March 2020

**Acoustic Measures of the Singing Voice in Secondary School Students**

Elizabeth M. Wallace  
*Louisiana State University and Agricultural and Mechanical College*

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ACOUSTIC MEASURES OF THE SINGING VOICE
IN SECONDARY SCHOOL STUDENTS

A Dissertation
Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The School of Music

by

Elizabeth M. Wallace
A.A. & S., Southwest Virginia Community College, 2005
B.S., Old Dominion University, 2009
B.M., Old Dominion University, 2009
M.M.E., Old Dominion University, 2010
May 2020
To my husband, Wesley Wallace,

and in memory of two special music educators:

Beatrice Leist and Dr. Lee Teply.
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Abstract

Descriptions of voice quality in vocal and choral music often rely on subjective terminology, which may be perceived differently between individuals. As access to software used in acoustic measurement becomes more widespread and affordable, music educators can potentially combine traditional descriptive terminology with objective acoustic descriptors and data, which may improve both teaching and singing. The secondary school choral music educator has specific challenges, in that they teach students who experience drastic physical and acoustic changes of the voice as they grow from children to adults. The purpose of this study was to objectively analyze various acoustic characteristics of the singing voice in secondary school students. In this study, secondary school students (N = 157) from three different schools who were enrolled in choir (n = 89) or instrumental music classes (n = 68) recorded voice samples singing five vowels, /i/, /e/, /a/, /o/, and /u/. Research questions investigated (a) descriptive statistics for vibrato rate, vibrato extent, singing power ratio, and amplitude differences between specific harmonic pairs; (b) differences in vibrato rate and extent between students enrolled in choir and students not enrolled in choir; (c) between-subjects and within-subjects comparisons in singing power ratio (SPR) between singers based on choir enrollment and voice part for five different vowel productions; and (d) between-subjects and within-subjects comparisons for differences in amplitude between specific harmonics between singers based on choir enrollment and voice part for five different vowel productions. Vibrato rate (M = 4.58 Hz, SD = 1.45 Hz), vibrato extent (M = 1.45% or 25 cents, SD = 0.86% or 15 cents), and SPR (M = 24.67 dB, SD = 10 dB), and various amplitude differences were not different between students enrolled in choir and students not enrolled in choir. There were significant within-subjects differences for singers by vowel, as well as significant within-subjects interactions for vowel and voice part with SPR.
and amplitude differences between harmonic pairs. There were also significant differences between voice parts for amplitude difference between harmonic pairs. Implications for choral music educators and suggestions for further research based on these findings were discussed in Chapter 5.
Chapter 1. Introduction and Research Problem

Sound in choral singing arises from a complex combination of components, where physical, acoustic, and psychological factors may be considered in forming the characteristic sound of a choral ensemble. Each individual voice in the choral ensemble is unique and may sound different in different sets of circumstances.

Unlike in most man-made musical instruments, in which an attempt is made to preserve a distinct timbre of the instrument by simultaneously tuning multiple harmonics to resonances, the biological vocal instrument relies on highly variable vocal tract shapes to adjust the output spectrum. (Titze, Maxfield, and Walker, 2017, p. 13)

In this chapter, I will present my research problem, followed by a summary of three common methods used for describing voice quality, or timbre: (1) Descriptions of Western classical vocal tone, and “ideal” attributes of Western classical tone as defined by vocal and choral pedagogues; (2) Describing the voice using instrumental analogies; and (3) Describing the voice as a complex acoustic phenomenon. Afterward, I will explore how choral and vocal pedagogues understand and use individual vocal tone in the context of choral tone. Finally, I will present a rationale for the significance of this study.

Research Problem

In the past, choral and vocal pedagogues have used descriptive words to identify qualities of the voice. “Vocal pedagogy is loaded with personal terminology which remains unclear to most people, except, hopefully, the user him/herself… but one cannot take for granted that it means the same thing when used by others” (Sundberg, 1988, p. 11). Descriptive words lack precision and are often understood on a continuum. In addition, there is a lack of non-anecdotal evidence for defining typical voice characteristics for different age groups, different types of singers, singers in different singing contexts, and singers with different levels of voice training. Miller (1996) ascribed to the importance of embracing science and vocal acoustics in order to be
able to teach in a language that students of all learning styles can understand. In addition, a deep understanding of the anatomical, physiological, mechanical, and acoustic principles driving the voice is necessary, and that in order to be a “great teacher of singing… [one] must combine mechanistic information with psychological and aesthetic understanding” (p. 219). In this study, I will use spectrography to describe vocal timbre in an effort to define acoustic characteristics of the secondary school singing voice more objectively.

**Western Vocal Tone**

Beauty is in the “ear” of the beholder (Emmons and Chase, 2006, p. 116), and an individual’s preference for voice quality or timbre can depend on multiple factors, including one’s culture, previous experiences, and the context of the voice. While there is no universally ideal voice timbre, there are multiple practices for describing the voice qualitatively. As the researcher in this study, I acknowledge that there is no singular “ideal” or “perfect” vocal timbre, nor should there be, as preference for timbre is subject to multiple factors, not the least of which is culture and the purpose of the music. However, as much of choral music education and choral music educator training in the United States is driven by western vocal music, much of the literature cited in this study was centered around western vocal music and preferences for timbre associated with western vocal music.

While admitting [tonal] beauty is in the “ear” of the beholder, Emmons and Chase differentiated between the ideal tone in Western music as opposed to music in the Eastern hemisphere. Again, as with other choral pedagogues, their definition of beautiful tone includes a list of components. Since the terms for these components are descriptive and subjective, the authors offer contrasting attributes. This is summarized in Table 1.
Table 1. Beautiful Tone in Western Vocal Music (Emmons & Chase, 2006, p. 103).

<table>
<thead>
<tr>
<th>Qualities</th>
<th>Contrasting Qualities</th>
</tr>
</thead>
<tbody>
<tr>
<td>True, just intonation</td>
<td>Flat or sharp intonation</td>
</tr>
<tr>
<td>A “spin” of the tone (balanced vibrato)</td>
<td>Wobble, bleat, straight tone, vibrato that is too slow, vibrato that is too fast, vibrato that is too wide</td>
</tr>
<tr>
<td>Ease of emission</td>
<td>Forced or pushed tones, excessive tension</td>
</tr>
<tr>
<td>Core, focus, clarity, carrying power</td>
<td>Breathy, shallow, or unsupported delivery</td>
</tr>
<tr>
<td>A warm, full tone quality</td>
<td>Thin, shrill, or harsh tones</td>
</tr>
</tbody>
</table>

Some choral pedagogues emphasized choice in choral tone based on several components, but still provided guidelines for “good” or “ideal” tone. While Brandvik (1993) emphasized the extensive influence of several contextual determining factors on choral tone, he still identified four qualities of sound in “good singers”: (1) Freedom from tension in the larynx and articulators; (2) Resonance, focus, and ring with vocal efficiency; (3) Energy; and (4) Expression (p. 150).

Chiaroscuro is an Italian art term combining chiaro (bright, or clear) and oscuro (dark, or obscure), or referring to the distribution of both dark and light in a work of art (Random House, 2020b). Mancini was first credited with applying the term “chiaroscuro” to voice quality in 1774 (p. 95). When the same book was translated to English, his translator used “true expression” in place of “chiaroscuro.” (Mancini, 1912, p. 113). Just as Mancini used the chiaroscuro as the ideal combination of dark and light timbres, the idea of tone being a combination of dark and light qualities has been popular for centuries. Garcia (1894) described timbre as a function of the placement of the larynx and soft palate, with two opposing but supplementary qualities “clear (bright) or open, and the dark or closed” (p. 11). According to Garcia, different combinations of
dark and light timbre, combined with the physical attributes and configurations of the larynx and vocal tract, can produce an “infinite variety of shades apart from intensity. Each of these is a timbre.”

In choral pedagogy, the combination of dark and light timbres is still used as a vocal technique for choral tone and balance. Fagnan (2008) suggested that if individual choral singers used the chiaroscuro resonance strategies of balancing both light and dark timbre qualities, the resulting choral sound would be more balanced, blended, and would have more acoustic energy. In addition, Fagnan used a spectrogram of an SATB choir singing et spiritu sancto on a single pitch to demonstrate this increased acoustic energy, with brighter harmonic bands that are more consistent from vowel to vowel. According to Fagnan, chiaroscuro singing naturally adjusts the voice’s resonators to amplify only those overtones that are naturally part of the harmonic series of the vowel and note being sung thereby enabling choristers’ voices to blend together more harmoniously. If all singers are encouraged to exploit this complete, bright-warm quality, conductors will greatly increase both the quantity and quality of their ensembles’ sound without the risk of having voices ‘stick out.’ (p. 53-54)

With different vowels and different pitches, however, there is a different balance of dark and light, which can complicate the process of achieving the ideal tone throughout a singer’s registration. Zabriskie (2010) explained chiaroscuro as the combination of placement and resonance strategies in vocal technique, writing “the balanced chiaroscuro sound is achieved by working for a somewhat centered placement of the sound while maintaining proper resonant space” (p. 16). Neuen (2002) suggested the use of imagery to teach placement of the tone, imagining vocal tone as a cone shape. This “cone of tone” has a base at the forehead/face with a point radiating out, “similar in shape to that of a unicorn’s horn” (p. 35). The point of the cone is a “beautiful, resonant, ringing, and highly focused tone” (p. 35), while the base of the cone can be expanded to make the sound fuller.
Stark (1999) identified *chiaroscuro* as the “ideal voice quality” for *Bel Canto* style singing which is associated with the traditional Italian school of classical singing. A *Bel Canto* singer has learned to adjust the vocal tract and its associated resonances for a preferred blend of dark and light timbres. According to Stark, this could be accomplished:

through several means, including the age-old methods of demonstration and imitation, suggestive use of descriptive adjectives, resonance imagery, and finally formant tuning. As well, male singers, especially tenors, have learned to ‘cover’ the voice so as to extend the chest register upward beyond its normal limits. This too relies on adjustments of the vocal tract, especially the lowering of the larynx. (p. 56)

Bartle (2003) wrote about the “musical challenges” that accompany instructing a children’s chorus to sing something other than *bel canto* style for the sake of expression. “This is difficult because directors spend a great deal of time teaching children to sing with a beautiful tone. The performance of *Carmina Burana*, however, is a wonderful opportunity for children to experiment with a more raucous, raw sound” (p. 119). Bartle described four components of “exquisite tone” from the perspective of a successful children’s choir director:

1. Ringing, or resonance (carrying power): “The overtones enable even a small voice to be heard in a large hall” (p. 15).

2. Purity: “A pure tone, unencumbered by excessive vibrato or a distinctive color, has clarity and sweetness” (p. 16).

3. Brightness: “A bright tone is easy to tune and blend. It glimmers and shines. There is a hint of the ‘oo’ vowel sound in every vowel sung” (p. 16).

4. Freedom (without tension). “A free tone is completely unrestricted. It is without any form of tension. It is not driven or forced. It brings a sense of composure to the listener” (p. 16).
Vocal Timbre as Described by Orchestral Instruments

Swan (1973) described six schools of choral singing in America, including one that followed the techniques espoused by Father William J. Finn, in which “a singer’s tone is like the color of each orchestral instrument and should be developed accordingly” (p. 9). In this school of choral singing, voices can be described as four types of instruments, (1) flutes, (2) strings, (3) reeds, (4) and horns. Just as *chiaroscuro* was said to be manipulated with vowel modification (an adjustment of the vocal tract shape), Finn asserted that these instrument timbres could be achieved by rehearsing with target vowel shapes. For example, flute timbre could be approximated with /u/, string timbre with /i/, reed timbre with /a/, and horn timbre with /ɔ/. In addition to these core timbres, combinations of any two could be created by mixing two of the target vowels.

In addition to using instrumental timbres as target sounds for vocal expression, choral directors like Thurman, Hansen, and Theimer (2001) utilize these instrumental timbre analogies to inform acoustic choral formation. Molnar (1950) also suggested matching tone qualities for voice placement within the ensemble, using instrumental timbre analogies to describe characteristic tone. In a three-row ensemble the front row would be comprised of “flute-like” voices, the middle row would be equipped with “string-like” voices, and the back row would house the “reed-like” voices. Opheim (Regier, Opheim, & Wise, 1962) practiced a similar technique, placing brighter voices with “ping” in the back of the choir and darker, flutier voices in the front of the choir.

Timbre as a Complex Acoustic Phenomenon

McCoy (2019) approached timbre as an acoustic phenomenon, in terms of fundamental frequency, overtones, and amplitude, which coordinate to form the spectral envelope. Along with
this definition of timbre he illustrated that a power spectrum display (providing information on frequency and amplitude of a complex sound wave) provided information for differentiating the spectral envelope patterns of different instruments, voices, and even different vowels.

While timbre may be an acoustic phenomenon, McCoy considered that descriptive words are often used to articulate perceptions of voice quality. Therefore, he developed a method for describing voice quality, which he used to approach timbre quantitatively. In this method, McCoy used combinations of 15 paired contrasting words to describe different components of voice quality, with each descriptor pair existing on a continuum. Although his description of the diction continuum includes “good diction,” and “poor diction” (p. 9), he emphasized intelligibility in the selection of good and bad, and throughout the chapter returned to the purely descriptive nature of these pairs of terms. These 15 descriptive pairs are listed in Table 2.

Table 2. Word pairs for describing voice quality, McCoy (2019, p. 3-10).

<table>
<thead>
<tr>
<th>Bright</th>
<th>Dark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twang</td>
<td>Loft</td>
</tr>
<tr>
<td>Forward</td>
<td>Back</td>
</tr>
<tr>
<td>Lyric</td>
<td>Dramatic</td>
</tr>
<tr>
<td>Clear</td>
<td>Breathy</td>
</tr>
<tr>
<td>Clean</td>
<td>Raspy</td>
</tr>
<tr>
<td>Healthy</td>
<td>Damaged</td>
</tr>
<tr>
<td>Conversational</td>
<td>Ringing</td>
</tr>
<tr>
<td>Nasal</td>
<td>Non-Nasal</td>
</tr>
<tr>
<td>Free</td>
<td>Forced</td>
</tr>
<tr>
<td>Vibrato</td>
<td>Non-Vibrato</td>
</tr>
<tr>
<td>Wobble</td>
<td>Flutter</td>
</tr>
<tr>
<td>In Tune</td>
<td>Out of Tune</td>
</tr>
<tr>
<td>Good Diction</td>
<td>Poor Diction</td>
</tr>
<tr>
<td>Stylistically Correct</td>
<td>Stylistically Incorrect</td>
</tr>
</tbody>
</table>
While many voice pedagogues and choral pedagogues have provided a list of components of voice quality or tone, McCoy applied quantitative analysis using these 15 paired words and rating continuum simplified through a Likert-type scale of 1 to 5, with 1 being 100% the left descriptor, and 5 being 100% the right descriptor. Using this quantitative analysis to show the multivariate nature of vocal timbre, he provided collective ratings of evaluator perceptions for five operatic voices (three sopranos, a bass-baritone, and a tenor), three commercial voices (a soprano, a soprano/mezzo-soprano, and a baritone), two tenor voices with a combination of operatic and commercial experience, and a baritone beginning voice student.

Doscher (1994) also approached defining timbre from an acoustic perspective, examining the properties of tone as a complex sine wave which can be examined as fundamental frequency and its corresponding overtones, which she called partials. According to Doscher, every timbre has a characteristic sound spectrum, with 6 primary contributing factors, detailed in Table 3.

Table 3. Acoustic Factors of Timbre, Doscher (1994, p. 96-97).

<table>
<thead>
<tr>
<th>Factor</th>
<th>Description of Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of partials</td>
<td>More partials = more brilliant/rich timbre</td>
</tr>
<tr>
<td>Distribution of partials</td>
<td>“Each human voice has its own particular timbre, just as each person has a distinctive set of fingerprints” (p. 97).</td>
</tr>
<tr>
<td>Relative intensity or strength of partials</td>
<td>Some partials are boosted due to resonance and the shape of the vocal tract, while others are dampened.</td>
</tr>
<tr>
<td>Inharmonic partials (not part of the natural harmonic series)</td>
<td>Add “rough, unpleasant, or strident” qualities to the timbre.</td>
</tr>
<tr>
<td>Fundamental Tone</td>
<td>Naturally higher fundamental tones (the perceived pitch) tend to sound bright, while naturally low fundamental tones tend to sound dark.</td>
</tr>
<tr>
<td>Total Intensity</td>
<td>Greater total intensity = greater number of partials present.</td>
</tr>
</tbody>
</table>
Individual Vocal Tone in a Choral Context

Many choral directors consider timbre or acoustic characteristics of individual singers in the context of choral blend (Swan, 1973). Swan described “‘choral characteristics’ which every conductor must hear, analyze and teach,” including the tonal elements of the individual voice and the tonal elements of the chorus, as well as the individual elements are directly related to the group choral characteristics of blend, balance, intonation, diction, and rhythmic vitality. (p. 41)

According to Swan (1973), the choral element of blend related to the individual elements of “pronunciation, amplitude, color, and vibrato rate,” while the choral element of balance related to the individual elements of amplitude and range extension. (p. 41). Later, Titze (2008) described choral blend as a combination of “loudness, pitch, timbre, vowel, and vibrato,” (p. 40). Goodwin (1980) simply described choral blend as “an ensemble sound in which individual voices are not separately discernible to a listener” (p. 119).

