Effects of Vocal Training on the Acoustic Parameters of the Singing Voice

*Ana P. Mendes, †Howard B. Rothman, †Christine Sapienza, and †W.S. Brown, Jr.
Aveiro, Portugal and Gainesville, Florida, USA

Summary: Vocal training (VT) has, in part, been associated with the distinctions in the physiological, acoustic, and perceptual parameters found in singers’ voices versus the voices of nonsingers. This study provides information on the changes in the singing voice as a function of VT over time. Fourteen college voice majors (12 females and 2 males; age range, 17–20 years) were recorded while singing, once a semester, for four consecutive semesters. Acoustic measures included fundamental frequency (F0) and sound pressure level (SPL) of the 10% and 90% levels of the maximum phonational frequency range (MPFR), vibrato pulses per second, vibrato amplitude variation, and the presence of the singer’s formant. Results indicated that VT had a significant effect on the MPFR. F0 and SPL of the 90% level of the MPFR and the 90–10% range increased significantly as VT progressed. However, no vibrato or singers’ formant differences were detected as a function of training. This longitudinal study not only validates previous cross-sectional research, ie, that VT has a significant effect on the singing voice, but also it demonstrates that these effects can be acoustically detected by the fourth semester of college vocal training.

Key Words: Voice—Singing—Vocal training—Phonational Range—Acoustics.
INTRODUCTION

Since Garcia,¹ vocal training (VT) has been promoted as the major factor for enhancing the singing voice. It is also considered to be, in part, a factor in developing those parameters that make a singer’s voice different from that of a nonsinger’s.²⁻⁷ Singing efficiency, including maximizing vocal frequency and intensity range, optimizing vocal quality, as well as sustaining tones for long periods of time, has been reported to be the result of VT and experience.⁶⁻⁸⁻¹⁰ The effects of VT have been documented primarily in cross-sectional studies, and although powerful to some degree, these designs do not allow continuous examination of the effects of VT on a particular group of singers followed over time. The rationale for this study, therefore, was a longitudinal study, where the vocalizations of a group of college voice majors were examined across four semesters of vocal training.

Western classical vocal training¹¹ involves the following: (1) developing proper posture¹²; (2) strengthening the abdominal muscles with breathing exercises⁸,⁹,¹³,¹⁴; (3) vocal function exercises¹²,¹⁵; and (4) articulatory precision exercises.¹¹,¹⁶ Maximum phonational frequency range (MPFR), vibrato, and the singers’ formant have all been found to be enhanced with VT. MPFR provides information about basic vocal ability and reflects the physical limits of the phonatory mechanism.¹⁷ MPFR is defined as the range of vocal frequencies encompassing both the modal and falsetto registers; its extent is from the lowest tone sustainable in the modal register to the highest in falsetto, inclusive—pulse or fry register is excluded.¹⁸ Comparative studies between singers and nonsingers show that singers have a larger MPFR.³,¹⁹ However, discrepancies exist as to the extent of the range. It has been reported that, overall, female singers have a MPFR five to seven semitones (ST, re: 16.35 Hz) greater than nonsingers, with the extension occurring mostly at the high end of the frequency range.³ Trained singers, in general, have a significantly greater MPFR than nonsingers: 38.4 ST and 29.1 ST, respectively.³ It has been postulated that professional singers exhibit this larger MPFR, in comparison to nonsingers, due to their mastery of vocal technique.

Vibrato, a rhythmic modulation of the fundamental frequency that is characteristic of the singing voice, is perceived as a pulsation of pitch, and it is usually accompanied by synchronous pulsations of loudness and timbre, giving “grace” to the tones.²⁰ Acoustically, vibrato pulse rate is usually found to be between 4.5 to 6.5 pulses per second.²¹⁻²³ The frequency variation of the vibrato pulse above and below the mean can vary from 0 to ±3%, or from one-half to more than two ST.²³,²⁴ Moreover, vibrato has a range of 2–3 dB to 8–10 dB.²¹⁻²³ Even though vocal vibrato appears to be exclusive to the singing voice, its production is not well understood and has been reported as being produced by laryngeal,²⁵,²⁶ respiratory,²⁷ or supralaryngeal muscles²¹ as well as by changes in subglottal pressure,²⁵,²⁶ or resonance-harmonic interaction.²⁴ Recent literature suggests a physiological tremor in the cricothyroid and thyroarytenoid muscles.²³,²⁸ Regardless of the cause, however, the question remains as to how the singer develops vocal vibrato. Sundberg¹⁶ reported that almost all professional opera singers develop vibrato during VT, subconsciously. He pointed out that, “vibrato develops more or less by itself as voice training proceeds successfully.”¹⁶

Lastly, singers have been reported to have an extra formant called the singers’ formant, which adds clarity, projection, and timbral differentiation to the voice.²⁹⁻³¹ This formant presents a strong area of energy centered around 2800–3500 Hz, and it is generally found among the third, fourth, and fifth formants.¹⁶ It has been stated that the practical reason for the singers’ formant is that it permits the singer to be heard above the orchestra.¹⁶ The highest SPL produced by a symphony orchestra is found at approximately 500 Hz. A singer is audible due, in part, to the singers’ formant, as its frequency between 2.8 and 3.5 KHz is located where the orchestra’s sound is weak.

