances that didn’t line up, the second performance was better over all because they not only had a richer and fuller sound but there also weren’t as many ‘sh’ and ‘ch’ sounds. I heard a drastic change in the tone quality of the choir. The first choir was very soft, flat, and spread. Whereas the second was full and in tune [sic.].”

“1: shallow tenor, lack of balance in alto, intonation off, poor balance; 2: louder, blend across ensemble. 1: individual voices stuck out, especially in the alto section; 2: volume was louder, or was it just better projection due to unified vowels and tone?”

“The second recording seemed much fuller and louder. The first seemed to suffer in tone quality because of lack of volume/support.”

Pair three: Rehearsal Room (RR) and Performance Hall (PH).

Comments from listeners who preferred the Performance Hall.

“The quieter performance had better balance and intonation.”

“The second one seemed more in tune.”

Comments from listeners who preferred the Rehearsal Room.

“It seemed like there were more people per part in the first recording. The second seemed thinner and almost a bit lethargic.”

“First group blended better and had a better sound.”

“First one is more in tune.”

“Individuals stick out the second time.”

“First performance – energized sound; Second – sluggish, intonation problems. First performance – louder recording volume, energetic tempo and rhythms [equaling] better pitch/intonation. Inner voices at beginning of sound clip not as clear.”

“Heard the wrong pitches [sic.] more clearly in the second recording. Sounds [much] brighter.”

“Hard to choose between [elements] because the second one is not very energizing because of [tempo and tone quality].”

"Again, the intonation of the second [recording] seemed to suffer, although I prefer the clarity of the diction in the second over the first."

"The second one seemed more in tune."

"First [recording] had better blend."

"The second one sounded flat and not blended. The volume on the first felt better."

"Volume was slightly less on [second recording], but tone was [a] big deal."

"The first [recording] sounded so much more full – the second [recording] sounded like less people."

"The second group's females were off, I believe. [I] also liked the first group's sound. Slight intonation problems in second group."

"Those poor little tenors. Second [recording] sounded flat."

"First [recording] was louder and had fuller sound. Sounders sounded more timid in the second performance, as if they were holding back, which caused the balance to suffer."

"First recording was a fuller and warmer sound, recording two seemed tinny and thin."

"Second [recording] sounded less full. Resonance in the first performance, full, vibrant; second one deflated."

"First performance was supported and the blend within sections was much better."

"The first choir was fuller and more in tune, both choirs struggled with cutoffs, but the second choir sounded smaller. This time [volume] and [intonation] were tied; volume was the biggest difference but there were also areas of intonation."

"Bass – more low end in first recording."

"1: balance between all sections, sounded identical to second of second pair; 2: shallow tenor, flat pitches overall. Second recording [was] very flat."

"The second recording sounded listless and unsupported, which resulted in poor intonation and tone quality."

APPENDIX G

Human Subjects Approval Letter

KU RESEARCH & GRADUATE STUDIES
The University of Kansas

3/4/2013
HSCL #20695

Kathryn Hom
542 Frontier Rd, Apt. D415
Lawrence, KS 66049

The Human Subjects Committee Lawrence Campus (HSCL) has reviewed your research project application

20695 Hom/Daugherty (MEMT) The Effect of Two Different Rooms on Acoustical and Perceptual Measures of SATB Choir Sound

and approved this project under the expedited procedure provided in 45 CFR 46.110 (f) (6) Collection of data from voice, video, digital, or image recordings made for research purposes. As described, the project complies with all the requirements and policies established by the University for protection of human subjects in research. Unless renewed, approval lapses one year after approval date.

The Office for Human Research Protections requires that your consent form must include the note of HSCL approval and expiration date, which has been entered on the consent form sent back to you with this approval.

1. At designated intervals until the project is completed, a Project Status Report must be returned to the HSCL office.
2. Any significant change in the experimental procedure as described should be reviewed by this Committee prior to altering the project.
3. Notify HSCL about any new investigators not named in original application. Note that new investigators must take the online tutorial at https://rgs.drupal.ku.edu/human_subjects_compliance_training.
4. Any injury to a subject because of the research procedure must be reported to the Committee immediately.
5. When signed consent documents are required, the primary investigator must retain the signed consent documents for at least three years past completion of the research activity. If you use a signed consent form, provide a copy of the consent form to subjects at the time of consent.
6. If this is a funded project, keep a copy of this approval letter with your proposal/grant file.

Please inform HSCL when this project is terminated. You must also provide HSCL with an annual status report to maintain HSCL approval. Unless renewed, approval lapses one year after approval date. If your project receives funding which requests an annual update approval, you must request this from HSCL one month prior to the annual update. Thanks for your cooperation. If you have any questions, please contact me.

Sincerely,

Christopher Griffith, J.D.
Assistant Coordinator
Human Subjects Committee - Lawrence

cc:

Human Subjects Committee Lawrence
Youngberg Hall I 2385 Irving Hill Road I Lawrence, KS 66045 I (785) 864-7429 I HSCL@ku.edu I research.ku.edu