Some choral pedagogues differentiate between individual vocal tone qualities and conglomerate choral tone qualities. Webb (1993) suggested that choral singers can be expected to produce three characteristic choral tones: (1) solo sound, characterized as “a full sound with ample vibrato;” (2) ensemble tone, which is still characterized as “full,” but with less vibrato and active vowel modification for allophonic agreement; and (3) cathedral tone, characterized as “light” and “pure,” with negligible vibrato (p. 246). Brandvik (1993) posited that there were four components that determined choral tone, each with the same three sub-categories that impacted choral tone through specific contexts and perspectives. According to Brandvik, these “determiners” are interrelated and arbitrarily ordered. These are summarized in Table 4.

Webb (1993) partially differentiated each of his three characteristic choral tones by describing the degree of vibrato used in each tone type. In addition, he identified “control of vibrato” as a
core component of “perfect blend of sound” (p. 252). Preferences for vibrato in choral tone has been a discussion of interest to many choral directors (Daffern, 2017). Johnson (1978) even labeled singers with noticeable vibratos as those with “vibrato problems” in his discussion of voice placement. Haasemann and Jordan (1991) advised that singers with large vibratos should be surrounded by “plain” voices and should never be placed on the edges of the choir, and that two different types of vibrato placed next to each other will not blend (p. 147).

Some directors prefer a “straight tone” to one with vibrato because they believe that blend is diminished by vibrato. Titze (2008) referred to vibrato as a stabilizing element in vocal tone, in addition to providing color variations within the tone, due to the nature of the human ear and how we perceive pitch; we perceive the average of the pitch within a semitone rather than the separate high and low peaks of the vibrato (Titze, 2000).

Regardless of one’s preferences for vibrato in choral tone, recent research has supported the notion that when singers are asked to produce specific types of sound, they are able to control vibrato rate (or speed) and extent (or width) to a certain degree. However, in a study on vibrato rate and extent conducted simultaneously at multiple universities, college music majors demonstrated that while singers are capable of singing at various levels of vibrato with instruction, a perceived “nonvibrato” tone is actually less stable (Nix, Perna, James, & Allen, 2016).
Table 4. Four determiners of choral tone (Brandvik, 1993, p. 148).

<table>
<thead>
<tr>
<th>Determiner</th>
<th>Subcategory 1: Individual Singers</th>
<th>Subcategory 2: Choir and Director</th>
<th>Subcategory 3: Music</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Vocal Technique</td>
<td>Vocal Health, flow of breath, resonance, freedom in the vocal mechanism, vibrato, flexibility, endurance, energy</td>
<td>Intonation, tuning, use of falsetto, breathy tone, sotto voce, weight of sound</td>
<td>Range, tessitura</td>
</tr>
<tr>
<td>2. Mental Attitude</td>
<td>Ego, nerves, tension, relaxation, self-concept, personality, imagination, desire to learn, alertness</td>
<td>Common goals, ability to concentrate, perceived importance of rehearsals, perceived importance of performance, discipline of rehearsals, ambience of rehearsals</td>
<td>Acceptance of style, willingness to rehearse and perform, confidence</td>
</tr>
<tr>
<td>3. Musical Choices</td>
<td>Knowledge of the music, knowledge of history, understanding of music as communication</td>
<td>Balance, blend, strength of overtones, sung consonants, vowel spectrum chosen, diphthongs, balance of vowels and consonants, use of sung consonants, articulation, energy and direction of phrases</td>
<td>Dynamics, tempo, harmonic pull</td>
</tr>
<tr>
<td>4. Environment</td>
<td>Age of singers, musical maturity, general health, intelligence, length of rehearsals, frequency of rehearsals, time of rehearsals, time of performance</td>
<td>Size of ensemble, singing formation of the choir, conductor’s ear, conductor’s attitude, conductor’s intelligence and imagination, acoustics of rehearsal space, acoustics of performance space, activities prior to and following rehearsal or performance</td>
<td>Style of music, difficulty of music, language, amount and rapidity of text in a piece, existence of choral-speaking, existence of humming, length of piece, texture, voicing, length of phrases</td>
</tr>
</tbody>
</table>
Study Significance

Many renowned choral and vocal experts (Swan, 1973; Titze, 2008; Webb, 1993; Brandvik, 1993) consider that individual tone characteristics as contributors to overall choral tone. Under this assumption, knowledge of typical individual tone qualities of choral singers of different ages, experience levels, and training would benefit the choral director by providing baseline information for planning appropriate instruction on vocal technique. Without an objective system for describing the voice, however, one must rely on descriptive terminology which are subjective and may be interpreted differently than intended. Common interpretations of descriptive terminology are not guaranteed. In their study of the perceptual structure of pathologic voice quality, Kreiman and Gerratt (1996) found that “differences between listeners in perceptual strategy are so great that the fundamental assumption of a common perceptual space must be questioned” (p. 1787).

Doscher (1994) and McCoy (2019) described physical acoustic correlates for several components of vocal blend, however there is little research providing information about typical vocal characteristics of singers based on age, gender, experience levels, or levels of voice training. While some choral directors may be able to describe a subset of typical choral characteristics based on decades of experience with specific groups, this knowledge is not readily accessible or quantitatively defined for the benefit of beginning choral music educators. Normative baseline data on acoustic correlates of some components of tone quality would make this data accessible and clearly defined, and provide valuable information on the vocal abilities and needs of different groups of singers that choral music educators may encounter. Miller (1996) conveyed the necessity of having clear, objective descriptors for voice quality, and the ability to differentiate between groups of singers with common characteristics, writing that “A
good teacher must be able to objectify the components of performance and convey them to the student, regardless of the student’s vocal category… Most singers [need] precise technical information that goes beyond the language of imagery” (p. 3).

In a call for more objectivity in describing tone quality, Seashore (1942) described four foundational factors involved in describing tone quality, (1) pitch; (2) intensity; (3) time; and (4) timbre; he further stated that “we may assume that since these are correlated with the characteristics of the sound wave, there can be no other factors, either artistic or erratic” (p. 127). The spectrogram is a visual display of three dimensions: frequency (Hz), amplitude (dB), and time (s), where frequency is displayed along the y-axis, time is displayed along the x-axis, and amplitude or intensity is shown through color (Miller, 2008). Sound is a broken down from a complex entity to frequencies in the spectrogram through Fourier transformation, a mathematical transformation which Titze (2000) described simply as “the process of transforming events in time to frequencies.”

The spectrogram allows for an objective measure of the difference components of vocal sound. According to McCoy (2019), they “provide information about vowel and consonant integrity, legato, timbre, onset and release of tones, and vibrato” (p. 15). Spectrography is more accessible than in the past because of VoceVista, Praat, Sing and See, and other free or low-cost software. Considering the issues presented in this chapter, it would be helpful for vocal and choral pedagogues as well as singers to have an enhanced, objective understanding of the acoustic characteristics of the singing voice in secondary school students..

In this chapter I summarized common descriptive methods of describing voice quality in western classical solo and choral singing. At the end of this chapter I have included a glossary of terms used in acoustic voice science that may be helpful in reading this study. In the next
chapter, I will describe some of the research focusing on acoustic qualities of the singing voice, with a specific focus on differences between trained and untrained singers, young singers, and differences in singing styles.

**Glossary of Acoustic Terminology**

**Acoustics.** “the branch of physics that deals with sound and sound waves” (Random House, 2020a).

**Amplitude.** In acoustics, amplitude is the magnitude, or size, of a soundwave, measured in decibels (dB). The musical correlate to amplitude is loudness.

**Balance.** In choral music, “balance refers to a musically appropriate proportion in loudness within each voice part and between each voice part” (Ternström, Jers, and Nix, 2018, p. 33).

**Bel Canto.** Singing style associated with the traditional Italian school of classical singing. A Bel Canto singer has learned to adjust the vocal tract and its associated resonances for a preferred blend of dark and light timbres (Stark, 1999).

**Blend.** In choral music, “blend is the degree to which multiple voices are perceived as a single unit/whole, rather than as individuals; this is achieved through a matching of pitch, volume, timbre, vowel, and timing” (Ternström, Jers, and Nix, 2018, p. 33).

**Chiaroscuro.** The ideal combination of dark and light timbres (Mancini, 1774, 1912). Stark (1999) identified chiaroscuro as the ideal timbre for Bel Canto style singing.

**Focus.** A descriptive word sometimes used to describe the ring of the voice, or resonance.

**Formant.** A resonant frequency of the vocal tract. (Hixon, Weismer, and Hoit, 2020).

**Frequency.** The physical correlate to musical pitch; measured by the number of times the sound sources vibrates per second, with the unit cycles per second or Hertz (Hz). “A440” vibrates or oscillates at 440 Hz (cycles per second).
Fundamental Frequency. The frequency (rate of vibration/oscillation) of the sound source (the vocal folds). Harmonics of a sustained, phonated sound are integer multiples of the fundamental frequency (Hixon, Weismer, and Hoit, 2020). For example, if a fundamental frequency (H1) is 100 Hz, the harmonic above it (H2) would be 200 Hz. Perceptually, when we identify a specific musical pitch, we identify it by the fundamental frequency.

Harmonics. Sometimes referred to as overtones or partials, harmonics are integer multiples of the fundamental frequency. Fundamental frequency is considered the first harmonic (H1), while the second harmonic is 2x the fundamental frequency. H3 (the third harmonic) is 3x the fundamental frequency, etc. (Hixon, Weismer, and Hoit, 2020). The overtone series is a set of harmonics.

Harmonic bands. In this study, harmonics and harmonics bands refer to the same thing.

Intensity. In acoustics, intensity refers to the loudness of a sound; intensity, or loudness is “related to the square of the amplitude of the wave” (Robertson, 2003, p. 95). Intensity is generally measured in watts per meter squared. (In this study, amplitude is used to refer to loudness).

Jitter. a measure of fundamental frequency disturbance, in percent of “frequency variation from cycle to cycle” (Teixeria et al., 2013, p. 1113).


Overtones. another word for harmonics.

Non-singer. Several studies compare singers with “non-singers,” which is often defined as people who have not had voice training.
Partials. another word for harmonics.

Pitch. the perceptual correlate of fundamental frequency.

Power Spectrum. A visual display of a single sound, mapping frequency and amplitude on two axes. The power spectrum allows for a snapshot of the relationship between harmonics in a musical sound.

Register/Registration. Registers in the voice are discussed in multiple ways with different descriptive terminology. (Nix, 2018), however most agree that there are two physical mechanisms that distinguish registration, “those where [thyroarytenoid (TA) muscle] activity is dominant, and those where [cricothyroid (CT) muscle] activity is dominant” (Callaghan, Emmons, and Popeil, 2018). These two muscles work together in different relative activity levels throughout the singing voice (Titze, 2000). For the purposes of this study I will talk about two registers, “chest voice” which is TA dominant and in which the “harmonics above H1 are stronger than H1” (Nix, 2018, p. 18), and head voice, which is CT dominant and in which H1 and F1 (formant 1) closely align.

Resonance. Resonance is “the intensification and enriching of a musical tone by supplementary vibration” (Merriam-Webster, n.d.). Resonance is also sometimes described as “focus” or “ring” in singing. Robertson (2003) provided a physical definition for resonance, “the phenomenon in which one object responds strongly to outside vibrations” (p. 99).

Resonant Frequencies. “The frequencies to which an object responds strongly” (Robertson, 2003, p. 99). The unique shape of an object will respond to a specific frequency (or frequencies) and amplify (or resonate) that frequency. A resonant frequency of the vocal tract is called a formant.
**Ring.** In classical western music, ring is sometimes associated with resonances of the vocal tract that line up with the Singer’s formant bandwidth, approximately 2500 – 3000 Hz. Vennard (1967) described the “ring” of the voice” as an added partial or strong overtone in the voice that gives the voices its “carrying power.” (p. 191).

**Secondary School.** Students in middle school and high school (typically grades 6-12).

**Shimmer.** a measure of fundamental frequency disturbance, in percent of amplitude variation from cycle to cycle (Teixeria et al., 2013).

**Singer’s Formant Cluster.** Sundberg (1974, 1995) defined the singer’s formant as “a high spectrum envelope peak near 3kHz typically occurring in voiced sounds produced by male singers and altos in western operatic singing,” further explaining that the singer’s formant is “a major difference between untrained voices and operatic singing voices” (1995, p. 83). Sundberg provided evidence suggesting that the singer’s formant is actually the result of a formant cluster of F3, F4, and F5 rather than a single formant as initially hypothesized.

**Singing Power Ratio (SPR).** The SPR is a measurement of amplitude differences between peak harmonics in the regions of 0-2 kHz and 2-4kHz. Omori et al. (1996) validated the Singing Power Ratio (SPR) as a new quantitative measure of voice quality in sung samples, which described “the desired richness of the singer’s voice” (p. 490).

**Source-Filter Theory.** A theory of speech production in which airflow from the vibrating vocal folds is the source of phonation, while the vocal tract filters, or modifies, the harmonic spectrum, dampening some harmonics while boosting other harmonics (Fant, 1960). Titze (2000) summarized this source-filter interaction, “whereas the glottis produces a sound of many frequencies, the vocal tract selects (filters) a subset of these frequencies for radiation from the mouth” (p. 149).
Spectral slope. Usually measured in decibels per octave (dB/octave), spectral slope is a psychoacoustic measure of timbre, or voice quality. Titze (2000) defined spectral slope as “a measure of how the amplitudes of successive components decrease with increasing harmonic number” (p. 131). Smaller spectral slopes represent spectra with more higher harmonics than larger spectral slopes, which changes the perception of the sound.

Spectrogram. The spectrogram is a visual display of three dimensions: frequency (Hz), amplitude (dB), and time (s), where frequency is displayed along the y-axis, time is displayed along the x-axis, and amplitude or intensity is shown through color (Miller, 2008). Sound is a broken down from a complex entity to frequencies in the spectrogram through Fourier transformation, a mathematical transformation which Titze (2000) described simply as “the process of transforming events in time to frequencies.”

Spectrum. See “power spectrum.” In this study, the term “spectrum” refers specifically to the power spectrum.

Vibrato extent. Width of the vibrato, measured in cents or %.

Vibrato rate. Speed of the vibrato, measured in Hertz (Hz), or cycles per second.
Chapter 2. Review of Literature

While normative data for adult solo singers is valuable information for the general knowledge base in vocal pedagogy and music education, there are special considerations for secondary school-aged students, including the acoustic changes that occur at the onset and completion of puberty, physical adjustments to these acoustic changes, and confidence issues for beginning singers which may interfere with vocal development. Titze (2000) classified four critical periods of vocal change, (1) childhood; (2) adolescence (beginning with the onset of puberty and continuing until approximately 20 years of age); (3) maturity (which is relatively stable between the age range of approximately 20 to 60 years); and (4) advanced age.

From birth to adulthood, major anatomical and physiological changes in the respiratory system (including laryngeal anatomy) as the body grows are faster and more frequent than in adulthood. Both males and females progress similarly through these changes until puberty, when males experience a much larger change in vocal tract and vocal fold size (Titze, 2000). Males and females tend to be vocally similar until puberty, with marked differences after puberty. In Welch’s (1998, 2015) research on children, singing, and vocal development, he identified four physiological phases of human voice development through childhood, (1) infancy; (2) early childhood; (3) older childhood; and (4) adolescence. In this model, older childhood and adolescence are separated by the onset of puberty, but a large variation in the age of onset of puberty makes voice analysis of these two groups difficult. “With any given age group likely to encompass several stages. It is possible for an individual to pass through all stages of adolescent voice change in twelve months, but it is also possible for this process to be much slower and to last for several years” (Welch, 2015, p. 453). Not only does puberty onset vary between individuals, pubertal voice change has been described in several substages (Cooksey, 2000;
Gackle, 2011). While changes in anatomy and physiology between older childhood and adolescence are difficult to categorize with a set age-range, the amount of singing nurturing, encouragement, or training received by the child may be related to voice quality in young singers (Welch, et al., 2011). Considering this, investigations of voice quality in young singers grouped by experience with choral groups or individual voice training in either of these two phases (ages 10-19) may provide more clear data on the secondary school aged voice.

