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Effect of Voice Matching on Individual Vocal Characteristics of Singers Performing in  
Duet

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**Abstract**

Effect of Voice Matching on Individual Vocal Characteristics of Singers Performing in Duet

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The purpose of this study was to examine interactions of voices performing in duet to determine the relationship of individual vocal characteristics to perceived blend. Male ( $N = 8$ ) and female ( $N = 6$ ) vocalists from the choral ensembles of a major university were recorded singing with each other in every combination within the same gender, in both left-right and right-left configurations. Each pair was recorded singing the first phrase of “My Country Tis of Thee” using both pair and individual microphones. A panel of professional and student choral conductors ( $N = 48$ ) rated the pair recordings for blend. Singers’ vocal characteristics were quantified by singing power ratio, vibrato rate, and vibrato extent. Analysis showed a combination of four factors accounted for 79% of the variability in perceived blend, with low natural vibrato extent, similar natural vibrato extent, higher singing power ratio, and reduction of vibrato extent producing the highest

perceived blend. Singers with similar vibrato extents tended to decrease their vibrato extents when paired with one another, while singers with large differences tended to increase. Results suggest voice matching is an optimization algorithm that places voices next to the ones to which they are most similar and this enhances perceived blend by subconsciously inducing the section to produce the smallest vibrato extent of which it is healthfully capable. Vibrato rate and resonance were unaffected, suggesting voice matching is an effective tool to enhance blend while simultaneously making the choral environment more hospitable to healthy singing.

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The researchers who have investigated choral acoustics empirically form a fellowship, few in number, and united across seas. Honoring the Ancient Greek tradition of the Polymath, they are artists who have dared to be scientific, and scientists who have dared to be artistic. They serve the belief that the world's problems are most effectively solved, and its greatest aspirations most speedily realized, when disparate disciplines meet in a collegial nexus of creative effort and intellectual rigor. This dissertation is a humble attempt to take a few steps down their hallowed path.

**To Geoffrey Boers**, you continue to teach me that love is the most powerful sound a person can make. Without it, all our music is nothing but silence. With it, we can sing anything. If I ever become half the man you are, I will have achieved something indeed.

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Without these individuals, and many others, this dissertation would not have been possible. To all, I offer my profound and humble gratitude and pledge to honor you by serving our art as best I can, for as many years as God gives me.

## DEDICATION

לֹא לְנוּ יְהוָה לֹא לָנוּ כִּי־לְשִׁמָּה תָּנוּ כְבוֹד עַל־חַסְדֶּיךָ עַל־אַמְתֶּךָ:

κατὰ σκοπὸν διώκω εἰς τὸ βραβεῖον τῆς ἄνω κλήσεως τοῦ Θεοῦ ἐν  
Χριστῷ Ἰησοῦ.

~ *Soli Deo Gloria* ~

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## Chapter 1: Introduction

### Statement of the Problem

Choral conductors and voice teachers are often in discussion with one another regarding the vocal health and development of their shared students. While voice teachers are primarily concerned with crafting a free, resonant, and economical (producing maximal volume with minimal effort) singing voice, choral conductors must also seek to meld voices with diverse timbres and vibrati into a cohesive whole. Although there is an increasing trend among conductors to attempt to accomplish both goals, unifying them often proves challenging (Bragg, 2012; Ferrell, 2010). The vocal traits upon which conductors may focus in making blend assessments are manifold (Folger, 2002), yet there are two principle areas of technique which are both easily quantifiable and of particular import to voice teachers: singers' formant intensity and vibrato. These traits have thus received a significant amount of attention in the research.

Among voice teachers it is generally agreed that the presence of a large amount of acoustical energy in the range of 2000-4000 Hz, commonly known as the "singers' formant, makes a voice both beautiful and healthy. However, both professional and novice singers tend to instinctively reduce singers' formant resonance when they find themselves in the choral environment (Goodwin, 1980a; Rossing et al., 1986; Ford, 2003). Furthermore, while the increased resonance of the singers' formant imbues vocalists with the necessary sonic power to be heard over an orchestra, this proves to be a liability in the choral context. Vocalists with a strong singers' formant find themselves "sticking out" unless the other choir members are similarly resonating (Katherine et al., 2007), and this adversely affects the conductor's goal of ensemble unity.

In addition to the concerns inherent in incorporating a developed singers' formant in the choral ensemble, vibrato complicates things even further. While voice teachers generally agree that the presence of a healthy vibrato contributes greatly to the overall resonance, health, and efficiency of the human singing voice, many choral conductors find an inordinate amount of vibrato to detract from their goals of ensemble unification (Ekholm, 2000; Ternström 1993b). Trained singers, accordingly, tend to reduce their vibrato when singing in ensemble (Rossing et al., 1986), except in certain rare ensembles in which vibrato usage is particularly encouraged, such as an opera chorus (Katherine et al., 2007).

Thus trained vocalists who sing in choir are commonly faced with an ever-present challenge: remain faithful to the healthy vocal technique they have worked so hard to acquire and negatively affect the ensemble's blend, or engage in a constant, often physically uncomfortable (and potentially vocally damaging), effort to modify their vocal production to preserve blend.

It is therefore easy to see why many voice teachers discourage their students from participating in choir. Yet many choral conductors would argue that it is not the attributes of *healthy* singing that prove incompatible with ensemble blend, but rather, *operatic style*, with its particular technical conventions, and that it is quite possible to sing in a healthy manner while still preserving ensemble blend. These conductors would thus assert that a necessary part of any vocalist's training should be the cultivation of the ability to sing healthfully regardless of whatever vibrato and tonal characteristics a particular musical style may require.

## Need for the Study

Many choral conductors have attempted to resolve the apparent conflict between healthy opera vocal technique and the preservation of ensemble blend through cleverly devised standing arrangements, encouraging choristers to sing with their full resonance while placing them in very specific positions within the ensemble to maintain blend (Knutson, 1987). The most methodically refined manifestation of this philosophy is “acoustic standing,” a practice made popular by Weston Noble at Luther College (Giardiniere, 1991). The procedure has been shown to be successful both in achieving greater perceived choral blend and greater vocal comfort among singers (Killian, 2007; Ekholm, 2000). The means by which this is achieved, however, is not clear and has typically been honored among choral professionals as somewhat of a mystery. One common assumption is that the blend achieved is due to factors relating to the physical interaction of the sound waves of singers’ voices. However, it is also possible that it is due to a psychoacoustic component in which the standing arrangement causes singers to subconsciously alter their vocal characteristics (Jers, 1998).

Conjecture regarding the means of efficacy of standing arrangements abounds within the choral art, yet to this day precious few scientific investigations have been conducted. The American choral community has thus far proceeded under the assumption that the acoustic standing works for *some* reason, but has preferred to leave specifics regarding its inner workings to scientists, who are traditionally treated as occupying a different niche within the professional musical sphere. In recent years, however, efforts to promote mutual exchange between the scientific and performance disciplines, particularly within the realm of choral acoustics, blend, and group vocal

technique, have greatly nourished the musical art, providing information capable of facilitating more efficient pedagogy and healthier performances. The field is ripe for exploration and it is important such endeavors continue.

In particular, greater scientific understanding of how the choral blend attained by voice matching effects vocal production would assist choral conductors in utilizing the practice in a way that is both effective and cohesive with the goals of voice teachers. Such scientific study would also provide valuable evidence that choral conductors' methods, designed to promote healthful singing in the choral ensemble while preserving healthy vocal technique, indeed perform as advertised.

### **Purpose of the Study**

The purpose of this study is to examine the interaction of voices while performing in duet in order to determine the relationship of singers' individual vocal characteristics to the resulting perceived blend of the pair.

### **Description of the Study**

In this study male and female singers were paired and recorded with each other in various combinations, within the same gender, on both the left and right sides of one another. Each pair was recorded singing the first phrase of "My Country Tis of Thee" using both stereo room microphones (for blend assessment) and bilaterally acoustically isolated close microphones (for analysis of individual vocal characteristics). A panel of choral conductors, both professional (defined by employment) and student (defined by current attendance of a program of choral conducting study at an institution of higher education) rated the room recordings for blend using an online assessment tool. Blend

was then correlated to changes in vocal characteristics. To further investigate the results, several other statistical analyses were conducted.

### **Limitations**

Voice matching in an ensemble context is a multifaceted and complex phenomenon which suffers from a lack of standardization within the choral art. As this was the first study to investigate how it affects the acoustic characteristics of individual voices, a simple research design was preferred. The chosen design limited the number of variables requiring control, kept the process closely attuned to what would take place in a normal rehearsal, and focused on the most basic interaction of which voice matching consists: the duet. Study did not discriminate between voice types because pilot testing showed no significant effect on blend under these experimental conditions. The key of G major was thus chosen in order to place performance within the common upper chest range of all singers, regardless of voice type. The study was limited to duets for several additional reasons:

1. Voice matching typically begins with duets. These pairs form the foundation upon which the rest of the section is ordered. Therefore, it was concluded that any line of research into the process should begin with duets.
2. Utilizing trios increases the amount of ambient *reflected* sound and off-axis *direct* sound received by the close microphones, increasing risk of inter-singer contamination of the recordings. Therefore, it was reasoned that research using larger groups should only be utilized after strong evidence was obtained that adequate acoustic isolation could be achieved using pairs.

3. Lateral asymmetry was an interest in this study since a common observation among choral conductors is that reversing the order of two singers can profoundly effect the resulting sound. Asymmetry could be more readily quantified when vocalists received direct sound from another singer in only one ear.
4. The effect each voice has on the other could be more readily correlated.
5. Use of trios would have necessitated choosing between recording only some of the possible combinations of singers, or making the data collection excessively time-consuming. In either case, the quality of data would have been diminished.
6. Research using larger groups must be preceded by that of smaller groups so that the operant variables may identified, and appropriate strategies of control devised, prior to expanding the research methodology.

Additionally, though it is possible that voice matching may owe a portion of its effectiveness to rhythmic entrainment or tempo integrity, because of the particular goal of producing results that serve to further unify the vocal pedagogy of choral conductors with that of voice teachers, this study was limited to investigating individual acoustic aspects of the singing voice.

In order to preserve the integrity of the operational definition of singers' formant intensity utilized in this study (see definition of "self-to-other ratio below), only singers whose singers' formant peak occurred at less than 4 kHz were utilized (certain rare high voice types may have singers' formant peaks above 4 kHz).

University students were chosen as a study population because they are often engaged in choral and solo vocal performance simultaneously while in the midst of formative vocal development.

### **Research Questions**

The research questions addressed in this study are:

1. Do certain natural characteristics of singers' voices enable them to blend more effectively?
2. Do singers change the acoustic properties of their sound when singing with someone versus alone?
3. Is there a relationship of particular within-subject acoustic changes to perceived pair blend?
4. Does the acoustic similarity between singers' voices contribute to perceived blend?
5. How do the operant variables identified combine to determine the perceived blend achieved by a pair of singers?

The answers to these questions should assist conductors in encouraging the vocal health and development of their ensembles while maintaining choral blend.

### **Definition of Terms**

*Approach.* The angle at which a microphone is oriented in relation to a sound source.

*Formant.* A peak observed in the spectrum of a sound denoting a higher relative amount of acoustic energy in a particular frequency band.

$F_0$ . The fundamental frequency of a sung pitch.

$F_1$ - $F_2$ . Vowel formants. The relative amounts of acoustic energy in these peaks is what makes vowel type salient to human perception.

$F_3$ - $F_5$ . When these peaks are clustered tightly together in frequency, they produce the singers' formant.

*LTAS*. Long-term Averaged Spectrum. A spectrogram that shows the average spectral characteristics of a sound over a long period of time. Frequencies are segregated into blocks and an average decibel level is calculated for each frequency block for the entire sample. It is displayed as a frequency-decibel plot (x, y, respectively) and is obtained by averaging multiple Fast-Fourier Transform analyses, the "snap-shot" analysis of sounds used in standard spectrograms. The resolution of a LTAS is defined by how many of these snap-shots are taken per second. The size of the LTAS is defined by how many frequencies are clustered together when averaging the decibel level for that band (larger = smaller bands, higher resolution).

*Self-to-other Ratio*. A decibel ratio describing the relative volume of sound a singer hears from his/her own voice versus the voice of another singer, or singers.

*Singers' Formant*. A close clustering of the third through fifth formants in a frequency range within which orchestral instruments have little energy and the human ear is particularly sensitive. It lies between 2 kHz and 4 kHz in most singers and is what enables a trained singer to be heard over an orchestra.

*SPR*. Singing Power Ratio. A ratio describing the relative strength of acoustic energy from 0 to 2 kHz compared to that from 2 to 4 kHz. It describes the strength of the singers' formant (lower = more intense) in a manner that is not dependent upon overall sung volume. Since decibels are logarithmic the ratio is calculated through subtraction,

not division. Because decibels are often reported negatively (counting backwards in volume from a maximal level defined as “0”), it is calculated using the following equation:  $\text{abs}((\text{max dB level, 2-4 kHz}) - (\text{max dB level, 0-2 kHz}))$ .

*SPR Deviation.* A variable describing how much the SPR of the individual singer deviated from their average solo SPR observed in control recordings. In statistical analysis, this number was analyzed both absolutely (with positive or negative change removed) and directionally. A SPR deviation of 1 means that the vocalist increased his/her SPR by 1.

*SPR Difference.* A variable quantifying the degree of mismatch between the SPR's of two singers.

*Vibrato Extent.* A measurement of average vibrato width, in semitones, between the lowest fundamental frequency of a sustained pitch and the highest.

*Vibrato Extent Deviation.* A variable describing how much the vibrato extent of the individual singers deviated from their mean solo vibrato extent observed in control recordings. In statistical analysis, this number was analyzed both absolutely (with positive or negative change removed) and directionally. A vibrato extent deviation of .5 means that the vocalist increased his/her vibrato extent by .5 semitones.

*Vibrato Extent Difference.* A variable quantifying the degree of mismatch between the vibrato extents of two singers.

*Voice Matching.* A process by which singers are placed into a particular choral standing order designed both to enhance blend and allow them to use their natural solo vocal characteristics without adversely effecting blend.

*Vibrato Rate.* Cycles per second of frequency modulation in a sustained pitch.

## **Chapter 2: Review of Literature**

### **Introduction**

A thorough review of the research on choral blend reveals three areas relating to this study: the singers' formant itself, voice use in solo versus choral settings, and finally, how standing arrangements affect choral blend. The research served not only to create a conceptual progression of inquiry leading naturally to the questions this dissertation seeks to answer, but also suggested various options for study design, highlighting their associated strengths, weaknesses, and options for control.

### **Singers' Formant as a Measure of Voice Quality and Training**

In the 20<sup>th</sup> century scientists and voice teachers made increased efforts to collaborate in the academic arena. This synergy has become increasingly beneficial for vocal studies because the information it has produced provides a welcomed supplement to metaphor-based pedagogy, which can sometimes confuse students due to its subjectivity. Increased understanding of the acoustic and biomechanical processes involved in producing what is commonly thought of as a "good" tone in classical singing can indeed be quite useful to the voice teacher, and refreshing to the student vocalist. But before such investigations could be initiated, it was first necessary to explore what a "good" vocal tone actually is.

This question was explored by Bartholomew (1934), who attempted to construct an acoustic definition of "good" singing by analyzing recordings of singers. He looked at 46 different vocalists, who were categorized as "trained" or "untrained" according to conventional standards of the day. The singers were recorded individually and reviewed by a panel of "teachers with experienced musical taste." The panel rated vibrato

separately on a second pass. The recordings were then acoustically analyzed to determine if there were particular spectral qualities associated with the judgments of the panel.

Four common traits were observed among the highest rated singers: tonal intensity, a strong  $F_1$ , a strong high formant and vibrato. The trait of “tonal intensity” describes how consistent the spectrum of the voice was over a wide range of dynamics. Vibrato was positively associated with the best recordings chosen during the initial pass. The highest rated vibrato tended to be that which had a consistent rate of variation of 6-7 Hz. Interestingly, “variation” was defined as not only a modulation of pitch, but also of volume and timbre.

The results of Bartholomew’s study suggest that vibrato is an element of the timbre we perceive as resonance and the elements of vibrato must vary at the same time, and in sync, in order to be received positively. The researcher also noted that when the elements of vibrato did not vary in sync with one another, muscular tension was often observed in that singer and his or her vibrato rate tended to be faster than the 6-7 Hz ideal, which tended to remain relatively stable among the singers regardless of other resonant factors.

Sundberg (1974) studied how the acoustic spectrum of the singing voice was altered through physiological articulation of the larynx. He discovered that the acoustic region of the singers’ formant was enhanced through laryngeal position. A low larynx altered the length of the vocal tract to absorb harmonic energy in the range between the vowel formants ( $F_1$ -  $F_2$ ) and singers’ formant (which is actually a close clustering of three formants:  $F_3$ -  $F_5$ ).