The singers’ formant has been observed primarily in professional male singers and concert performers.³² This formant is clearly present in trained tenors and bass-baritones, more sporadic in trained mezzos, and hardly distinguishable from other harmonic clusters in trained sopranos.⁷ However, although it is relatively common, little is known about how singers develop this formant. Weiss and Brown⁷ suggested that the presence of the singers’ formant seems to be largely a factor of voice training.
In summary, the experimental literature comparing singers’ and nonsingers’ voices reveals that there are several spectral differences that distinguish these two populations. Singers have a wider MPFR, especially at the higher end. Also, vibrato and the singers’ formant seem to be exclusive vocal characteristics of the singers’ voice and develop with VT. Most of the research on the singing voice has only compared singers with nonsingers. There are no reports, however, on the changes in a group of singers’ voices over time as a result of VT.

Purpose
The primary purpose of this study was to longitudinally determine the acoustic effects of vocal training on the singing voice of voice majors, specifically on the MPFR, vibrato, and singers’ formant. The specific question addressed was, are there statistically significant differences in MPFR, vibrato, and singers’ formant produced by voice majors after four semesters of vocal training among the voice classes or level of training?

METHOD
Participants
Fourteen voice majors participated in this investigation: 12 females and 2 males (age range, 17–20 years). They were recruited from a population of undergraduate voice students enrolled in voice studio classes at the University of Florida’s School of Music. Inclusion criteria for participation included the following: (1) ages between 17 and 25 years; (2) native American-English speakers with normal speech and hearing abilities as judged by a certified and licensed speech-language pathologist; (3) no history of respiratory or voice disorders; and (4) symptom-free of allergies or colds on the days of testing. Exclusion criteria for the participants were (1) smokers and (2) professional singing experience. Information about subjects’ age, voice classification, singing experience, number of semesters of VT, and number of hours practiced per week can be found in Table 1.

Procedures
All singing samples were recorded in a sound-treated environment at the Laryngeal Function Laboratory in the Institute for the Advanced Study of the Communication Processes, University of Florida. Each participant performed the tasks in a standing position. Before recording, subjects briefly warmed up their voices by performing phonational and dynamic range exercises.

Singing tasks consisted of the production of MPFR and the singing of “America the Beautiful.” The MPFR encompassed frequencies from the lowest in modal register to the highest in falsetto register; vocal fry was not included. A semitone chart and a keyboard were used to provide reference frequencies and audio feedback to both the researcher and the subject. The discrete-step task and the pitch-matching procedure were performed three times. Subjects were allowed a 1-minute rest period between trials. The lowest and the highest sustained /æ/ represented the 0% and the 100% levels of the MPFR. Each subject also sustained the vowel /æ/ at the 10% and 90% levels of the MPFR for 6 seconds. The 10% and the 90% levels were chosen for analysis instead of the 0% and 100% levels of the MPFR because not all subjects were able to perform the latter levels with a good vocal quality and for the required time (ie, 6 seconds).

The last task consisted of singing the first stanza of the song “America the Beautiful.” During this sung task, subjects were instructed to sustain the vowels of the words “sea” and “God” for 4 seconds, ie, /i, ɑ/.

Equipment
All voice productions were obtained using a high-quality cardioid head-worn microphone (Audio-Technica, Model ATM73a) positioned at a constant distance of 2 cm from the right corner of the mouth. The samples were preamplified with a Rane MS1 amplifier. An H-P350D Hewlett-Packard attenuator was activated for loud phonations to avoid peak clipping. Voice samples were recorded to a 60ES Sony digital audiotape recorder (DAT).

For calibration purposes, a 500-Hz tone at 80-dB SPL with a 2-cm distance from sound source to microphone was recorded on to each audiotape. Prior to measuring each subject’s productions, the calibration tone was digitized and served as a reference tone calculated by the Computerized Speech Lab Model 4300B (CSL, Kay Elemetrics Corp., Lincoln Park, NJ).
Acoustic analyses were obtained using CSL, and a MATLAB custom-designed software, *Frequency Characterization of Singer’s Vibrato (FCSV)*. This software required a Sound Blaster 16 Wave Studio to download samples from the DAT tapes to *FCSV*. Samples were digitized at a rate of 25.0 kHz. An antialiasing rectangular filter with a cutoff frequency of 5 kHz was used before digitization.

