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Vibrato Rate Adjustment

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Summary: The goal of the present study was to document the acoustic changes that occur as singers attempt to increase or decrease their vibrato rate to match target stimuli. Eight advanced singing students produced vowels with vibrato in three registers, both naturally and while attempting to match faster or slower rate stimuli. Slower rates were associated with lower intensity and less steady vibrato. Faster rates involved increased vibrato extent in the chest register and increased intensity in the head register. Singers whose spontaneous vibrato rates were naturally either slower or faster tended to also be relatively slower or faster when matching target rates. This ability to modify rate may have beneficial effects on the artistic quality of the voice for performance.

Key Words: Vibrato—Acoustic—Modulation.

INTRODUCTION

Vocal vibrato is a characteristic feature in the singing of performers trained in the Western classical tradition. Seashore[1] provided one of the earliest comprehensive descriptions of vocal vibrato. His systematic research is cited to this day, as is his definition: “A good vibrato is a pulsation of pitch, usually accompanied with synchronous pulsations of loudness and timbre, of such extent and rate as to give a pleasing flexibility, tenderness, and richness to the tones” (p. 349).

Robison, Bounous, and Bailey[2] studied the concept of “vocal beauty” and sought to identify the salient acoustic characteristics that correspond to listeners’ perceptions of a performing voice. The samples were taken from 19 classically trained lower male voices and 8 trained female belt singers. These authors concluded that the most beautiful voices had certain acoustical features in common, including constant and smooth vibrato rates with moderate extent. Some singers experience difficulties in producing an appropriate vibrato. Davis[3] described a singer displaying a wider pitch fluctuation and slower rate of vibrato. This type of oscillation is referred to by voice teachers as a “wobble.” Singers producing a vibrato with a narrower pitch modulation and faster rate may be considered to have a “bleat.”

In addition to subjective ratings of vocal beauty, objective measurements can be valuable in describing the singing voice. Winholtz and Ramig[4] described an analog device for the quantification of either pathological vocal tremor or singers’ vibrato, but subsequent advances in commercially available software products have limited the adoption of this technology. Recent studies have used software modules of the Kay Elemetrics Computerized Speech Lab (CSL), such as the Multi-Dimensional Voice Program (MDVP) or the Motor Speech Profile (MSP). These systems allow a demodulation of a

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microphone recording of vibrato or tremor. The analyses produce separate contours which display the variations in the voice in both fundamental frequency (F_0) and intensity. Amplitude modulation (AM) represents rhythmic increases and decreases in vocal intensity relative to its mean level. Similarly, frequency modulation (FM) quantifies the oscillating pattern of the F_0 contour.

Both vocal tremor and vibrato can be described acoustically by the rate, extent and periodicity of the modulations in the frequency and amplitude of the voice. Vibrato rate describes how rapidly the modulations occur, and is expressed in Hz. Typical values range from 4 to 7 Hz. Extent describes how large or small the modulations are relative to average frequency or amplitude during the vibrato cycle. Periodicity refers to the steadiness or repeatability of the modulations. Periodicity is considered to best reflect the skill of the singer; the smoother the vibrato, the more beautiful the singer's voice is perceived to be[2].

Because vibrato typically involves both FM and AM, it is informative to examine the relationship between the two. Horii and Hata[5] reasoned that as the F_0 of the voice modulates, harmonic frequencies also change proportionally. This causes individual harmonics to alternately move closer to or farther from the resonance peaks in the vocal tract transfer function, resulting in an increase or decrease of the sound pressure level (SPL) of the voice as it leaves the lips. Similarly, Schutte and Miller[6] studied the spectral acoustic properties of tenor high notes and found that "timbre and amplitude vibrato can result from the periodic movement of the harmonics of the voice source among the more stationary formants of the vocal tract" (p. 221). Imaizumi, Saida, Shimura, and Hirose[7] also demonstrated that, in addition to this mechanism, voice source spectral fluctuations and vocal tract wall vibrations can contribute to the detailed acoustic characteristics of vibrato. It appears that the primary mechanism of Western classical vibrato is the skilled modulation of F_0, and that modulations in amplitude may arise from the acoustic interaction of harmonics and resonances in the vocal tract. This view appears to be supported by data reported by Horii[8], who found that FM during vibrato was much more regular than AM.