Magill and Jacobson compared the singers' formants of professional and student singers (1978). Their sample included four basses, five baritones, four tenors, five mezzo-sopranos and five sopranos, of whom nine were college voice students with three or less years of training, and 13 were professionals who had extensive solo experience in addition to five or more years of training. Each of the voice types were represented in both the student and professional groups. Participants sang sustained [i], [a] and [u] vowels, sustained on a note in the upper middle of each voice range (e.g., E5 for tenors, etc.), and sang an octave arpeggio centered in mid range.

Besides showing that singers' formant intensity was overwhelmingly correlated with increased training and professional experience, the researchers highlighted some interesting implications of their work as it related to vocal technique and the role of the reduction of tension in producing a resonant and pleasing vocal tone. Just as is the case when crafting and utilizing reeds with woodwind instruments, the stiffer the vibrational material of the reed, the slower it can change direction. This results in the sound containing quieter upper harmonics and the waveform is smooth and gradual. When a reed player desires a "darker" sound, he/she will use a harder, or thicker reed.<sup>1</sup> Conversely, the softer the vibrational material, the faster it can change direction, resulting in more higher harmonics. As they progress in vocal development, singers not only learn to use less vocal tension (resulting in a softer vibrational body that emphasizes the upper

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<sup>1</sup> As reed crafting is a complex art, these are only the most obvious and gross tools at the skillful reed player's disposal. The removal of vibrational material from specific parts of the reed is where the true artistic genius of a great reed crafter lies.

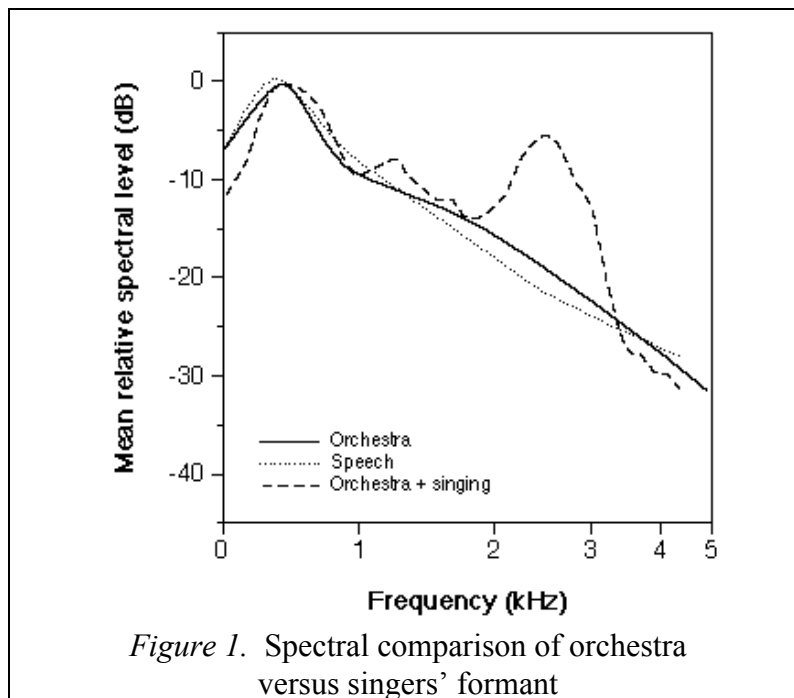
harmonics of the singers' formant) but also seem to learn to better control the rate at which their vocal folds release air during each vibrational cycle. They learn to alter the slope of the vocal waveform, making it more steep or shallow, without altering the fundamental frequency. In accordance with Sundberg, the researchers also noted that there was a vocal tract component to the singers' formant as well.

Coleman (1994) studied the difference in vocal dynamic range between trained and untrained singers when performing in choirs. Participants were recorded individually while singing choral excerpts. Interestingly, no substantial differences in maximal volume were found between trained and untrained vocalists, while substantial difference in minimal volume were observed. Trained vocalists were able to sing softer than untrained vocalists. These results suggest that the common presumption that trained singers are able to sing much louder is untrue and that trained singers simply *seem* to sing louder because the singers' formant shifts acoustic energy into a frequency range to which the human ear is more sensitive. Alternatively, the differences in loudness observed may be because of psychological factors related to the rehearsal environment rather than actual physical capability. Trained singers may not only be more *comfortable* using their maximal volume because of confidence gained through long hours of study and development, but may also be more *wiling* to do so due to their having been immersed in an artistic culture where louder singing is ubiquitously rewarded. Within the average choral environment, this is not normally the case (with the obvious exception of perhaps gospel and show choirs).

Regardless of how one interprets the data, they are suggestive of the possibility that the right standing arrangement may encourage novice voices to more fully resonate.

Such a scenario will serve to create a choral environment that, instead of requiring the more resonant voices to dampen their tone, encourages the less resonant voices to be more resonant. Subsequent research that has bestowed additional insights into this possibility will be explored later (Katherine, 2007).

The suggestions of Coleman's study regarding the singers' formant being not an actual volume increase, but a shift of acoustic energy into a range of more sensitive human hearing, creative an *illusion* of increased loudness, was one of the ideas explored by Morris and Weiss (1997). The researchers found that the singers' formant lies within 2.5-3.5 kHz for most choral voice types and that energy in this range was far more prevalent in trained vs. untrained voices. They noted that the human ear is particularly sensitive to frequencies in this range and that LTAS analysis of orchestral recordings shows that orchestras generally lack energy in this area. This is what allows trained voices to be heard over an orchestra.



### **Voice Use in Solo versus Choral Settings**

The above research provides a solid basis for using the singers' formant as an objective measure of healthy and efficient singing. If choral conductors are to partner with voice teachers in its pursuit, a logical next step of inquiry is to examine how the choral environment modulates this variable, particularly with respect to its relationship to choral blend.

Goodwin (1980a) studied how sopranos changed their voice spectrum when they sang as members of a choir as compared to solo singing. 30 sopranos from the North Texas State choral ensembles participated in the study. Each singer was first recorded singing vowels in the style of their solo singing at three different pitches spanning their vocal registers. Next, each singer was recorded singing the same vowels while hearing a pre-recorded soprano section via headphones. The recorded soprano section was "well blended." This was defined as the inability of the sopranos to hear their individual voices, or the voices of any of the others, in the recording. The soprano section sang at a moderate dynamic level, with vibrato present.

In the blended situation, singers reduced the amount of acoustical energy in the singer's formant, increased acoustical energy on the fundamental, and reduced the amount of energy in between formants in general.

Rossing et al. (1986) replicated this study with bass-baritones, using greater controls, additional measures, and a slightly more ecological design. The researchers utilized three professional and five amateur bass-baritones in order to see if there would be differences in the way the singers modified their vocal resonance in the choral setting based on training. Each singer was asked to sing in both choral and solo mode, wearing

headphones that simulated the choral or solo experience respectively. The headphone recording was played at a variety of sound volumes for each mode. For the choral mode, singers heard the Poulenc *Gloria*, as recorded from within a choral bass section. In this way this choral stimulus recording was more ecological, since it was a reproduction of the actual acoustic environment choral singers experience when performing. Subjects were instructed to sing as they would in a choral context. For the solo mode, singers heard the piano accompaniment to a short song written especially for the study, which included many of the same vowels used in the *Gloria*. Singers were instructed to sing as they would in a solo context. In addition to audio recording, data were collected using a vocal fold spectrograph, in order to distinguish between laryngeal and vocal tract action in the alteration of vocal spectrum.

Singers sang louder than the recording volume while in solo mode, but roughly equal to it while in choral mode. In both trained and amateur singers, when singing in choral mode, singers' formant was reduced, with acoustic energy moved to the fundamental and  $F_1$ , except when singing at a loud dynamic level, where the singers' formant remained prominent. This effect was seen in both laryngeal and vocal tract measures, however, professional singers differed in that they had a more intense, and more tightly clustered, singers' formant ( $F_3$ -  $F_5$ ). This effect was also more pronounced in the microphone recording than in the laryngeal data, suggesting that the singers' formant is created primarily through vocal tract orientation, not through laryngeal processes.

A particularly interesting observation in this study was that the singers moved acoustic energy to  $F_0$  and  $F_1$  using a primarily laryngeal modification. They increased the

flow of air by decreasing vocal fold adductive pressure. This allowed the vocal folds to stay open for a greater portion of the vibratory cycle, allowing additional air to pass. This method of vocal production is called “flow phonation,” and is often associated with increased vocal fatigue.

While singers enhanced  $F_0$  and  $F_1$  primarily through laryngeal processes, they enhanced the singers’ formant primarily through vocal tract modification. The researchers also noted that choral mode was strikingly similar to speech in spectrum and that, when singing quietly, singers decreased their singers’ formant three times as much in the choral mode compared to solo mode. Rossing et al. (1987) replicated this study with five highly trained amateur sopranos and two professional sopranos and found the same results.

Letowski et al. (1988) recorded trained and untrained singers performing with a choir and as soloists. Like previous studies, they found that trained singers dampened their singers’ formant while singing with the choir. However, results were particularly noteworthy in regard to the untrained singers, who tended to increase their singers’ formant while singing with the choir, as compared to singing as soloists (though the total amount of singers’ formant was still small relative to the trained singers). These results suggest that the act of singing adjacent to vocalists with a strong singers’ formant can have a positive influence on the vocal development of untrained singers.

Ford (2003) studied preferences for strong or weak singer’s formant resonance in choral tone quality. Eight graduate voice students performed various excerpts of homophonic choral pieces, with two on each choral part. 139 raters of various musical experience levels evaluated the samples for blend. The singers performed in two

conditions intended to replicate the “choral” and “soloistic” modes established by Rossing (1968, 1987), with increased  $F_0$  and  $F_1$  in the choral mode, increased singers’ formant in the solo mode. The singers used real-time feedback from a computer running voice analysis software to ensure they sang according to the prescribed conditions. This was conformed by LTAS.

The raters preferred the low singers’ formant mode for blend. However, as was the case with previous studies requiring singers to consciously alter their vocal spectrum, it was not clear whether they may have altered their performance in others ways beyond the required singers’ formant changes. In solo mode, they may have increased vibrato or failed to match tempo, vowel, articulation or pitch with the rest of the ensemble. Nevertheless, the results of this study confirm previously observed trends, and it may thus be taken as suggestive that, in assessing blend, listeners do in fact prefer less singers’ formant. For the purposes of this dissertation, this study suggested that observations regarding solo and choral mode could be made objective by looking at singers’ formant, and made quantifiable, if a reliable measure of singers’ formant could be found (SPR).

Ternström and Sundberg (1989) examined the formant frequencies of choir singers in speech and singing. In this study, the researchers attempted to answer the following questions: 1) How are vowels pronounced differently in choral singing, solo singing and speech, and 2) Do choir singers adjust to the vowel articulation of the ensemble in real-time, or as a result of long-term training with the group (or perhaps both). Eight participants were recruited from the bass section of a reputable amateur Swedish choir. All eight were native residents of Stockholm with similar speech dialect (to control for linguistic differences in vowel articulation). Singers were asked to speak

the text of a piece they were performing in their choir four times and then sing it four times. Vocal output was measured using a microphone and a laryngeal spectrograph.

Though this study was primarily aimed at examining vowel use, it is important for the purposes of the phenomena examined in this dissertation because of ancillary observations related to the singers' formant. Contrary to studies previously mentioned, the singers' LTAS was typical of that of "choral mode" (with a reduced singers' formant and enhanced  $F_0$  and  $F_1$ ), even when they sang alone. Furthermore, in contrast to Sundberg (1986), which showed increased singers' formant when singing forte in choral mode, these singers showed no such difference. Rather than this being indicative of a contradictory trend, the difference may be because the singers in this study did not include those that would have fallen into the categories defined as "trained" in the previous studies. Singers in the Sundberg study had developed solo voices, with the associated ability to well-define the singers' formant, while singers in this study were amateur choral singers, whose singers' formant resonance was perhaps significantly less.

Thus, taken together, Sundberg (1986) and Ternström and Sundberg (1989) suggest some noteworthy implications for the purposes of this dissertation. The vocal training of the individual vocalists in a choir determines how much singers' formant resonance they use when singing forte. Perhaps even more provocatively, it may be possible for a strong singers' formant be used in the choral environment without compromising blend if the majority of singers are using it and/or are trained vocalists.

Such a scenario was finally examined by Katherine et al. (2007) using 26 members of the chorus of Opera Australia. Three singers of each voice type were selected for solo singing. These singers were recorded performing in the ensemble and

individually, using an omnidirectional microphone. The singers were separated by voice type and made a series of circles in the rehearsal room at the Sydney Opera House. The singer being recorded stood in the middle of the circle and was told to “sing as part of the ensemble.” Literature used was the last 21 bars of the Easter Hymn (a choral work from Mascagni’s “Cavalleria Rusticana”). Four conditions were reordered for each solo singer, using 1 and 2 meter circle radii, with recorded vocalist singing and not singing. This created a total of 12 recordings.

Finally, an individual recording was made for each of the 12 designated singers performing the last 16 bars of “Torna a Surriento” by Ernesto Di Curtis. The researchers intentionally chose such different literature in order to maximize the stimulus for singers to change between choral and solo mode. The singers were instructed to “sing as a soloist.” A sophisticated acoustical isolation method was employed to control for the effect of sound from the surrounding singers, as well as reverberation in the room (which was well dampened to begin with). Recordings were then analyzed for SPR and energy ratio.

Contrary to previous studies, singers used more singers’ formant in choral mode than in solo mode. Vibrato remained unchanged and singers sang louder in solo mode.

In confirmation of the suggested implications of Coleman (1994), the results of this study suggested that the manner in which trained singers modify their singers’ formant when performing in a group is greatly related to the amount of singers’ formant in the tone of the other singers making up that group. Results also suggest that if the cultural of the ensemble is one in which a strong singers’ formant is rewarded (such as an opera chorus), the previously observed tendency of singers to dampen the singers’

formant when performing in an ensemble may actually be reversed. Singing around people with a lot of singers' formant can cause singers to enhance their own.

Nevertheless, this study must be approached with caution, since blend was not included in analysis. The results may simply be because maintenance of blend was not a priority for these opera singers.

Carter (2007) examined how the stage of singers' vocal development can affect how they respond to the choral environment. The sample was stratified to create three categories of vocal development. Nine bass-baritone voice students at the University of Texas at Austin participated in the study, three underclassmen, three upperclassmen and three graduate students. In addition to studying voice privately, all the students were experienced choral singers. For the choral stimulus, a choir was recorded singing the *Hallelujah Chorus* using a simulated binaural microphone configuration from within the bass section. For solo singing, a recording was used of a piano accompaniment of the National Anthem of the United States of America. Students were recorded in a voice lab singing with both excerpts. LTAS analysis was subsequently conducted.

The results showed increased prominence of the singers' formant as vocal training progressed. Additionally, the more trained the singer, the less they decreased their singers' formant in the choral environment. Untrained singers showed the most variation in their vocal spectrum. The results of this study suggest that the effect of voice matching is more pronounced, and of the most benefit, when singers are in the foremost stages of their vocal development, and reveals why this particular population was chosen for use in this dissertation.

## **Standing Arrangement and Choral Blend**

The aforementioned research on voice use in the choral environment highlights a problem: the requirement to blend in choral performance seems to encourage unhealthy vocal habits. Research on how standing arrangements affect blend may suggest possible solutions to the problem.

The research of Tocheff (1990) was the first notable foray into research on in this area. Standing arrangement was manipulated and a total of 32 different experimental conditions were recorded. Judges were asked to select the best. Due to the potentially confounding results of such a design, the value of this study lies not in its direct results (which must be approached with caution), but in the way in which it illuminated the many complexities inherent to research on choral blend. As such, the study pointed the way forward for future researchers.

The doctoral dissertation of Giardinieri (1991) provided the first detailed written record of the voice matching procedure utilized by Weston Noble. It served as an essential research asset for future studies and suggested that vibrato and singers' formant resonance are two of the primary variables modulated by voice matching in enhancing perceived blend.

The research of Daugherty (1999) on the effect of space between singers on choral blend and vocalist preference stood out among the corpus of literature for its careful attention to implementing controls. An intact 46-member high school choir participated in the study. The choir was recorded singing a homophonic section of Maurice Durufle's *Ubi Caritas*. The selection of a choral piece that utilizes foreign language is noteworthy. The researchers noted that during the pilot study, this type of

literature seemed to facilitate greater concentration on tonal aspects among both choir members and raters. To control for any effect physical gesture might have on the choir's performance, a video was made of their conductor and this recording was played on a television placed at the conductor's normal standing position.

Six conditions were recorded. Mixed and block sectional arrangements of choir members were recorded for each of three different spacings: close (1 inch, measured from shoulder to shoulder between choir members), lateral (12 inches) and circumambient (lateral spacing, plus skipping a row on risers). 160 auditors of varying age, gender, experience, and training (screened against hearing loss) listened to pairs of the recordings on a CD and rated them for preference and uniqueness. The order of presentation on the CD was controlled to eliminate fatigue, bias, and other potential confounding variables from influencing results. The choir members also rated the different arrangements and shared their thoughts afterward.