Spectral measurements and formant trajectory measurements were obtained using the CSL Model 4300B coupled to a Pentium computer. Some of the resulting values were converted to semitone levels, because the music frequency scale is logarithmic (log2) in nature.

**Acoustic analysis**

Some of the 0% and 100% level samples of the MPFR manifested vocal quality deterioration as judged by the first author, eg, a screechy vocal quality and/or pitch breaks. Therefore, they were excluded, and the vocalizations of the 10% and the 90% levels were ultimately used for the acoustic analysis of the MPFR. The middle portion of the sustained vowel /æ/ was analyzed with the CSL to derive the following dependent variables: (1) $F_0$ of 10% and 90% levels of the MPFR ($F_{010}$ and $F_{090}$ in semitones, ST); (2) $F_0$ range between the 10% and the 90% levels ($F_{090–10}$); (3) relative SPL of 10% and 90% levels (SPL10 and SPL90 in decibels); (4) relative SPL difference between the 10% and the 90% (SPL90–10).

Vibrato was defined as the periodic, rather sinusoidal, modulation of the $F_0$. Its analysis was obtained with *FCSV*, from the middle portion of the vowels /i/ and /ɑ/ from the words “sea” and “God” from the song “America the Beautiful.” Vibrato variables were as follows: (1) vibrato pulse rate (pps), which specifies the number of cycles or pulses per second of the modulation and (2) amplitude variation (dB), defined as the peak-to-peak distance during a vibrato cycle.

Lastly, the vowels /i/ and /ɑ/, as described above, were also used to analyze the presence or absence of the singers’ formant. A fast Fourier transform (FFT) power spectrum (Hz and dB) was performed using CSL. Three judges, with 10 to 30 years of experience in research, teaching, and publication in experimental phonetics, in particular, dealing with the acoustics of the singing voice and formant trajectories, were asked to independently look at the 106 FFT printouts and identify the presence of the singers’ formant. For reliability purposes, only the samples with 100% agreements were included.

**Error of measurements**

To minimize the lack of stability in the continuous response variables, brief warm-up vocal sessions...
were held with the singers. Before each recording session, subjects performed phonational and dynamic range tasks in a glissando manner. The same researcher administered each experimental session to provide consistency of instruction and procedure. To minimize error in the measurement instruments, calibration procedures were performed at the beginning of each experimental session.

Statistical analysis

This was a longitudinal study with an incomplete repeated measures design. That is, the majority of the subjects (11) were recorded four times. The others (3) were recorded only three times. The acoustic data were analyzed using a repeated measures analysis of variance. The primary factor was vocal training, ie, semesters of VT. This quantitative factor had four levels, ie, each level representing the four semesters of VT. Additional factors were voice classification (sopranos, mezzo sopranos, alto, tenor, and baritone), weekly hours of practice, and years of singing experience prior to entering UF.

All continuous acoustic variables were statistically analyzed using the Proc Mixed SAS procedure. The response variables were modeled against the following independent variables: vocal training, voice classification, singing experience, and weekly hours of practice. If weekly hours of practice and singing experience did not significantly affect the model, then only vocal training and voice classification were retained. A Scheffé’s multiple comparison analysis across the semesters of VT revealed that, when compared with the first semester, F090 showed a significant increase on the third (p = 0.0230) and on the fourth semesters (p ≤ 0.0001). Also, F090 values of the second semester and the third semester were significantly lower than the values of the fourth semester (p ≤ 0.001 and p ≤ 0.005, respectively).

The range F090–10 showed a significant increase as VT progressed (F(3, 36) = 6.44, p ≤ 0.0013). A Scheffé’s multiple comparison analysis across the semesters revealed that during the fourth semester, F090–10 was significantly higher than the first (p ≤ 0.0001), second (p ≤ 0.0009), and third semesters (p = 0.008) (see Figure 1).

Within subjects analysis. For the F090 variable, the within-subject analysis revealed that for the eight sopranos, the F090 range was between approximately 64 and 74 ST during the four semesters of VT (Figure 3). Seven of the eight sopranos produced the lowest tone of the F090 during their first semester. These seven sopranos showed consistent increases in their ability to produce higher tones within the F090 as VT progressed. For the two mezzo-sopranos and two altos, F090 ranged from approximately 62 to 72 ST during the four semesters of VT. For the tenor, F090 ranged from approximately 55 to 63 ST during the four semesters of VT. All mezzo-sopranos, altos, and the tenor produced the lowest tone of the F090 during their first semester and increased their ability to produce higher tones within the F090 as VT progressed. This pattern was not observed with the baritone, who presented a F090

RESULTS

Maximum phonational frequency range
Fundamental frequency

Spectral measures of the MPFR consisted of fundamental frequency at the 10% and 90% levels of

The phonational range (F010 and F090, respectively). The difference between these two measures was also calculated, ie, F090–10. The F090–10 is representative of the 10% and 90% range of the MPFR. The means and standard deviations of these variables for the four semesters of VT are expressed in semitones (ST) in Table 2.