In the past, multiple acoustic parameters have been used to quantitatively describe voice quality. A systematic literature review of acoustic analysis of singers’ voices by Gunjawate, Ravi, and Bellur (2018) found that studies approach acoustic measures of voice quality used one or more techniques like spectral analysis, analyzing singer’s formant, calculating the Singing Power Ratio (SPR), analyzing vibrato rate and extent, or calculating multiparameter measures like the Dysphonia Severity Index (DSI). Gunjawate, Ravi, and Bellur also emphasized “the lack of consensus for standard regulations regarding technical specifications of instrumentation and data acquisition procedures” (p. 49). In the last few years, a panel of experts from the American Speech-Language-Hearing Association developed recommended protocols for acoustic voice analysis of the speaking voice (Patel et al., 2018), but presently no recommendations have been made specifically for acoustic analysis of the singing voice.

In this chapter, I will describe some of the research focusing on acoustic qualities of the singing voice, with a specific focus on differences between trained and untrained singers, young singers, and differences in singing styles. These studies were organized by acoustic parameter: (1) vibrato rate and extent, (2) timbre and harmonic relationships, (3) the singer’s formant, and (4) the Singing Power Ratio.
Vibrato Rate and Extent

Acknowledging that most research on vibrato rate and extent has been focused on the professional singer, Amir, Michaeli, and Amir (2006) investigated the relationship between acoustic properties and perceptual evaluation of the vibrato of singing students. A key rationale for this research was the assumption of steady vibrato (periodicity in pitch contour) that can be made with the professional singer cannot be assumed in the investigation of the vibrato of a non-professional singer or a student singer. In this study, each of the singing students (ages $M = 18.62$ years, S.D. 3.2 years) had some previous training ($M = 5.4$ years, S.D. 2.9 years), however the sample size was relatively small ($n = 20$), and all participants were female. The researchers concluded that there was a high level of agreement on the perception of the existence of vibrato and the acoustic measurement of the presence of vibrato, but there was only a moderate correlation between perception of vibrato quality and the acoustic correlates; in addition, there was only moderate interrater reliability in this measure.

Nix, Perna, James, and Allen (2016) also investigated the vibrato quality (rate and extent) of undergraduate singing students ($n = 75$, median age = 22 years, median training = 6 years). In this repeated measures study, the researchers compared vibrato rate and extent for each participant using three modes of voice production, which they labeled habitual, best classical, and nonvibrato productions. In addition to three modes of voice production, vibrato rate and extent were measured using each of five vowels. The researchers found that there were no significant differences in vibrato rate and extent between vowels, but that there were significant differences in vibrato rate and extent between modes of production, suggesting “that vibrato is primarily a result of neuromuscular and biomechanical factors” (p. 37) since singers were able to consciously change their vibrato quality between modes of production. There were no
differences between male and female singers’ vibrato extent (with the exception of extent in the nonvibrato productions of /i/ and /u/, which could be indicative of perturbation rather than vibrato), but there were significant differences in vibrato rate between males and females in the best classical mode of production, with males producing a slightly slower vibrato rate (4.85-4.98 Hz) than females (5.15-5.31 Hz). In addition to these findings, the researchers suggested further research on the relationship between choral ensemble participation and vibrato quality.

Kuhlewind (2014) also investigated the vibrato rates and extents of undergraduate singers, but with a focus on differences in the singer’s preferred style. In this study of six singers, the three classical singers had significantly higher vibrato rates and vibrato extents than the three jazz singers, suggesting that there is a difference in vibrato preferences among singing styles and possibly in training for those singing styles.

The amount of voice training a singer has completed may also have an impact on singing voice quality. In a perceptual and acoustic study, Brown, Rothman, and Sapienza (2000) found that listeners were able to tell whether a recorded sung excerpt was sung by a trained singer or an untrained singer with 87%. Furthermore, acoustic analysis of the samples used in the study revealed that the two most distinguishing differences between trained and untrained singers in the recorded samples were the presence of vibrato, and the presence of the singer’s formant cluster when singing.

**Timbre and Harmonic Relationships**

Spectral slope, usually measured in decibels per octave (dB/octave), is a psychoacoustic measure of timbre, or voice quality. Titze (2000) defined spectral slope as “a measure of how the amplitudes of successive components decrease with increasing harmonic number” (p. 131).
Smaller spectral slopes represent spectra with more higher harmonics than larger spectral slopes, which changes the perception of the sound.

McCoy (2019) estimated the glottal spectral slope of a “healthy, well-trained singer” to be approximately 12 dB/octave, saying that “at this rate, harmonics lose a little more than half their subjective loudness for each octave higher they rise above the fundamental” (p. 43). Titze (2000) correlated a “brassy” sound with approximately 6 dB/octave, a “normal” voice with 12 dB/octave, and a “fluty” or “breathy” voice with approximately 18 dB/octave. Miller (2008) characterized the spectral slopes of head register and belting as being relatively steep and relatively shallow, respectively.

Fant’s (1960) source-filter theory of speech production helped explain why the direct measurement of spectral slope is not possible for the human voice. In this theory, airflow from the vibrating vocal folds is the source of phonation, while the vocal tract filters, or modifies, the harmonic spectrum, dampening some harmonics while boosting other harmonics. Titze (2000) summarized this source-filter interaction, “whereas the glottis produces a sound of many frequencies, the vocal tract selects (filters) a subset of these frequencies for radiation from the mouth” (p. 149). The selected frequencies that are magnified in this filtering processes are called formants, or resonances of the vocal tract. The spectral envelope of the live human voice includes the effects of these filtered harmonics and formants.

According to the source-filter theory, vowel sounds are distinguished by two parameters of tongue placement, (1) tongue height; and (2) tongue advancement. Figure 1 depicts the general physical placement all five of the vowels used in this study with respect to tongue advancement and tongue placement. This figure shows that the vowel sequence /i/ → /e/ → /a/ → /o/ → /u/ advanced from most anterior (front) tongue advancement to most posterior (back).
tongue advancement. Both /i/ and /u/ are high vowels (the tongue is lifted higher toward the roof of the mouth), but they differ in tongue advancement; the arch of the tongue is more anteriorly placed in /i/ (a front vowel) than in /u/ (a back vowel).

![Vowel Quadrilateral Chart](image)

Figure 1. Vowel Quadrilateral Chart for /i/, /e/, /a/, /o/, and /u/ (Mr KEBAB [username], 2017).

Researchers have investigated different harmonic relationships in an effort to approximate spectral slope from spectrum analysis. Alipour, Scherer and Finnegan (2012) investigated spectral slope and harmonic relationships using a canine excised larynx model. Their investigations supported the idea that sound pressure level and subglottal pressure are positively correlated, generally throughout all harmonics. However, when considering differences between the first two harmonics (H1 and H2), spectral differences were highly variable, and “may be an inconsistent measure of glottal source” (p. 9).

Considering the variability of differences between the first two harmonics, Garellek, Samlan, Gerratt, and Kreiman (2007) created a model using differences in amplitude between four harmonic pairs (H2-H1, H4-H2, 2kHz-H4, and 5kHz-2kHz), which they found represented four “non-redundant acoustic and perceptual aspects of voice quality” (p. 1404). When “overall spectral roll-off” (calculated using the difference in amplitude between 5kHz and H1) was considered as a covariate, as much as 87% of the variance in relationships between the four
variables were explained (p. 1406). The researchers concluded that these parameters may be able to be used to create an objective model for voice quality.

Singing style can affect timbre, even in adolescent singers, as demonstrated by Barlow and LoVetri (2010). Barlow and LoVetri conducted one of the only published investigations into the acoustics of the adolescent singing voice using spectral analysis, comparing closed quotient, long-term average spectrum (LTAS) curves, and spectral slope for two different singing styles produced by twenty young singers training at a choral academy. They identified a statistically significant difference for each of these three measures when comparing voice production in classical style and musical theater style for these singers, suggesting that adolescent singers with training are capable of adjusting their singing style using resonance strategies. While the sample in this study only considered students with voice training at the same institute, they suggested further research considering age, gender, and level of training.

As the vocal tract shape and size are adjustable to a certain extent by moving the articulators (the tongue, lips, jaw, etc.), vocal timbre may also be adjustable with these movements and changes, with changes in the spectral envelope due to different formant frequencies. Titze, Maxfield, and Walker (2017) studied the formant range profile (FRP) of singers by plotting the first two formants (F1 and F2) of four vowels produced in each of three mouth shapes. These researchers found that an individual may be able to adjust the area of the vowel quadrangle (a plot of F1-F2 placement) by as much as a factor of 2, although they did suggest further research. Titze (2016) wrote that the FRP could be used to predict individual timbre and to provide information on vowel modification depending on singer style.

In Resonance in Singing, Miller (2008) discussed differences in the characteristic tones or timbres of two famous tenors as a difference in resonance strategies, in which the singer aligned
the formant patterns of the vowels being sung with specific harmonics of the fundamental frequency. The relationship between formants and harmonics has been called resonance balance, which Schutte and Miller (1984) claimed was an essential element of timbre, “regardless of vowel, frequency, or sound intensity” (p. 289).

**The Singer’s Formant**

A singer’s vocal production in solo singing often differs from the same singer’s production in choral singing as the members of the ensemble work to blend their tones (Ekholm, 2000; Goodwin, 1980; Rossing, Sundberg, & Ternström, 1986, 1987). The use of higher formant frequencies to aid intonation in the choral ensemble has also been studied (Ternström & Sundberg, 1989). In western classical solo singing, “vocal ring,” or the “singer’s formant cluster” is a desirable effect of the vocal sound, aiding in projection and allowing the solo singer to sing over an orchestra. Vennard (1967) called this the “‘ring’ of the voice,” which he described as an added partial or strong overtone in the voice that gives the voices its “carrying power.” (p. 191).

In simple, numerical terms, the singer’s formant cluster is a “clustering of higher formant frequencies to raise the spectral content in the 3000 Hz region,” (Titze, 2001, p. 525) although the exact region of the cluster can be higher or lower by a few hundred Hz, depending on the size of the epilarynx tube. Based on his earlier research, Sundberg (1974, 1995) defined the singer’s formant as “a high spectrum envelope peak near 3kHz typically occurring in voiced sounds produced by male singers and altos in western operatic singing,” further explaining that the singer’s formant is “a major difference between untrained voices and operatic singing voices” (1995, p. 83). Sundberg provided evidence suggesting that the singer’s formant is actually the result of a formant cluster of F3, F4, and F5 rather than a single formant as initially hypothesized. Interestingly, the singers’ formant is not present in the high and mid frequency
singing of the soprano voice, as confirmed by Weiss, Brown, and Morris (2001), possibly because the higher pitches already have strong harmonic bands near these frequencies due to higher fundamental frequencies.

Singing style impacts the spectral distribution, including the presence of the singer’s formant. The presence of the singer’s formant is a preferred quality in Western classical and operatic singing because the resonance in the singer’s formant bandwidth allows the voice to be heard over an orchestra (Titze, 2000, p. 265) but the singer’s formant is not necessarily a preferred characteristic in all styles of singing.

Cleveland, Sundberg, and Stone (2001) found that the LTAS distribution of samples sung by trained country singers was more similar to that of speech than classical singing, in that the sung excerpts did not show the presence of a boost in energy at the range of the singer’s formant. Instead, this singing style is more characterized by a gradually decreasing spectral shape, with a slight peak in the singer’s formant range that is also present in the speaking voice sample, suggesting the possibility of a “speaker’s formant” (p. 59) in a healthy, resonant speaking voice which is more subdued than the singer’s formant, but in a similar bandwidth.

As the region of the singer’s formant is largely dependent on the anatomy of the individual singer, Titze (2008) warned that vocal ring within the vocal ensemble might create an unpleasant sound in the choral ensemble. This unpleasant sound is “because the central frequency of the ring is specific to an individual and does not change much with pitch, multiple strong ringing frequencies in an ensemble can compete and create a dissonance in an overall sound” (p. 40). Goodwin (1980) found fewer high formant frequencies in recorded choral blend. Ford (2003) found that the majority of a sample of graduate voice students preferred choral singing samples without a resonant singer’s formant, which he called “non-resonant choral tone”
(p. 29). However, Quist (2008) found that several world-class choirs display a high level of energy in the singer’s formant cluster region, and suggested that it is possible to utilize the singer’s formant cluster to increase the vibrancy, unification, and intonation of choral sound.

**The Singing Power Ratio (SPR)**

In 1996, Omori et al. validated the Singing Power Ratio (SPR) as a new quantitative measure of voice quality in sung samples, which described “the desired richness of the singer’s voice” (p. 490). The SPR is a measurement of amplitude differences between peak harmonics in the regions of 0-2 kHz and 2-4kHz. While many researchers have measured the presence or absence of the singer’s formant, the singer’s formant is less reliable as an acoustic measure for females (specifically sopranos) than males, and the presence of the singer’s formant is also dependent on singing style or genre. In contrast, the singer’s formant considers peak harmonic frequencies in two ranges, the first of which (0-2 kHz) encompasses most fundamental frequencies and lower harmonics, while the second (2-4 kHz) encompasses higher harmonics including the singer’s formant that may indicate a ring in the voice. Omori et al found that there were significant differences in SPR when comparing singers with 4 or more years of training with singers who had less than 4 years of training.

Usha, Geetha, and Darshan (2017) used SPR to differentiate between trained and untrained prepubertal female singers using Matlab and norms developed manually by the researchers. They found that they were able to predict whether a singer was trained using the software with 86% accuracy, further confirming that SPR is an effective predictor of voice training, and adding that SPR may be used as an objective measure of voice quality with young singers. The researchers suggested further investigation into using SPR as a predictor of untrained but talented singers.
Watts et al. (2006) investigated SPR in untrained singers in an attempt to determine whether judgements of talent corresponded SPR. They found that singers with more energy in the 2-4 kHz bandwidth (and thus a smaller SPR and theoretically lower spectral slope) were also independently adjudicated as perceptually more talented. While this study involved a small sample size ($n = 39$, with 33 subjects included in the final analysis), and adjudicators were both voice faculty in the university setting (which may cause a possible bias for preference in timbres), the correlation between low SPR and judgements of talent may be worth investigating further.

Omori et al also found that SPR differentiated between the sung and spoken samples of trained singers, but Lundy et al. (2000) found no differences between the sung and spoken samples of undergraduate singing students. Like Omori et al, Pillot-Loiseau and Vaissière (2007) found that SPR varied with vocal task, using samples from connected speech, and from multiple singing tasks. Just as SPR was independent of singing style or genre, Pillot-Loiseau and Vaissière found that SPR values also were consistent regardless of language. Cesari, Iengo, and Apisa (2012) took multiple physical and acoustic measurements of the singing voice in 48 professional opera singers. In their study, they considered jitter, shimmer, singing formant (specifically, between 2.5 and 3.2 kHz) and SPR as acoustic measures of voice quality, and found that SPR was most correlated with years of singing experience, being highly positively correlated ($r = 0.84$). In addition, SPR was so highly correlated ($r = 0.95$) with subjective assessment of the singing voice by a phoniatrician that they recommended SPR could be used as the “electroacoustic equivalent of the subjective judgment of vocal focus” (p. 304). Another potentially valuable result of the study was that the researchers concluded that SPR may also be consistent for singers even among different singing styles, being as it could be used as a
voice quality measure “for those singing categories not requiring a formant concentration in a
defined area of the vocal spectrum” such as the singer’s formant. (p. 308).

**Acoustics and the Choral Music Educator**

Choral acoustics are of interest to the choral director in that a change in acoustics of the
choir as a whole may positively or negatively impact a singer’s sound. Experienced choral
directors often devise methods of placing singers in the most acoustically optimal arrangement
for their choirs. Multiple acoustic factors impacting choral sound have also been identified,
including the “Lombard Effect” (Tonkinson, 1994), a singer’s “Self-to-Other Ratio” (Ternström
1995, 1999; Ternström, Cabrera, & Davis, 2005), choral spacing (Daugherty, 1999, 2003b, 2005,
2013; Barrett, 2003), venue acoustics (Hom, 2013; Daugherty, 2005), and choral formation or
placement (Giardiniere, 1992; Tocheff, 1990; Killian & Basinger, 2007; Noble & Shrock, 1991,
Ekholm, 2000).