Auditors and singers alike showed preference differences. Sectional arrangements were liked by bass singers and male raters, and disliked by sopranos and female raters. Spacing had a greater effect on ratings and preferences than did the type of formation. Less confident and less experienced singers (as reported by the choir's director) preferred closer spacing. These results are suggestive of the self-to-other ratio factors that would ultimately be explored by Ternström (1999, 1995).

This study highlighted the need to avoid conducting gesture and control for order of presentation in rater evaluations. It also provided valuable suggestions in interpreting potential study implications, namely, in the strong correlation observed between rater and singer preferences. Scenarios singers felt most comfortable with were also those rated

highest for blend. Thus, to enhance feasibility and reduce participant fatigue, singer preference was not examined in this dissertation, being reasonably assumed to be adequately represented by the blend ratings themselves.

Eckholm (2000) conducted research intended to further explore the relationship between standing arrangement, voice mode, and choral blend. An ad-hoc ensemble of 22 voice performance majors at a major research university was recorded singing excerpts in four conditions: 1) voice matched solo mode, 2) voice matched blended mode, 3) random sectional solo, and 4) random sectional blended. The ensemble contained a balance of voice types. The singers were voice-matched utilizing the acoustic standing procedure described by Giardiniere (1991).

Matching decisions were made by a panel of three choral conductors, who “demonstrated high agreement in the judgments rendered.” For “solo mode,” singers were asked to “maintain their normal solo vocal production while attending to the musical style of the piece and all other aspects of ensemble singing.” Recording took place in a 100-seat recital hall. Singers performed homophonic excerpts from multiple stylistic periods. Singers rated their vocal comfort and choral sound on a 5-point scale. Two singers in each section were recorded via a head microphone singing with the group and also recorded later singing their parts as soloists. Three experienced choral conductors and one experienced choral singer evaluated the conductor’s performance via videotape to ensure consistency. Recordings were ordered by Latin square and placed on a CD. 102 evaluators (37 choral conductors, 33 voice teachers and 32 professional instrumentalists) evaluated the group recordings for blend/homogeneity, diction, dynamic range, phrasing, pitch precision, rhythmic precision, and overall tone quality. 12

professional voice teachers evaluated the solo singers in group and solo performance and rated them for “how well the singer [was] using his/her voice.”

The results of this study were contrary to those of others. The researchers noted that the voice teachers did *not* rate solo mode singing as better than choral mode singing. However, this may have been the result of several potential experimental confounds.

First, researchers reported that the singers tended to over sing when in solo mode. It is therefore likely that when performing in solo mode, these singers were not utilizing the same type of vocal production normally used during their private lessons. Thus, contamination of the solo mode recordings brought what would have likely been higher ratings into the same negative territory usually occupied by choral mode singing in the opinion of voice teachers.

Second, the effect of voice teacher rating of individual singers whose overall production they did not like was not statistically isolated in comparisons of solo to choral singing. The negative vocal production traits of individual singers cannot be as easily discerned by listeners when hearing a large ensemble as they can when listening to singers individually. Thus, the statistical results may not have truly reflected solo singing versus choral singing, but rather, how salient vocal deficiencies are to voice teachers when they listen to singers alone versus as part of a choir.

Third, individual solo singing was ranked significantly higher for intonation and vocal production than choral singing in either mode. However, if raters had been able to hear the choir singing in the background on the close recordings of the singers during the group condition, intonation issues that would have been unnoticeable in the solo singing may have been made more salient by as the choir provided a stronger tonal context for

the evaluators to rate against. More information about how the researchers dealt with these issues would be useful. It is quite possible they had a control in place that was not reported.

Fourth, the definition of “intonation” may not have remained the same for individual performance and group performance. “Good intonation” when performing alone is commonly defined as remaining true to the pitch of one’s own performance lineally, while “good intonation” when performing as a member of a choir requires individual singers to match the others horizontally. By partially isolating the individual singers’ voices during the group performance, the requisite intonation adjustments singers made in order to match the group may have registered to evaluators as being an expression of poorer intonation. If this took place, results would have been skewed in favor of the solo performances.

Finally, almost the same amount of negative comments were made regarding lack of vocal freedom for blended mode as were made for solo mode (50 versus 41) and only seven negative comments were made for solo singing. This seems to suggest an inadequate differentiation between the modes among the singers. The voice teachers may have been biased against choral singing, or the singers may not have maintained a consistent solo mode across both solo and group conditions. An ANOVA comparison of the different modes would be enlightening to see whether solo and choral modes remained distinct across the evaluations.

This study was important in revealing methodological issues that would need to be addressed in this dissertation in order to report clear results. It is difficult to get reliable performances when asking singers to self-adjust between choral and solo modes

while in the choral context. The instinct to blend while singing in the context of a group is so powerful, and so subconscious, that researchers may introduce a foreign condition into experimental design simply by asking the vocalists to sing in solo mode. In that scenario singers may have difficulty distinguishing between other elements of unification they are not supposed to change, such as rhythm, diction, intonation, vibrato synchronization, and singing mode. When asked to sing in solo mode, singers may thus inadvertently abandon additional elements of unification beyond those related to resonance. This may have skewed results against solo mode singing in this study.

Thus, for the purposes of this dissertation, the instruction to “sing soloistically” was abandoned in favor of a more hands-off approach where singers were encouraged not to worry about changing how they normally sing. When singers asked what type of vocal production they should be using, researchers simply said: “Don’t worry about it... just sing naturally. Sing well.” The singers who participated in this dissertation study had a common understanding of what that meant from having performed together and studied with the same voice teachers in their private lessons. Choral conductors may find that using similar verbal cues when conducting voice-matching procedures may produce better outcomes.

Given these results, for the purposes of this dissertation, varying standing arrangement, rather than asking choristers to vary singing mode, was determined to be a more fruitful way forward for study of choral blend. This procedure was deemed more likely to produce results that are not subject to singers’ subjective interpretation of what researchers want, or singers’ ability to produce what they believe researchers are asking for.

Woodruff (2002) sought to disprove the implications of Daugherty (1999) by examining the effect of standing arrangement on vocal production. He believed that Daugherty's research suffered from several potential confounds due to inadequate controls and was therefore skeptical of the conclusion that spacing between singers is a stronger variable in the determination of blend than standing arrangement.

Two groups of three basses were recording singing individually and while performing together. What was sung was not reported. In the latter condition the basses were recorded using an individual microphone to collect their individual sound, as well as via an omnidirectional microphone to collect the group sound. The researcher states that each possible permutation of standing order and amount of space between singers was recorded, though because it is not immediately apparent how this was accomplished it is impossible to assess. A group of auditors evaluated the recordings based on blend and vocal change, though it is not reported what manner what utilized. The recordings were analyzed to determine how standing arrangement changes affected voice spectrum, but the particular method used was not reported.

Results showed that standing formation affected the variables studied more than spacing between singers. The specific variables studied were not listed. Voice matched standing orders showed less spectrum change, and greater blend, when compared to solo singing. Greater spacing showed positive results, but not as much as those observed with voice matching.

An examination of the study methodology reveals several potential confounds that may have occurred. Data collection proceeded in an ad-hoc fashion, with the particular type of standing arrangement and order of recording not controlled and the sample was

too small to produce statistically significant results. Years of training, background of the singers, etc., were not listed in the results. Variables such as conductor contamination, fatigue, literature choice and cross contamination of recording data between the three microphones used during group singing are said to have been controlled, but the means by which this was accomplished is not explained. The study intended to examine whether standing order or spacing was more important for limiting voice spectrum change, yet it appears there was no statistical analysis done to determine the quantitative significance of co-variation. If analysis was done, the data were not included.

The assertion that the data show that voice matching has a greater effect than spacing on voice spectrum variation is thus not statistically verified based on the information available in the study write-up. The preference rating among auditors was obtained in a manner that may not have been adequately controlled (“I like X better than Y”). Several additional potential confounds can be discerned from the auditor portion of the study procedure, including microphone placement and type, auditor fatigue due to the many permutations presented, order of presentation, internal reliability of measures used for rating, etc.

However, despite these issues, this study was very helpful in its suggestion of potential operant variables in choral blend. In particular, it highlighted the need to examine the effect of individual acoustic changes on blend, which prompted the inclusion of SPR Deviation from Solo, Vibrato Rate Deviation from Solo, and Vibrato Extent Deviation from Solo as variables in this dissertation.

The following year, Daugherty responded (2003) with a study similar to his first (1999), this time utilizing a standing arrangement (referred to as “synergistic”) intended

to employ the same principles utilized in voice matching. 20 college choir singers from an intact chamber ensemble participated. 60 raters evaluated the samples in a similar manner to the previous study. The results of the previous study were replicated, this time with increased superiority of the greater spacing condition. However, it is not clear how closely the synergistic standing arrangement mirrored actual voice matching, as previously defined.

Overall, these studies, which incorporated voice-matched standing arrangements, yet did not specify exactly how they were created, served to highlight the complex, confounding nature of the voice-matching process itself as a variable that must be controlled in some manner. Conductors may vary greatly in how they make decisions during the process (or perhaps, they may not). This reality suggests that the phenomenon of voice-matching may be best examined by quantifying the underlying trends at play in the *pairing* of voices, leaving to subsequent studies the question of whether whatever trends may be observed hold true within context of the larger voice matching process.

Aspaas et al. (2004) looked at the effect of standing arrangements on choral blend and preference among vocalists. A choir composed of 30 graduate students at Florida State University was recorded singing a polyphonic piece and a homophonic piece in block sectional, mixed and column sectional standing arrangements. The singers were asked to rate several aspects of the different formations and a panel of judges was asked to rate the formations on a numerical scale for several aspects of blend. LTAS analysis was conducted on the combined sound of the entire choir.

No difference was found in LTAS between the different formations. Men preferred the column formation to the others, with basses preferring it more than tenors.

Women preferred the column formation less than the others, with sopranos disliking it more than altos. There was no significant difference between the mixed or block formations. The polyphonic pieces showed slightly more singers' formant.

These observations are likely the result of the self-to-other ratio changes noted by Ternström (1999, 1995). The increased acoustic energy of the soprano voice, due to its higher frequencies, may cause such singers to need more space between each other to keep the self-to-other ratio within ideal ranges. Conversely, the lowest voices (basses) require a closer spacing to maintain their ideal self-to-other ratio. It is plausible that the increase in singers' formant observed in the polyphonic pieces was because the linear nature of polyphonic singing encouraged singers to utilize solo mode more often.

Additional investigations into the effect of choir formations on the acoustical attributes of the singing voice were conducted by Adkinsdon (2006) and Wang (2007). However, due to their small sample size and certain issues with design, these studies have limited application.

The Swedish researcher Sten Ternström has worked for the past two decades on a line of research of particular importance with regard to choral standing arrangements. He has investigated the "self-to-other ratio of decibels," a number reflecting the ratio between the volume of sound a chorister hears from his/her own voice to the volume of sound he/she hears from other singers both directly (from those immediately surrounding) and indirectly (via the room acoustics). He found the average self-to-other ratio in a choir under typical conceptions to be 3-4 dB (1994; 1995), but found the average preferred self-to-other ratio to be 6 dB (1999). In a study of "vocal perturbations in choral singing" in 1988, Ternström and Sundberg, found that intonation suffered when

a) the self-to-other ratio was not within the preferred range, b) *other* had unfavorable spectral properties, or c) textual articulator maneuvers of *other* were not matched.

From these results it is clear that, in general, the typical choir formation does not afford the chorister the ability to hear him/herself adequately. The research suggests the importance and efficacy of standing arrangements that a) match voices for spectral timbre, b) utilize greater space between singers. It also hints at the importance of intonation as the primary evaluation tool when creating an acoustic standing arrangement (the exact method is not standardized through the corpus of research) as well as the importance of textual unity in choral performance. The research seems to suggest that the efficacy of voice matching is at least partially found in its ability to inadvertently manipulate the self-to-other ratio. Spacing between singers may also be a more effective, reliable, replicable, and less time-consuming way of manipulating the self-to-other ratio.

When designing any study it is important to anticipate the possible implications of all possible results. Such considerations may highlight the need to incorporate additional analyses or implement additional controls, the end goal being to clarify and facilitate easy application. Two studies fulfilled this role in design of this dissertation: Fagnan (2005) and Killian and Basinger (2007).

In his doctoral dissertation, Fagnan (2005) explored how training in *Bel Canto* vocal technique could change the tonal characteristics of choirs. This study suggested the possibility that the best treatment, when dealing with a few resonant voices adversely affecting the blend of an ensemble, is to increase overall singers' formant resonance in the rest of the choir, rather than by encouraging a few particularly resonant singers to decrease theirs.

Five choirs were recorded singing a series of vocal exercises prior to, and after, instruction in *Bel Canto* technique. The amount of singers' formant resonance was quantified using a software program designed specifically for this purpose at IRCAM (EnergSimple). Recordings were normalized so that volume would not be a confounding variable.

Choirs showed a decreased in SPR as a result of training. If previous studies are to be trusted, this meant the groups would have perhaps been accordingly rated as having diminished blend. However, the chorus effect was diminished as a result of training as well. This made the group sound like fewer members were singing. These results suggest that group blend may not be adversely affected by an increase in singers' formant resonance as long as the entire group is making the change. This study highlighted the need to analyze the difference in resonance between singers as a determiner of blend in this dissertation, and gave rise to the incorporation of SPR Difference between singers as a variable.

Killian and Basinger (2007) conducted a study to examine the reliability of various analysis tools and methods for use in future studies. Although largely beyond the scope of this dissertation, some interesting observations were made that are applicable. In regard to singer placement in standing arrangements, blend was consistently rated higher when the vibrato of the section was more in sync. These results suggest that one of the means by which voice-matched standing arrangements increase blend is by synchronizing vibrato. This study highlighted the need to analyze some component of vibrato matching as a determiner of blend in this dissertation, and gave rise to the

incorporation of Vibrato Rate Difference Between Singers and Vibrato Extent Difference Between Singers as variables.

Basinger's 2006 study of changes in overall group voice spectrum during an actual acoustic standing process served as the primary inspiration for this research. The results were incredibly provocative and revealed that much could be gleaned from further study if a method of individual voice analysis could be devised. Evaluation was primarily qualitative and visual based on the appearance of the spectrographs of the various combinations. Several interesting trends for successful matches were suggested, such as vibrato synchronization and the filling in of formant gaps. However, what was actually happening to the individual voices during the matching process could not be uncovered with this methodology due to lack of individual acoustic isolation. A study that incorporated individual acoustic analysis of the singers' voices was suggested by the author as a necessary next step.

Folger (2002) devised a method of acoustic isolation and conducted a study of how singers' vibrato rate and extent changed in response to voice matching. Forty two undergraduate university students, 21 sopranos and 21 baritone/basses, were recorded individually, using headset microphones, as they sang an excerpt of the Bach-Gounod *Ave Maria* in six different trio configurations. The singers were subsequently recorded individually three times to obtain a solo mean for comparison.

Though there were not enough data points to conduct statistical analysis, the researcher observed a strong qualitative relationship between changes in trio standing order and the vibrato characteristics of the singers. However, because perceived blend was not used as a variable in this study, it was not possible to determine how the changes

in vibrato characteristics induced by the standing orders affected blend. This dissertation seeks to fulfill that role, both for vibrato and singers' formant prominence.

The aforementioned studies have identified the basic phenomena and operational variables which pertain to choral blend, standing arrangement, and vocal characteristics. However, much remains to be discovered about the way in which these facets interact in the choral environment. This dissertation will therefore serve as an introductory study into the interrelationship between the choral blend, standing arrangement, and vocal characteristics variables.

## Chapter 3: Methodology

### Introduction

The first two chapters of this dissertation create a framework concerning the importance of this study and the previous research that has led to its conception and design. Choral singing, while providing a valuable forum for the development of essential skills that contribute to success as a professional singer, such as ensemble sensitivity, sight-reading, intonation, stylistic integrity, diction, collegiality, and others, may also create pitfalls that are detrimental to the technical training of the solo singing voice when not properly managed. As asserted earlier, acoustic factors related to performing as a member of a choir can have a profound impact on whether the experience proves educationally invaluable to the developing professional singer, or counterproductive. This study investigates how the vocal characteristics of singers are affected by voice matching.

The investigation, application and integration of the effect of standing arrangements on choral blend, and individual vocal comfort, has become increasingly popular in recent years, as evidenced by the success of Weston Noble's DVD *Achieving Choral Blend Through Standing Position* (2005). There is much conjecture about the means by which standing arrangements do what they do and not much is known concretely about how the results are achieved. The purpose of this study was to determine what happens to individuals' singers' formant and vibrato characteristics in response to vocal pairings that enhance blend. This information will assist choral directors to unify their goals with those of voice teachers and encourage positive vocal

development within ensembles. This study was submitted for Human Subjects Review Board approval on February 4<sup>th</sup>, 2013 and approval was granted on February 14<sup>th</sup>, 2013.