Titze and colleagues[9] used electromyography to study vibrato, and extended their experiment to measure the effects on laryngeal muscle activity of artificial electrical stimulation. Pairs of hooked-wire electrodes were inserted into a singer's cricothyroid (CT) and thyroarytenoid (TA) muscles in order to directly measure muscle activation. The same electrodes were used to apply electrical stimulation. Results indicated that the rate of vocal vibrato could be modified slightly by artificial stimulation of the CT. "Specifically, the data suggest that the oscillating mechanism responsible for vocal vibrato can be entrained by an external oscillator that twitches the muscle in a periodic fashion" (p. 222). However, the degree to which the oscillation could be artificially entrained was limited to about 0.5 Hz away from the natural rate.

A voluntary change in vocal vibrato is a topic that has received little attention in the research literature. King and Horii[10] studied 9 trained singers and their ability to control the rate and extent of FM during vibrato. Each singer was asked to match synthetic target stimuli with three differing rates or extents, at three pitch levels. The investigators found that vibrato rate was easier to match than extent. The singers were better able to match slower than faster target rates. This study revealed that trained singers were able to volitionally adjust certain aspects of their vibrato.

The work of King and Horii[10] suggests that vibrato is not necessarily "hard wired" through neurologic and biomechanical factors in an individual. This finding has important implications for teachers of singing, who may encounter students with a vibrato that is judged to be too fast or too slow. The possibility of adjusting vibrato rate suggests that individuals can modify their vibrato in order to improve its aesthetic quality. Further investigation is needed to identify in greater detail the changes that take place as singers match faster or slower vibrato rates. For example, it is not clear how rate adjustments might influence vibrato steadiness or extent. The primary goal of the present study was to conduct a detailed acoustic analysis of the phenomenon of vibrato adjustment to learn which parameters are affected during these volitional adjustments. Specifically, we set out to learn more about the relationships between vibrato rate, extent, and steadiness.

METHOD

The present study consisted of two components. The first involved making recordings of 12 singers' voices in order to collect vowel samples with vibrato at a variety of natural rates. The second phase of the experiment involved 8 singers who had intermediate vibrato rates. They attempted to match the fastest and slowest rates that had been sampled previously.

Participants

For the initial recordings, students in vocal performance or vocal pedagogy in the School of Music at Brigham Young University received a brief oral description of the study and volunteered to participate by signing a consent form. Twelve participants, all females, ranging in age from 19 to 28 years, took part in this phase the study. For this group of students, the number of years in training varied from 2.5 to 11 years with a mean of 6.5 years. All participants reported that they were in good health and had no evidence of hearing or voice disorders. Eight singers with intermediate vibrato rates (as determined by initial acoustic analyses) participated in the second phase of the experiment two months later. Five had taken part in the first phase of the study, while three were new volunteers.

Equipment

All recordings were made in a sound booth with a head-mounted microphone (AKG C-420, Vienna, Austria). A 4 centimeter lip-to-microphone distance was maintained throughout the experimental trials. Acoustic signals from the microphone were preamplified (Samson Mixpad 4, Syosset, NY) and recorded with a digital audio tape (DAT, Secaucus, NJ) recorder (Panasonic SV-3800). Vocal intensity was measured with a sound level meter (Larson Davis 720, Provo, UT) and its output was recorded with the DAT recorder. A 100 cm mouth-to-sound level meter distance was maintained throughout the experimental trials. Signals were subsequently digitized at 25 kHz using the Computerized Speech Lab (CSL 4300B, Kay Elemetrics, Lincoln Park, NJ). For the rate-matching part of the experiment, singers heard digitized recordings of the faster or slower vibrato rates played back from CSL via headphones (Beyerdynamic DT 211, Farmingdale, NY) as a continuous loop.

Procedure

During the initial phase of the experiment, when a range of natural vibrato rates was sought, each participant performed the following vocal exercises in a standing position. The singers were asked to sustain a C4 /ɑ/ vowel at a comfortable effort level in the chest register for about 5 seconds. This task was performed three times. They subsequently produced three tokens of a G5 /ɑ/ in the head register, followed by three tokens of a B5 /ɑ/ in the mixed register. A pitch pipe was used to assist in targeting the required note. The third author, who has been singing professionally and teaching vocal performance for 25 years, was present for all the recordings in the initial phase. He ensured that the singers produced the vowel not only at the target pitch, but also in the requested register by providing feedback and guidance as required. Because the goal was to obtain the most natural production for each singer, no instruction was given regarding vibrato rate. The purpose of this initial phase was to collect samples of vibrato from singers who differed in their natural rate. The fastest and slowest vibrato samples collected in each register were subsequently used as stimuli for the matching experiment.