Repeated measures analysis revealed that the mean of F090 increased as the number of semesters of VT increased (Table 3). Both vocal training and voice classification had a significant effect on F090, (F(3, 36) = 7.06, p ≤ 0.008 and F(4, 9) = 22.71, p ≤ 0.0001, respectively). A multiple comparison analysis across the semesters of VT revealed that, when compared with the first semester, F090 showed a significant increase on the third (p = 0.0230) and on the fourth semesters (p ≤ 0.0001). Also, F090 values of the second semester and the third semester were significantly lower than the values of the fourth semester (p ≤ 0.001 and p ≤ 0.005, respectively).

The range F090–10 showed a significant increase as VT progressed (F(3, 36) = 6.44, p ≤ 0.0013). A Scheffé’s multiple comparison analysis across the semesters revealed that during the fourth semester, F090–10 was significantly higher than the first (p ≤ 0.0001), second (p ≤ 0.0009), and third semesters (p = 0.008) (see Figure 1).

Within subjects analysis. For the F090 variable, the within-subject analysis revealed that for the eight sopranos, the F090 range was between approximately 64 and 74 ST during the four semesters of VT (Figure 3). Seven of the eight sopranos produced the lowest tone of the F090 during their first semester. These seven sopranos showed consistent increases in their ability to produce higher tones within the F090 as VT progressed. For the two mezzo-sopranos and two altos, F090 ranged from approximately 62 to 72 ST during the four semesters of VT. For the tenor, F090 ranged from approximately 55 to 63 ST during the four semesters of VT. All mezzo-sopranos, altos, and the tenor produced the lowest tone of the F090 during their first semester and increased their ability to produce higher tones within the F090 as VT progressed. This pattern was not observed with the baritone, who presented a F090
TABLE 2. Means and Standard-Deviations for Spectral Measures Obtained from Maximum Phonational Frequency Range (MPFR) during Four Semesters of Vocal Training

<table>
<thead>
<tr>
<th>Vocal Training Measures (units)</th>
<th>1st Semester</th>
<th>2nd Semester</th>
<th>3rd Semester</th>
<th>4th Semester</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>F010 (ST)</td>
<td>44.03</td>
<td>3.03</td>
<td>44.25</td>
<td>4.27</td>
</tr>
<tr>
<td>F090 (ST)</td>
<td>64.13</td>
<td>5.36</td>
<td>65.38</td>
<td>5.24</td>
</tr>
<tr>
<td>F090-10 (ST)</td>
<td>20.10</td>
<td>3.27</td>
<td>21.13</td>
<td>5.11</td>
</tr>
<tr>
<td>SPL10 (dB)</td>
<td>83.10</td>
<td>7.91</td>
<td>81.27</td>
<td>10.68</td>
</tr>
<tr>
<td>SPL90 (dB)</td>
<td>99.80</td>
<td>5.77</td>
<td>105.16</td>
<td>9.55</td>
</tr>
<tr>
<td>SPL90-10 (dB)</td>
<td>16.70</td>
<td>9.52</td>
<td>23.89</td>
<td>12.79</td>
</tr>
</tbody>
</table>

F010, F090 and F090-10 = Fundamental frequency of 10%, 90% and 90-10 levels of the MPFR; SPL10, SPL90 and SPL90-10 = Sound pressure level of 10%, 90% and 90-10% levels of MPFR.

range between 52.58 and 52.70 ST across the four semesters.

For the F090–10 variable, within-subject analysis revealed that for the eight sopranos, the F090–10 range was from approximately 18 to 32 ST during the four semesters of VT (Figure 4). Seven of the eight sopranos produced the lowest tone of the F090–10 during their first semester. These seven sopranos showed consistent increases within the F090–10 as VT progressed. The two mezzo-sopranos showed different patterns. One increased 6 ST, and the other increased 9 ST as VT progressed. The two altos’ F090–10 range was between 19 and 31 ST during the four semesters of VT. They produced the lowest tone of the F090–10 during their first semester. The baritone’s F090–10 variable ranged between 14 and 19 ST. The tenor’s F090–10 range was between 14 and 26 ST. His F090–10’s highest tone was achieved during the last semester of VT.