### **Background of the Design**

Since a goal of this study was to produce knowledge that would be immediately useful to choral conductors, a primary goal for its design was to create a methodology that allowed for controlled quantitative analysis, while remaining as organic as possible to how voice matching procedures are normally conducted as part of a choral rehearsal. One of the reasons this research had not already been conducted was that a way had not yet been devised to acoustically isolate voices from one another for the purpose of analysis. To overcome this problem, some researchers, such as Ternström, have placed singers in an anechoic chamber and provided the stimulus sounds of other singers via headphones. However, what is gained by this method in terms of isolation, is potentially lost, since validity now depends on the researchers (and the singers, in some designs) anticipating and duplicating the exact operational variables of the choral rehearsal that contribute to the phenomena being studied. In using such a design, researchers risk observing how singers perform in an anechoic chamber with headphones rather than how they perform in actual choral performance. Therefore, it was immediately decided that use of an anechoic chamber, and recording the singers in separate rooms using headphones, was not preferable.

Formant balancing has been advanced as a theory of voice placement effectiveness wherein voices are paired in such a way that the strong frequencies of one fill in for the weaker frequencies of the other (Basinger, 2006). There is no direct evidence of this in the extant research and such an effect is difficult to quantify and

objectively assess. Therefore, singers' formant modulation was favored as an operant variable in voice matching, given the large body of experimental results that already show it to be an active determiner of perceived blend, and the controversial implications of discouraging singers' formant production in the choral environment.

While placing the singers next to one another, as would be the case in a typical choral rehearsal, had tremendous advantage in duplicating the phenomena being studied, a huge problem remained: how to separate the recordings of the individual singers from one another such that each individual's vocal characteristics would not contaminate analysis of the other. Many acoustic professionals were consulted for help on this problem and several solutions were offered:

1. Move the singers farther apart. Since the research of Ternström (1994, 1995, 1999) suggests that an operant variable in choral performance is the self-to-other ratio of decibels, and the research of Daugherty (2003) confirms that altering this ratio through increasing distance between singers has a positive effect on choral blend, it was assumed that increased space would not only be inconsistent with how most choirs rehearse and perform, but would also serve to dilute the changes this study was designed to observe<sup>3</sup>. Therefore, this solution was rejected.

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<sup>3</sup> It may very well be that the self-to-other ratio is the true controlling variable accounting for most changes in choral blend, including the voice matching procedure. Thus, part of the genius of voice matching may lie in its ability to subtly manipulate the self-to-other ratio *without* changing space between the singers. This is a fertile subject for future research.

2. Place a barrier between the singers. This solution was rejected for the same reasons as #1.
3. Angle singers inward at a 45 degree angle in order to move each one's sound further from the axis of sensitivity of the other's microphone. This solution, once again, modifies the standing arrangement from what is typical within a choral rehearsal. Nevertheless, it was tested within pilot studies for use in case a more preferable solution could not be found.
4. Encase the microphones in a custom designed sheath of acoustic isolation foam to reduce pickup of off-axis sound. This solution was selected for pilot study.
5. Utilize shotgun microphones. These microphones are extremely directional and are of a design well suited for picking up far away sounds. They are commonly used to pick up the dialogue of actors in movies (usually covered with a large fuzzy wind screen) and the voice of the quarterback in football games. The audio technicians greatly disagreed over whether this would be an adequate solution. Some believed the directional qualities of the microphones would not be as effective at close range, and if used at far range, would be largely mitigated by the acoustics of the room (the other singer being picked up via reflection into the microphone's sensitive axis). Therefore, it was determined to pilot these microphones in a close configuration in order to compare them to standard cardioid microphones.
6. Utilize audio processing techniques to remove the sound of one voice from the recording of the other. Several techniques for accomplishing this were

piloted. Each of them, though seemingly mathematically valid, ultimately produced a sound that was sufficiently distorted so as to belie the idea that what remained was an accurate representation of the singer intending to be studied. Furthermore, the possibility of inadvertently removing tonal characteristics of the primary voice that happened to be very similar to the voice being removed could not be ruled out. Therefore, lest in gathering the weeds the tares be rooted up along with them, it was concluded that the best approach would be to focus on minimizing the signature of the other voice using the recoding technique itself.

Since acoustic isolation was an essential control for a study of this nature, it was thoroughly piloted (explanation below).

Besides the aforementioned reasons, study was limited to duets to reduce participant fatigue and preventing the data analysis from becoming too unwieldy. Investigating the phenomena at play with only two singers provides not only a solid basis from which the choral conductor may make many decisions, but also provides a solid foundation upon which further research may build. It also has the advantage of being of sufficiently limited scope as to enable the analysis to include every possible combination of the singers who participated, in both left-right and right-left arrangement. Such would not be feasible if trios were included.

### **Recording Device**

In choosing a recording device there were several considerations. The device needed to utilize a digital recoding format to facilitate ease of computer file transfer, subsequent acoustic analysis, and retention for potential additional analysis in future

studies. Because it was anticipated that significant piloting of recording techniques and strategies would be required, portability was an important factor. The advancement of digital recording technology was thus of great benefit to this study because it allowed for the creation of devices could be both extremely portability and also capable of exceeding the recording quality used in many previous studies of the phenomena in question.

Concordantly, it was decided that the device to be used in this study should be capable of recording in 16-bit, 44kHz WAV quality (many record only in MP3 format). The requirement to choose between condenser microphones (which utilize a power supply from the device called “phantom power”) and dynamic microphones (which do not), within the pilot process, made it essential that the recording device be able to provide both functions. The device would need to be capable of simultaneous recording of at least four tracks to handle input from the close microphones of both singers individually, and left and right far microphones in stereo, in order to pick up the combined sound of the singers for blend assessment. It would also need to accept the XLR plug-in format common to the type of high quality microphones intended for use in the study.

Since the absolute volume of the recorded sound would be irrelevant to the analytical methods to be used in the study, and only the ratios between individual frequencies in the sound spectrum were important, the decision was made to utilize the recording device’s onboard gain auto-control function. Had this function been designed to adjusted left and right recording tracks individually, this would have caused inter-singer contamination. During pilot study, it was found that when using an independent track auto-leveling feature, if a more resonant singer was paired with a less resonant one, gain would automatically be increased on the less resonant singer’s track, leading to

greater pickup of reflected sound from the more resonant other singer. Thus, the device chosen for the study needed to be capable of simultaneous track auto-leveling calibrated to the loudest signal among the tracks.

The Zoom H4N was chosen among only a few potential devices on the market capable of meeting all these requirements. It was not only the most affordable and readily available, but also had a few added advantages, the most important of which being the inclusion of a very high quality array of onboard stereo microphones, whose directivity, polar pattern, orientation, and sensitivity were similar, and in many ways superior to, any which could be provided by external microphones. This feature thus not only decreased the costs associated with conducting the study, but also significantly simplified the recording technique. The utilization of onboard microphones of a digital recorder had been previously shown to be successful by Basinger (2006). Transferring recording files from the unit to computer was as easy as plugging in a USB cable and dragging-and-dropping onto the desktop. The H4N's two onboard XLT inputs were also able to receive ¼ inch cable input with no physical alteration, increasing the unit's versatility. An additional bonus feature was the device's marking feature, which enables the user to place digital markers on an ongoing recording in real-time, with a single push of a button. This was useful in locating the various singers' performances during post processing and separation of the recordings for analysis.



Figure 2. Features of the Zoon H4N Audio Recorder

## Microphone

Since it was important in this study to utilize a recording environment that was as similar as possible to that used in actual choral rehearsal, a significant amount of reflected sound was anticipated. Therefore, a shotgun polar pattern was chosen for its ideal balance between limiting sensitivity to directional sound from the other singer, and limiting sensitivity to reflected sound. A microphone distance of three inches was identified during pilot study as the ideal range to both maximize the difference in volume between the intended and other singer and also preclude the possibility that particularly resonant singers would inadvertently overdrive the transducer. Since the ratio of lower to upper frequencies of the singers' voices was a key variable in this study (SPR), the Neumann KMR 82i (long shotgun microphone) was selected because its directivity remains relatively unchanged as frequency increases. An additional advantage to the KMR 82i was its relatively flat frequency response, which enabled a quantitative analysis that was truer to the way in which human ears assess performance.

High pass filter was switched off in order to keep the frequency response as flat as possible. Robust shock mounts were utilized instead to partially offset any rumbling transmitted through ground vibration or microphone stand resonance. Since recording portions were only ten seconds long, noise contamination could be dealt with by re-recording.

The high frequency enhancement feature was switched off since high frequencies would not be attenuated due to the close placement of the microphone, and the distorting effect of sibilants would more likely be encountered at such a close placement. To further mitigate potential sibilant distortion, windscreens were utilized.



*Figure 3. Neumann KMR 82 i (long shotgun microphone)*

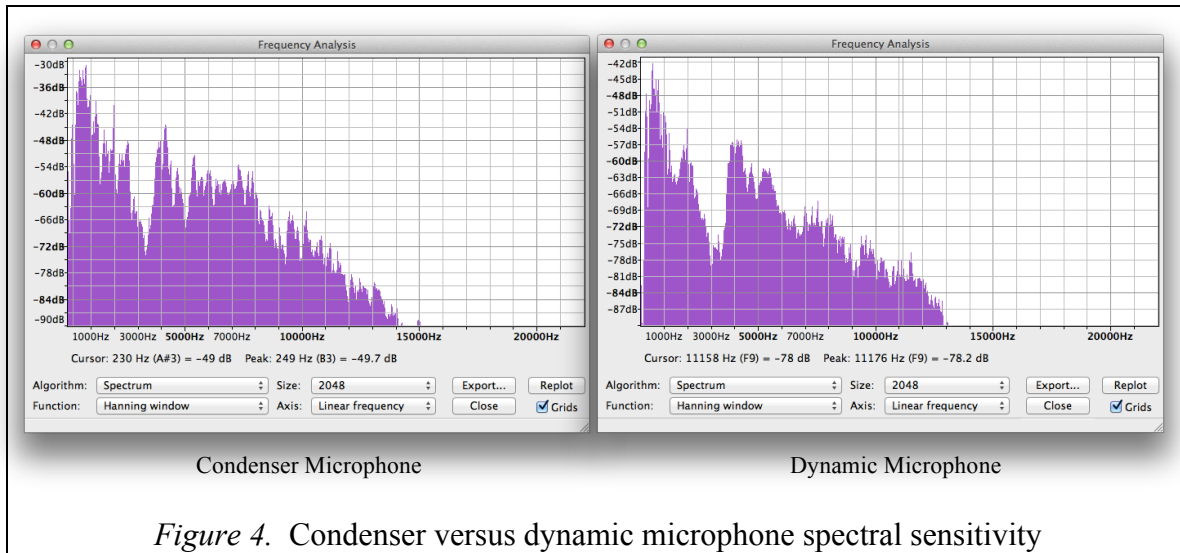
### Pilot Phase 1: Choice of Equipment and Analytical Techniques

The purpose of the first phase of pilot study was to determine how data would be collected, processed and analyzed. The following goals were undertaken and successfully achieved:

1. A determination was made as to what equipment should be used and how it would be utilized.

2. Potentially confounding variables were identified and assessed. Appropriate corresponding methods for control were devised, evaluated, and proven adequate.
3. Determination was made as to what type of data analysis would be most effective to answer the main questions of the study.
4. The analytical techniques chosen were explored and refined; and procedures and tools were developed to make them as efficient as possible.

**Dynamic versus condenser microphones.** Condenser microphones were compared to dynamic microphone. Dynamic microphones contain a smaller baffle, do not utilize phantom power, and are significantly less expensive. Dynamic microphones were found to have significant sensitivity roll-off as frequency increased and did not pick up any partials above 13 kHz. Condenser microphones, however, recorded partials as high as 15 kHz and had a higher recorded level under controlled recording of the same sound. An increase in Singing Power Ratio of 2-4 dB was observed when using a condenser microphone as compared to a dynamic microphone. Therefore, it was predicted that the increased sensitivity of condenser microphones to higher frequencies would lead to larger observed changes in the singers' formant range of 2-4 kHz, enhancing statistical significance of study results. These data were observed with a small sample, and inter-sample spectrum variation was not controlled. However, since most of the studies of singing power ratio have utilized condenser microphones, these observations needed not be conclusive, but merely provide cursory justification for the additional cost of purchasing and utilizing condenser microphones. The primary motivation for consideration of dynamic microphones was their lesser expense.



**Microphone distance.** For the individual microphones, 36 inches was compared to 24 inches. No significant difference in singing power ratio was observed. Therefore it was concluded that microphone placement could be up to 36 inches without influencing calculated SPR. The question of what distance would be ideal for the purpose of sound isolation was to be subsequently undertaken in phase 3 of pilot study.

Since it was deemed to be the most organic to what would occur in an actual choral rehearsal, placement of the combined sound microphones (onboard the digital recorder) in the typical position and distance in which the conductor stands to make voice placement judgments was examined and determined to be sufficient.

**Controlling for inter-sample volume changes.** Attempts were made to discover a method of controlling for inter-sample singing volume change as a potential confound of singers formant dB levels. Several methods of audio normalization were investigated:

Peak normalization. This post-processing technique brings the largest dB frequency down to a prescribed level, but leaves the rest of the spectrum untouched. Since the largest frequency peak is always the first or second formant, this would

artificially inflate singing power ratios as this level is compared to those in the singers' formant frequency range. Therefore, peak normalization was rejected as a viable control.

Loudness normalization. With a goal of making the sound seem balanced to the human ear, this technique adjusts individual frequency peaks to match a level that presumably matches the frequency sensitivities of the human ear. This was rejected due to its rampant interference with formant ratios.

Volume normalization. After the failure of the other two techniques of normalization, this was investigated as a potential alternative. Volume normalization as a technique may include any number of different algorithms which each have strengths and weaknesses that make them more or less effective in achieving overall goals. Algorithms that utilize root mean square (RMS) analysis to measure the overall energy of the sample, and then adjust it to match a user-defined level, were selected for evaluation. This method was the best potential choice because it did not adjust the ratios between the various frequency peaks. However, the amount of adjustment necessary to achieve an equal volume between multiple samples is not standardized, and is ultimately based upon the subjective opinion of the user, who must listen, adjust, and listen again until the samples seem equal.

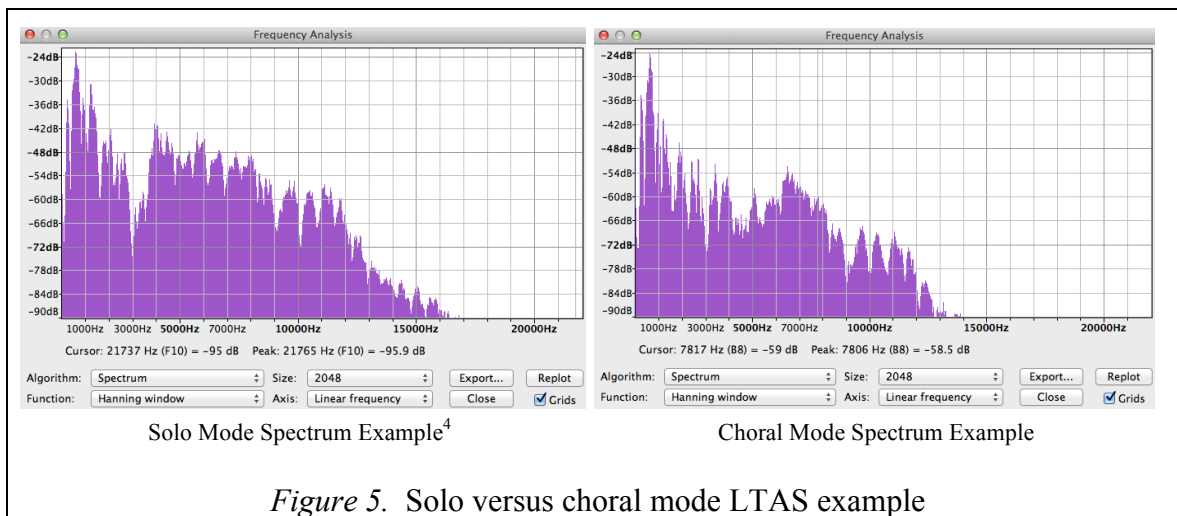
Because any kind of signal processing is a potentially confounding interference variable, and no ideal means of controlling for inter-sample volume change could be found, the possibility of abandoning dB level comparison as a analysis method was considered and favored. Therefore, an alternative method of quantification of singers' formant intensity was sought.

**Singing Power Ratio.** This measure was investigated as a possible alternative to looking at dB levels in order to control for volume variability. Because SPR compares the ratio of the highest peak within the lower formant range of 1-2 kHz to the highest peak within the singers' formant range of 2-4 kHz, inter-sample volume is rendered irrelevant. It is the *ratio* that is significant in SPR, not the absolute dB values. SPR is a well-established method of analyzing singers' formant intensity. This method of analysis was tested on several samples and found to be effective, regardless of volume changes.

