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Laryngeal level amplitude modulation in vibrato

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Abstract

Objectives: The goal of this investigation was to test a new methodology for measuring amplitude modulation (AM) at the level of the vocal folds during vibrato in trained singers, because previous research has suggested that AM arises in large part as an acoustic epiphenomenon through an interaction of the harmonics in the laryngeal source with the resonances of the vocal tract as the fundamental frequency oscillates.

Study Design: A within-subjects model was used to compare vocal activity across three pitch and three loudness conditions.

Methods: Seventeen female singers with a range of training and experience were recorded with a microphone and an electroglottograph. Fluctuations in the ratio of closing to opening peaks in the first derivative of the electroglottograph signal were employed as an index of laryngeal level AM.

Results: Evidence of laryngeal AM was found to a greater or lesser extent in all the singers, and its extent was not related to the degree of training. Across singers and pitch conditions, it was more prominent at lower intensities.

Conclusions: The differentiated electroglottograph signal lends itself to the measurement of AM at the level of the larynx, and the extent of the modulation appears more related to the level of vocal effort than to individual singer characteristics.

Key words: vibrato, amplitude modulation, electroglottography, acoustic

Introduction

Vocal vibrato has long been a hallmark of Western classical singing. “To the singer it is not a question of whether or not he will use the vibrato; the question is: What kind is to be cultivated and tolerated?” (1). Numerous studies have documented the modulation of both frequency and amplitude (FM and AM) in vibrato. The fluctuations of frequency and amplitude in the voice may be associated with oscillations in the respiratory, laryngeal, and articulatory musculature. However, “the source of these oscillations is not well understood” (2). Laukkanen, Vilkman, and Unto (3) suggested that singers produce vibrato using laryngeal musculature, or subglottal pressure (Psub) pulses, or a combination of the two. In some popular and non-Western styles, vibrato is indeed achieved primarily through modulation of Psub using rhythmic abdominal muscle contractions. This varying drive to the vocal folds also results in corresponding F0 fluctuations (4). In Western classical music, however, vibrato has traditionally been understood as a series of neurologically-driven laryngeal and respiratory adjustments, being mainly characterized by rapid increases and decreases in activation of the cricothyroid (CT) muscle; this is the muscle primarily responsible for lengthening the vocal folds and thus increasing pitch (5,6). These rhythmic changes in the level of CT contraction cause corresponding fluctuations of the singer’s fundamental frequency.

Some have suggested that vibrato may be a type of “stabilized physiologic tremor” (7) of the laryngeal muscles, driven by central and peripheral oscillators in a “reflex resonance model” (6). In this model, a central oscillator creates low-amplitude, wide-band oscillations at 4-6 Hz. These oscillations activate the CT and thyroarytenoid (TA) muscles, which act antagonistically in adjusting vocal fold length and tension. Stretch receptors in the CT and TA stimulate a peripheral oscillator, which then stabilizes the oscillations into a narrower-band, periodic vibrato. This interaction may provide the feedback necessary for a closed-loop reflex that creates its own oscillations. The elevated gains and neural transmission delays lead to resonance in the reflex loop, so that the "broad spectrum of central tremor frequencies" is refined into "a narrower band, which is known as vibrato" (6).

While this model offers an explanation for FM, the origin of AM is less clear. Vennard (8) observed that "much of what we seem to hear as variation in intensity is really our ears' interpretation of the pitch variation. However, there is some true intensity vibrato, at least part of the time," which "results in fluctuation in timbre, which is not quite so noticeable" (8). Horii noted that while FM is considered the main component of vibrato, with AM being mostly derived from it, the exact mechanisms deserve further attention (5). Accordingly, some have recommended that researchers not overlook the importance of amplitude variation, which they asserted has "an enormous relevance in the perception of the vibrato" (9). These authors cited experiments in the literature using synthesized voice, in which synthetic vibrato does not sound complete until amplitude variations resembling those in the human voice are properly included, because they are "crucial to produce warmth and natural quality" in vibrato (9).