TABLE 3. Repeated Measures Analysis Examining the Effects of Vocal Training (VT) and Voice Classification (VC) on Spectral Measures Taken from the MPFR Samples

<table>
<thead>
<tr>
<th>Measures</th>
<th>NDF</th>
<th>DDF</th>
<th>F - value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>F010 VT</td>
<td>3</td>
<td>36</td>
<td>0.47</td>
<td>0.7056</td>
</tr>
<tr>
<td>F010 VC</td>
<td>4</td>
<td>9</td>
<td>19.00</td>
<td>0.0002*</td>
</tr>
<tr>
<td>F090 VT</td>
<td>3</td>
<td>36</td>
<td>7.06</td>
<td>0.0008*</td>
</tr>
<tr>
<td>F090 VC</td>
<td>4</td>
<td>9</td>
<td>22.71</td>
<td>0.0001*</td>
</tr>
<tr>
<td>F090-10 VT</td>
<td>3</td>
<td>36</td>
<td>6.44</td>
<td>0.0013*</td>
</tr>
<tr>
<td>F090-10 VC</td>
<td>4</td>
<td>9</td>
<td>3.38</td>
<td>0.0599</td>
</tr>
<tr>
<td>SPL10 VT</td>
<td>3</td>
<td>36</td>
<td>1.95</td>
<td>0.1386</td>
</tr>
<tr>
<td>SPL10 VC</td>
<td>4</td>
<td>9</td>
<td>0.11</td>
<td>0.9746</td>
</tr>
<tr>
<td>SPL90 VT</td>
<td>3</td>
<td>36</td>
<td>7.67</td>
<td>0.0004*</td>
</tr>
<tr>
<td>SPL90 VC</td>
<td>4</td>
<td>9</td>
<td>2.65</td>
<td>0.1124</td>
</tr>
<tr>
<td>SPL90-10 VT</td>
<td>3</td>
<td>36</td>
<td>3.48</td>
<td>0.0256*</td>
</tr>
<tr>
<td>SPL90-10 VC</td>
<td>4</td>
<td>9</td>
<td>0.85</td>
<td>0.5297</td>
</tr>
</tbody>
</table>

*Statistically significant at P ≤ .05.

Sound pressure level

SPL measures were obtained from the samples of the 10%, 90%, and 90–10% levels of the MPFR. The means and standard deviations of these variables are presented in Table 2. The results of the repeated measures analysis can be viewed in Table 3. The sound pressure level of the 90% level of the MPFR (SPL90) increased significantly as the numbers of the semesters of VT increased, F(3, 36) = 7.67, p = 0.0004. A multiple comparison analysis across the semesters of VT revealed that SPL90 in the fourth semester was significantly higher than the SPL90 in the first (p ≤ 0.0001), second (p ≤ 0.0016), and third semesters (p ≤ 0.003). Also, the SPL90 mean of the third semester was significantly higher than the one for the first semester (p = 0.02). No differences were found for voice classification.

The SPL90–10 significantly increased as VT increased, F(3, 36) = 3.48, p = 0.02. A multiple comparison analysis revealed that when compared with the first semester, SPL90–10 showed a significant increase during the second semester (p = 0.02) and during the fourth semester (p = 0.0120). Figure 2
FIGURE 1. Maximum phonational frequency range changes as a function of vocal training. Trends of F0\textsubscript{10}, F0\textsubscript{90}, and F0\textsubscript{90–10} as the semesters of vocal training increased.

presents the trends of SPL\textsubscript{10}, SPL\textsubscript{90}, and SPL\textsubscript{90–10} as VT progressed. Even though the means of SPL of the 10% of the MPFR (SPL\textsubscript{10}) increased as the VT progressed, neither VT nor voice classification showed a significant effect.

Within subjects analysis. For the SPL\textsubscript{90} variable, within-subject analysis revealed that for the eight sopranos, the SPL\textsubscript{90} ranged from approximately 81 to 125 dB during the four semesters of VT (Figure 5). Five of the eight sopranos produced the softest SPL\textsubscript{90} during their first semester. These five sopranos showed consistent increases within the SPL\textsubscript{90} as VT progressed. The two mezzo-sopranos also increased SPL\textsubscript{90} as the VT progressed, with the exception of the last semester, where one mezzo-soprano decreased SPL\textsubscript{90}. The two altos presented the softest and the loudest SPL\textsubscript{90} during the first and last semester of VT, respectively. Both the baritone and tenor presented the loudest SPL\textsubscript{90} during the last semester of VT, 108 dB and 125 dB, respectively.