**Salience of vocal mode changes within the SPR measure.** SPR had been established as an effective control for volume variability. However, it remained to be seen whether it was capable of detecting the vocal changes this study intended to investigate. This was examined.

SPR was calculated for a single subject singing in solo mode and then again in choral mode. SPR for solo mode was found to be 18.3. Choral mode was found to be 25.9. The change in SPR from solo to choral mode was 7.6. Examination of solo spectrograms of this particular subject revealed that the singers' formant was in the 4 kHz range, yet the highest peak in the typical 2-4 kHz range used to calculate SPR for the choral mode sample was at 2.7 kHz. Thus the SPR calculation was clearly not calibrated to this specific vocalist's singers' formant. Therefore, for comparison, the SPR calculation was modified to focus more specifically on this singer's demonstrated singers' formant frequency of just over 4 kHz limit. This yielded a SPR of 30.8. Given this calculation, the change in SPR from solo to choral mode for this subject was 12.5. It is relatively easy to determine where a vocalist's singers' formant lies from analysis of solo recordings. Therefore, use of a modified SPR calculation that focuses on a particular

vocalist's singers' formant frequency was considered for this study. It would need to be seen whether the level of training and/or singers' formant prominence in the individual singers who would participate in this study would affect the feasibility of calculating SPR in this manner before making a final determination. When the main study was conducted, visual inspection of the spectrums of the participants revealed that a custom-designed SPR was not necessary – the highest singers' formant peak of every participant was within the 2-4 kHz range. This is likely because the subject used for pilot phase 1 testing was a *leggiero*, with the unique spectrum characteristics typical of this voice type which placed his singers' formant just above the 4 kHz limit of typical SPR calculation.



**Sound isolation.** It had previously been established that precluding inter-singer contamination of voice spectrum analyses was a goal best pursued through the recording

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<sup>4</sup> The highest singers' formant peak of this singer occurred just barely above 4 kHz, but is not readily observable in this spectrogram due to it exceeding the resolution capabilities of the software for visual output. It was quantifiably observed when the spectrum analysis was exported numerically.

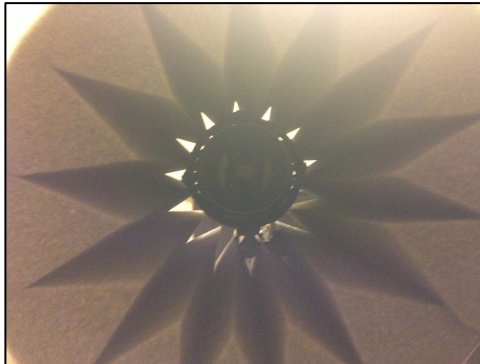
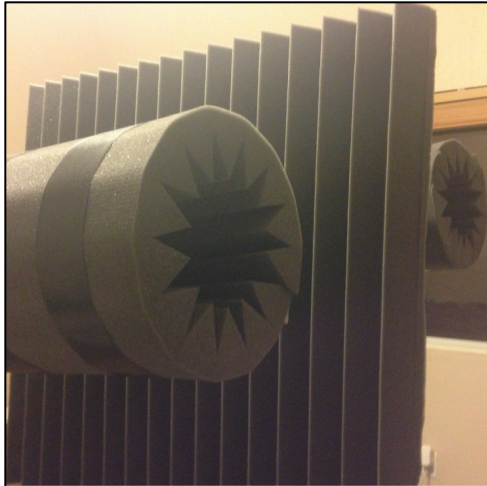
techniques themselves, rather than through signal post processing.<sup>5</sup> As mentioned earlier, two recording techniques were suggested in consultation with sound professionals for examination in pilot study: 1) placing the singers at a 45 degree angle from each other in order to further offset each of their sound vectors from the axis of sensitivity of each other's microphones,<sup>6</sup> or 2) surrounding each microphone with a custom-made sheath of acoustic foam to absorb off-axis sound. The first was less preferable due to it modifying the procedure from how choirs normally sing and perform. Therefore, it was determined that this solution would only be pursued if the second proved ineffective.

Therefore, a setup for off-axis sound absorption was designed, constructed, and tested. The design featured tightly bound sheaths of acoustic foam, a modification to the shock mounts to act as both a vibrational barrier between the sheaths and the microphones and a mount for the sheaths themselves, and a vertical panel of acoustic isolation foam placed between the microphones, but not the singers (see insert).

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<sup>5</sup> See remarks on Design Background earlier in this chapter.

<sup>6</sup> The option of leaving the singers directly abreast of each other while placing the microphones in the center angled 45 degrees away from center toward each singer (thus creating a 90 degree angle between the microphones) was rejected. While this had the benefit of removing the other singer's sound further from the axis of sensitivity of each microphone, it also moved the intended singer's voice to 45 degrees off center. Thus, any benefit gained was nullified.



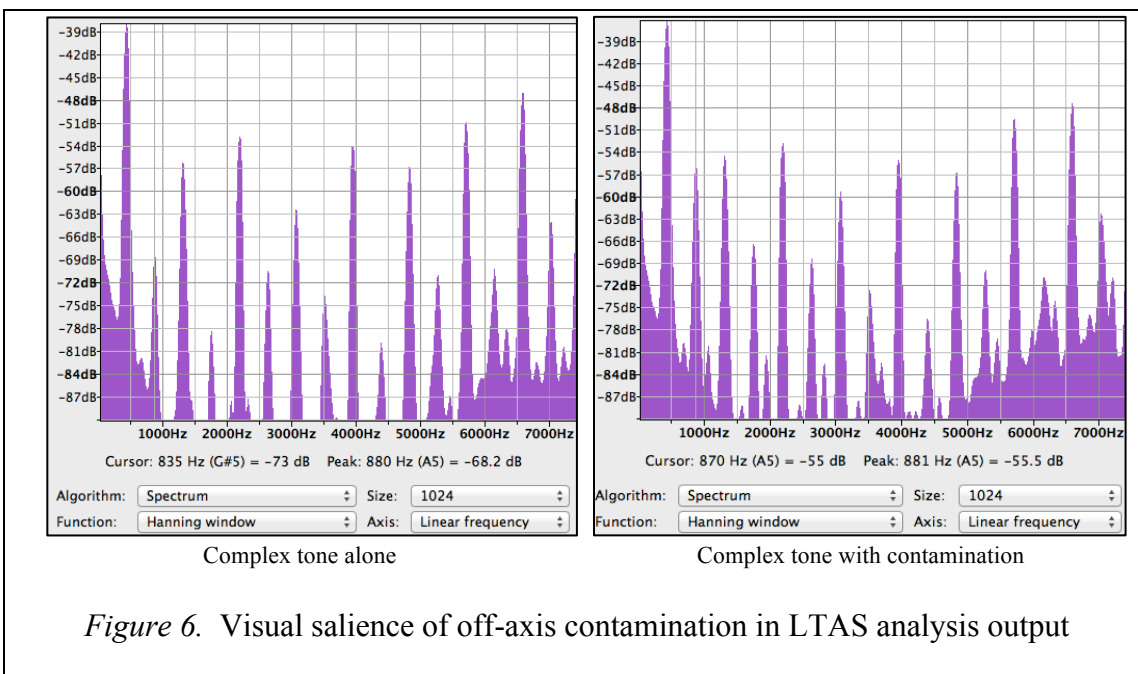
Sound professionals were in disagreement as to whether the foam sheaths would help or hinder, with some asserting that the physics of microphone cardioid patterns are such that in order for off-axis sound to be effectively rejected, it must arrive at the microphone unimpeded. Quite counterintuitive, advocates of this view essentially predicted that by deadening off-axis sound, the sheaths would actually make the microphones pick up *more* of the other singer rather than less. This highlighted the need for testing.

Testing was commenced with vocalists using standard condenser cardioid microphones. Results showed the sheaths had no effect on how much the microphones picked up the other singer. Furthermore, the placement of absorptive material so close to the singers themselves proved to have a readily discernable effect on the acoustic feedback each singer received from reflected sound, thus altering the way they heard both themselves, and each other. Therefore, the use of acoustic sheaths was rejected as a sound isolation solution.

Analysis of the voice spectrum of the singers in this test seemed to suggest that contamination was not occurring, however, this was inconclusive. Therefore a more controlled test was undertaken, utilizing two complex tones, played from the onboard

speakers of two iPhone's. The spectrums of the tones chosen were the inverse of each other, with peaks in each having little acoustic energy in the other. In this way, the degree to which the tones contaminated each other's spectrum analysis could be easily evaluated and quantified.

The largest area of contamination was in the low frequency area at 880 Hz where contamination caused a 10 dB increase in volume from -68 to -56 dB. However, the largest adjacent peak at 443 Hz was -36 dB. Because SPR is not calculated from difference peaks, but the same ones, this amount of contamination from the other sound source proved to be not enough to add significant acoustic energy to the overall dB measurement, and thus would not likely alter SPR (recall that the dB is log-rhythmic). However, the visual presence of contamination suggested that additional methods of isolation should be pursued, including the use of shotgun microphones.



The goals of the first phase of pilot testing were achieved. Therefore the next phase could be initiated, wherein the data collection procedure and analysis could be tested on a larger sample set, in an actual voice placement process.

### **Pilot Phase 2: Testing**

The purpose of the second phase of pilot study was to test the equipment chosen in phase 1, refine data collection procedures, validate controls, refine analytical methods, and establish preliminary statistical significance of results. Three males and three females were recorded singing in every possible combination within their respective genders, in both left-right and right-left configurations. Analysis techniques for SPR, vibrato extent, and vibrato rate were conducted and proven effective. Variation was found in all three variables of sufficient quantity to suggest the hypothesized phenomena were indeed in operation under the experimental conditions.

Inter-singer contamination of individual audio samples followed expectations previously established in phase 1 pilot testing. However, the unintended singer's voice was slightly salient when listening to the individual recordings, further highlighting the need to explore the use of shotgun microphones to further isolate in phase 3 pilot testing. Singers were placed at approximately 9 inches from the microphones. The larger distance was required to preclude the presence of the acoustic sheath from altering singer perception of natural reflected sound. Because the acoustic sheaths proved ineffective at further isolating the individual singers' sound from one another's microphones, the sheaths could be removed and the singers moved closer to the microphones in future recordings. The ideal closer distance would be determined in phase 3 testing.

For the purpose of SPR calculation, the spectrogram function in the Audacity software program was utilized. However, during this process it became apparent that the resolution of the visual spectrographic analysis exceeded the size of a single pixel on the computer monitor. This made it impossible to place the cursor on the loudest peak at times, making it impossible to obtain exact dB ratings. Furthermore, under certain circumstances, the loudest peak was invisible, which necessitated having to systematically move the cursor across the spectrogram hunting for the loudest dB reading. Alternate methods of obtaining this data from the Audacity spectrogram “export” function were thus explored and found sufficient.

### **Pilot Phase 3: Singer Isolation**

The purpose of the third phase of pilot study was to devise, test, and validate solutions to the singer isolation issues revealed during phase 2 testing. Audio engineers at Action Audio in North Hollywood, CA were consulted and several test recordings were made at their warehouse facility in North Hollywood, CA. The use of the warehouse was chosen as a recording environment due to its high level of reflected sound and background noise. If effective sound isolation could be achieved under these circumstances, future effectiveness within a standard choral rehearsal room could be safely assumed. The Neumann KMR 82i (long shotgun microphone) was used for all recordings. Multiple microphone distances, distances between singers, and angles of singers both in relation to each other, and to the microphones, were explored.

Sound isolation was evaluated under recording conditions by observing signal levels in a microphone placed at the position of the intended singer while a vocalist sang from the position of the unintended singer. This microphone was moved in real time as

the unintended vocalist sang, in order to observe how potential configurations would positively or negatively affect the amount of contaminating sound recorded. A microphone distance of 3 inches was identified as ideal for minimizing the recorded level of the unintended singer relative to the intended singer, while also precluding any potential overdriving of the transducer that could be encountered with particularly resonance voices.

A microphone angle of approach of 45 degrees vertical axis, 0 degrees horizontal axis was found to be ideal for both minimizing recorded level of the unintended singer in relation to the intended singer, while also precluding sibilant popping or altering of the singers' perceived reflected sound via the foam windscreen. This angle was also preferable due to its less-ostentatious approach; it did not seem to interfere as much psychologically with the singers, thus aiding them in performing the way they normally would in choral rehearsal.

A distance between singers of 24 inches was found to be ideal in maximizing the effect of the singers upon each other. This distance was also chosen because it more closely reflected typical distances found in choral performance and controlled for the effect of increased space between singers observed in Daugherty (1999, 2003).

Utilizing the factors described above, the contaminating sound level was demonstrated to be considerably less than levels measured during phase 2 pilot study and was not salient when listening to the recordings. It was therefore concluded that the sound isolation techniques finally achieved through pilot testing were successful in controlling for inter-singer contamination.

## **Main Study**

Data collection. 14 singers (8 males and 6 females) were recruited from the auditioned choral ensembles at a major research university. Singers had varying levels of choral experience and private vocal training and were of various voice types and choral parts. All had singers' formant peaks between 2 and 4 kHz.

Data collection was conducted in a small rehearsal room at the university, within which the participants were accustomed to rehearsing. Individual singer microphones were placed in such a manner that the axis of sensitivity was oriented at a 45 degree vertical angle, directly toward the juncture of the back wall and ceiling of the room, with the singer's mouth intersecting that line at a distance of 3 inches from the microphone (including wind screen). This angle aided in the prevention of sound from inadvertently entering the small acceptance angle of the microphone via reflection off the back wall or ceiling. To further prevent this, absorptive material was placed on the wall surfaces immediately behind and in front of the singers. This material also served to dampen the room acoustics to what they would have been had the room been occupied by a full ensemble (wherein additional absorption would have been provided by the choir member's bodies). Thus, the acoustic environment was closer to that to which the participants would have been most accustomed.

Two tape markers were placed on the floor to serve as guides for the singers to position themselves during data collection. These markers were placed 24 inches from one another. The microphones were oriented accordingly. Singers were instructed not to touch the microphones and the small adjustments required to accommodate height differences among the participants were made solely by research personnel. The 3-inch

singer distance from the microphones was maintained and verified using tape measure. Researchers visually ensured the singers maintained proper distance throughout data collection.

A 24" x 24" acoustic barrier, constructed by draping a blanket over a music stand, was placed between the microphones, to further aid in eliminating off-axis sound contamination. The barrier did not physically contact the microphones or microphone stands in any way. Research personal and participants observed that the presence of the acoustic barrier did not significantly alter singers' perception of their own or the other singer's sound.

The group stereo microphones, onboard the recording device, were placed on a music stand at the position at which the conductor would normally stand. Researchers directed data collection from a piano located directly behind the recording device. The cue to sing was given by playing three successive staccato notes at G4 (392 Hz) on the piano, which communicated the key and tempo to be utilized. Research obtained the tempo by following the visual output of a silent metronome at the piano between each recording. All cues were given at 100 beats per minute, though singers varied in the degree to which they adhered to this tempo once they began singing. All singers sang the first phrase of "My Country 'Tis of Thee" in the key of G major ("my country 'tis of Thee, sweet land of liberty, of Thee I sing"). Participants filled out a survey prior to data collection that recorded their singing experience and demographic data.

After a test of sound recording levels, data collection began with the females. Each singer was recorded singing alone into the right side (from the singer's perspective) microphone in order to obtain baseline acoustic characteristics. An additional channel

recorded each singer's sound from the vacant microphone in order to provide data for assessment of inter-singer contamination. After all singers had been recorded as individuals, they were systematically recorded in pairs. After each pair had sung, their configuration was reversed (left switching to the right side, and vice versa) and they were recorded again. After this, a new singer was rotated in and the process was repeated. After all pairs and configurations had been recorded, each singer was recorded singing alone a second time, this time into the opposite microphone (the left) to provide additional baseline individual acoustic characteristics data and assess contamination. This concluded data collection for the females. At the encouragement of researchers, most of female participants remained in the rehearsal room in order to keep the acoustic conditions constant for the males. Male data collection then proceeded in exactly the same fashion as for the females.

**Blend Assessment.** For the purposes of establishing the relative success or failure of the voice matches, a panel of 48 professional choral conductors and student conductors was recruited. An online survey was written using QuestionPro web software that enabled the conductors to take the survey at their own leisure using personal computer or web-capable smart phone. The data collected via the stereo group microphones on board the digital recorder were converted to MP3 format with a bitrate of 256 to enable ease of web access. The first portion of the survey collected general demographic data. In the second portion of the survey, the conductors were presented with all the group recordings of one gender, followed by those of the other. The order of presentation of the genders was randomized, as was the order of the recordings within each gender's respective screen. Conductors were asked to rate each sample in terms of

blend on a 7-point Likert scale, with 7 being the “best” and 1 being the “worst.”

Conductors could listen to the samples as many times as they wished and change their answers at any time. All the samples of each gender were presented on the same survey window. Conductors were instructed to rate the samples only in comparison to each other, not to any external standard, such as their own choir, and were advised that, in so doing, there should therefore be at least one “7” rating and one “1” rating. The survey took approximately 30-45 minutes to complete.