For the matching phase of the experiment, which was conducted two months later, each participant performed the following vocal exercises in a standing position, while wearing headphones and a head-mounted microphone. Directions were given explaining to the participants that they were first to produce an /ɑ/ vowel as they normally would in one of the registers at a self-selected comfortable pitch and loudness level. Following three tokens of this vowel, they were asked to match the pitch and vibrato rate they heard in the headphones for the stimulus in that register. The recorded fast or slow vibrato was introduced into the headphones at a comfortable loudness level selected by the singer. The fast and slow matching stimuli were digital recordings from the singers in the initial phase of the study who had the fastest and slowest natural vibrato rates. While the samples were selected on the basis of FM rate rather than periodicity, the steadiness of the FM rate was similar to that of

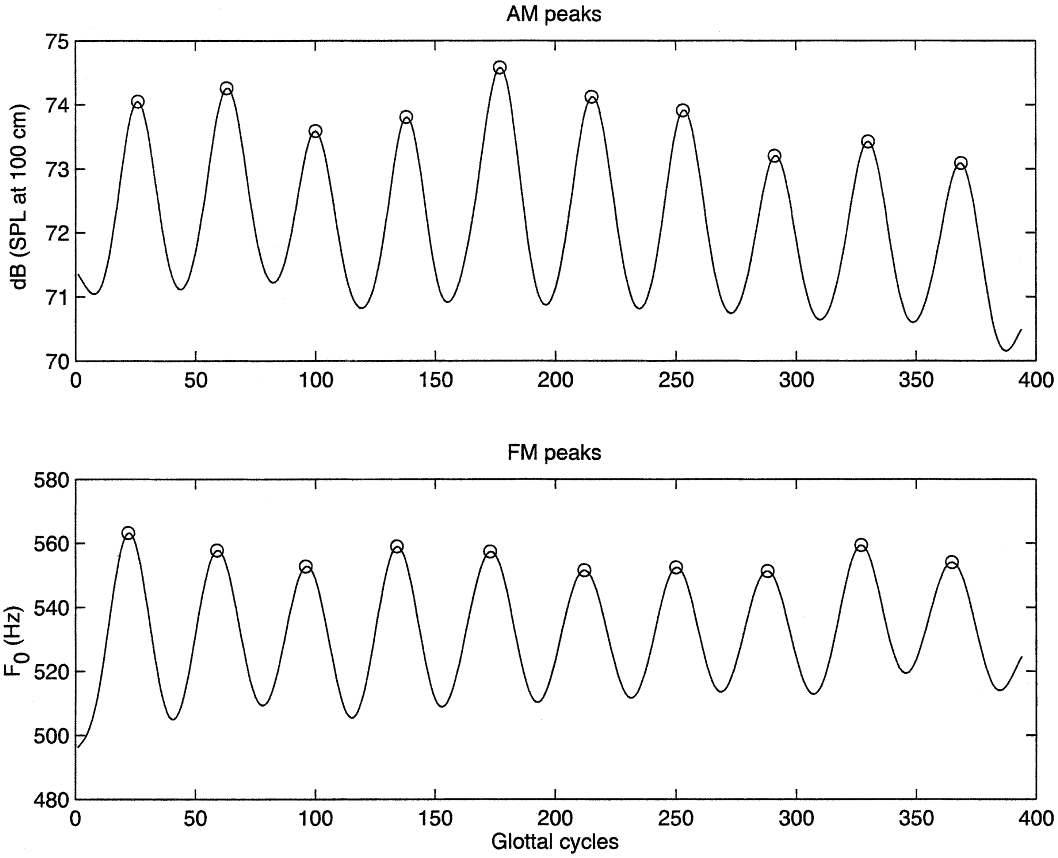

FIGURE 1. AM (upper) and FM (lower) for mixed register phonation without rate matching at a self-selected pitch, prior to rate and pitch matching in the second phase of the study. Note the general similarities in the periodicity of the AM and FM patterns.

the natural condition phonation of the singers who took part in the matching procedure. These sound files had been trimmed so that they started and ended at the same pitch and phase of the vibrato cycle. This allowed them to be played back continuously from CSL without any perceptible onset or offset artifacts. The continuous playback allowed the singers to hear the stimulus for as long as they wanted, which would not have been possible had they heard a simple playback of a vowel. Immediately after hearing the recorded vibrato, the singer attempted to match the rate of her own vibrato with the rate of the recorded stimulus. The stimulus continued during phonation. These tasks were completed in the mixed, head, and chest registers at both fast and slow rates of vibrato three times each. The sequence of registers for the matching tasks was counterbalanced across participants.