While venue acoustics are not necessarily easily manipulated, other acoustic
considerations are within the scope of the choral director’s control. When singers sing with
others, they experience decreased auditory feedback of their own voices, and so choral singers
tend to sing louder with other as opposed to by themselves in an effort to hear their own voice.
This is described as the Lombard Effect (Tonkinson, 1994). Through his research, Tonkinson
suggested that singers could learn to resist the Lombard Effect once they were made aware of the
phenomenon. In a similar thread of research, Ternström (1995, 1999) researched the “Self-to-
Other Ratio,” or SOR, as having an impact on individual voices, recommending optimal SOR for
different circumstances. In general, Ternström and Karna (2002) recommended a fairly spread
placement of voices in a choir, with singers being able to hear their own voices more strongly
than other voices, by approximately 6 dB. Research on choral spacing related to chorister and auditor preferences has supported preferences for a spread placement of voices in the choir (Daugherty, 2003b, 2005, 2013; Adams, 2019). Choral spacing and choral formation may help address issues and solutions related to the Lombard effect or SOR.

Researchers in choral and vocal acoustics have provided evidence for a characteristically different sound production between the same singers in “solo mode” compared with “choral mode” (Eckholm, 2000; Goodwin, 1980; Rossing, Sundberg, & Ternström, 1986, 1987; Nix, Perna, James, & Allen, 2016). This difference has contributed to what Daugherty (2003a) called “a historied debate among choir directors and voice teachers about desirable choral tone quality” (p. 1), prompting research such as Ford’s (2003) investigation into preferences for Singer’s Formant in choral singing, Ternström and Sundberg’s (1989) investigation into higher frequencies in choral sound, and Ternström’s (1993) investigation into pitch scatter and formant scatter from differences in voice types in choir singing.

According to Ternström (1993), a larger spread of formant frequencies in the higher formants (F3 – F5) due to differences in voice part (or vocal tract length) contributes to a larger difference in perceptual quality. Later, Ternström (2003) wrote that “it seems clear that the tasks of solo singers (to be clearly heard) and choir singers (to contribute but blend) are acoustically quite different modes of voice production” (p. 8). Rossing et al. (1987) also found acoustic differences between in the higher frequency region of 2 to 4 kHz when examining choral singers in solo mode versus choral mode. Vibrato characteristics also differ between solo and choral singing mode; Mann (2014) found significant differences in vibrato extent, rate, and duration between solo and choral singing modes in female undergraduate singers. Coleman (1994) found significant differences in dynamic range between trained and untrained singers within the same
choral group, suggesting that solo training may impact choral singers in choral mode as well as in solo mode. Therefore, differences in vibrato characteristics, acoustic energy, harmonic spread and spectral slope between voice parts and between trained and untrained singers may be important for choral music educators to understand, particularly in the higher frequency ranges, such as those between 2 and 5 kHz or 2 and 4 kHz.

Research Purpose

The purpose of this study was to objectively analyze various acoustic characteristics of the singing voice in secondary school students.

Research Questions

1. What are the descriptive statistics (mean, standard deviation, minimum, and maximum values) for the singing voice in secondary school students using the following acoustic characteristics:
   a. Vibrato Rate.
   b. Vibrato Extent.
   c. Singing Power Ratio.
   d. Differences between selected harmonics.

2. Are there differences in vibrato rate or in vibrato extent between students who participate in choir and students who do not participate in choir?

3. Is there a difference in Singing Power Ratio (SPR) within subjects based on vowel, or between groups of secondary school singers:
   a. Enrolled in choir and not enrolled in choir?
   b. With solo voice training and without solo voice training?
   c. Of different voice parts?
4. In a repeated measures analysis of variance, are there within subjects (using each of the five vowels) or between subjects (by choir enrollment and/or by voice part) differences in the harmonic differences variables used to approximate spectral slope?
Chapter 3. Materials and Methods

In the past, choral directors and singers have relied on descriptive terminology to describe the voice. Now, free or low-cost software is available to objectively determine some of these voice characteristics, which may assist the beginning choral directors and singing teachers in determining strategies that are most relevant and beneficial to their students. The purpose of this study was to objectively analyze various acoustic characteristics of the singing voice in secondary school students, providing exploratory data for normative values and comparisons of these characteristics based on age group, gender, voice training, and choral experience.

In Chapter 2, I described research focusing on the acoustic qualities of the singing voice, with a specific focus on differences between trained and untrained singers, young singers, and differences in singing styles. These studies were organized by four acoustic parameters: (1) vibrato rate and extent; (2) timbre and harmonic relationships; (3) the singer’s formant; and (4) the Singing Power Ratio. In this chapter I outlined the methods and materials for this study, including instrument development, pilot testing, independent and dependent variables, sampling, data collection and planned data analysis.

Instrument Development

I developed a questionnaire to gather information used in grouping variables, defined parameters for acoustic data analysis, developed and pilot tested a recording procedure.

Survey Development. During survey development, I considered grouping variables for the analysis of variance of acoustic parameters, which would be determined based on answers to the survey such as number of years with private voice training, or number of years of instrumental or choral music training. Question wording, order, and clarity were refined after consultation with a content validity panel of music educators. This panel consisted of three practicing music
educators: one high school choir teacher, one high school band director, and one K-12 music teacher with a background in choral music education. Each of these experts was asked to provide commentary on the understandability of the questions, question wording, and the relevance of demographic information collected. They were encouraged to provide suggestions for relevant demographic data, and for making the survey easier and/or more efficient to complete. Several questions in the survey were originally worded with yes/no answers, however these questions were changed to multiple choice questions in an effort to reduce the number of questionnaire items. Questions indicating self-awareness of vibrato characteristics and questions regarding standing preference in choral ensembles were also included, as these questions were relevant to an earlier design of the study which were eliminated prior to data collection. However, these questions were not used in data analysis.

Demographic information collected in the questionnaire included name, age, grade, choir, voice part, and number of years choir experience. Information about preferences while singing in a choir will include the types of singers a student prefers to stand by while singing: louder, softer, those with vibrato or no vibrato, those that sound like the student, singers in the same or different sections, and whether the student prefers to stand close to or farther away from another singer. Information about how a student characterizes his or her own voice will include whether the student believes he or she is louder or softer, has a wide or narrow vibrato, has a fast or slow vibrato, or whether the student feels he or she has no audible vibrato. The last portion of the questionnaire addressed whether the student consciously alters his/her voice production while singing with others, asking if he/she sings louder beside a loud singer, and if he/she tries to match the voice quality of the singers they stand beside. The full questionnaire given to participants can be found in Appendix C.
Recording Procedure Pilot Testing. I pilot tested procedures for acoustic data collection using participants from a local high school choral program. During pilot testing, I recorded students from a local high school choir ($n = 20$). These students were different than the students used in the study. Students were asked to sing an excerpt from a choral piece they were working on in class, followed by the five vowel syllables, /mi/, /me/, /ma/, /mo/, /mu/. After recording, students were asked to provide feedback on their experience with recording, including what helped them feel comfortable in recording, what made them uncomfortable or nervous, and suggestions for making the recording process more natural in the future.

During pilot testing, many students were nervous at the beginning of recording, but after singing a few measures they were more comfortable. As a result of this observed behavior during pilot testing and in an effort to reduce threats to validity due to nerves, I changed recording procedures, deciding to have students sing the five-vowel portion at both the beginning and end of the recording sample, with a buffer song between these vocalises. I decided to take measurements from the vocalise at the end, after students were more comfortable with the recording procedure, and I changed the buffer song to “Happy Birthday,” as many students were also nervous about singing their part in a choral excerpt isolated from the other parts of the choir. Titze (1994) recommended “Happy Birthday” as a familiar song for standardized procedures in acoustic voice analysis. I also decided to incorporate written instructions for the student to follow along with the verbal instructions given during the recording process, including musical notation for the five-vowel step at the beginning and end of sample recording. The addition of musical notation was meant to provide a visual cue for singing each vowel for a longer period of time so that a valid measurement of vibrato rate and extent could be extracted.
I developed separate questions to collect information for grouping variables and covariates in analysis of variance of the collected acoustic characteristics. The target information from the survey design were summarized in Table 5.

**Table 5: Independent (Grouping) Variables**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Variable Unit</th>
<th>Category Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choral Voice Part</td>
<td>Category</td>
<td>Soprano</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alto</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tenor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I’m not sure</td>
</tr>
<tr>
<td>Choral Participation</td>
<td>Category</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Previous but not currently</td>
</tr>
<tr>
<td>Private Voice Study Participation</td>
<td>Category</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Previous but not currently</td>
</tr>
<tr>
<td>Age</td>
<td>Years</td>
<td></td>
</tr>
<tr>
<td>Choral Experience</td>
<td>Years</td>
<td></td>
</tr>
<tr>
<td>Private Voice Study Experience</td>
<td>Years</td>
<td></td>
</tr>
</tbody>
</table>

Prior to data collection, I selected acoustic parameters for analysis and comparison between groups. These parameters are each measurable with spectrography, and align with at least one of three dimensions of characteristic tone quality in the voice: (1) intensity, (2) timbre, and (3) vibrato. Vibrato was measured in two components, vibrato extent (or width) in Hz, and vibrato rate (or speed), in percent. I measured the relative amplitude of 7 specific harmonics to find quantitative approximations of intensity and timbre: harmonic 1 (H1), harmonic 2 (H2), harmonic 4 (H4), the loudest harmonic between 0-2kHz (H0-2kHz), the loudest harmonic
between 2-4 kHz (H2-4kHz), the harmonic closest to 2kHz (H2kHz), and the harmonic closest to 5kHz (H5kHz). From these 7 harmonics I calculated amplitude differences between six pairs of harmonics, the first of which represented the Singing Power Ratio, while the next five were used to represent spectral slope approximations. The amplitude differences from the six pairs of harmonics were summarized in Table 6.

Table 6. Amplitude differences between harmonic pairs

<table>
<thead>
<tr>
<th>Measure</th>
<th>Abbreviation</th>
<th>Description of Differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singing Power Ratio (SPR)</td>
<td>H2-4kHz – H0-2kHz</td>
<td>Amplitude of Harmonic Peak between 0 – 2 kHz subtracted from amplitude of harmonic peak between 2 – 4 kHz</td>
</tr>
<tr>
<td>5 Spectral Slope Approximations:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>First Octave Difference</td>
<td>H2 – H1</td>
<td>Amplitude of H1 (fundamental frequency) subtracted from amplitude of H2</td>
</tr>
<tr>
<td>Second Octave Difference</td>
<td>H4 – H2</td>
<td>Amplitude of H2 subtracted from amplitude of H4</td>
</tr>
<tr>
<td>Third Difference</td>
<td>H2kHz – H4</td>
<td>Amplitude of H4 subtracted from amplitude of harmonic closest to 2 kHz.</td>
</tr>
<tr>
<td>Fourth Difference</td>
<td>H5kHz – H2kHz</td>
<td>Amplitude of harmonic closest to 2 kHz subtracted from amplitude of harmonic closest to 5 kHz</td>
</tr>
<tr>
<td>Overall Spectral Roll-off</td>
<td>H5kHz – H1</td>
<td>Amplitude of H1 subtracted from amplitude of harmonic closest to 5 kHz</td>
</tr>
</tbody>
</table>

The six harmonic differences were collected for each of the five vowels [mi], [me], [ma], [mo], and [mu] for a total of 30 spectral measurements per sample; vibrato rate and extent were collected once for each participant, as no significant differences in vibrato rate or extent have been found between vowels (Nix, Perna, James, and Allen, 2016). All of the dependent variables were summarized in Table 7.
Table 7. Dependent Variables: Acoustic measurements

<table>
<thead>
<tr>
<th>Measure</th>
<th>Unit</th>
<th>Description</th>
<th>Instances measured</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3 Vibrato Calculations:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibrato Rate</td>
<td>Hz</td>
<td>Vibrato speed</td>
<td>Once</td>
</tr>
<tr>
<td>Vibrato Extent</td>
<td>%</td>
<td>Vibrato width</td>
<td>Once</td>
</tr>
<tr>
<td>Vibrato Extent</td>
<td>Cents</td>
<td>Vibrato width</td>
<td>Once</td>
</tr>
<tr>
<td>Singing Power Ratio (SPR)</td>
<td>dB</td>
<td>H2-4kHz – H0-2kHz</td>
<td>[i], [e], [a], [o], [u]</td>
</tr>
<tr>
<td><strong>5 Amplitude Differences:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First Octave Difference</td>
<td>dB</td>
<td>H2 – H1</td>
<td>[i], [e], [a], [o], [u]</td>
</tr>
<tr>
<td>Second Octave Difference</td>
<td>dB</td>
<td>H4 – H2</td>
<td>[i], [e], [a], [o], [u]</td>
</tr>
<tr>
<td>Third Difference</td>
<td>dB</td>
<td>H2kHz – H4</td>
<td>[i], [e], [a], [o], [u]</td>
</tr>
<tr>
<td>Fourth Difference</td>
<td>dB</td>
<td>H5kHz – H2kHz</td>
<td>[i], [e], [a], [o], [u]</td>
</tr>
<tr>
<td>Overall Spectral Roll-off</td>
<td>dB</td>
<td>H5kHz – H1</td>
<td>[i], [e], [a], [o], [u]</td>
</tr>
</tbody>
</table>

**Singing Power Ratio.** Omori et al (1996) validated the Singing Power Ratio (SPR) as a quantitative measure of voice quality in sung samples, which described “the desired richness of the singer’s voice” (p. 490). The SPR is a measurement of amplitude differences between peak harmonics in the regions of 0-2 kHz and 2-4kHz, and is more resistant to changes in singing style and voice type than evaluating the presence of the singer’s formant.

**Amplitude Differences Between Harmonic Pairs.** The spectral slope is defined as the rate of systematic decrease of amplitude as harmonic frequencies increase (Titze, 2000). The spectral slope is typically a measure of timbre from the glottal source, however since all sound is filtered through the vocal tract, a direct, *in vivo* measurement of the spectral slope is not possible. (Hixon, Weismer, and Hoit, 2020). Because a direct measurement of spectral slope is not possible, and I did not have access to inverse filtering procedures commonly used to calculate...
spectral slope, I used the differences in amplitude for five pairs of harmonics to approximate the spectral slope at those five bandwidths. Garellek, Samlan, Gerratt, and Kreiman (2007) validated these measurements as an objective representation of voice quality.

**Vibrato Rate and Extent.** Titze (2000) described vocal vibrato as a pattern created from the “fluctuation in fundamental frequency and amplitude” (p. 312), with acceptable rates, or speeds, of 4.5 to 6.5 Hz, and acceptable extents, or widths, of 0 to ±3 percent, which is approximately 0 to ±50 cents. Because vibrato analysis is not yet available on VoceVista Video Pro, I will use an older version of VoceVista to analyze vibrato using the same audio file, collecting information on vibrato rate (Hz) and vibrato extent (cents). An example of vibrato analysis using VoceVista can be found in Appendix C, in which approximately 1 second of the voice was analyzed for vibrato at the fifth harmonic. This specific example showed a vibrato rate, or speed, of 4.6 Hz, or 4.6 cycles per second, and a vibrato extent, or width, of 3.1 percent, or 55 cents.

**Sampling**

Participants (N = 157, ages 10-19) in this study were taken from a convenience sample of three school music programs from two states in the Southeastern United States. Each of the three schools provided some diversity to the sample regarding socioeconomic status and choral music opportunities for students. A summary of school information was provided in Table 8, followed by brief descriptions of each school’s music program.
Table 8. Demographic Information for Schools Sampled

<table>
<thead>
<tr>
<th></th>
<th>School 1</th>
<th>School 2</th>
<th>School 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approximate School Enrollment</td>
<td>2,391</td>
<td>2,542</td>
<td>200</td>
</tr>
<tr>
<td>Approximate Town Population</td>
<td>26,500</td>
<td>24,300</td>
<td>7,100</td>
</tr>
<tr>
<td>Public or Private?</td>
<td>Public</td>
<td>Public</td>
<td>Private</td>
</tr>
<tr>
<td>Grades Enrolled</td>
<td>9-12</td>
<td>9-12</td>
<td>7-12</td>
</tr>
<tr>
<td>Choir class available for all grades?</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Non-auditioned Choir Available?</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Free and Reduced Lunch Percentage</td>
<td>31.12%</td>
<td>74.9%</td>
<td>Data Unavailable</td>
</tr>
</tbody>
</table>

**School 1.** All of the participating students from this school were members of the school’s auditioned treble chamber ensemble. This school was located in a suburban community with a high school enrollment of 2,391 students, 31.12% of which were “economically disadvantaged,” as determined by the Louisiana Department of Education (2019). Choral music offerings at the school included a beginning treble choir, an advanced treble choir, and an advanced SATB choir; the choral program also includes a smaller extracurricular SATB choir with a focus on popular repertoire.