### Acoustic Voice Matching Blend Assessment

8%

[Exit Survey](#)

Dear Colleague,

You have likely heard of acoustic voice matching. This process, originally championed by Weston Noble, is designed to yield a standing order that will (among other things) allow singers in your choir to use their full resonance without compromising group blend. Many conductors agree that the process works, but there is currently little scientific data on why.

We ran 8 males and 6 females through an acoustic voice matching procedure while collecting individual vocal data to see how they were changing their technique in response to the various pairings. Now, with your help, we will link those vocal changes to how well the singers blended.

You will rate the blend of some male and female duets singing a 10-second snippet of "My Country 'Tis of Thee." Rating will be done using a 7 point scale, with 1 being the WORST among the pairs and 7 being the BEST.

Thank you very much for your time and support! To start the survey now click the CONTINUE button below.

[Continue](#)

### Acoustic Voice Matching Blend Assessment

58%

Questions marked with an \* are required [Exit Survey](#)

**Your personal information is confidential and will be used solely for analysis purposes and to communicate study results to you, once published.**

First Name:

Last Name:

Email Address:

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**Date of Birth**

Month Day Year

---

**Gender**

Male

Female

---

**Are you a professional choral conductor or choral music educator? \***

Yes

No

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**Are you a choral conducting or choral music education student? \***

Yes

No

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**Were you present during any portion of the making of the recordings used in this study? \***

Yes

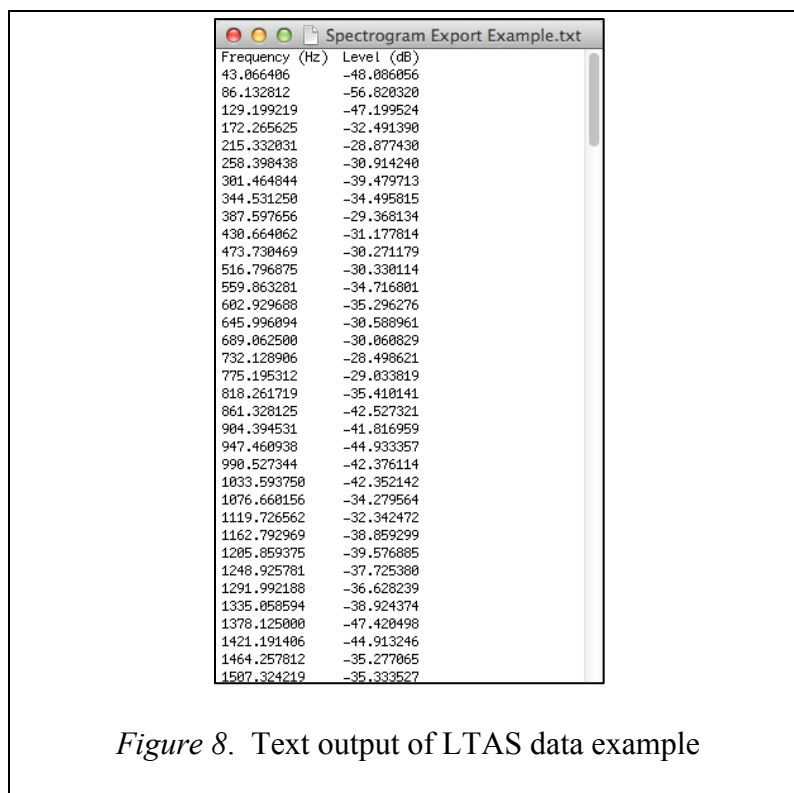
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frequency examined, with its corresponding average dB level. Spectrographic results were exported for every sample and a computer program was written using the OSX 10.7.5 program “Automator” in order to examine the samples sequentially and export the data to spread sheet. An array function was written in Microsoft Excel to identify the maximum dB levels between 0-2 kHz and 2-4 kHz, subtract one from the other to calculate SPR, and export the results for further analysis. This identification method vastly improved both the efficiency and accuracy of the SPR analysis process used during pilot testing.



**Vibrato Analysis.** Vibrato extent was calculated for each sample using Praat voice analysis software. The pitch display function was utilized and calibrated to display the fundamental. Once displayed, the individual syllables of the sung phrase could be easily determined. The three longest sustained vowels of the phrase were used for

analysis in all samples, all of them [I] vowels: “tis,” “li” (in “liberty) and “sing.” These vowels were isolated and the number of vibrato cycles was visually counted. A script was written for Praat that would, given the number of vibrato cycles for each sustained vowel of the sample, calculate the distance in semitones between the minimum and maximum frequencies of the vibrato and output that average value of all three sustained vowels in the sample. The script also determined the duration of each sustained value and, using the previously inputted number of vibrato cycles, calculated the vibrato rate and outputted the average of all three sustained vowels in each sample.

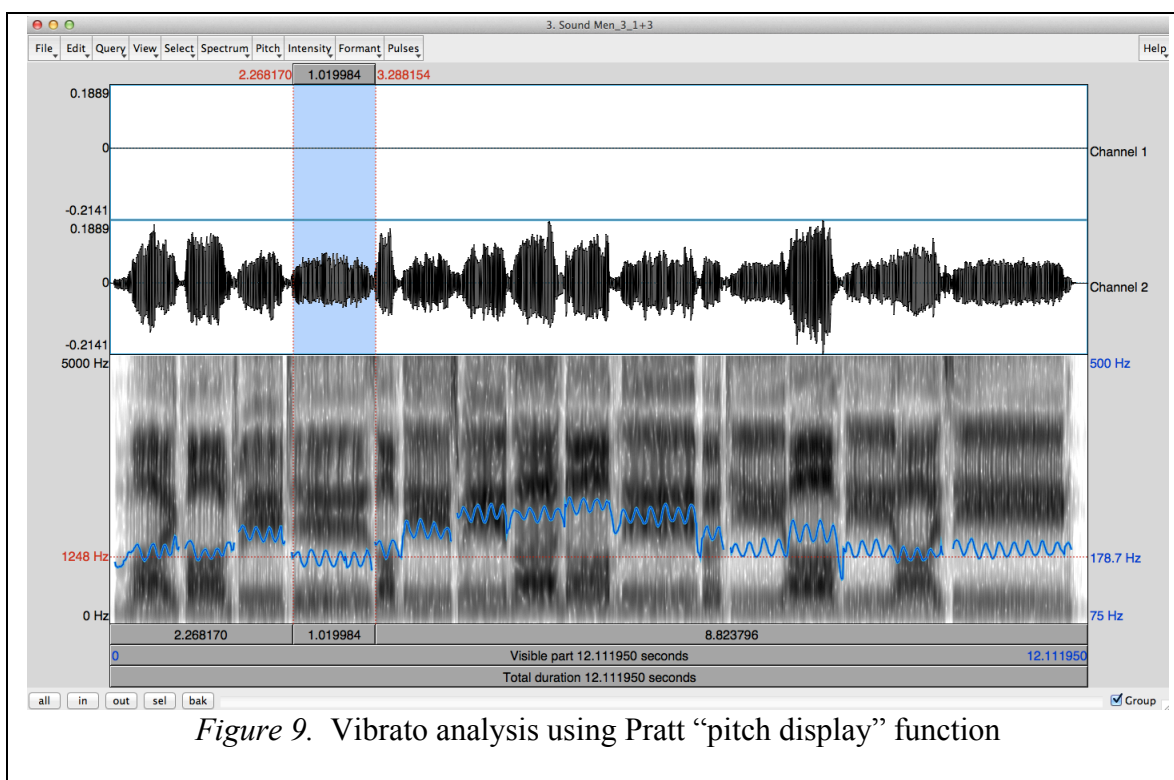


Figure 9. Vibrato analysis using Praat “pitch display” function

**Statistical Analysis.** Additional variables were calculated from Blend, SPR, Vibrato Rate and Vibrato Extent. All variables were inputted into the statistical analysis program SSPS, along with demographic data, and analyses were conducted.

## Chapter 4: Results

### Descriptive Statistics

Fourteen total participants took part in the singing portion of the study. Eight of the participants were male while the remaining six participants were female. Baritone was the most-frequent voice type (four) while bass was the most-frequent voice part (five). Frequencies and percentages for participant demographics are presented in Table 1.

Table 1

*Frequencies for Participant Demographics*

Demographic	<i>n</i>
<u>Gender</u>	
Male	8
Female	6
<u>Voice type</u>	
Baritone	4
Bass	1
Mezzo	3
Soprano	3
Tenor	3
<u>Voice part</u>	
Alto	3
Bass	5
Soprano	3
Tenor	3

Participants were an average of 23 years of age, with an average of 5 years of private voice instruction and 13 years experience singing in choir. Means and standard deviations for participant demographics are presented in Table 2.

Table 2

*Means and Standard Deviations for Participant Demographics*

Demographic	<i>Min</i>	<i>Max</i>	<i>M</i>	<i>SD</i>
Age	18	37	23.29	5.21
Years of lessons	0	21	5.46	5.49
Years in choir	4	23	12.79	6.00

Data were collected on the pairs of singers. Data were collected on vibrato rate, vibrato extent, SPR, and blend. The differences between the vocal characteristics for the singers in each pairing were calculated (vibrato rate difference, vibrato extent difference, and SPR difference). Each singer's deviation from his/her average solo characteristics was calculated. Positive and negative numbers represent increases and decreases from solo characteristics. Table 3 presents the minimum, maximum, mean, and standard deviation for each of the collected and derived variables used in subsequent analysis.

Table 3

*Minimum, Maximum, Mean and Standard Deviation for Singing Data*

Singing variable	<i>Min</i>	<i>Max</i>	<i>M</i>	<i>SD</i>
Right vibrato rate	3.20	6.60	5.73	0.51
Right vibrato rate deviation from solo	-1.57	+0.52	-0.16	0.27
Left vibrato rate	4.56	6.51	5.73	0.43
Left vibrato rate deviation from solo	-1.16	+0.30	-0.15	0.26
Vibrato rate difference between singers	0.06	1.98	0.50	0.31
Right vibrato extent	0.30	1.31	0.74	0.26
Right vibrato extent deviation from solo	-0.32	+0.27	-0.01	0.12
Left vibrato extent	0.28	1.37	0.75	0.27
Left vibrato extent deviation from solo	-0.27	+0.25	0.00	0.11
Vibrato extent difference between singers	0.02	0.95	0.29	0.18
SPR difference between singers	0.07	12.96	4.75	3.52
Right SPR	5.39	27.47	14.94	5.25
Right SPR deviation from solo	-5.67	+6.79	0.31	2.79
Left SPR	5.88	25.33	14.42	4.88
Left SPR deviation from solo	-6.35	+5.07	-0.21	2.49
Blend rating	1.92	6.21	4.11	1.10

Five analyses of variance (ANOVAs) were conducted to assess if blend rating was significantly different by gender, voice type, and voice part (treating right and left position separately). The results for the ANOVAs showed no significant difference in blend rating by gender, voice type, or part. Table 4 presents the results of the ANOVAs.

Table 4

*ANOVA's on Blend Rating by Gender, Voice Type, and Voice Part*

Group	<i>F</i>	<i>df</i>	<i>p</i>
Gender	2.69	1, 84	.105
Right voice type	1.48	4,81	.215
Left voice type	1.58	4, 81	.188
Right voice part	1.05	3, 82	.374
Left voice part	1.08	3, 82	.363

Pearson correlations were also conducted to establish baseline relationships between age, years of lessons, years of choir, and blend rating. The results of the correlations showed significant negative correlations between blend rating and years of lessons ( $r = -.80, p < .001$ ). This suggests that as the number of years of lessons increased, blend rating tended to decrease. Results of the correlations are presented in Table 5.

Table 5

*Correlations for Age, Years of Lessons, and Years of Choir with Blend*

Demographic	Blend rating
Age	-.04
Years of lessons	-.80**
Years of choir	.08

*Note.* \*  $p < .05$ . \*\*  $p < .01$ .

### Research Question 1

Do certain natural characteristics of singers' voices enable them to blend more effectively? *Yes*: singers with greater vibrato extent tend to blend less-effectively and the more years of lessons singers have, the greater their vibrato extent tends to be.

A multiple linear regression was conducted to assess if singers' mean solo vibrato rate, vibrato extent, and SPR predicted their mean blend. Data were examined at the singer level, averaging left and right positioning across all pairs. Results of the linear regression showed significance,  $F(3, 10) = 5.59, p = .016, R^2 = .63$ , suggesting that solo SPR, vibrato rate, and vibrato extent together accounted for 63% of the variation in singers' mean blend scores. Significance was found for vibrato extent ( $B = -7.20, p = .014$ ), suggesting that as solo vibrato extent increased by ten cents, mean blend decreased by .72. Despite the small number of cases (14), the correlation was markedly strong, and thus able to produce statistically reliable results as verified by  $f$  testing. Results of the regression are presented in Table 6.

Table 6

*Results for Regression with Solo Vibrato Rate, Vibrato Extent, and SPR predicting Mean*

*Blend*

Source	$B$	$SE$	$\beta$	$t$	$p$	Part $r^2$
Solo SPR	0.01	0.08	.03	0.14	.892	.02
Solo Vibrato Rate	1.97	1.84	.24	1.08	.308	.10
Solo Vibrato Extent	-7.20	2.43	-.65	-2.96	.014	.47

In order to determine if the negative correlation between years of lessons and blend observed in preliminary analysis was a result of a relationship between years of voice lessons and the development of blend-adverse vocal characteristics, several Pearson correlations were conducted. Results of the correlations showed significance for years of lessons relating solo vibrato extent ( $r = .60, p = .023$ ) and paired vibrato extent ( $r = .65, p = .011$ ). This suggests that as the number of years of lessons increases, solo vibrato extent and paired vibrato tended to increase. These traits then tend to inhibit blend with other singers. No other significance was found throughout the correlations. Results of the correlations are presented in Table 7.

Table 7

*Pearson Correlations between Years Lessons, Years Choir, and Age with Acoustic Properties*

Property	Years of lessons	Years of choir	Age
Solo Vibrato Extent	.60*	.20	.02
Solo Vibrato rate	-.23	.10	-.01
Solo SPR	-.21	.35	.17
Paired Vibrato Extent	.62*	.16	.02
Paired Vibrato Rate	-.12	-.08	-.15
Paired SPR	-.23	.40	.17

*Note.* \*  $p < .05$ . \*\*  $p < .01$ .

## Research Question 2

Do singers change the acoustic properties of their sound when singing with someone versus alone? *Yes*: singers' natural vibrato extent, vibrato rate, and SPR are all affected by singing in duet.

Pilot testing suggested that singers affect each other in different ways depending on their acoustic characteristics, with some combinations inducing the same singer to increase while others induce a decrease. Given this observation, it was predicted that Pearson correlations between solo and paired measurements would show a misleading lack of significance as singers' increases and decreases in the various acoustic characteristics cancelled each other out in the statistical model. This indeed proved true. Therefore, for the purposes of answering this research question a one sample *t* test was utilized focusing on the degree of change.

Three one sample *t* tests were conducted to assess if there were significant differences in the acoustic properties when the singers were alone versus when they were paired with another singer. The data were examined at the individual singer level, assessing the differences between singers' vocal traits when singing solo versus paired. The absolute values of the differences were taken so that only the amount of difference was taken into account, and not the direction of change. The tests assessed if the absolute value of the differences was significantly different from 0.

Prior to analysis, the assumption of normality was assessed with Kolmogorov Smirnov (KS) tests. The results of the test showed only significance for vibrato rate ( $p < .001$ ), therefore a Wilcoxon signed ranks test was conducted for vibrato rate. Results of the *t* tests and Wilcoxon test showed significance for differences in all three acoustic

properties ( $p < .050$  for all). This suggests that when paired, the singers significantly changed their properties. Results of the one sample  $t$  tests are presented in Table 8, and results of the Wilcoxon signed ranks test are presented in Table 9.

Table 8

*Results for One Sample  $t$  Tests for Solo versus Paired SPR and Vibrato Extent*

Absolute difference between solo and paired				
Test value = 0.00				
Property	$M$	$SD$	$t(13)$	$p$
SPR	1.13	0.73	5.77	.001
Vibrato Extent	0.09	0.05	6.05	.001

Table 9

*Results for Wilcoxon Signed Rank Test for Solo versus Paired Vibrato Rate*

		N	Mean Rank	Sum of Ranks
SPRd – SPR Deviation	Negative Ranks	8(a)	4.50	36.00
	Positive Ranks	0(b)	0.00	0.00
	Ties	6(c)		
	Total	14		

*Note.*  $Z = -2.52, p = .012$ . (a)  $SPRd < SPR$  Deviation from Solo. (b)  $SPRd > SPR$  Deviation from Solo. (c)  $SPRd = SPR$  Deviation from Solo.

### Research Question 3

Is there a particular relationship of within-subject acoustic changes to perceived pair blend? *Yes*: as singers decrease their vibrato extent from their solo characteristics

perceived blend increases and when singers are paired with similar solo vibrato extents, they tend to decrease their vibrato extent, resulting in better perceived blend.