Data analysis

Preliminary analysis of each singer's vibrato was accomplished using the Motor Speech Profile (MSP) module of CSL. A 2-second segment from the temporal midpoint of each approximately 5 second vowel phonation was spliced out of the digital record and saved as a sound file for subsequent acoustic analyses. Thus, three files were saved for each register and each matching condition. By selecting a segment from the original vowel midpoint, phonation onset and offset effects were avoided. As vibrato seldom begins at the instant phonation starts, the midpoint segment was reasoned to allow a stable measure of vocal performance. The MSP software generated text files representing the FM and AM components of phonation. For each glottal cycle, a value representing the F_0 or amplitude was listed. The FM and AM files were thus of equal length.

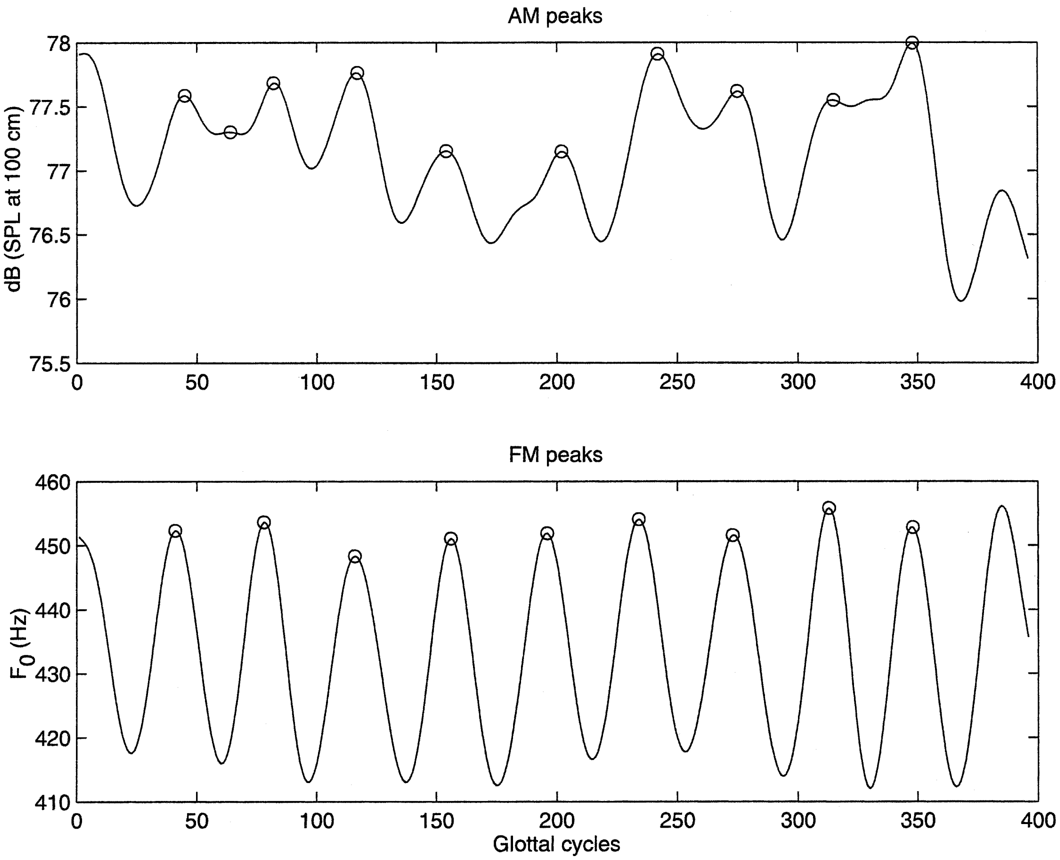

FIGURE 2. AM (upper) and FM (lower) for mixed register phonation without rate matching at a self-selected pitch, prior to rate and pitch matching in the second phase of the study. Note the irregular AM and the relatively periodic FM patterns.