Horii (5) suggested two possible explanations for the origin of AM in vibrato. First, it could result from a 'resonance-harmonics interaction' (RHI) due to modulation of the fundamental frequency and therefore its proportionally spaced harmonics. Second, AM could occur independently of FM as a result of a separate, active oscillation generator (5,10). Horii and Hata showed that most amplitude modulations could in fact be explained in terms of the RHI: if the resonant properties of the vocal tract are held constant, they wrote, overall amplitude is, "in essence, the sum of the height (strictly speaking, the sum of the square of the height) of the harmonics" which they termed the "intensity function" (10). The vocal tract configuration for a given vowel results in a resonance contour of intensity peaks and valleys. Some partials will be boosted if they occur at an upward slope or peak of this contour, while others will be attenuated if they encounter a downward slope or valley. During vibrato, F0 oscillates regularly rather than remaining fixed; as it fluctuates, its harmonics also systematically and proportionally fluctuate in frequency. As these partials oscillate, they travel back and forth along the formant skirts in the vocal tract transfer function, and thus the overall intensity of the voice fluctuates along with the F0. Figure 1 shows an example of how phonation at two different F0 levels would result in changes in the amplitude of the voice because of the alignment of the harmonics with either a peak or a trough in the transfer function.

Applying the intensity function to six fundamental frequencies from 100-450 Hz, Horii and Hata (10) found that the RHI could accurately predict the overall AM in nearly all cases. Horii's model assumed that at the laryngeal level, the only change taking place is in the modulation of frequency, not of amplitude. However, it is possible that laryngeal mechanisms may also be involved in the modulation of amplitude, the modulation of timbre through adjustments in the quality of vocal fold closure, and/or the control of subglottal pressure and airflow contributions to vibrato.

Arroabarren et al. (9) contended that while vibrato is essentially considered a modulation of the fundamental frequency, this alone does not completely account for changes in amplitude of F0 or the partials during vibrato. They suggested, furthermore, that "decomposing a signal into its AM and FM parts is ill-posed, in the sense that there exist an unlimited number of possible combinations in such components;" because of this, "the appropriate decomposition, if it exists, will depend on the context," and information regarding other vibrato parameters and mechanisms should be included in that context (9). Other researchers likewise questioned the "previously-accepted dichotomy" of FM and AM, suggesting that these categories need further clarification or adjustment (11,12). Rothenberg and colleagues suggested that "there may be a number of physiological factors present that might cause a vibratosynchronous variation in acoustic amplitude" (12). Horii (5) acknowledged the necessity of delineating amplitude modulations passively produced through the RHI, and those "actively produced by singers," suggesting that the RHI "does not preclude" Psub as an additional mechanism (5). He raised the possibility that still other mechanisms could also be at work; for example, he reiterated Ladefoged's suggestion (13) that pitch modulation is a function of the positioning of the arytenoid cartilages, and intensity modulation is a function of the spacing between them, which contributes to the amount of force used as they come together.

Shipp, Doherty and Haglund (14) suggested two mechanisms of vibrato, each producing different degrees of AM: in the first, termed laryngeally-mediated vibrato, F0 oscillations are produced by periodic contractions of the CT muscle; this can only occur when the vocal folds are properly placed at midline for optimum vibration. Vibrato produced by signals restricted to the CT muscles, as opposed to extralaryngeal structures in general, is considered more efficient and desirable in the Western classical tradition. In this view, while "more effective singers are somehow able to inhibit the AC neural activation transmitted along the RLN [recurrent laryngeal nerve]," less-skilled singers exhibit undulations of pharyngeal and oral cavity structures as well, contributing to increased amplitude vibrato (14).

In the second mechanism, known as abdominally-mediated vibrato, F0 oscillations are produced when the intrinsic laryngeal musculature provides continuous contraction "against which abdominally induced Psub pulses act" (14). This creates pulses of airflow, resulting in corresponding fluctuations in both amplitude and fundamental frequency. This type of vibrato is found primarily in non-Western styles, but may also be found in Western classical vibrato to a lesser extent (12).

More recently, Sundberg asserted that there are three possible sources of AM in vibrato. First, the "amplitude of the strongest spectrum partials, i.e. the partial closest to the first formant" is typically equal to overall amplitude, so that frequency oscillations of particular harmonics toward and away from the first and other formants create proportional amplitude variations (4). Second, the voice source is not necessarily held constant, as previously considered, and "in certain types of vibrato, the voice source varies in amplitude," due to, for example, fluctuations in Psub and glottal configuration (4). Finally, the shape of the vocal tract, and therefore its formants, may oscillate, creating another source of varying amplitude. Rothenberg et al. (12) noted that there could be different neural sources for the various types of activation and oscillation which the laryngeal and respiratory muscle groups experience during vibrato. These sources could then combine to create synchronous oscillations in amplitude as well as frequency, which contribute to AM.