To examine this question a multiple linear regression analysis was conducted to assess if singers' average deviations from their solo traits when paired (vibrato rate, vibrato extent, and SPR) predicted blend. Positive and negative values were utilized, not absolute values, since the intention of the model was to evaluate the effect of increases and decreases on perceived blend. Data for the regression was averaged across each recording for the three vibrato segments. Because conductors normally observe a change in sound between left-right right-left configurations, these were treated as separate cases in the statistical model.

The results of the regression were statistically significant,  $F(3, 82) = 8.89, p < .001$ . Examination of the individual predictors revealed that vibrato extent deviation was the only unique and significant predictor of blend. As singers' increased their vibrato extent from their solo averages by ten cents, blend decreased by ( $B$ ) .59. No other predictors in the model were significant. Results of the regression are presented in Table 10.

Table 10

*Results for Regression with SPR Deviation, Vibrato Extent Deviation, and Vibrato Rate Deviation Predicting Blend*

Model	<i>B</i>	<i>SE</i>	<i>t</i>	<i>p</i>	Part $r^2$
SPR Deviation	0.02	0.06	0.39	.699	.00
Vibrato Rate Deviation	-5.90	1.23	-4.81	.001	.22
Vibrato Extent Deviation	-0.15	0.58	-0.25	.802	.00

*Note.* SPR Deviation = xyz, Vibrato Rate Deviation = abc, Vibrato Extent Deviation = ghi.

In question two it was observed that singers' natural vocal traits accounted for a large portion of the perceived blend they were able to achieve when paired. In order to examine within-subject acoustic changes without this effect simultaneously influencing results, an additional multiple linear regression was conducted to observe how vocalists' deviations from their mean acoustic traits affected deviations from their mean blend scores across all pairings. Utilizing singer's means across all their performances allowed statistical tests to be conducted without the singers' natural advantages and disadvantages influencing results.

Singers' mean blend scores across all pairings were calculated and the difference between their mean blend and the blend achieved in each particular pairing was calculated. This created a *deviation from mean blend* variable for each singer in each pairing. A multiple linear regression was then conducted correlating deviation from solo

traits (vibrato rate, vibrato extent, and SPR) and deviation from mean blend (with left-right and right-left treated as separate cases).

The result of the regression was significant for vibrato extent,  $F(3, 82) = 10.66$ ,  $p < .001$ ,  $R^2 = .28$ , suggesting that as singers decreased their vibrato extent from their mean across all pairings by ten cents, the blend they achieved in that particular pairing increased by ( $B$ ) .775. No other predictors were significant. Results of the regression are presented in Table 11.

Table 11

*Results for Regression with Deviation from Mean SPR, Deviation from Mean Vibrato Extent, and Deviation from Mean Vibrato Rate Predicting Deviation from Mean Blend*

Model	$B$	$SE$	$t$	$p$	Part $r^2$
Deviation Mean SPR	0.04	0.05	0.76	.449	.01
Deviation Mean Vibrato Extent	-7.75	1.40	-5.52	.001	.27
Deviation Mean Vibrato Rate	0.21	0.46	0.46	.647	.00

In order to determine if the vibrato changes experienced by singers when paired was associated with the degree of match between their natural vibratos, a Pearson correlation was conducted between the difference in the solo vibrato extents of the singers in the pair and the mean vibrato extent deviation (increase or decrease) each singer in the pair experienced. The results of the correlation were significant,  $r = .48$ ,  $p < .001$ . This suggests that when singers were paired with other singers with whom they had a dissimilar vibrato extent, they tended to respond by increasing their vibrato extents,

and conversely, when singers with similar vibrato extents were paired, they tended to reduce their vibrato extents.

#### **Research Question 4**

Does the acoustic match between personnel contribute to blend? *Yes*: the more similar singers' vibrato extents are, the better the perceived blend.

To examine research question four, a linear regression was conducted to assess if vibrato rate difference, vibrato extent difference and, SPR difference predicted blend.

Data for the regression was averaged across each recording for the three vibrato segments, and left-right right-left were treated as separate cases. Normality and homoscedasticity were assessed using scatterplots and the assumptions were met.

Results of the linear regression were significant,  $F(3, 79) = 10.53, p < .001, R^2 = .29$ . Examination of the individual predictors indicated that the difference in vibrato extent was a unique and significant predictor of blend. As the difference between singers' vibrato extents increased by ten cents, blend decreased by .311. This suggests that the closer in vibrato extent that the singers were, the better the blend was. No other predictors in the model were significant. Results for the regression are presented in Table 12.

Table 12

*Results for Linear Regression with SPR Difference, Vibrato Rate Difference, and Vibrato Extent Difference Predicting Blend*

Model	<i>B</i>	<i>SE</i>	<i>t</i>	<i>p</i>	Part $r^2$
SPR Difference	-0.01	0.03	-0.44	.660	.00
Vibrato Rate Difference	-3.11	0.58	-5.33	.001	.26
Vibrato Extent Difference	-0.12	0.34	-0.36	.719	.00

### Research Question 5

How do operant variables interact to determine the blend achieved by a pair of singers? Using the variables identified as active in previous questions, a multiple linear regression analysis was conducted to assess if singers' solo vibrato extent, solo SPR, difference in vibrato extent between singers while paired, and singers' deviation in vibrato extent from their solo scores while paired predicted perceived blend. Data were measured at the pair-level.

Results of the regression were significant,  $F(4, 78) = 20.90, p < .001, R^2 = .52$ . All four variables were significant predictors. Solo SPR had a positive relationship with perceived blend while solo vibrato extent and vibrato extent difference between singers had negative relationships. Solo vibrato extent deviation from solo also had a negative relationship, showing that as singers increased their vibrato extent, perceived blend decreased. As solo SPR increased by one decibel, blend also tended to increase by .05 units. As solo vibrato extent, vibrato extent difference, and vibrato extent deviation from solo decreased by ten cents, blend tended to decrease by .1, .23 and .737 respectively. Results of the regression are presented in Table 13.

Table 13

*Regression with Solo SPR, Solo Vibrato Extent, Vibrato Extent Difference, and Vibrato Extent Deviation from Solo Predicting Blend*

Model	<i>B</i>	<i>SE</i>	<i>t</i>	<i>p</i>	Part $r^2$
Solo SPR	0.05	0.02	2.58	.012	.08
Solo Vibrato extent	-1.01	0.33	-3.10	.003	.11
Vibrato Extent Difference	-2.30	0.49	-4.72	.001	.22
Vibrato Extent Deviation	-7.37	1.69	-4.36	.001	.20

### **Checks for Inter-Singer Contamination**

dB levels from the empty microphone collected during solo control recording were assessed. The dB levels of the highest peak between 0-2 kHz and the highest between 2-4 kHz were determined. These amounts were subtracted from the corresponding dB levels recorded by the intended microphone to determine how much contaminating sound had been removed from the other singer's microphone by the isolation procedures. This amount was averaged for all singers. The average contamination dB level was 12.99 dB for the 0-2 kHz band and 18.89 for the 2-4 kHz band. These energies stand in sharp contrast to those being recorded for the intended singer, suggesting voice power ratios of intended to unintended singer of 4.33 and 6.3, respectively. Considering that an increase of 3 dB equates to a doubling in power, this means that each singer's microphone captured intended sound that was approximately five times stronger than that of the unintended singer. Because decibels are not additive

in nature, but log rhythmic, this amount was not significant enough to alter spectral qualities in the analysis.

This was checked by further statistical analysis of SPR changes induced through singer pairings. If the sound of the unintended singer had been contaminating spectral analysis, it could be expected, for instance, that a singer with a high solo SPR would have consistently shown a lower SPR when paired with a low solo SPR singer (who's singers' formant resonance would have been picked up by the unintended microphone, inducing an SPR decrease through contamination).

For analysis, singers were grouped by Low SPR and High SPR. A paired sample *t* test was conducted to compare singers' average SPR with a Low SPR partner to those with a High SPR partner. Singers did not show a consistently diminished SPR when paired with a low SPR singer or consistently increased SPR when singing with a high SPR singer,  $t(27) = -0.09, p = .931$ . This lack of correlation suggests that the controls implemented were sufficient and that the residual inter-singer audio contamination present after isolation measures were implemented was not significant enough to affect analysis.

### **Conductor Evaluator Checks**

Conductor evaluators were grouped by age, gender, and the use of headphones in listening to the samples. ANOVA tests revealed no significant differences in blend assessments between the groups.

## Chapter 5: Discussion

The current study aimed to determine the relationship of the acoustic characteristics of singers performing in duet to perceived blend, in order to investigate the processes involved in voice matching. Singers were simultaneously recorded both individually and collectively as they performed in various pairs in both left-right and right-left configurations. These recordings were evaluated for blend by a group of choral conductors. The singers were also recorded performing as soloists. Statistical analyses were conducted to determine how individual vocal characteristics relate to perceived blend, as well as how voice matching affects this relationship.

Such examination was undertaken in order to provide information for choral conductors and voice teachers on how the act of singing in an ensemble affects students' vocal technique, for better and for worse, and to determine whether voice matching, which has enjoyed increasingly prevalent use in America's choral ensembles, actually enables singers to utilize their solo vocal technique without adversely affecting ensemble blend, as is proposed. This information may serve to de-mystify the phenomenon of vocal blend and enable conductors and voice teachers to partner more effectively in the vocal development of students. This chapter will summarize research results, discuss implications of the correlations observed (or lack thereof), suggest applications, address limitations, and provide suggestions for future research.

### **Predicting Blend**

This study revealed that, in the voice matching procedure, where singers are encouraged to sing with their natural voice, the blend of pairs is determined primarily by the relative blendability of the individual voices of which the pair is composed, to a lesser

degree the similarity of natural vibrato traits between the singers, and to a small degree changes in individual vibrato that occur in response to the difference in vibrato between the two singers. These variables accounted for 79% of the overall variability observed in blend.

### **Blendability of Voices**

Carter (2007) showed that the more years of lessons singers had, the greater their singers' formant prominence. Ford (2003) showed that audiences preferred a weak singers' formant in choral performance. The results of this study confirm both observations. The more years of private voice lessons the participants had, the greater their singers' formant prominence and the worse they tended to be assessed for blend. However, this study also revealed that vibrato extent had an even more prominent negative effect, being strongly correlated with diminished blend. Voices with a narrow natural vibrato and, to a lesser degree, a low amount of singers' formant resonance, were able to blend more readily with other singers. The manner in which these two vocal characteristics affected blend was, however, quite different.

The negative effect of vibrato was shown to be mitigated to a certain extent when the vibrato characteristics of the singers matched. In such a scenario, blend was never as good as that of singers with a narrower vibrato, yet a reasonably high degree of blend was attained. This suggests that it is very much possible for ensembles to attain acceptable blend, even though they contain singers with high vibrato, as long as pedagogical steps are taken to enable the singers to both match their vibrato envelopes and sing at the low end of their various ranges of natural vibrato extent.

It should be stated in pursuit of this goal, that researchers have noted the relative inability of the human voice to remain statically fixed on a given frequency and that some variation is always occurring. Vibrato therefore, may be a means of making the inevitable pitch variations of the human voice *regular* and thus enhancing the salience of a distinctly in-tune central pitch (Titze, 1991; Ternström, 1989). Consequently, the results of this study should not be taken to reflect straight tone singing as an ideal, but rather, small vibrato extent singing.

The manner by which singers' formant resonance affected blend was different than that of vibrato extent. The negative effect of high singers' formant resonance was *not* shown to be mitigated by matching, and increases in SPR from solo traits were not shown to correspond to better blend. This is contrary to the experience of many conductors, who note that singers' formant resonance is not necessarily a liability to blend as long as all singers are similarly resonating (Katherine et al., 2007; Fagnan, 2005).

The results of this study must be approached with caution and not taken as disproving this common observation. The difference in SPR between singers may become a statistically significant predictor of their perceived blend only when the number of singers performing together is larger than those used in this study. With only two voices singing together, similar *strength* in singers' formant may have been overruled by the unique *structure* of each vocalist's singers' formant in making his/her voice distinguishable (Sundberg, 1972; Bartholomew 1934). As more voices are added, the *structure* may become less salient, allowing SPR to emerge as a significant factor.

Clearly additional study is required to uncover the means by which singers' formant prominence affects blend, particularly in low vibrato extent singers. Replication of this study using a larger grouping of singers may reveal SPR difference between singers as a significant variable in blend.

### **Choosing Singers**

The results of this study suggest that choral conductors seeking to create the best blend possible, and having the luxury of selecting from a large pool of talent, would be best served by choosing voices that can healthfully perform with low vibrato extent (not straight-tone). In such ensembles, voice matching may not be necessary.

However, since voices with higher vibrato extent also tend to have more pronounced singers' formant resonance, which adds tremendous vibrancy and excitement to the choral sound (Fagnan, 2005), conductors must should seek to balance the quest for overall vibrancy with that for blend. Both goals may be achievable if singers who are capable of healthfully performing with a pronounced singers' formant, yet low vibrato extent, are recruited. For many American conductors having ready access to a large number of such singers would be a rare luxury. A more feasible alternative is for the conductor to achieve blend and vibrancy simultaneously through adopting a program of focused group vocal pedagogy that enhances singers' formant resonance while also diminishing vibrato extent while maintaining a healthy, relaxed, free vocalism.

When a conductor chooses to admit high vibrato extent singers, the best blend may be achieved by selecting singers whose vibrato extent, though large, is similar. Voice matching may offer the most benefit for ensembles composed of singers with such

dissimilar vibrato extents. The conductor may utilize a voice matching procedure during callbacks to determine which voices are most similar in vibrato extent.

### **Effect of Singers on One Another**

The power of vibrato characteristics in creating blend is something many conductors recognize and some even attempt to manipulate, both directly and/or indirectly (Smith & Sataloff, 2006). The question of “what to do with the singer with a particularly wide vibrato?” is addressed in any number of choral forums, from formal seminars, to questions asked during Q&A, to teaching/grading in adjudications, to practical considerations in preparing honor choirs. A common tenet observed by the researcher in performing with, and observing, jazz choirs is that, when singing a sustained pitch, vocalists are encouraged to begin by utilizing straight tone and, after a time, gradually bring in vibrato, taking care to synchronize in both pitch and rate with the other singers the entire time. Early music often involves similar artistic control of vibrato use. The average conductor will be acquainted with the (perhaps false) presumption that “renaissance should be sung straight tone while romantic should be sung with full vibrato” (Foster, 2007). The penchant of Scandinavian choirs for small vibrato extent singing (often with a very low SPR – a rare combination indeed) may be the key to their typically exhilarating tonal characteristics (Quist, 2008; Skelton, 2004).

While choral conductors are eminently aware of the power of vibrato to positively and negatively affect the sonority of their ensembles, voice teachers are quite aware of the power of vibrato manipulation to negatively affect vocal health (Olson, 2010, 68-77). They generally do not wish the vibrato or resonance of their students to be manipulated in the choral rehearsal. Therefore, an important goal of this study was to examine what

correlations exist, if any, between voice matching and these characteristics. Results showed that singers did not significantly affect one another's vocal production when paired.

Singers did not try to match one another in vibrato or singers' formant resonance. This shows that voice matching performed as advertised – for the most part, it did indeed enable singers to utilize their natural voice without destroying blend. Thus, voice matching is a great asset in the quest to unify the pedagogical objectives of choral conductors and voice teachers.

This is true with one exception: when singers with a large difference in solo vibrato extent sang together, rather than tending to change to match one another (as one might expect), they both tended to *increase* their vibrato extent. Conversely, when singers with a similar solo vibrato extent sang together, they reduced their vibrato extent. 57% of the variation in singers' vibrato extent was due to the pairings they experienced. This observation is likely the means by which voice matching accomplishes its work. Though it accounted for only 3% of the overall blend produced by the singers in this study, the effect may become more pronounced when multiplied over a larger number of singers, as would be the case in a typical choir section. Even with only two singers, this 3% was enough to be detectable to the raters and factored into their blend scores.

### **Means of Effectiveness of the Voice Matching Procedure**

These results suggest that encouragement of an overall diminished vibrato extent is the primary means by which voice matching works to increase blend. Though vibrato extent modulation only accounted for 3% of the overall blend score, in a given choir, where the blendability and vibrato extent difference of individual voices cannot be

changed, the effect of this 3% may be particularly salient. The effect may also increase as the number of singers increases. This is clearly a subject fruitful for additional study.

Accordingly, the positive effect of voice matching on singer comfort can be attributed to its placement of singers adjacent to others with whom they have the smallest difference in natural vibrato characteristics. 57% of the variation singers experienced in their vibrato extent was due to the vibrato extent characteristics of the singer they were paired with.