These files were imported into Matlab (Natick, MS) and examined with a custom analysis routine. This was used to calculate the rate and relative extent of the oscillations based on a peak-picking algorithm (see Figures 1 and 2). The mean vibrato rate was defined as the inverse of the mean duration between the peaks located by the algorithm. The extent was calculated as the mean of the maximum minus the minimum value between two successive peaks, divided by the mean extent value for the sample between the first and last peaks, expressed as a percentage. The same process was used for both FM and AM. The mean of the values from the three repetitions represented performance under each matching condition.

Measures reflecting the steadiness of the vibrato rate and extent were also calculated. FM or AM "jitter" was operationally defined as the coefficient of variation across the modulation cycle durations. In calculating this measure, the peaks of the modulation were identified, and the periods between them were measured. The standard deviation of these periods was divided by their mean. Likewise, FM or AM "shimmer" was derived by measuring the extent of modulation (maximum minus minimum) between adjacent peaks in the 2-second sample. The standard deviation of these modulation extents was divided by their mean. A highly periodic vibrato, therefore, would have lower values for the "jitter" or "shimmer" measure, whereas an unsteady modulation pattern would lead to higher values. As with modulation rate, the mean of the three values from the three tokens of each condition was used in the statistical analysis across conditions.

TABLE 1. *Individual singers' FM rates (in Hz) for the natural and matching conditions in the chest register. The targets for matching are in parentheses in the column headings*

Singer	Slow (4.5)	Natural	Fast (6.1)
1	4.5	4.7	5.2
2	4.6	4.5	5.0
3	5.0	5.0	5.5
4	4.9	5.3	5.4
5	5.4	5.8	6.0
6	4.6	5.1	5.3
7	4.7	4.7	5.7
8	4.8	5.0	5.6
Mean	4.8	5.0	5.5

TABLE 2. *Individual singers' FM rates (in Hz) for the natural and matching conditions in the mixed register. The targets for matching are in parentheses in the column headings*

Singer	Slow (4.5)	Natural	Fast (6.3)
1	4.9	5.1	5.1
2	4.6	4.9	5.3
3	4.2	5.1	5.5
4	4.9	5.1	5.3
5	5.1	5.4	5.8
6	5.0	5.1	5.8
7	4.9	4.9	5.3
8	4.6	4.9	5.7
Mean	4.8	5.1	5.5

The numeric data were analyzed with Statistical Package for the Social Sciences (SPSS, Chicago, IL) 10.0. The primary analysis was a repeated measures analysis of variance (ANOVA) with post-hoc Bonferroni adjusted pairwise comparisons to test between individual conditions. As the acoustic analyses of the 2-second phonatory samples were automated, measurement reliability was not evaluated. Repeated measurement yielded identical results.

RESULTS

FM Rate

Individual singers' FM rates for the natural and target matching conditions are reported in Tables 1 to 3. Inferential statistics are reported in Table 4. FM rate changed significantly across the natural and matching conditions in the chest, head, and mixed registers. Pairwise comparisons revealed that the fast rate differed significantly from the natural condition in all three registers and the slow rate differed significantly from the natural condition in the head register. These data show, therefore, that individuals differed in their ability to match the vibrato rates they heard as stimuli in each register.

TABLE 3. *Individual singers' FM rates (in Hz) for the natural and matching conditions in the head register. The targets for matching are in parentheses in the column headings*

Singer	Slow (4.1)	Natural	Fast (6.1)
1	4.5	5.2	5.2
2	4.9	5.2	5.6
3	4.6	5.2	5.7
4	4.3	5.1	5.3
5	5.3	5.5	5.6
6	5.5	5.7	5.8
7	5.2	5.4	5.6
8	4.2	4.9	5.4
Mean	4.8	5.3	5.5

TABLE 4. *Repeated measures ANOVA and Bonferroni corrected pairwise comparisons for FM rate in each register across the natural and matching conditions*

Register	ANOVA *f*-ratio	ANOVA *P*-value	Slow comparison *P*-value	Fast comparison *P*-value
Chest	31.624	<0.001**	0.153	0.008**
Mixed	19.655	<0.001**	0.063	0.009**
Head	27.096	<0.001**	0.005**	0.034*

*$p < 0.05$.
**$p < 0.01$.

Table 5 reports the Pearson correlations between natural and matched FM rates. In the chest register, there was a significant correlation between the singers' natural FM rate and their rates for slow or fast matching. For the head register, there was a significant correlation between the natural and slow conditions. Thus, those singers with slower natural FM rates achieved slower rates when matching. Those who were naturally faster were also faster when matching the target stimuli under the indicated register and rate conditions.