For the SPL\textsubscript{90–10} variable, within-subject analysis revealed that for the eight sopranos, the SPL\textsubscript{90–10} ranged from approximately 5 to 42 dB during the four semesters VT (Figure 6). Four sopranos and all other voice classification groups produced the softest tone of the SPL\textsubscript{90–10} during their first semester. Mezzo-sopranos’ and altos’ SPL\textsubscript{90–10} ranged from approximately 5–35 dB and 10–55 dB, respectively. The baritone’s SPL\textsubscript{90–10} ranged from 10 to 25 dB during four semesters. The tenor’s SPL\textsubscript{90–10} ranged from approximately 7.5 to 22.5 dB and increased during the four semesters of VT.

FIGURE 2. SPL changes as a function of vocal training. Trends of SPL\textsubscript{10}, SPL\textsubscript{90}, and SPL\textsubscript{90–10} as the semesters of vocal training increased.

Vibrato

The means and the standard deviations of the vibrato pulses per second in semitones for the vowels /i/ and /ɑ/ (VP\textsubscript{i} and VP\textsubscript{a}, respectively) and vibrato amplitude variation in decibels (VA\textsubscript{i} and VA\textsubscript{a}, respectively) are displayed in Table 4. It can be seen in Table 5 that the repeated measures analysis of variance did not yield any significant differences for the vocal training and voice classification.

Singers’ formant

The three judges unanimously identified 14 out of 53 singers’ formants for the vowel /i/ and 17 out of 53 singers’ formants for the vowel /ɑ/ from the 106 FFT printouts. The number and distribution of the identification of the singers’ formant can be found in Table 6. An exact chi-square test was run for each semester to see if voice classification was associated with the presence or absence of the singer’s formant in each vowel. For the vowel /i/, voice classification was not associated with the presence or absence of the singer’s formant in each vowel. For the vowel /ɑ/, voice classification was associated with the absence of the singers’ formant at any of the four semesters of the vocal training. For the vowel /ɑ/, voice classification was associated with the absence of the singers’ formant in the third semester of vocal training, χ\textsuperscript{2} 4, N = 8.011, p = 0.047. This significant association revealed that for 87.5% of the sopranos, the singers’ formant was absent for the vowel /ɑ/ during the third semester of VT.
However, this is a weak association due to a \( p \) value close to 0.05, and a small sample size. Moreover, it was only observed during the third semester. The other semesters did not show a significant association between voice classification and the presence or absence of the singer’s formant.

**DISCUSSION AND CONCLUSIONS**

The effect of VT on the singing voice was examined by measuring selected acoustic variables of sung samples produced by 14 voice majors during four consecutive semesters. The results of this investigation revealed that VT had a significant effect on the MPFR with respect to fundamental frequency and vocal intensity, but not on vibrato or the singer’s formant.

Four semesters of VT had a significant effect on the fundamental frequency at the 90% level of the MPFR (\( F_{0.90} \)). \( F_{0.90} \) increased significantly by four STs during the VT period. Also, the range in fundamental frequency between the 90% and the 10%
levels ($F_{0}90–10$) increased significantly by 5.7 ST. That is, $F_{0}90–10$ was 20.10 ST in the first semester and increased to 25.80 ST in the fourth semester of VT. Within-subject analysis revealed that, in general, all voice classification groups produced the lowest values of $F_{0}90$ and $F_{0}90–10$ during the first semester. These groups increased their ability to produce higher $F_{0}$ values as VT progressed. These findings suggest that voice majors engaged in ongoing VT are able to significantly expand their singing $F_{0}$ range.

Although MPFR is typically measured without regard to musical quality of phonation, in this study...
Within-subject changes of the SPL90 variable. This criterion was taken in consideration; i.e., samples with screechy vocal quality deterioration were excluded. This would apparently make these results less comparable with other MPFR studies; however, they still confirm the findings of the cross-sectional studies that compared singers with nonsingers; i.e., with VT, singers develop a larger MPFR, especially toward the higher frequencies. Moreover, the present results provide evidence that this effect can be seen with only four semesters of college VT. Most likely, this MPFR increase is a consequence of the more effective use of the laryngeal and respiratory systems by the trainee. For example, during VT, voice majors practice respiratory exercises in order to increase strength and coordination of inspiratory and expiratory breathing during singing.
These exercises can include postures of the rib cage and rapid manipulations of the abdominal muscles. The objective is to maximize production of high subglottal pressure necessary for the laryngeal system during high F0 productions. Hollien et al\(^4\) reported that regulation of F0 in the falsetto register may be more closely associated with aerodynamic factors than the myoelastic properties of the vocal folds. However, it could also be that vocal function exercises used during VT could also produce increases of the MPFR. These exercises focus primarily on strengthening the cricothyroid muscle, which, when contracted, increases the length of the vocal folds and, therefore, increases their vibratory rate. It may be postulated, then, that interaction, through training, of these two mechanisms (ie, respiratory and laryngeal) may help to achieve the larger MPFR.