Results of this study seem to favor the following explanation for how the voice matching process proceeds: A model voice is chosen. As each singer is rotated into duet with this model voice, the one that demonstrates the lowest vibrato extent difference stands out as having the highest blend. This is because the low vibrato extent difference induces an overall decrease in vibrato extent among the singers in the pair. Thus, the best-blended duet is the one in which both singers have the smallest similar vibrato extent. Additional study with larger groups of singers may subsequently observe that as a third singer is rotated in to join the pair, the one with the next most similar vibrato extent tends to evoke the best blend from the trio.

Thus, the voice matching procedure is essentially an optimization algorithm for the discovery of an order that places the most dissimilar voices as far apart from one another as possible, with voices in between gradually spanning the difference. In such an arrangement each voice tends to find itself next to the voices to which it is most similar. The overall effect is to induce the section to produce the smallest vibrato extent of which it is naturally capable, with each singer performing at the low end of what is possible for him/her to accomplish without compromising healthy vocal technique.

### **Subconscious Vibrato Extent Modulation in Voice Matching**

The impetus for the use of the voice matching process is the desire to enable singers to use the same vocal production they utilize in solo singing in the choral environment, without destroying blend. Conductors and audiences rate voice-matched choirs as having better blend and singers have shown a preference for voice-matched standing arrangements, reporting greater vocal comfort and ease of singing (Ekholm, 2000). The procedure therefore seems quite successful.

Why might this be? A common assumption for the way in which the procedure accomplishes its positive effects is that it creates a physical arrangement of the singers that nullifies the acoustic aspects that makes singers' voices individually salient to listeners via constructive and destructive interference, enabling singers to perform with their natural resonance without fear of "sticking out" (Giardinieri, 1991). One of the primary objectives of this study was to examine whether or not this was in fact true.

Given that singers utilizing low vibrato extent in the choral environment are consistently rated as having better blend, and given the nature of the physics of sound wave propagation, it was the hypothesis of the author that voice matching achieves blend through a psychoacoustic effect, not a physical one – it *subconsciously* induces singers to decrease their vibrato extent. It was further hypothesized that the reason singers have reported greater vocal comfort in voice matched standing arrangements is not because they no longer needed to change their vocal production in order to blend, but rather, because they *felt* they no longer needed to change. The psychological effect of *feeling* free to sing with their natural voice was enough to enable them to have greater vocal freedom, even though they were actually decreasing their vibrato extent a bit.

The results of this study are consistent with this hypothesis. In all cases, vibrato extent was negatively correlated with blend and singers enhanced blend when they decreased vibrato extent from their solo characteristics. Speed of the vibrato had no affect on blend. This shows that voice matching is highly cohesive with the goals of voice teachers since it enhances blend not by *removing* vibrato, but by reducing its width. Thus performing in voice-matched configurations may allow singers to blend more effectively while still retaining the relaxing, voice-preserving effect of vibrato on the vocal musculature (Stark, 1999; Seashore, 1931).

These results therefore suggest that the negative vocal tension typically experienced by developing singers in the choral environment is not a result of the physiological modifications in vocal technique they must utilize to achieve blend, but rather, their *conscious perception* that such modifications are needed, particularly with regard to removing vibrato altogether, or manipulating its rate. When freed of this burden, they sing with greater vocal freedom and psychological comfort.

If this is true, another effect of the voice matching procedure is to create a standing order ideal for inducing a small subconscious vibrato extent reduction. It does this by keeping the necessary change in vibrato extent within a threshold small enough that it is unnoticed, being solidly within the natural range of what the singers are capable of doing healthfully, without changing their overall resonance or vibrato rate.

### **Vocal Technique and Perception of the Need to Blend**

This suggests that the assumptions about the vocal detriment of certain performance requirements or mediums may be more tied to the psychological effects of performing in those environments than the tonal requirements of the performance itself.

This is good news because it suggests that the apparent incompatibility between the vocal demands of the choral environment and those of classical singing are, after all, a myth, and that conductors and voice teachers can partner in pursuit of healthy vocalism without compromising either of their artistic or pedagogical priorities. It is not a particular tonal color that is the essence of vocal health, but rather, the ability to produce whatever sound the situation may demand, with a vocal technique that is always tension-free, supported, connected to breath, ever flexible, and supremely efficient. As the technique of singers solidifies and becomes more instinctual, the range of tonal qualities they can produce healthfully increases.

Voice teachers can therefore enable their students to enjoy all the positive musical growth to be had from choral singing, while minimizing the potential pitfalls, when they allow the above philosophical conviction to permeate their teaching. A distinction must be made elucidating which components of vocal technique must never be compromised, and which may be healthfully tuned to a particular performance situation. This type of training will not only serve singers well during their developmental years, but will also afford them the necessary vocal flexibility to be as marketable as possible, as the number of potential jobs increases with their ability to sing in multiple genres. They will have the confidence, technical solidarity, and psychological constitution to sing styles other than classical, should the situation require it – and do so *well*.

Along with voice teachers, choral conductors have much to contribute to the vocal health and development of developing vocalists. The results of this study suggest that the psycho-vocal state of ensemble members is of *paramount* importance to their ability to sing healthfully. Conductors do well to make the physiological singing process as

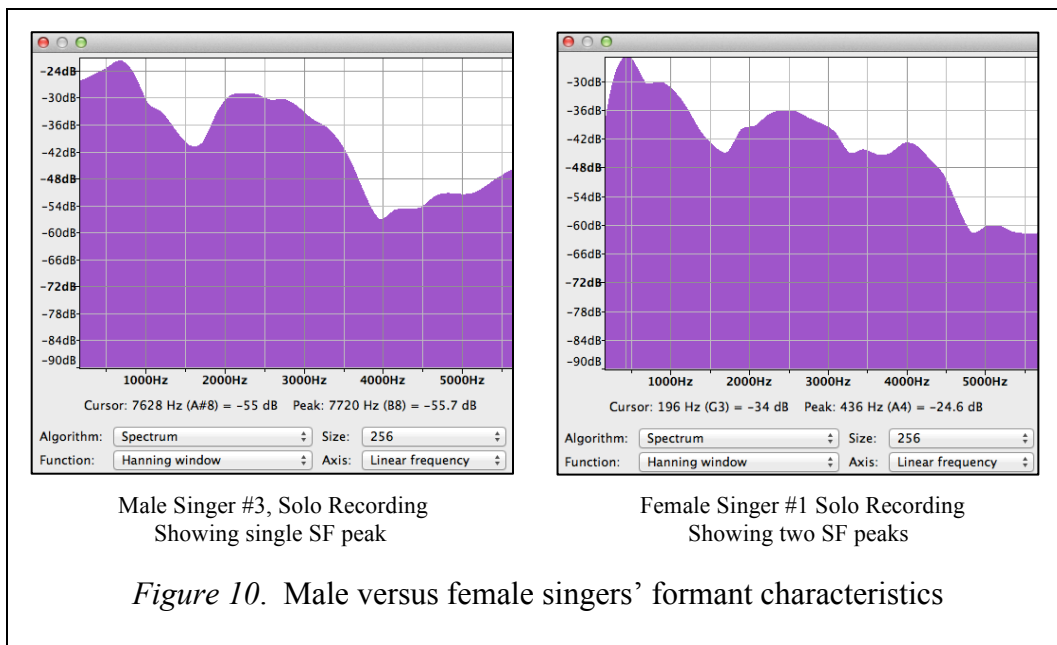
subconscious to choir members as possible and avoid giving the impression that they wish singers to alter their tone. In such a pursuit, the use of standing arrangement is one of a triumvirate of physical pedagogical tools the astute choral conductor may master and utilize to establish positive vocalism. The other two are conducting gesture and the use of physical gesture among the singers to enforce group vocal technique during rehearsal (Wis, 1993).

### **Soprano Voices and SPR**

Statistical checks showed that, among the singers, voice part, voice type, age, and gender showed no significant variation in the trends observed. However, the *strength* of correlation, in almost every case, was stronger in the men than in the women, who did not follow the trend as tightly. This is likely because of the unique spectral qualities of the soprano voice. Women's voices have a higher total power level than men's, due to the higher frequencies involved. As such, sopranos have been observed to require greater spacing to remain within the ideal ratio of hearing their own sound versus hearing the sound of their neighbors (Aspaas et al., 2004). It may be that by placing the women 24 inches apart in this study, a ceiling effect was observed in which the effect normally produced by the voice pairings was limited because, at that close distance, the non-ideal sound ratio trumped it. It may be that replication of this study with a greater distance between women (36 inches, for example) may yield stronger results.

Furthermore, soprano voices do not utilize the singers' formant in the same way that men do. Oftentimes, sopranos have two peaks instead of one and it is not clear whether these peaks are utilized and clustered in the same way as other voice types. Sopranos may utilize a process of tuning their formants harmonically to create

constructive interference that increases the amplitude of the sung sound, rather than employing a singers' formant as currently understood. SPR was utilized as a measure for soprano voices in this study because it is not subject to the shape or construct of the singers' formant in its ability to quantify the ratio between lower and upper partial peak dB levels. ER (see chapter 1 for an explanation) was not utilized since it has been shown to largely mirror SPR results in similar studies (Detwiler, 2008; Katherine et al., 2007). However, this different structure of upper partial energy may have been salient to the choral conductors, and they may have utilized it in their assessments of blend. Additional study is clearly required to determine how voice matching works to enhance blend in soprano voices.



### Automation of the Voice Matching Procedure

The implications of the high level of predictive power of the statistical models utilized in this study are noteworthy. It may be possible to automate the voice matching

procedure. The vocal characteristics of singers could be determined through solo recording. Computer software could be created that conducts acoustic analysis of the solo recordings and creates a standing arrangement using an optimization algorithm that places singers in the ideal order such that the difference between each singer's vibrato extent and those of his/her neighboring singers is smallest, except in the event that doing so causes total vibrato extent range of the section to be above a certain threshold. Several experimental algorithms were created and tested using the data in this study, with promising results.

### **Directions for Future Research**

This dissertation reveals several areas of fertile ground for future research. Most prominently, this study demonstrated the effectiveness of a simple method of acoustic isolation for the examination of singers in an ecological performance environment. With operant variables identified, and methods of analysis and data processing proven efficient and reliable, this study may now be replicated with larger groups of singers. Since the addition of singers vastly increases the potential combinations to record, the recording of a live voice matching procedure may be more feasible and afford greater ecology. The confounding effect of conductor subjectivity introduced by such a design may be offset to a certain degree by use of a panel of conductors to make matching decisions. It would be even more effective if these conductors were not familiar with one another's work. Such a study would uncover to what degree the trends observed in this dissertation hold true for entire sections of singers (and not just duets) and reveal if SPR difference and vibrato extent deviation from solo become more significant determiners of blend as the number of singers increases.

It is not yet clear to what degree singers' formant prominence is a liability in choral blend. It would be of immediate use to choral conductors in establishing healthy vocalism to determine if low SPR singers can achieve as good a level of blend as high SPR singers as long as all vocalists are similarly resonating, as has been suggested by Katherine et al., 2007 and Fagnan, 2005. For this reason it may be advantageous to examine the role of SPR Difference more directly via ANOVA analysis of high and low SPR singers, with similar vibrato extent, performing in duet.

One variable that was not examined in this study was the effect of tempo and rhythm synchronization on blend assessment. In analyzing the samples, it was immediately obvious that some pairs tended to lag behind the tempo dictated by the singing cue, while others stayed relatively accurate in tempo. This suggests that an underlying phenomenon is at work worthy of study.

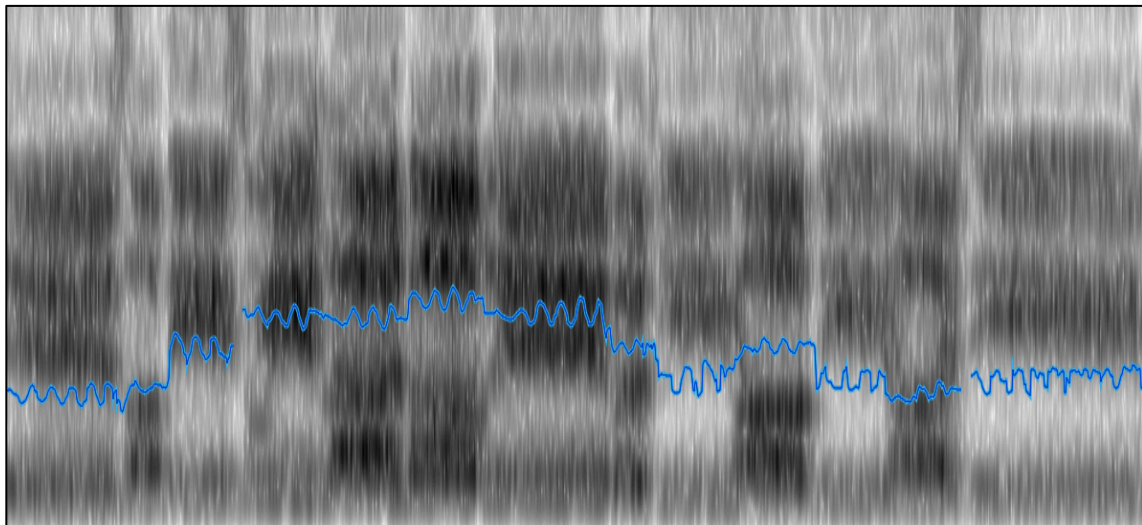
Furthermore, it was not determined to what degree this rhythm synchronization played a part in how the professional choral conductors rated the blend of the samples. If a manner can be found to quantify this variable, additional study may be fruitful.

The research of Ternström (1999; 1995) has shown that the self-to-other ratio has a profound effect on many aspects of the individual singer's performance in the choral environment. It is possible that voice matching owes part of its effectiveness to the manipulation of the self-to-other ratio. Future research may investigate this connection by including self-to-other ratio measurement in statistical analysis.

Since soprano voices seem to function somewhat differently, with a ceiling effect possibly observed, this study should be replicated with only sopranos, using greater distance between singers (perhaps 36 inches). Additionally, researchers should consider

employing an alternate measure of quantifying resonance for these voices beside SPR or ER.

Though this study was suggestive of the power of vibrato synchronization in blend, it was not quantified directly. As was the case in Jers and Ternström (2005), when the combined sound spectrographs were examined, a high qualitative correlation was observed between low vibrato extent difference and synchronization of the vibrato envelope. It was easy to observe when the vibrato was not synchronized, as it created a jagged fundamental pitch line that did not conform to a standard sine wave.



Combined Sound of Singers M4+M3, Displaying Synchronized and Non-Synchronized Vibrato Envelopes  
The singers show increasing disagreement after the halfway point

*Figure 11.* Visual salience of vibrato synchronization in combined LTAS analysis

Future research should investigate the effect of vibrato synchronization on blend using either a quantitative measure that remains to be devised, or alternatively, a means of qualitative characterization from group spectrographic analysis. For quantitative analysis, it is possible to create a computer program that analyzes vibrato envelopes in

the combined recordings using a goodness-of-fit function compared to a model sine wave. This option was explored for use in this study but proved elusive because a slight change in combined vibrato rate or vibrato extent translated to a diminished goodness-of-fit even if the singers remained synchronized. If a computer program is written, it must re-adjust the model sine wave to which it compares the singers for each vibrato cycle.

The conditions under which high vibrato extent singers are induced to lessen vibrato extent, and the ideal means of creating these conditions, has yet to be firmly established. Future study of a cohort of high vibrato extent singers is needed wherein the singers are measured under two conditions: paired with a low vibrato extent singer and paired with a medium vibrato extent singer. Low vibrato extent pairings were shown in this study to induce a further vibrato extent increase in the high vibrato extent singer, since the vibrato extent difference was large.

This study was suggestive of the operant effect of psychological perception of the need to blend in creating vocal tension and discomfort. Additional study is needed to demonstrate this conclusively. One potential method would be to examine two groups of singers under the same blend modifying conditions (paired with same types of singers on the same side, etc.). One group would be verbally encouraged to blend, while the other would receive no verbal instruction, or perhaps, a verbal instruction not related to voice spectrum or vibrato in any way.

The results of this study with regard to SPR are indicative that there may be aspects of vocal resonance that listeners take into account when assessing blend that are not adequately quantified using the SPR measure. The concept of “formant balancing,” in which the formants of two voices fill in each other’s weak frequency bands, is one

alternative; however, examination of the spectrograms of the samples used in this study makes this seem unlikely. Additional research is needed to learn more about how vocal resonance affects choral blend.

Based on the high prediction level of the multiple regression model described above, an optimization algorithm could be created and tested on several choirs.

### **Conclusion**

The role of standing order in enhancing choral performance is still in the beginning stages of exploration. Much remains to be discovered about the way in which voice matching, in particular, affects individual voices in the enhancement of blend. This study has served as a first look. The manner of data collection utilized was shown to be effective and can serve as a reliable method in further research. The data collected in this study may also be subjected to further analyses, including those suggested above.

The results of this study lend credibility to the claim that voice matching makes the choral environment more cohesive with the goals of voice teachers. Conductors who dedicate intentional rehearsal time to its systematic use will maximize benefits to both ensemble and singer. For all who wish to promote healthful singing and enhance blend in choral performance, voice matching is heartily recommended.

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