TABLE 5. *Pearson correlations between natural FM rate and matched slow or fast rates for each register*

	Slow		Fast	
Register	***r*-value**	***P*-value**	***r*-value**	***P*-value**
Chest	0.819	0.013*	0.726	0.042*
Mixed	0.505	0.202	0.428	0.290
Head	0.933	0.001**	0.643	0.085

*$p < 0.05$.
**$p < 0.01$.

FM Extent

Pearson correlation coefficients were calculated between FM rate and FM extent across the natural and matching conditions in each register. In the chest register, the two variables were positively correlated (r 0.732, $p < 0.001$). Vowel samples with higher FM rates were associated with increased modulation extent in this register.

FM "Jitter"

This variable quantifies the steadiness of the vibrato rate. A smaller value is indicative of a more regular FM rate. Across all rate and register conditions, there was a general tendency for FM "jitter" to increase for slower FM rate, and decrease as the vibrato became faster. In other words, slower vibratos were less steady in their rate. Pearson correlations were calculated after pooling the natural and matching data for each register. In the chest register, this was reflected in a negative correlation between FM rate and FM "jitter" ($r - 0.588$, $p = 0.003$). In the head register, the same pattern was seen ($r - 0.426$, $p = 0.038$).

FM "Shimmer"

This variable quantifies the steadiness of the vibrato extent. A smaller value is indicative of a more regular FM extent. As with the "jitter" measure, slower vibratos were found to be less steady in their extent. In the chest register, there was a negative correlation between FM rate and FM "shimmer" ($r - 0.654$, $p = 0.001$). The same pattern was observed in the mixed ($r - 0.742$, $p < 0.001$) and head ($r - 0.775$, $p < 0.001$) registers.

TABLE 6. *Repeated measures ANOVA and Bonferroni corrected pairwise comparisons for SPL in each register across the natural and matching conditions*

Register	**ANOVA *f*-ratio**	**ANOVA *P*-value**	**Slow comparison *P*-value**	**Fast comparison *P*-value**
Chest	9.627	0.002**	0.042*	1.000
Mixed	5.953	0.013*	0.005**	1.000
Head	6.907	0.008**	0.041*	0.042*

*$p < 0.05$.
**$p < 0.01$.

SPL

The singers' SPL in the natural condition changed significantly across registers (F [2,14] 172.035, $p < 0.001$). Bonferroni corrected comparisons indicated that SPL in the mixed register (59.9 dB) was higher ($p = 0.004$) than in chest (53.6 dB) register, and SPL in the head register (79.3 dB) was higher ($p < 0.001$) than in the mixed. All intensity values represent dB SPL at 100 cm. Within each register, vibrato rate adjustments significantly affected SPL. Matching the slow rate resulted in a significant decrease in SPL in all three registers; fast rate matching involved an SPL increase in the head register. Table 6 reports the statistical details for these analyses.

AM Rate, Extent, "Jitter," and "Shimmer"

Because previous research has identified FM as the primary contributor to vibrato, AM was analyzed primarily in its relationship to FM, rather than in detail across the matching conditions. In many cases, the waveforms representing AM tended to be less regular in their appearance than those for FM. Figures 1 and 2 show AM and FM patterns for two samples of phonation in the natural rate condition in the mixed register, which the singers produced on a self-selected note without pitch matching. In each case, the FM is nearly periodic. The AM in Figure 1 is in phase and of similar smoothness to the FM. In Figure 2 the AM is irregular in its pattern.

AM rate was significantly correlated with FM rate in the chest (r 0.744, $p < 0.001$), mixed (r 0.544, $p = 0.006$) and head (r 0.709, $p < 0.001$) registers.

The extents of AM and FM were only significantly correlated in the mixed register (r 0.521, $p = 0.009$). The rate and extent of AM were modestly negatively associated in the head register ($r - 0.426$, $p = 0.036$). The singers with the more rapid AM rate, therefore, had reduced AM extent.

AM rate was not correlated with AM "jitter" or "shimmer." However, there was a negative correlation between AM extent and AM "jitter" ($r - 0.615$, $p = 0.001$) and AM "shimmer" ($r - 0.461$, $p = 0.023$) in the chest register. In the mixed register, AM extent was negatively correlated with AM "jitter" ($r - 0.577, p = 0.003$). The singers with the largest amplitude modulations, therefore, tended to have more steady AM in both rate and extent.