**School 2.** Participants from the second school were students attending a large public high school with Title I funding in addition to a separate international baccalaureate curriculum. 2,542 students were enrolled at this school, located in suburban community; 74.9% of those students were eligible for free and reduced lunch in 2019-2020 (Florida Department of Education, 2020). Multiple music classes were available to students, including non-auditioned and auditioned choirs, guitar classes, piano classes, orchestra classes, and band/wind-ensemble classes.

Participants from this school were sampled from the choir, orchestra, and band classes.
School 3. Participants from the third school were students in grades 7 through 12. This private, Pre-K-12 parochial school was located in a suburban community (population \(\approx 7,100\)) with approximately 200 students enrolled in grades 7 through 12. Elementary students in the school were offered weekly music classes as part of a core curriculum, and students in grades 7 and 8 elect to take choir classes. Students in grade 11 are offered choir as an elective choice, but those in grades 9, 10, and 12 were only offered choir as part of an extracurricular program with the purpose of providing choral music for religious ceremonies at the school.

Data Collection

There were two phases to data collection, (1) a demographic survey, collecting information for grouping variables, and (2) acoustic data collection, comprised of a recorded audio sample for each participant. All of the data collected was stored on the researcher’s MacBook Air, which is an early 2015 model (2.2 GHz Intel Core i7, 8GB, 1600 MHz DDR3, Intel HD Graphics 6000 1536 MB). All of the software being used for data collection was also be installed on this MacBook, including PC software, which was accessed on the MacBook through a virtual PC desktop.

Demographic Survey. Prior to individual voice recording, each participant completed a consent form (Appendix B) and a demographic questionnaire (Appendix C). To avoid excluding students based on special needs for accommodations, as well as to include students without a device with internet access, the survey was offered online as well as on paper. Most participants completed the survey online using Google Forms.

Reliability and Validity. I recorded each participant with a Blue Snowball USB microphone interfacing with VoceVista Video Pro for Mac. I controlled for distance from the microphone using a string of yarn, with one end tied to the base of the microphone, and the other was loose. I
instructed participants to hold the tip of the string at their chin while recording. This ensured that participants maintained approximately the same distance from the microphone during recording, and also reduced variation in microphone distance between participants.

Depending on the school’s procedures and contingencies for permission to record students, some students were able to record in a room separate from other students, while others recorded in the same room with a small group of other students, taking turns to record individually.

The ambient noise in the rooms chosen for recording between schools varied. I attempted to decrease the effects of ambient noise using the cardioid microphone setting (setting 2), with a -10 dB “pad,” which “reduces mic sensitivity so loud instruments or vocalists come in crystal clear and distortion free. In addition, the Blue Snowball records using a “frequency response polar pattern,” which is dependent on orientation to and distance from the microphone, and dampens very high and very low frequencies that are not possible with the human voice but are common in ambient noise (Blue Microphones, 2018).

**Acoustic Data Collection.** During final acoustic data collection, I recorded each participant singing five vowels, [mi], [me], [ma], [mo], and [mu], then singing “Happy Birthday,” then singing five vowels again, [mi], [me], [ma], [mo], and [mu]. I included “Happy Birthday” as a buffer song so that students would have time to become more familiar and comfortable with the recording process; data was collected from the last set of five vowels. In order to characterize voices according to the specific acoustic qualities, I asked each student to sing individually, recording and analyzing their singing with VoceVista Video Pro. Participants were instructed to sing in their best voice production style. The sequence of events in this procedure is detailed in Appendix A. As formant frequencies change according to vocal tract shape (Titze, 2000), I asked
each student to sing five syllables with five different vowels: [mi], [me], [ma], [mo], and [mu]. During data collection, each participant sang three selections: (1) five syllables, [mi], [me], [ma], [mo], and [mu]; (2) the “Happy Birthday” song in F major; and (3) five syllables, [mi], [me], [ma], [mo], and [mu].

Participants were given reference pitches appropriate to their section in choir. For the five vowels (singing selections 1 and 3 for each student) students were instructed to sing on either an F3, C4 (middle C), F4, or C5 for basses, tenors, altos, and sopranos, respectively. These pitches were chosen to align with a previous study dealing with acoustic properties of the singing voice conducted by Nix, Perna, James, and Allen (2016). “Happy Birthday” was sung in F major, since both F and C are primary pitches in this key, on the first and fifth scale degrees. In addition, the wide range of pitches in Happy Birthday stayed within a tessitura that was mostly comfortable for singers of all voice parts.

Students were given verbal instructions which aligned with the written instructions provided in Appendix A. There were four variations of the instructions, with differences only in the voice part label, and the pitch notated on the music staff, which aligned with the pitches chosen for the vowels. Participants were allowed to ask questions at any point in the instruction reading process, and were given the opportunity to practice the vocalise in small groups or individually if they chose to do so. Prior to data collection I made the decision to allow participants to record again if they were unhappy with their initial recording, placing a recording limit of 3 times before excluding data from that participant. No participant asked to record their voice sample more than two times.

**Data isolation.** Following data collection, I isolated a pitch-stable audio sample (approximately 300 ms) from each vowel in the final set of vowels for each participant, generating a long-term
average spectrum (LTAS) to use for analysis. Spectral Analysis was completed in VoceVista Video Pro for Mac. For spectral analysis, the software generated a list of up to 20 harmonic peaks above -60 dB for each vowel for the selected LTAS. For the harmonics not included in this list, I isolate that peak in the LTAS output to record for data analysis. Harmonic peaks (amplitudes for the selected harmonics) were recorded for VoceVista Video Pro did not have a current option for vibrato analysis, so a previous version of Voce Vista was used to analyze the sample audio sample for vibrato extent and rate.

**Data Analysis**

The purpose of this study was to objectively analyze various acoustic characteristics of the singing voice in secondary school students. Data analysis was planned to address each research question, using descriptive statistics and comparisons of means through multivariate analysis of variance. All of the dependent variables used were summarized in Table 7 above.

**Research Question 1.** What are the descriptive statistics for the singing voice in secondary school students using the following acoustic characteristics: (a) vibrato rate, (b) vibrato extent, (c) singing power ratio, and (d) differences between selected harmonics?

This question asked the descriptive statistics for vibrato rate, vibrato extent, singing power ratio (SPR), and amplitude differences between selected harmonics, (described in Table 6). Descriptive statistics calculated included mean, standard deviation, minimum and maximum, as well as lower and upper bounds of a 95% confidence interval.

**Research Question 2.** Are there differences in vibrato rate or in vibrato extent between students who participate in choir and students who do not participate in choir?
I used a multivariate analysis of variance (MANOVA) to answer this research question. The independent, or grouping, variable was choir enrollment. The dependent variables were vibrato rate (Hz) and vibrato extent (in both cents and %).

**Research Question 3.** Is there a difference in Singing Power Ratio (SPR) within subjects based on vowel, or between groups of secondary school singers: (a) enrolled in choir and not enrolled in choir; (b) with solo voice training and without solo voice training; or (c) of different voice parts?

I used a repeated measures MANOVA to answer this research question. Independent (grouping) variables were choir enrollment and voice part. Voice training was a planned independent variable but was not used because very few participants had taken voice lessons. Dependent variables were SPR measurements (the amplitude of the harmonic peak between 0 – 2 kHz subtracted from amplitude of the harmonic peak between 2 – 4 kHz) from each of the five vowels.

**Research Question 4.** In a repeated measures analysis of variance, are there within subjects (using each of the five vowels) or between subjects (by choir enrollment and/or by voice part) differences in the harmonic differences variables used to approximate spectral slope?

I also used a repeated measures MANOVA to answer this research question. Independent (grouping) variables were choir enrollment and voice part. Dependent variables were amplitude differences between specific harmonic pairs, described in Table 6 above.
Chapter 4. Results

In this study, I collected audio samples of a sampling of school musicians, surveyed the same students on their demographics and experiences with choir and private voice training, used spectrographic analysis to identify specific voice qualities in each of the audio samples, and used statistical analysis to identify and compare voice parameters for different groups of students. In Chapter 3, I outlined the methods and materials for this study, including sampling, instrument development, pilot testing, independent and dependent variables, data collection and planned data analysis. I ended with the following research purpose and four research questions. In this chapter, I will provide demographic information for the participants of the study. Then I will report the results of each of the four research questions. In the fifth chapter, I will discuss these results, their implications for choral music education, and suggest further research based on these findings.

Research Purpose

The purpose of this study was to objectively analyze various acoustic characteristics of the singing voice in secondary school students.

Research Questions

1. What are the descriptive statistics (mean, standard deviation, minimum, and maximum values) for the singing voice in secondary school students using the following acoustic characteristics:
   a. Vibrato Rate.
   b. Vibrato Extent.
   c. Singing Power Ratio.
   d. Differences between selected harmonics.
2. Are there differences in vibrato rate or in vibrato extent between students who participate in choir and students who do not participate in choir?

3. Is there a difference in Singing Power Ratio (SPR) within subjects based on vowel, or between groups of secondary school singers:
   a. Enrolled in choir and not enrolled in choir?
   b. With solo voice training and without solo voice training?
   c. Of different voice parts?

4. In a repeated measures analysis of variance, are there within subjects (using each of the five vowels) or between subjects (by choir enrollment and/or by voice part) differences in the variables used to approximate spectral slope?

Study Sample

Students \( (N = 157) \) from three secondary schools in two southern states participated in this study. Both females \( (n = 98) \) and males \( (n = 59) \) participated. Students’ ages ranged from 10 years to 19 years, with a mean age of 15.18 years \( (SD = 2.18 \text{ years}) \). Student demographics separated by school were presented in Table 9.

<table>
<thead>
<tr>
<th></th>
<th>School 1</th>
<th>School 2</th>
<th>School 3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Females</td>
<td>11</td>
<td>59</td>
<td>28</td>
<td>98</td>
</tr>
<tr>
<td>Males</td>
<td>0</td>
<td>38</td>
<td>21</td>
<td>59</td>
</tr>
<tr>
<td>Soprano</td>
<td>3</td>
<td>22</td>
<td>14</td>
<td>39</td>
</tr>
<tr>
<td>Alto</td>
<td>8</td>
<td>38</td>
<td>22</td>
<td>68</td>
</tr>
<tr>
<td>Tenor</td>
<td>0</td>
<td>7</td>
<td>6</td>
<td>13</td>
</tr>
<tr>
<td>Bass</td>
<td>0</td>
<td>30</td>
<td>7</td>
<td>37</td>
</tr>
<tr>
<td>Ages 10-13</td>
<td>0</td>
<td>1</td>
<td>29</td>
<td>30</td>
</tr>
<tr>
<td>Ages 14-16</td>
<td>7</td>
<td>59</td>
<td>13</td>
<td>79</td>
</tr>
<tr>
<td>Ages 16-19</td>
<td>4</td>
<td>37</td>
<td>7</td>
<td>48</td>
</tr>
<tr>
<td>Mean Age</td>
<td>16.27</td>
<td>16.10</td>
<td>13.12</td>
<td>15.18</td>
</tr>
<tr>
<td>Age SD</td>
<td>0.65</td>
<td>1.30</td>
<td>2.38</td>
<td>2.18</td>
</tr>
<tr>
<td>Enrolled in Choir</td>
<td>11</td>
<td>40</td>
<td>17</td>
<td>89</td>
</tr>
<tr>
<td>Not Enrolled in Choir</td>
<td>0</td>
<td>57</td>
<td>32</td>
<td>68</td>
</tr>
<tr>
<td>Total Students</td>
<td>11</td>
<td>97</td>
<td>49</td>
<td>157</td>
</tr>
</tbody>
</table>
Of the 157 study participants, 93 presented with vibrato that was able to be analyzed using VoceVista version 3.3. Vibrato analysis using this software was limited to samples that were consistent in mean pitch and in SPL curve periodicity. Several samples did not meet these consistency requirements criteria \((n = 64)\), which excluded nearly a third of the samples from comparison using vibrato. Recordings that did meet these criteria \((n = 93)\) were used in the analysis for research question 2, and for the descriptive statistics involving vibrato in research question 1.

One participant did not sing the last vowel, /u/, so 156 recordings were used in the analysis for research questions 3 and 4 as well as for the descriptive statistics not involving vibrato in research question 1. The number of participants in each of the data analysis sets were presented in Table 10. Only five participants indicated that they were currently taking voice lessons, although 9 others indicated that they had taken voice lessons in the past. Of those fourteen participants, only 3 of those participants had taken lessons for 4 or more years. Considering this information, an accurate comparison of students with solo voice training and students without solo voice training would not be possible, therefore this independent variable was not included in data analysis.

Table 10. Number of participants in each data set for analysis

<table>
<thead>
<tr>
<th></th>
<th>Vibrato Analysis (RQ2)</th>
<th>SPR, Amplitude Differences (RQ 3, 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enrolled in Choir</td>
<td>40</td>
<td>68</td>
</tr>
<tr>
<td>Not Enrolled in Choir</td>
<td>53</td>
<td>88</td>
</tr>
<tr>
<td>Soprano</td>
<td></td>
<td>39</td>
</tr>
<tr>
<td>Alto</td>
<td></td>
<td>68</td>
</tr>
<tr>
<td>Tenor</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>Bass</td>
<td></td>
<td>36</td>
</tr>
<tr>
<td>Total</td>
<td>93</td>
<td>156</td>
</tr>
</tbody>
</table>
Research Question 1. Descriptive Statistics

The first research question of this study was “What are the descriptive statistics for secondary school singers’ vibrato rate, vibrato extent, singing power ratio, and differences between selected harmonics?” Descriptive statistics were summarized below in Tables 11 and 12. I presented descriptive statistics for vibrato rate, vibrato extent, and singing power ratio part in Table 11, and descriptive statistics for amplitude differences between specific harmonics, organized by voice part in Table 12.