The present results also revealed that four semesters of VT had a significant effect on the sound
TABLE 4. Means and Standard Deviations for Spectral Measures Obtained from Vibrato Samples During Four Semesters of Vocal Training

<table>
<thead>
<tr>
<th>Vocal Training Measures (units)</th>
<th>1st Semester</th>
<th>2nd Semester</th>
<th>3rd Semester</th>
<th>4th Semester</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>VPi (pps)</td>
<td>5.63</td>
<td>0.75</td>
<td>5.49</td>
<td>0.68</td>
</tr>
<tr>
<td>VPa (pps)</td>
<td>5.69</td>
<td>1.07</td>
<td>5.33</td>
<td>0.54</td>
</tr>
<tr>
<td>VAi (dB)</td>
<td>3.02</td>
<td>1.13</td>
<td>3.28</td>
<td>1.63</td>
</tr>
<tr>
<td>VAA (dB)</td>
<td>2.39</td>
<td>1.48</td>
<td>2.78</td>
<td>1.70</td>
</tr>
</tbody>
</table>

VPi = vibrato pulse rate of /i/; VPa = vibrato pulse rate of /a/; VAi = vibrato amplitude variation of /i/; and VAA = vibrato amplitude variation of /a/.

pressure level at the 90% level of the MPFR (SPL90). SLP90 increased significantly by 16.62 dB from the first to the fourth semester of VT. Moreover, the SPL range between the 90% and the 10% levels (SPL90–10) increased significantly by 10.12 dB from the first to the fourth semester of VT. Within-subject analysis revealed that, in general, all voice classification groups tended to produce the lowest values of SPL90 and SPL90–10 during the first semester. This suggests that these voice majors appeared to be able to increase their singing SPL capabilities as VT progressed, as was the case for F0.

These results also confirm cross-sectional research, in that the participants developed an increased MPFR with higher SPL. Moreover, these data show that such changes develop during the early stages of the voice majors’ VT. As was the case of F090 and F 090–10, this finding appears to depend on the singer’s ability to develop higher subglottal air pressures. Although the exact mechanism of the increased subglottal pressure generation cannot be determined, it is clear that VT dramatically improved two important variables for enhancing singing performance: F0 and SPL. The substantial changes in SPL over the four semesters are likely related to improvements in respiratory control and strength because laryngeal manipulation used for increasing SPL would only result in an approximate 3-dB SPL increase, whereas increasing subglottal pressure would cause a more substantial increase due to the mechanism of increasing air particle velocity and glottal flow.

On the other hand, four semesters of VT did not have a significant effect on F010 and SPL10. Even though few trends can be observed in these two acoustic variables, it may be that four semesters of VT is not enough time to show a change in the production of lower frequency productions.

Vocal classification was significantly related to the F010 and F090 levels of the MFPR, as one would expect. Previous studies that compared singers to nonsingers reported that there is a prominent trend for the sopranos, at least, to shift their MFPR toward the higher frequencies and, therefore, become differentiated from the other classification groups. This longitudinal study not only confirms this trend, but also it indicates that this trend starts during the early years of college vocal training. Moreover, it was revealed that the hierarchies of voice classification groups start to be acoustically differentiated during

---

TABLE 5. Repeated Measures Analysis Examining the Effects of Vocal Training (VT) and Voice Classification (VC) on Spectral Measures Taken from the Vibrato Samples

<table>
<thead>
<tr>
<th>Measures</th>
<th>NDF</th>
<th>DDF</th>
<th>F - value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>VPi VT</td>
<td>3</td>
<td>36</td>
<td>0.47</td>
<td>0.7059</td>
</tr>
<tr>
<td>VPi VC</td>
<td>4</td>
<td>9</td>
<td>0.48</td>
<td>0.7530</td>
</tr>
<tr>
<td>VPa VT</td>
<td>3</td>
<td>36</td>
<td>2.25</td>
<td>0.0990</td>
</tr>
<tr>
<td>VPa VC</td>
<td>4</td>
<td>9</td>
<td>0.39</td>
<td>0.8133</td>
</tr>
<tr>
<td>VAi VT</td>
<td>3</td>
<td>36</td>
<td>0.72</td>
<td>0.5477</td>
</tr>
<tr>
<td>VAi VC</td>
<td>4</td>
<td>9</td>
<td>2.39</td>
<td>0.1282</td>
</tr>
<tr>
<td>VAA VT</td>
<td>3</td>
<td>36</td>
<td>0.26</td>
<td>0.8509</td>
</tr>
<tr>
<td>VAA VC</td>
<td>4</td>
<td>9</td>
<td>1.26</td>
<td>0.3552</td>
</tr>
</tbody>
</table>
TABLE 6. Identification of the Presence of Singers’ Formant per Subject