In all three registers, AM "jitter" and "shimmer" were significantly higher than FM "jitter" and "shimmer" in paired-samples t-tests (see Table 7).

Singers' Subjective Observations

The singers who took part in the second phase of the study were questioned about the experience. They reported that they felt more comfortable singing in the mixed register, as this was the one they used most often during performance, followed by the head and then chest registers. When asked about the adjustments to their vibrato rate, most singers indicated that it was harder to match the slower and easier to match the fast target rate. The singers were asked what they did to speed up or slow down their vibrato. One commented that matching required controlling the voice and vibrato, instead of letting it happen naturally. A few explained that placement is important; placing the voice more forward sped up the vibrato and placing it further back in the head slowed it down. They suggested that more breath support caused the vibrato rate to speed up and less breath support caused the vibrato rate to slow down. One singer stated that to speed up the vibrato, she pulled in the abdomen more.

DISCUSSION

Rate matching in vibrato has received limited attention in the literature. King and Horii[10] are among the few researchers who have studied this topic, and the results of the present study are in some ways similar to theirs. The nine male professional singers in their study were asked to match tones at low, middle, and high pitch levels, similar to present study, in which female singers were asked to match tones at three pitches in different registers. Both studies required the singers to attempt to match rates that were slower and faster than the singers' normal vibrato rate. The mean values reported by both studies showed similar FM rate trends when matching; as singers matched fast target stimuli, the FM rate increased and as singers matched slow target stimuli, the FM rate decreased. King and Horii[10] found their singers to be more successful when matching slower than faster rates of vibrato. Their matching of the 3 Hz stimulus was significantly better than for 7 Hz.

Previous literature has identified frequency modulation as the primary acoustic correlate of vibrato.[11,12] Therefore, the current study focused mainly on this variable. The natural FM rate of the singers was highest in the head register and lowest in the chest register, although these differences were not statistically significant at $p < 0.05$. The more rapid natural vibrato rate in the head register, where the CT is presumably more active, suggests that the mechanism responsible for the tension modulations associated with FM operates more rapidly. This finding appears consistent with the vocal vibrato model proposed by Titze and colleagues.[9] They suggested that the modulation signal generated by a central neural oscillator may interact with the biomechanical properties of the laryngeal muscles. According to their hypothesis, delays in feedback loops and overcorrection of tension may contribute to the rhythmic contractions of the CT. Research into the dynamics of both limb and articulatory motor control has suggested that more rapid movements can be achieved by increasing muscle stiffness.[13–15] In vibrato, it could be hypothesized that the modulation of muscle tension that underlies FM occurs more rapidly when the overall tension level is higher, as it would be in the upper register. This would be similar to a more rapid limb movement when the muscles are stiffer.

The present data indicate that singers in training were able to volitionally make changes to their vibrato rate in each register when matching slower and faster target stimuli. Some singers were more able than others to make the requested adjustments, but

TABLE 7. *Paired-samples t-tests for modulation "jitter" and "shimmer" measures comparing between FM and AM. Data were pooled across natural and matching conditions in each register. For Bonferroni correction, the original p-values have been multiplied by 6*

Register	*t* for jitter	*p* for jitter	*t* for shimmer	*p* for shimmer
Chest	3.296	0.019*	3.693	0.007**
Mixed	6.807	<0.001**	9.641	<0.001**
Head	5.039	<0.001**	6.108	<0.001**

*$p < 0.05$.
**$p < 0.01$.

the overall observation is that vibrato rate can be modified, and does not seem to be "hard wired" on the basis of an individual's phonatory anatomy. The correlation between the natural and matched FM rates indicates that those with a slower vibrato in the natural condition tended also to have a slower rate when matching the target stimuli. It is possible that individual anatomic and physiologic differences dispose a given singer to a faster or slower vibrato, and that these differences influence the range of rate adjustments the singer can make. Decreases in the rate and increases in the extent of vibrato are known to occur with senescence.[16] Titze and colleagues,[17] in discussing their reflex resonance model of vibrato, have suggested that slower nerve conduction and muscle contraction may account for this phenomenon. However, some performers (e.g., Alfredo Kraus or Eleanor Steber) were able to maintain their vibrato with little change even at an advanced age. For the young adult singers in the present study, the average natural FM rate across the three registers (5.1 Hz) was comparable to values reported elsewhere.[18,19]

An examination of the degree to which singers adjusted their vibrato rate revealed that they were able to increase FM rate more in the chest and mixed registers, and decrease more in the head register. Given that the head register had a faster vibrato rate in the natural condition, there would appear to be more latitude for rate reduction in this register. The exact mechanism of vibrato rate adjustment cannot be inferred from the present data. If a reduction in muscle stiffness were to cause the vibrato rate to slow down, it would also be expected to lower the pitch. However, the singers' ability to reduce vibrato rate while maintaining a target pitch suggests that mechanisms other than an overall tension reduction are involved. Their comments following the experiment suggest that adjustments to respiratory support may have played an important role. The slower natural FM rate in the lower registers appears to allow more room for FM rate increase.