Table 11. Descriptive Statistics: Vibrato and SPR.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>N</th>
<th>Mean</th>
<th>SD</th>
<th>Std. Error</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibrato Rate (Hz)</td>
<td>93</td>
<td>4.58</td>
<td>1.45</td>
<td>0.15</td>
<td>4.28</td>
<td>4.88</td>
<td>1.2</td>
<td>7.9</td>
</tr>
<tr>
<td>Vibrato Extent (Cents)</td>
<td>93</td>
<td>25.07</td>
<td>14.75</td>
<td>1.53</td>
<td>22.03</td>
<td>28.10</td>
<td>7.0</td>
<td>102.0</td>
</tr>
<tr>
<td>Vibrato Extent (%)</td>
<td>93</td>
<td>1.45</td>
<td>0.86</td>
<td>0.09</td>
<td>1.27</td>
<td>1.62</td>
<td>0.4</td>
<td>5.9</td>
</tr>
<tr>
<td>SPR /i/ (dB)</td>
<td>156</td>
<td>18.66</td>
<td>10.59</td>
<td>0.85</td>
<td>16.99</td>
<td>20.34</td>
<td>-2.9</td>
<td>56.3</td>
</tr>
<tr>
<td>SPR /e/ (dB)</td>
<td>156</td>
<td>17.07</td>
<td>10.05</td>
<td>0.81</td>
<td>15.48</td>
<td>18.66</td>
<td>1.1</td>
<td>44.2</td>
</tr>
<tr>
<td>SPR /a/ (dB)</td>
<td>156</td>
<td>24.67</td>
<td>10.00</td>
<td>0.80</td>
<td>23.08</td>
<td>26.25</td>
<td>6.6</td>
<td>53.0</td>
</tr>
<tr>
<td>SPR /o/ (dB)</td>
<td>156</td>
<td>30.97</td>
<td>11.04</td>
<td>0.88</td>
<td>29.23</td>
<td>32.72</td>
<td>8.8</td>
<td>61.3</td>
</tr>
<tr>
<td>SPR /u/ (dB)</td>
<td>156</td>
<td>34.89</td>
<td>13.14</td>
<td>10.05</td>
<td>32.82</td>
<td>36.97</td>
<td>-4</td>
<td>61.9</td>
</tr>
</tbody>
</table>
Table 12. Descriptive Statistics: Harmonic Differences by Voice Part

<table>
<thead>
<tr>
<th>Measure</th>
<th>N</th>
<th>Mean</th>
<th>SD</th>
<th>Std. Error</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2 – H1</td>
<td>Soprano 39</td>
<td>-4.34</td>
<td>6.47</td>
<td>1.04</td>
<td>-5.48</td>
<td>-1.38</td>
<td>-29.5</td>
<td>38.4</td>
</tr>
<tr>
<td></td>
<td>Alto 68</td>
<td>-4.29</td>
<td>6.65</td>
<td>0.81</td>
<td>-5.89</td>
<td>-2.70</td>
<td>-37.2</td>
<td>25.9</td>
</tr>
<tr>
<td></td>
<td>Tenor 13</td>
<td>-2.06</td>
<td>6.65</td>
<td>1.84</td>
<td>-1.58</td>
<td>5.70</td>
<td>-14.2</td>
<td>34.4</td>
</tr>
<tr>
<td></td>
<td>Bass 36</td>
<td>-4.21</td>
<td>6.48</td>
<td>1.08</td>
<td>2.08</td>
<td>6.35</td>
<td>-33.3</td>
<td>20.7</td>
</tr>
<tr>
<td>H4 – H2</td>
<td>Soprano 39</td>
<td>-26.05</td>
<td>8.88</td>
<td>1.42</td>
<td>-28.86</td>
<td>-23.24</td>
<td>-66.0</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>Alto 68</td>
<td>-19.38</td>
<td>9.13</td>
<td>1.11</td>
<td>-21.56</td>
<td>-17.19</td>
<td>-53.6</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td>Tenor 13</td>
<td>-12.29</td>
<td>9.12</td>
<td>2.53</td>
<td>-17.29</td>
<td>-7.29</td>
<td>-44.8</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td>Bass 36</td>
<td>-11.36</td>
<td>8.89</td>
<td>1.48</td>
<td>-14.28</td>
<td>-8.42</td>
<td>-69.8</td>
<td>24.7</td>
</tr>
<tr>
<td>H5k – H2k</td>
<td>Soprano 39</td>
<td>-23.34</td>
<td>8.64</td>
<td>1.38</td>
<td>-20.15</td>
<td>-20.60</td>
<td>-62.2</td>
<td>17.7</td>
</tr>
<tr>
<td></td>
<td>Alto 68</td>
<td>-17.32</td>
<td>8.88</td>
<td>1.08</td>
<td>-19.45</td>
<td>-15.19</td>
<td>-59.7</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>Tenor 13</td>
<td>-19.50</td>
<td>8.87</td>
<td>2.46</td>
<td>-24.36</td>
<td>-14.64</td>
<td>-49.5</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td>Bass 36</td>
<td>-17.30</td>
<td>8.65</td>
<td>1.44</td>
<td>-20.15</td>
<td>-14.45</td>
<td>-53.0</td>
<td>20.2</td>
</tr>
<tr>
<td>Overall</td>
<td>Soprano 39</td>
<td>-54.15</td>
<td>9.04</td>
<td>1.45</td>
<td>-57.01</td>
<td>-51.29</td>
<td>-89.6</td>
<td>-11.4</td>
</tr>
<tr>
<td></td>
<td>Alto 68</td>
<td>-49.47</td>
<td>9.28</td>
<td>1.13</td>
<td>-51.69</td>
<td>-47.24</td>
<td>-73.1</td>
<td>-15</td>
</tr>
<tr>
<td></td>
<td>Tenor 13</td>
<td>-45.13</td>
<td>9.29</td>
<td>2.57</td>
<td>-50.22</td>
<td>-40.05</td>
<td>-72.2</td>
<td>-15.5</td>
</tr>
<tr>
<td></td>
<td>Bass 36</td>
<td>-43.30</td>
<td>9.03</td>
<td>1.51</td>
<td>-46.28</td>
<td>-40.32</td>
<td>-97.5</td>
<td>-4.8</td>
</tr>
</tbody>
</table>
Research Question 2. Vibrato Analysis

Research Question 2 was “Are there differences in vibrato rate or in vibrato extent between students with choral music experience and students without choral music experience?” To answer this question, I compared vibrato rate (Hz) and vibrato extent (in both cents and %) for two groups of students, those enrolled in choir (n = 40) and those who were not enrolled in choir (n = 53). Descriptive statistics for vibrato analysis were presented in Table 13.

Table 13. Descriptive Statistics: Vibrato

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>SD</th>
<th>Std. Error</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibrato Rate (Hz)</td>
<td>Not in Choir</td>
<td>53</td>
<td>4.83</td>
<td>1.23</td>
<td>0.17</td>
<td>4.49</td>
<td>5.17</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>In Choir</td>
<td>40</td>
<td>4.25</td>
<td>1.65</td>
<td>0.26</td>
<td>3.72</td>
<td>4.77</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>93</td>
<td>4.577</td>
<td>1.45</td>
<td>0.15</td>
<td>4.28</td>
<td>4.88</td>
<td>1.2</td>
</tr>
<tr>
<td>Vibrato Extent (Cents)</td>
<td>Not in Choir</td>
<td>53</td>
<td>25.51</td>
<td>12.36</td>
<td>1.70</td>
<td>22.10</td>
<td>28.92</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>In Choir</td>
<td>40</td>
<td>24.48</td>
<td>17.56</td>
<td>2.78</td>
<td>18.86</td>
<td>30.09</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>93</td>
<td>25.07</td>
<td>14.75</td>
<td>1.53</td>
<td>22.03</td>
<td>28.10</td>
<td>7.0</td>
</tr>
<tr>
<td>Vibrato Extent (%)</td>
<td>Not in Choir</td>
<td>53</td>
<td>1.47</td>
<td>0.72</td>
<td>0.10</td>
<td>1.27</td>
<td>1.67</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>In Choir</td>
<td>40</td>
<td>1.41</td>
<td>1.02</td>
<td>0.16</td>
<td>1.09</td>
<td>1.74</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>93</td>
<td>1.45</td>
<td>0.86</td>
<td>0.09</td>
<td>1.27</td>
<td>1.62</td>
<td>0.4</td>
</tr>
</tbody>
</table>

To compare participants enrolled in choir (n = 40) with participants not enrolled in choir (n = 53), I performed an analysis of variance (ANOVA) using SPSS statistics software, with Vibrato Rate and Vibrato Extent as Dependent variables, and Choir Enrollment as the independent (grouping) variable. ANOVA results were presented in Table 14.
Table 14. ANOVA: Vibrato Analysis by Choir Enrollment Group (Enrolled or Not Enrolled)

<table>
<thead>
<tr>
<th></th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibrato Rate (Hz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>7.756</td>
<td>1</td>
<td>7.756</td>
<td>3.82</td>
<td>0.054</td>
</tr>
<tr>
<td>Within Groups</td>
<td>184.807</td>
<td>91</td>
<td>2.031</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>192.563</td>
<td>92</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibrato Extent (Cents)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>24.393</td>
<td>1</td>
<td>24.393</td>
<td>0.11</td>
<td>0.740</td>
</tr>
<tr>
<td>Within Groups</td>
<td>19979.220</td>
<td>91</td>
<td>219.552</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>20003.613</td>
<td>92</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibrato Extent (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Groups</td>
<td>0.075</td>
<td>1</td>
<td>0.075</td>
<td>0.10</td>
<td>0.751</td>
</tr>
<tr>
<td>Within Groups</td>
<td>67.255</td>
<td>91</td>
<td>0.739</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>67.330</td>
<td>92</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Research Question 3. Singing Power Ratio

I used a repeated-measures multivariate analysis of variance (MANOVA) to answer this research question, which involved comparison between groups of students, as well as comparisons of repeated measurements from the same student (within subjects), and any interactions grouping variables may have had with these repeated measurements. In Research Question 3 I investigated differences in Singing Power Ratio (SPR) between groups of singers, looking at three different independent (grouping) variables, (1) choir enrollment; (2) solo voice training; and (3) voice part. Of the 157 participants, only five indicated that they were currently taking voice lessons, although 9 others indicated that they took voice lessons in the past. Of those fourteen participants, only 3 of those participants had taken lessons for 4 or more years. Considering this information, an accurate comparison of students with solo voice training and students without solo voice training would not be possible, therefore this grouping variable was not included in analysis. Dependent variables were SPR measurements (the amplitude of the harmonic peak between 0 – 2 kHz subtracted from amplitude of the harmonic peak between 2 – 4 kHz) from each of the five vowels.
**Between Subjects Effects.** The estimated grand mean SPR was 25.253 dB (SD = 7.59 dB).

There were no significant differences between students enrolled in choir (n = 68) and students not enrolled in choir (n = 88). I also found no significant differences between students singing different voice parts, soprano (n = 39), alto (n = 68), tenor (n = 13), or bass (n = 36). In addition, there were no significant interactions between choir enrollment and voice parts. The full statistical results for between-subjects analysis were presented in Table 15.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
<th>Partial Eta Squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choir Enrollment</td>
<td>0.051</td>
<td>1</td>
<td>0.051</td>
<td>0.0</td>
<td>0.987</td>
<td>0.000</td>
</tr>
<tr>
<td>Voice Part</td>
<td>1335</td>
<td>3</td>
<td>445</td>
<td>2.26</td>
<td>0.083</td>
<td>0.044</td>
</tr>
<tr>
<td>Choir Enrollment x Voice Part</td>
<td>1367</td>
<td>3</td>
<td>456</td>
<td>2.32</td>
<td>0.078</td>
<td>0.045</td>
</tr>
</tbody>
</table>

**Within-Subjects Effects.** Each participant recorded sung excerpts of five isolated vowels, /i/, /e/, /a/, /o/, and /u/, and I calculated SPR for each of these vowels for each participant. Research Question 3 asked if there were within subjects differences in SPR between vowels. I used a multivariate repeated measured analysis of variance to investigate these differences, the results of which were presented in Table 16. Mauchly’s test of sphericity for differences between vowels was significant ($\chi^2 = 30.93, p < 0.001$), so sphericity could not be assumed, therefore I used the Greenhouse-Geisser correction in this calculation, which is robust to violations of sphericity in within-subjects tests (Tabachnick and Fidell, 2013). Using this correction, I found that SPR measurements were significantly different between vowels for individual participants ($F = 115.44, p < 0.001$), and there was also a significant interaction between vowel differences and voice part ($F = 4.14, p < 0.001$). There were not significant interactions between vowel and
choir enrollment, or between vowel, choir enrollment, and voice part. Complete within-subjects test results were presented in Table 16.

Table 16. Tests of Within-Subjects Effects: Singing Power Ratio (dB)

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
<th>Partial Eta Squared</th>
<th>Observed Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vowel</td>
<td>25163</td>
<td>3.59</td>
<td>7005</td>
<td>115.44</td>
<td>0.000</td>
<td>0.438</td>
<td>1.000</td>
</tr>
<tr>
<td>Vowel x Choir Enrollment</td>
<td>292</td>
<td>3.59</td>
<td>81</td>
<td>1.34</td>
<td>0.256</td>
<td>0.009</td>
<td>0.395</td>
</tr>
<tr>
<td>Vowel x Voice Part</td>
<td>2709</td>
<td>10.78</td>
<td>251</td>
<td>4.14</td>
<td>0.000</td>
<td>0.077</td>
<td>0.999</td>
</tr>
<tr>
<td>Vowel x Choir Enrollment x Voice Part</td>
<td>567</td>
<td>10.78</td>
<td>53</td>
<td>0.87</td>
<td>0.571</td>
<td>0.017</td>
<td>0.484</td>
</tr>
</tbody>
</table>

When comparing SPR by vowel production, SPR was lower for the vowels /i/ and /e/, with respective means of 18.67 dB ($SD = 10.59$ dB) and 17.07 dB ($SD = 10.05$ dB). The mean SPR for /a/ was 24.67 ($SD = 10.00$), closest to the grand mean SPR of 25.253 dB ($SD = 7.59$ dB). SPR was generally higher for /o/ and /u/, with respective means 30.97 dB ($SD = 11.04$ dB) and 34.89 dB ($SD = 13.14$ dB). These means also varied significantly between voice part, as presented in Table 17.
<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
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**Research Question 4. Amplitude Differences Analysis**

Research Question 4 was “In a repeated-measures analysis of variance, are there within-subjects (using each of the five vowels) or between-subjects (by choir enrollment and/or by voice part) differences in the variables used to approximate spectral slope?” For this research question, I used a repeated-measures multivariate analysis of variance of data from 156 recordings of each
of the five vowels to investigate this research question, with four harmonic amplitude differences as dependent variables, (1) the difference between H2 and H1, (2) the difference between H4 and H2, (3), the difference between the harmonic closest to 5,000 Hz (H5k) and the harmonic closest to 2,000 Hz (H2k); and (4) the overall spectral drop-off, calculated as the difference between the harmonic closest to 5,000 Hz and H1. Garellek, Samlan, Gerratt, and Kreiman (2007) also validated the difference between the harmonic closest to 2,000 and H4 as an objective measure of voice quality, however since Sopranos sang C5 in data collection for this study, H4 and the harmonic closest to 2,000 were the same harmonic. Considering this, I decided not to use the difference between H4 and the harmonic closest to 2,000 in statistical analysis.

**Between Subjects Effects.** In the repeated-measures MANOVA ($N = 156$) between-subjects comparisons, there were significant differences between voice part for all four harmonic differences; H2 – H1, H4 – H2, and Overall drop-off were all significant with $p < 0.001$, while H5k – H2k was significant with $p = 0.004$. There were no significant differences between students enrolled in choir and students not enrolled in choir, and there was also not a significant interaction between voice part and choir enrollment. I presented results for each of these comparisons in Table 18.

Scheffe post-hoc analysis grouped most measures in two homogenous subsets by voice parts for most measures, as summarized in Table 19. As group sizes were unequal, these subsets were calculated using the harmonic mean sample size of $n = 27.58$, although all four voice parts were calculated to be a homogenous subset for the difference at H5k – H2k.

**Within-Subjects Effects.** I also considered within-subjects effects for this data set ($N = 156$), for each of the five vowels. All main effects and interactions (vowel, vowel x choir enrollment, vowel x voice part, and vowel x voice part x choir enrollment) were statistically significant ($p <
0.001) in multivariate analysis, so I continued with a univariate analysis. Sphericity could not be assumed for based on Mauchly’s test of sphericity for three of the four measures across the five vowels, so I used the Geissner-Greenhouse correction for within-subjects comparisons.

Table 18. Between-subjects effects: Amplitude differences between selected harmonic pairs (dB)

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<td>Mean Square</td>
<td>F</td>
<td>Sig.</td>
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<td>604</td>
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<td>165</td>
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<td>418</td>
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<td>272</td>
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<td>0.416</td>
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<td>3</td>
<td>3287</td>
<td>15.72</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>H4 - H2</td>
<td>22881</td>
<td>3</td>
<td>7627</td>
<td>19.37</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>H5k - H2k</td>
<td>5101</td>
<td>3</td>
<td>1700</td>
<td>4.56</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>Overall Drop-off</td>
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<td>3</td>
<td>3994</td>
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<tr>
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<td>125</td>
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<tr>
<td></td>
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<td>773</td>
<td>1.96</td>
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<tr>
<td></td>
<td>H5k - H2k</td>
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<td>307</td>
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<tr>
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<td>Overall Drop-off</td>
<td>771</td>
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<td>257</td>
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Table 19. Scheffe post-hoc homogenous subsets for between-subjects effects

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<th>Subset 2</th>
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<td>Mean Diff. (dB)</td>
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<tr>
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<td></td>
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<tr>
<td>H2 – H1</td>
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<td>Alto</td>
<td>68</td>
<td>-4.33</td>
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<tr>
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<td>Soprano</td>
<td>39</td>
<td>-26.14</td>
</tr>
<tr>
<td></td>
<td>Alto</td>
<td>68</td>
<td>-19.50</td>
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<tr>
<td>H5k – H2k</td>
<td>Soprano</td>
<td>39</td>
<td>-23.39</td>
</tr>
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Results of the Within-Subjects univariate analysis were presented in Table 20, while descriptive statistics organized by vowel and by voice part were presented in Table 21. Based on these results, there were significant differences between vowels for each of the four harmonic differences \((p < 0.001)\), while there were significant interactions between vowel and choir enrollment in the higher harmonic differences, between \(H4 - H2\) \((p = 0.027)\) and \(H5k - H2k\) \((p < 0.001)\) but not for differences in the first octave \((H2 - H1)\) or in overall spectral drop-off. There were also significant interactions between vowel and voice part in the three harmonic differences of smaller bandwidths, \(H2 - H1\) \((p < 0.001)\), \(H4 - H2\) \((p < 0.001)\), and \(H5k - H2k\) \((p = 0.023)\), but not in overall spectral drop-off. There were significant interactions between vowel, choir enrollment, and voice part for \(H4 - H2\) \((p < 0.001)\), and in overall spectral drop-off \((p = 0.015)\), but not in \(H2 - H1\) or in \(H5k - H2k\).