<table>
<thead>
<tr>
<th>Subjects (ID)</th>
<th>Voice Classification</th>
<th>Vowel /i/</th>
<th>Semesters</th>
<th>Vowel /ɑ/</th>
<th>Semesters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1st</td>
<td>2nd</td>
<td>3rd</td>
<td>4th</td>
</tr>
<tr>
<td>AW</td>
<td>Soprano</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>BM</td>
<td>Mezzo Soprano</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CW</td>
<td>Alto</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>JD</td>
<td>Soprano</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>JH</td>
<td>Alto</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LB</td>
<td>Soprano</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>NR</td>
</tr>
<tr>
<td>MM</td>
<td>Soprano</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MN</td>
<td>Soprano</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RC</td>
<td>Soprano</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>RH</td>
<td>Mezzo Soprano</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SL</td>
<td>Soprano</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>NR</td>
</tr>
<tr>
<td>SG</td>
<td>Soprano</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>NR</td>
</tr>
<tr>
<td>JP</td>
<td>Tenor</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CH</td>
<td>Baritone</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Total of Singers’ Formant Identified: 14 and 17

NR = Voice was not recorded; 1 = Singers’ formant was identified; 0 = No singers’ formant was identified.

the first four semesters of VT, not only for the sopranos, but also for the other classification groups.

Four semesters of VT did not have an effect on vibrato pulse rate and amplitude measures. The vibrato pulse ranges for the sung vowels /i/ and /ɑ/ were between 5.45 and 5.65 pulses per second during the four semesters of VT, within normal limits. However, the vibrato pulse rates for these voice students were not stable throughout the four semesters of training. Moreover, the vibrato amplitudes of the sung vowels /i/ and /ɑ/ ranged from 2.2 dB to 3.28 dB during four semesters of VT with no significant increases as vocal training increased. Previous studies on the vibrato amplitude of professional singers reported that the optimal vibrato amplitude was 2–10 dB. In the present investigation, the vibrato amplitudes produced by voice majors during four semesters of VT were at the lower end of the optimal range. This would imply that even though voice majors already have some sort of vibrato ability during the early years of training, four semesters of VT may not be sufficient to develop a stable vibrato production. The most accepted explanation of vibrato production involves the coordination of the cricothyroid and thyroarytenoid muscles. It is probable that the coordination of these muscles is developed at later stages of the VT.

Lastly, the presence or absence of the singer’s formant derived from the sung vowels /i/ and /ɑ/ were analyzed and identified based on voice classification. Voice classification was significantly associated with the absence of the singer’s formant in the third semester of VT. That is, 83.5% of the sopranos did not have the singer’s formant on the third semester of VT. Previous research that analyzed the singer’s formant in professional singers reported that sopranos do not seem to exhibit this extra formant. This investigation revealed that by the third semester of VT, sopranos decreased their ability to produce this formant, at least for the vowel /ɑ/. Even though this was not observed for the vowel /i/, there is a trend for the presence of the singer’s formant in sopranos to decrease as the numbers of semesters of VT increased.

This decrease in the presence of the singers’ formant in sopranos is probably due to articulatory maneuvers. The production of the singers’ formant is the result of lowering the larynx and widening the bottom of the pharynx, resulting in this extra formant centered around 2800–3500 Hz. Sopranos,
on the other hand, in an effort to produce high fundamental frequencies with higher SPLs, increase the size of their oral cavity aperture. This causes the first formant to be raised so as to approximate the F0, which can cause an increase in SPL up to 30 dB. Females, generally, have a third formant located at approximately the same frequency as the singers’ formant. Vowel modification, especially as singing fundamental frequency increases, would cause the singers’ formant to decrease in amplitude because there would be no harmonic energy in the area of a formant peak to be maximized.

Finally, as the singers’ formant is more predominant in male singers, and only two males participated in the present study, no definitive statement can be made as to the number of semesters of training that are necessary for the development of the singers’ formant in males.

In conclusion, this longitudinal study reveals that four semesters of VT had a significant effect on the MPFR. The F0 and SPL of the 90% level as well as the 90–10% range increased significantly as the numbers of the semesters of VT increased. Four semesters of VT did not appear to have any effect on vibrato and the singer’s formant.

Acknowledgement: The authors thank Prof. Ronald Burrichter, Dr. Elizabeth Graham, and Dr. John Lafond for their assistance in subject recruitment. Lastly, we thank Dr. Lawrence Turton for editing support.

REFERENCES