FM extent was found to be correlated with FM rate in the chest register, but not in the other registers. In the chest register, the vocal folds are shorter and less tense than in the mixed or chest registers. The mechanism of FM relies on CT contraction to provide a rhythmic fluctuation of F_0 around a mean level.[20] In order to increase FM rate, the change in vocal fold length would require a more rapid CT contraction, which would likely require higher levels of motor neuron recruitment. This elevated level of recruitment would be predicted to result in increased force, which would result in a greater change in vocal fold length, and thus a larger extent of F_0 change. The dynamics of F_0 adjustment in the head register may be somewhat different. Because the CT is already highly active and the vocal folds much stiffer than at lower pitches,[20] the relationship between the rate and extent of F_0 change may be very different because the muscle and vocal fold dynamics are not the same. Muscles have been shown to produce the greatest force at intermediate lengths, where actin and myosin filaments overlap the most, thus allowing more cross-bridge formation.[21] When the CT is more fully contracted, a given modulation in the neural drive may result in a relatively smaller force change, and thus a weaker association between FM rate and extent in the head register.

FM "jitter" and "shimmer" were generally higher when singers reduced their vibrato rate. In other words, when the modulations in F_0—and by inference, the changes in muscle tension—occurred more slowly, they did so less steadily. One explanation is that the slow vibrato condition was unaccustomed, and the singers were not skilled at operating in a phonatory range that was not familiar. However, the fast vibrato condition would presumably be equally unfamiliar, and this condition was not associated with such high levels of FM "jitter" and "shimmer." Therefore, the slow vibrato condition, which the singers identified in their subjective comments as being more challenging, appears to involve decreased stability in the motor control of phonation. A parallel can be found in the articulatory kinematic literature, where slow speech has been found to be more variable in its motor execution than normal or fast speech.[22,23]

Sound pressure level increased from chest to mixed to head register, suggesting an increase in pulmonary effort in the upper registers. This effort may have been necessary to sustain phonation as the vocal folds became stiffer for these registers. These findings are consistent with those of Titze,[24] who has demonstrated that phonation threshold pressure increases with fundamental frequency. Another possible explanation for the increased SPL with higher pitched phonation is that the frequency of the first formant would be close to the first harmonic in the mixed voice, and the fundamental in the head voice. Both of these situations would be expected to lead to elevated intensity at the lips because of the alignment of the resonant frequency with strong components in the source spectrum.

The changes in SPL with vibrato rate matching appear consistent with the singers' subjective comments about using more breath support to speed up the vibrato, and less to slow it down. However, the increase in SPL when matching a faster rate is in contrast to an earlier study, which found no change in vibrato rate as a function of vocal effort or pitch,[25] but in agreement with a recent publication reporting increases in vibrato rate with vocal effort.[26] Differences in the singers under investigation, as well as the nature of the tasks performed, may account for these differences.

It is clear that the exact mechanism of vibrato rate change cannot be identified from the present data. Aerodynamic adjustments might play a role, but without electromyographic data, particularly from the CT, any speculation about muscular adjustments must remain cautious. It is possible that global adjustments were made that affected the stiffness of the laryngeal muscles, which in turn influenced the biomechanical properties of the vocal folds, and thus the hypothesized interaction between a central neural oscillator and the peripheral effectors.[9]

Because singers in training can volitionally control aspects of their vibrato, further research is needed to investigate whether or not they are able to maintain this adjustment in the long term and in the absence of auditory stimuli. Robison and colleagues[2] found vibrato to be of great importance in the perception of vocal beauty. Singers in training who have unusually fast or slow rates of vibrato may be able to make adjustments as the singers did in the present study to speed up or slow down their vibrato. If such adjustments prove to be stable in the long term, singing instruction could address this aspect of vibrato. Singers might thus be able to improve their vocal technique by refining the rate of their vibrato.

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