Table 20. Within-Subjects Effects: Harmonic Differences

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<th>Sig.</th>
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Chapter 5. Discussion and Implications

In the last chapter I presented the results of this study, answering four research questions focused on

(1) descriptive statistics for vibrato rate, vibrato extent, SPR, and amplitude differences between pairs of harmonic frequencies.

(2) whether there were differences in vibrato rate or vibrato extent between students who were enrolled in choir and students who were not.

(3) whether there were differences (between or within subjects) in Singing Power Ratio (SPR) based on vowel, choir enrollment and voice part.

(4) whether there were differences in amplitude among four pairs of harmonic frequency values based on choir enrollment or voice part, and for individual singers between vowels.

In this chapter, I will briefly summarize the main results from Chapter 4. I will then discuss the meaning of these results, focusing on the statistically significant findings for SPR values and the amplitude differences between harmonics. Finally, I will share some ways in which these results may influence or inform choral music education praxis, followed by suggestions for future research.

Vibrato Rate and Extent

There were no significant differences in vibrato between students in choir and students not in choir. The mean values for vibrato rate ($M = 4.58$ Hz, $SD = 1.45$ Hz) and vibrato extent ($M = 1.45\%$ or 25 cents, $SD = 0.86\%$ or 15 cents) were within the acceptable ranges for singers as described by Titze (2000). As the bottom boundary of vibrato rate described by Titze was 4.5 Hz, approximately the same as the mean in this study, investigation into the vibrato rate as it
correlates with vibrato extent may be warranted. For instance, if vibrato extent is significantly slower and narrower in choral singing than in solo singing, as described by Mann (2014), it may be possible that vibrato rates lower than 4.5 Hz be acceptable in a choral singing context.

**Singing Power Ratio**

I compared SPR for a group of students enrolled in choir and a group of students not enrolled in choir, finding no significant differences between singers in choir and singers not in choir. There were also no significant differences between singers of different voice parts, nor was there a significant interaction between choir enrollment and voice part. In this statistical comparison, enrolling and participating in choir classes suggested choral voice training, but not necessarily solo voice training; in reality, most of the students had little to no solo voice training. Only three participants had participated in solo voice training for 4 or more years. Previous studies have indicated that SPR is a reliable indicator of voice training (Omori et al., 1996; Usha, Geetha, and Darshan, 2017; Pillot-Loiseau and Vassiere, 2007), however, training criteria always included solo voice training, even when that training was in styles different than western classical solo voice training. In addition, Roessing et al. (1987) found that choral singers produced less acoustic energy in the 2 – 4 kHz range than solo singers, which may also have impacted the suitability of SPR as a measure of training or voice quality in choral singers.

The mean SPR (25.243 dB) aligns with SPR means for untrained singers in previous studies. Omori et al. (1996) found significant differences between the SPRs of trained and untrained singers, with a mean of 13.1 dB ($SD = 3.8$ dB) for professional trained singers, and a mean of 22.7 dB ($SD = 5.1$ dB) for untrained singers. Usha, Geetha, and Darshan (2017) investigated differences between trained and untrained prepubertal female singers using SPR, finding that it was reliable and valid for differentiating between these two groups. In their study,
all of the participants in the trained group had long-term solo voice training in Carnatic classical singing, an Indian classical singing style which is acoustically characterized by the absence of the singer’s formant. Trained singers had a mean SPR of 17.63 dB (SD = 7.75 dB), which was significantly different than the untrained group, with a mean of 26.45 dB (SD = 7.02 dB).

A concentration of students experiencing acoustic inconsistencies based on pubertal voice changes could also be a factor influencing this result. Omori et al. (1996) found no correlation between age and SPR with a sample of singers aged 19 – 60. Usha, Geetha, and Darshan (2017) found consistency in SPR measurements of prepubertal females. However, no studies have investigated SPR in relation to physiological changes of the voice and related acoustic inconsistencies. Watts et al. (2006) found that SPR was useful in differentiating talented and untalented untrained singers, with perceptually untalented participants having significantly higher SPR values. Watts et al. also found that pitch control was highly correlated to judgements of talent. It is possible that a singer experiencing a voice change associated with physical growth may have difficulty with pitch control, and thus may have higher SPR levels due to this instability.

I found significant within-subjects differences in SPR between vowels for participants and significant interactions between vowel and voice part when considering SPR. Pillot-Loiseau and Vaissière (2007) found significant differences between vowels in their study, noting that SPR generally decreased from /i/ to /a/ to /u/, with significant differences between /a/ and /u/, indicating “that the carrying power was generally the least important for /u/” and that “the differences between the sung vowels became more and more blurred with higher fundamental frequency” (p. 4). My findings agreed with their study, with generally rising SPR values from /i/ to /u/ in the sequence /i/ → /e/ → /a/ → /o/ → /u/, as depicted in Figure 2.
Figure 2. Singing Power Ratio by Vowel and Voice Part

Figure 1 referenced tongue placement for each of these vowels. In my findings, participants had lower SPR measurements for /i/ and /e/, both forward vowels. Participants had the highest SPR measurements for /o/ and /u/, which are placed toward the back of the mouth, and SPR measurements for /a/ fell approximately in the middle of these two sets of vowels.
In addition to these individual differences between vowels, there was a significant interaction between vowel and voice part. Figure 2 showed that the largest differences from these interactions are seen in the SPR measurements of the high vowels /i/ and /u/, while the SPR measurements for mid-height and low vowels were more stable across voice parts. These vowels are considered “corner vowels,” meaning that they represent extremes in the vowel quadrilateral space. Compared to other English vowels, the tongue is at the most anterior and high position for /i/. Similarly, compared to other English vowels, the tongue is at the most posterior and high position for /u/. These extremes in tongue placement are limited physiologically, as each individual has different flexibility with the tongue muscle, a different shape, and a different size. Therefore, distinguishing formant patterns at those extreme positions will vary more than with the neutral vowels which are not extended to extremes in either height or advancement of the tongue.

Formants are resonances of the vocal tract, and formant patterns may also help explain some of the variability in SPR by vowels in individual singers. The four corner vowels /i/, /e/, /a/ and /u/ represent the most extreme tongue positions (front high, front mid, back low, and back high, respectively) for English vowels production. Formant 1 (F1) is inversely associated with tongue height, while Formant 2 (F2) is directly associated with tongue advancement. Therefore, a front high vowel like /i/ would have a lower F1 and a higher F2; a back high vowel like /u/ would have a lower F1 and a lower F2.

When singing /i/, F1 would typically boost frequencies in the 0 – 2 kHz region, while F2 would typically boost frequencies in the 2 – 4 kHz region; both regions are used in calculating SPR). When singing /u/, F1 would still boost frequencies in the 0-2 kHz regions, but it is very likely that F2 would also affect frequencies in the 0-2 kHz region. Without the added boost from
F2 in the 2 – 4 kHz range, the difference between the two amplitudes would be greater, which would increase SPR. This was indicated in the results of this study, as the mean SPR for /i/ was much smaller (18.66 dB) than the mean SPR for /u/ (34.89 dB). Based on these observations, and paired with the differences in vowels in the Pillot-Loiseau and Vaissière (2007) study, it is possible that SPR is only a consistent acoustic measurement of carrying power when measured by a vowel in less extended position, like /a/.

**Harmonic Amplitude Differences**

While there was no significant difference between students enrolled in choir and students not enrolled in choir in this category, there were significant differences between voice parts when measuring all four amplitude differences between selected harmonic pairs. I found significant spectral differences between treble (soprano and alto) and bass (tenor and bass) voice parts, with the most contrast between differences in the first two octaves. Differences in the higher harmonic range (between 5 kHz and 2 kHz) were less contrasted. In overall spectral drop-off, there were differences between treble and bass voice parts, with the exception of the altos, who were considered part of a homogenous subset with both sopranos and the two bass parts (tenor and bass).

For the amplitude differences in the first octave (H2 – H1), there were significant within-subjects differences by vowel, with significant interactions with voice part, however even as the magnitudes of the differences varied by voice part, an “M” shaped pattern between vowels was relatively steady. This pattern was shown in Figure 3.

For most voice parts, H2 – H1 values for /i/ and /u/ were negative, while they were positive for /e/, /a/, and /o/. The average values for bass voices were all positive, while only the average value for /i/ was negative for tenor voices. A positive value indicated that H2 (the
overtone an octave above the sung pitch) was louder than H1, the fundamental frequency. Conversely negative value indicated that H2 was softer than H1. Harmonics generated from the vocal folds have steadily decreasing values with each consecutive harmonic, but when a resonance of the vocal tract (a formant) aligns with one of these harmonics, its amplitude will be boosted. In this case, a positive H2 – H1 value indicated that the first formant (F1) aligned with the second harmonic (H2). This H2/F1 coupling is characteristic of the chest register, also known as the modal register, or heavy mechanism. The other vowels in this study showed a positive H2 – H1 difference, indicating that the first formant (F1) aligned with the first harmonic (H1). H1/F1 tuning is associated with the head register, also known at the head voice, the light mechanism, falsetto, or loft (Nix, 2018). Stated more simply, most students consistently sang the same pitch in different registers, depending on the vowel. The target pitch for each voice part may have influenced the degree of difference between the two registrations, as well as why the average values for bass singers were all positive while other sections displayed both positive and negative values.

Figure 3. H2 – H1 (dB) by vowel and voice part
There were significant within-subjects differences across vowels for all of the amplitude difference measurements, including significant interactions in the two higher harmonic pairs for vowel and choir enrollment. There were significant interactions in the same higher harmonics and in overall spectral drop-off for vowel, choir enrollment, and voice part. Finally, I identified significant interactions between all three variables, vowel, choir enrollment, and voice part in the specific harmonic pairs, but no significant interaction in overall spectral drop-off. These harmonic differences may also be linked to registration, but patterns were less consistent between voice parts.

**Study Limitations**

As with any research study, the results of this study should be considered within the context of the study parameters and environment. There were some limitations to this study which should be considered in the interpretation of results and its subsequent implications. The first limitation of this study was in sampling; While random sampling would provide a more accurate depiction of the population, convenience sampling was used in this study. With 157 samples for this study, total sample size was adequate for the number of variables considered, however the sample size of the tenor subgroup \(n = 13\) was smaller than others, and may have limited study results. However, Tabachnick and Fidell (2013) suggested that this may be ok, as “different sample sizes among treatment groups pose no special difficulty” (p. 514). Group sample sizes may also have been different based on the choice of pitch given to those singers who were not enrolled in choir, and thus unsure of their voice part. The majority of these students chose to sing the lower pitch (between F4 and C5 for soprano/alto, and between F3 and C4 for bass/tenor), placing them in the alto or bass sections for the purposes of the study. In
addition, the large portion of samples that were excluded from vibrato analysis presented a limitation to the study.

The recording environment for data collection may have also presented uncontrolled variables. Some students sang by themselves with only the researcher present, while other students recorded in front of small groups. In addition, recording spaces were different between schools. At one school students recorded in a classroom with a very loud air conditioner, which may have caused students to sing louder or with more force in compensation for the louder ambient noise. Room acoustics between schools would be naturally different as well, depending on wall hangings, floor coverings, and the size and shape of the rooms.

Singing context may have also impacted acoustic data in this study. Participants in this study sang 5 isolated syllables after practicing these syllables once and singing a buffer song (“Happy Birthday”). Acoustic data may have been slightly different had the 5 syllables been taken from a connected singing context rather than in isolation.

**Implications for Choral Music Education**

Based on the findings of this study, choral singing students may benefit from vocal exercises and strategies that focus on specific areas such as vowel modification, registration, vibrato regulation, and strategies for navigating the acoustic and physical changes that accompany the pubertal voice change. Differentiated instruction that incorporates different resonance strategies for treble and bass voices could further benefit choral music students.

Vowels have been identified as a component of choral blend (Titze, 2008). Some choral directors also strive for vowel “uniformity.” Based on the significant differences between vowels for individuals singers in this study, a focus on vowels and vowel modification strategies may be beneficial for the choral music educators in secondary schools. Teaching vowel modification
strategies coupled with registration strategies may allow for optimal choral blend. Emmons and Chase (2006) suggested several approaches to teaching vowel modification techniques in a choral setting in addition to providing detailed vowel modification guidelines based on intended vowel, modified vowel, pitch, and voice part. Bozeman (2013) also presented multiple strategies for formant tuning through vowel modification that could be used with singers in multiple singing styles.

This study suggests secondary school singers would also benefit from learning vocalization strategies that help them differentiate between different registers of the voice, and to navigate transitions between registers. Nix (2018) provided a comprehensive table of register terminology, including common descriptors, acoustic properties, perceptual descriptors, and general ranges, which may help choral educators. In addition, Emmons and Chase (2006) provided some practical techniques for teaching registration.

As vibrato may result from a combination of neuromuscular and biomechanical processes (Nix, Perna, James, and Allen, 2016), choral students may benefit from exercises exploring vibrato regulation and changes in vibrato based on style and context. Further study on how to teach vibrato may also need to be explored. Kirkpatrick (2008) suggested “sustained dynamic exercises” for vibrato regulation, however more research into methods for teaching vibrato and vibrato regulation to choral students may be warranted. An expansion of this study in the interest of developing normative values for secondary school students’ singing voices would be beneficial. Information from those values could be used to develop voice training models for choral music classrooms based on the acoustic properties of the voices being trained. In addition, if user-friendly software with an automated version of data collection method were developed to gather information on SPR and harmonic relationships, choral music educators might feel
empowered to capitalize on individual voice qualities to enhance the ensemble sound. Voice matching techniques based on acoustic properties might be possible through such software. Noble (Noble and Shrock, 1991) emphasized that “care in placement of voices is important at all levels, grade school through adults. It is amazing how many problems in pitch, vowel color, alignment, and vibrato can be solved immediately by this process” (p. 10).

Choral directors knowledge of the voice, how it works, and how vocal function varies among singers of different voice parts are better able to differentiate instruction based on the needs of singers and the physical and acoustic differences between voice parts as described in this study. In general, vocal health and preventing vocal fatigue have also been discussed with respect to choral singing (Kirsh, van Leer, Phero, Xie, & Khosla, 2013), with certain “suboptimal vocal behaviors in the choral setting” being produced in an attempt to blend with other singers, lead a section, or sing in large ranges (p. 786-e26). At the institutional level, equipping choral music educators with a functional knowledge of the vocal mechanism during teacher training may also help choral directors curb unhealthy behaviors. Spurgeon (2004) found that many universities do not require vocal pedagogy in the choral music education curriculum:

An understanding of how voices work is vital to the success of choral conductors, yet it is often overlooked in undergraduate training… most universities do not require [vocal pedagogy] in a bachelor’s degree program in music education. A random sampling of ten flagship universities revealed that only one institution of the ten requires a course in vocal pedagogy for the undergraduate vocal music education degree.” (p. 28, 30)

Based on the findings of this study, a stronger emphasis on vocal pedagogy in choral music education programs would be beneficial to future music educators, as well as to their future students.
Suggestions for Further Research

This study was limited in that participants of the same voice part all sang the same predetermined pitch, and the vowels they sang were isolated from other musical contexts. One suggestion for further research would be to investigate SPR and differences between the amplitudes of specific harmonics using samples of the vowel /a/ taken from musical contexts at different pitches and in different registrations. In addition, a similar acoustic study with a larger random sampling of secondary school students across the country might provide more complete information about the acoustic qualities of secondary school students enrolled in American choral music programs.

More research on vibrato characteristics of secondary school singers would be beneficial. Information describing characteristic vibrato rate and extent for these students is necessary as well as investigation into the stability of these parameters during pubertal voice changes. It may be necessary to use more sensitive vibrato analysis software when approaching these studies. Investigation into vibrato shimmer and vibrato jitter might also provide unique insight into the voice change phenomenon. In addition, investigation into strategies for teaching vibrato regulation in the choral classroom using healthy vocalization techniques is an area with very little research.

There was most variability in the two corner vowels present in the study, both across vowels and between voice parts. Future studies might address whether teaching techniques for appropriate vowel modification in certain ranges and registrations could decrease this variability in carrying power and in harmonic patterns. Techniques for increasing the formant space in individuals could be beneficial to choirs, as an increased formant space would minimize variation between voice parts in the corner vowels. Titze Maxfield, and Walker (2017) have
investigated formant profile ranges for singers, graphing the first two vowel formants for /i/, /e/, /ə/ and /u/. In this study, they found F1 – F2 space outlined by these four corner vowels can be highly variable between individuals. They suggested further research to investigate whether voice training could increase this area, giving the individual more flexibility in voice production with respect to distinguishing between vowels and altering timbre. An increase in the F1 – F2 space may also benefit singers who sing as soloists as well as choristers; Titze (2016) posited that a personalized formant range profile may help singers sing in different styles, as they would be more informed about areas that required vowel modification in those styles.

Daugherty (2001) wrote about the potential impact of research in choral acoustics on choral pedagogy, and in considering the individual voice and its contributions to the choir, specifically referencing the study of “voice compatibility placement” (p. 71). In his review of choir acoustics, Daugherty (2005) stated that “a primary difficulty in conducting empirical research on the phenomenon of voice compatibility matching is that there are, as yet, no objective criteria or standardization procedures for the process. Each conductor’s method is largely idiosyncratic, i.e., not replicable by others” (p. 9). Based on the results of this study, investigating the use of SPR and amplitude differences between specific harmonic values as tools for voice matching could be warranted.
Appendix A. Written Instructions Provided by Voice Part
Soprano Vocalise
Dissertation Data Collection

Elizabeth Wallace

Instructions:

1. You will receive the starting pitch from the piano.

2. In your best voice, sing the five vowels notated below. Each note should be sung for about 4 seconds. You may breathe between notes if you need to.

3. After singing the vowels, you will receive the first five notes of the "Happy Birthday" song on the piano.

4. In your best voice, sing "Happy Birthday."

5. After singing "Happy Birthday," you will be given another pitch on the piano.

6. In your best voice, sing the five vowels notated below (the same as step 2.) Each note should be sung for about 4 seconds. You may breathe between notes if you need to.
Alto Vocalise
Dissertation Data Collection

Elizabeth Wallace

Instructions:

1. You will receive the starting pitch from the piano.

2. In your best voice, sing the five vowels notated below. Each note should be sung for about 4 seconds. You may breathe between notes if you need to.

3. After singing the vowels, you will receive the first five notes of the "Happy Birthday" song on the piano.

4. In your best voice, sing "Happy Birthday."

5. After singing "Happy Birthday," you will be given another pitch on the piano.

6. In your best voice, sing the five vowels notated below (the same as step 2.) Each note should be sung for about 4 seconds. You may breathe between notes if you need to.

\[ \text{\textbf{Mee}} \quad \text{\textbf{May}} \quad \text{\textbf{Mah}} \quad \text{\textbf{Moh}} \quad \text{\textbf{Moo}} \]

\[ \text{\textbf{[mi]}} \quad \text{\textbf{[me]}} \quad \text{\textbf{[ma]}} \quad \text{\textbf{[mo]}} \quad \text{\textbf{[mu]}} \]
Octave Treble Clef

Tenor Vocalise
Dissertation Data Collection

Elizabeth Wallace

Instructions:

1. You will receive the starting pitch from the piano.

2. In your best voice, sing the five vowels notated below. Each note should be sung for about 4 seconds. You may breathe between notes if you need to.

3. After singing the vowels, you will receive the first five notes of the "Happy Birthday" song on the piano.

4. In your best voice, sing "Happy Birthday."

5. After singing "Happy Birthday," you will be given another pitch on the piano.

6. In your best voice, sing the five vowels notated below (the same as step 2.) Each note should be sung for about 4 seconds. You may breathe between notes if you need to.

\[ \text{♩=60} \]

\[ \text{Mee} - - - \text{May} - - - \text{Mah} - - - \text{Moh} - - - \text{Moo} - - - \]

\[ \text{[mi]} - - - \text{[me]} - - - \text{[ma]} - - - \text{[mo]} - - - \text{[mu]} - - - \]
Instructions:

1. You will receive the starting pitch from the piano.

2. In your best voice, sing the five vowels notated below. Each note should be sung for about 4 seconds. You may breathe between notes if you need to.

3. After singing the vowels, you will receive the first five notes of the "Happy Birthday" song on the piano.

4. In your best voice, sing "Happy Birthday."

5. After singing "Happy Birthday," you will be given another pitch on the piano.

6. In your best voice, sing the five vowels notated below (the same as step 2.) Each note should be sung for about 4 seconds. You may breathe between notes if you need to.
Bass Vocalise
Dissertation Data Collection

Instructions:

1. You will receive the starting pitch from the piano.

2. In your best voice, sing the five vowels notated below. Each note should be sung for about 4 seconds. You may breathe between notes if you need to.

3. After singing the vowels, you will receive the first five notes of the "Happy Birthday" song on the piano.

4. In your best voice, sing "Happy Birthday."

5. After singing "Happy Birthday," you will be given another pitch on the piano.

6. In your best voice, sing the five vowels notated below (the same as step 2.) Each note should be sung for about 4 seconds. You may breathe between notes if you need to.

\[ \text{Mee} \quad \text{May} \quad \text{Mah} \quad \text{Moh} \quad \text{Moo} \]
\[ [\text{mi}] \quad [\text{me}] \quad [\text{ma}] \quad [\text{mo}] \quad [\text{mu}] \]
Appendix B. Consent Forms

Student Assent Form

I, _________________________________, agree to be in a study to exploring variation in voice quality parameters used in choral voice matching. I will be audio recorded while singing by myself. I will follow all the classroom rules, even when I am working with the researcher. I can decide to stop being in the study at any time without getting in trouble.

Student Printed Name: ____________________________________________ Age: __________

Student Signature: ______________________________________________ Date: __________

Witness Signature: _____________________________________________ Date: __________

* (N.B. Witness must be present for the assent process, not just the signature by the minor.)
1. **Study Title**
   Exploring Variation in Voice Quality Parameters Used in Choral Voice Matching

2. **Performance Site**
   Various Public Sites, including schools, churches, and voice studios.

3. **Investigators**
   The following investigators are available for questions about this study, Monday through Friday, 9:30 a.m. to 3:30 p.m.
   Elizabeth Wallace, (757)589-4938, ewall25@lsu.edu
   Dr. Dan Isbell, (225)578-3258, disbell1@lsu.edu

4. **Study Purpose**
   The purpose of this study is to compare voice quality data for various groups using spectrography as an objective tool for voice analysis.

5. **Subject Inclusion**
   Singers (both choral and non-choral) ages 10-80

6. **Subject Number**
   200

7. **Procedures**
   First, participants will complete a questionnaire about their preferences in choral formation. After questionnaires are completed, the primary investigator (Mrs. Wallace) will record individuals singing a short audio sample which will include vowel sequences and singing “Happy Birthday.” These recordings will be used to measure each participant’s vibrato rate, vibrato extent, spectral envelope, spectral slope, and intensity.

8. **Benefits**
   The researcher will provide a short tutorial about reading spectrographs to interested participants, and participants will be able to see a spectrograph of his/her voice.

9. **Risks**
   All data collection procedures are non-invasive; they include recording short, individual sound samples, and completing a questionnaires.

10. **Right to Refuse**
    Participants may choose not to participate or to withdraw from the study at any time without penalty or loss of any benefits to which they might otherwise be entitled.

11. **Privacy**
    Results of the study may be published, but no names or identifying information will be included in the publication. Subject identity will remain confidential unless disclosure is required by law.

12. **Financial Info**
    There is no cost for participation in the study, nor is there any compensation to the subjects for participation.

13. **Recording**
    Short sound samples of singing will be recorded using a password-protected laptop computer, and will be stored on a password-protected computer.

14. **Signature**: The study has been discussed with me and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. If I have questions about subjects’ rights or other concerns, I can contact Dennis Landin, Institutional Review Board, (225) 578-8692, irb@lsu.edu, www.lsu.edu/irb. I agree to participate in the study described above and acknowledge the investigators’ obligation to provide me with a signed copy of this consent form.

   Student Printed Name: ________________________________________________________

   Parent Printed Name: ________________________________________________________

   Parent Signature: __________________________________ Date: ________________
1. Study Title: Exploring Variation in Voice Quality Parameters Used in Choral Voice Matching
2. Performance Site: Various Public Sites, including schools, churches, and voice studios.
3. Investigators: The following investigators are available for questions about this study, Monday through Friday, 9:30 a.m. to 3:30 p.m.
   Elizabeth Wallace, (757)589-4938, ewall25@lsu.edu
   Dr. Dan Isbell, (225)578-3258, disbell1@lsu.edu
4. Study Purpose: The purpose of this study is to compare voice quality data for various groups using spectrography as an objective tool for voice analysis.
5. Subject Inclusion: Singers (both choral and non-choral) ages 10-80
6. Subject Number: 200
7. Procedures: First, participants will complete a questionnaire about their preferences in choral formation. After questionnaires are completed, the primary investigator (Mrs. Wallace) will record individuals singing a short audio sample which will include vowel sequences and singing “Happy Birthday.” These recordings will be used to measure each participant’s vibrato rate, vibrato extent, spectral envelope, spectral slope, and intensity.
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Ensemble Administrator Printed Name: ___________________________________________

Ensemble Administrator Signature: __________________________________________ Date: __________
### Elizabeth Wallace

#### Wallace Dissertation Consent Form

<table>
<thead>
<tr>
<th>Study Title</th>
<th>Exploring Variation in Voice Quality Parameters Used in Choral Voice Matching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance Site</td>
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</tr>
<tr>
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</tr>
</tbody>
</table>

| Study Purpose | The purpose of this study is to compare voice quality data for various groups using spectrography as an objective tool for voice analysis. |
| Subject Inclusion | Singers (both choral and non-choral) ages 10-80 |
| Subject Number | 200 |

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**14. Signature:** The study has been discussed with me and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. If I have questions about subjects’ rights or other concerns, I can contact Dennis Landin, Institutional Review Board, (225) 578-8692, irb@lsu.edu, www.lsu.edu/irb. I agree to participate in the study described above and acknowledge the investigators’ obligation to provide me with a signed copy of this consent form.

Administrator Printed Name: ____________________________________________________________

Administrator Signature: __________________________________________ Date: __________
Appendix C. Participant Questionnaire

Participant Questionnaire
For Elizabeth Wallace's dissertation data collection
* Required

Please complete the following information about yourself.

1. First Name *

2. Last Name *

3. Age *

4. Gender *
   * Required
   Mark only one oval.
   - Female
   - Male
   - Other: ___________________________

5. Voice Part *
   * Required
   Mark only one oval.
   - Soprano
   - Alto
   - Tenor
   - Bass
   - I'm not sure

6. Where are you recording your voice with Mrs. Wallace? *
   * Required
   Mark only one oval.
   - School
   - Church
   - Voice Studio
   - Other: ___________________________
7. Do you sing in a choir? *
   Mark only one oval.
   ☐ Yes
   ☐ No
   ☐ I have previously sung in a choir but I do not currently sing in one.

8. How many years have you sung in a choir? (Select 0 for never, select 1 if you are currently in your first year of choral singing.) *
   Mark only one oval.
   ☐ 0
   ☐ 1
   ☐ 2
   ☐ 3
   ☐ 4
   ☐ 5
   ☐ 6
   ☐ 7
   ☐ 8
   ☐ 9
   ☐ 10
   ☐ Other:

9. Do you take voice lessons? *
   Mark only one oval.
   ☐ Yes
   ☐ No
   ☐ I have previously taken voice lessons but I am not currently taking voice lessons.
10. How many years have you taken private voice lessons? (Select 0 for never, select 1 if you are currently in your first year of voice lessons.) *

Mark only one oval.

☐ 0
☐ 1
☐ 2
☐ 3
☐ 4
☐ 5
☐ 6
☐ 7
☐ 8
☐ 9
☐ 10
☐ Other: ____________________________

Singer Preferences

Please complete the following statements about your preferences when singing with others.

11. When I'm singing with other people, I prefer to stand next to *

Mark only one oval.

☐ People who sing louder than me.
☐ People who sing softer than me.

12. When I'm singing with other people, I prefer to stand next to *

Mark only one oval.

☐ People who sing with a straight tone (no vibrato).
☐ People who sing with vibrato.

13. When I'm singing with other people, I prefer to stand next to *

Mark only one oval.

☐ People who sound like me.
☐ People who sound different than me.

14. When I'm singing with other people, I prefer to stand next to *

Mark only one oval.

☐ People who are singing the same voice part as me.
☐ People who are singing a different voice part than me.
15. When I’m singing with other people, I prefer to stand *
   Mark only one oval.
   
   ☐ Very close to the other singers.
   ☐ At least an arm’s length away from other singers.

**Personal Voice Perceptions**

Please complete the following sentences about your voice.

16. I am usually *
   Mark only one oval.
   
   ☐ louder than other singers around me.
   ☐ softer than other singers around me.

17. When I sing, my voice *
   Mark only one oval.
   
   ☐ Has a wide vibrato.
   ☐ Has a narrow vibrato.
   ☐ Has no vibrato.

18. When I sing, my voice *
   Mark only one oval.
   
   ☐ Has a fast vibrato.
   ☐ Has a slow vibrato.
   ☐ Has no vibrato.

19. If I am standing next to a person who is singing louder than me, *
   Mark only one oval.
   
   ☐ I sing louder.
   ☐ I sing softer.
   ☐ My volume does not change.

20. When I am singing with other people *
   Mark only one oval.
   
   ☐ I try to match my voice to the voices around me.
   ☐ I sing the same as when I sing by myself.
   ☐ My voice matches with the voices around me, but I don’t try to do that.
Appendix D. Example of Vibrato Analysis in VoceVista 3.3

Vibrato Rate and Extent, Measured by VoceVista
Female Voice, D. [a], 7th harmonic isolated

Between 4 and 5 cycles/second
Appendix E. IRB Approval Form

ACTION ON EXEMPTION APPROVAL REQUEST

TO: Elizabeth Wallace
Music Education

FROM: Dennis Landin
Chair, Institutional Review Board

DATE: October 1, 2018

RE: IRB# E11232

TITLE: Acoustical Choral Formation: Investigating the Use of Spectrography as an Objective Tool for Acoustic analysis and Voice Matching


Review Date: 9/27/2018

Approved X Disapproved

Approval Date: 10/1/2018 Approval Expiration Date: 9/30/2021

Exemption Category/Paragraph: 1; 2b

Signed Consent Waived?: No

Re-review frequency: three years unless otherwise stated

LSU Proposal Number (if applicable):

By: Dennis Landin, Chairman

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING – Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants, including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
8. SPECIAL NOTE: When emailing more than one recipient, make sure you use bcc. Approvals will automatically be closed by the IRB on the expiration date unless the PI requests a continuation.

* All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at http://www.lsu.edu/irb
References


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Pillot-Loiseau, C., & Vaissière, J. (2007, September). Spectral correlates of carrying power in speech and western lyrical singing according to acoustic and phonetic factors. 15th International Congress of Acoustics (ICA), 1-6. https://hal.archives-ouvertes.fr/hal-00530207


Vita

Elizabeth Mitchell Wallace (b. 1985) is the choir director at Ingleside United Methodist Church, and an academic coach with the Center for Academic Success at Louisiana State University. In addition to a Ph.D. in music education, Mrs. Wallace is pursuing an M.A. in Speech Language Pathology at Louisiana State University, with aspirations of working with singers and other professional voice users toward voice habilitation and rehabilitation goals. Prior to her time at LSU, Mrs. Wallace taught high school choir at Friendswood High School in Friendswood, Texas, St. Joseph’s Academy in Baton Rouge, LA, and St. Amant High School in Ascension Parish, LA. During her tenure as a high school choir director, Mrs. Wallace’s choirs consistently received Sweepstakes and Superior awards at district and state festivals. In 2014, Mrs. Wallace received the Louisiana Music Educators Association “Outstanding Young Music Educator” award. Mrs. Wallace enjoys working as a guest clinician and adjudicator for choirs and festivals; recently she has served as an adjudicator and clinician for multiple events in Louisiana, including Parish and District honor choirs, and LMEA performance assessments, solo and ensemble festivals, and honor choir auditions. In 2018-2019, Mrs. Wallace co-founded the Prism Project at LSU, providing music and theatre education to area students with special needs, ages 6-16.

Mrs. Wallace received a Master of Music Education, Bachelor of Music in Music Performance, and Bachelor of Science in Biochemistry at Old Dominion University in Norfolk, VA. She is in the process of becoming an NCVS-trained Vocologist through the National Center for Voice and Speech in Salt Lake City, Utah, with an anticipated completion date of July, 2020. Her current research interests are voice health, the use of spectrography in the choral classroom, music education degree persistence, music technology education, and community college music.