While the modulation of F0 is still viewed as the primary contributor to vibrato through the RHI, as Seashore observed, there is more than one way to achieve vocal vibrato, and variations exist among singers, even within the Western classical style, in terms of their natural mechanisms and learned skills. There may be, for example, several physical sources and/or learned techniques contributing to modulations in amplitude during vibrato. Identifying these, and measuring their relative contributions, may increase singers' awareness of AM present in their vibrato, so they can cultivate it for maximum effect. Horii (5) recommended that any amplitude modulations not explained by the RHI be examined in more detail, in order to more fully understand the mechanisms of vibrato.

The purpose of this study was to explore in more detail whether amplitude modulations arise at the laryngeal level in trained singers, or whether they derive purely from frequency modulations through the RHI. Non-invasive methods were used to detect modulation in the amplitude of vocal fold vibration by examining changes in the electroglottograph (EGG) signal.

Method

Singers

Seventeen female college-aged singers trained in Western classical opera participated in this study. Five singers were advanced opera students (graduate students); six were intermediate-level students (university juniors and seniors), and six were beginning-level students (university freshmen and sophomores, and theater company students). All participants reported no history of voice or hearing disorders, and were in good general health. The experimenters listened to the participants' speech to confirm that it was perceptually within normal limits. No audiometric testing was undertaken.

Each signed a consent form approved by the university's institutional review board. The singers' characteristics are listed in Table 1.

Equipment

Recordings were made in a sound booth, using a head-mounted microphone (AKG C-420) with a constant lip-to-microphone distance of 4 cm. To measure vocal intensity, a sound level meter (Larson-Davis 712) was positioned 100 cm from the singers' lips. An electroglottograph (EGG – Glottal Enterprises EG2) was used to measure changes in vocal fold contact area during phonation. The continuous analog signals from these instruments were routed into a multi-channel analog-to-digital conversion system (Windaq 720), which sampled the data at a rate of 25 kHz on a laboratory computer. This rate was found during pilot work to be sufficiently high to allow extraction of the relevant peak amplitudes in the differentiated EGG signal (see Analysis, below). The resultant recordings represented the simultaneous signals from the microphone, sound level meter, and EGG. Prior to sampling, the microphone signal was low-pass filtered at 12 kHz with a Frequency Devices (9002 series) Butterworth filter.

Procedure

Following several minutes of vocal warm-up (specific exercises were chosen by each singer), the participants were asked to produce five-second tokens of sustained /ɑ/ with vibrato in each of nine conditions: three pitches, each at three levels of loudness. Three tokens in each condition were obtained, for a total of 27 samples per singer. The three pitches, which were requested in randomized order from each singer, were selected to represent low, medium, and high notes in the singer's upper middle register. These pitches were: G4 (392 Hz), D5 (587 Hz), and A5 (880 Hz). They were chosen by the third author to sample a wide but achievable range of fundamental frequencies, based on his extensive experience with vocal performers. Each participant sang each pitch first at a comfortable level of loudness, and then either at soft then loud levels, or loud then soft levels. The requested sequence of loudness levels was randomized across participants. The specific loudness levels selected by the individual singers were not linked to any decibel targets.

Data Analysis

The middle two seconds of each token were used in the data analysis. Praat acoustic analysis software (version 4.4.07) was used to create amplitude and frequency modulation contours from the head-mounted microphone signal. These data were then saved as text files and imported via Microsoft Excel into Matlab, where custom analysis routines were used to perform additional numerical analyses of these acoustic signals as well as of the EGG and sound level meter recordings. Upward and downward peaks in the first derivative of the EGG waveform were automatically identified, and a ratio of the magnitude of the closing to the opening peak was calculated. This measure has previously been defined as the *EGG speed quotient* (15) because the rate of increase in vocal fold contact area during closure exceeds the rate of decrease as the folds separate during phonation. This measure has been found to vary in proportion to vocal intensity (15). In the present study, the exact timing of the instants of opening or closing was not important, because open quotient was not calculated. Previous work has outlined a number of challenges in calculating such a measure from the differentiated EGG waveform because of the noise inherent in such signals (16). In the present study, the *magnitude* of the peaks

– rather than their timing – was the relevant factor in the analysis, and this was not affected by the presence of double peaks in either the opening or closing part of the glottal cycle. Because the EGG speed quotient is sensitive to vocal intensity (15), it was reasoned that any rhythmic fluctuations in this measure would be evidence of AM at the level of the vocal folds. To test the premise that laryngeal AM could be measured by this means, a non-singing individual induced rhythmic subglottal pressure pulses by manually applying pressure to the abdominal wall during a sustained vowel. Figure 2 shows the parallel between the AM in the microphone signal, the EGG waveform, and the EGG first derivative. The AM in the differentiated EGG and acoustic signal, along with the accompanying FM for each signal source are shown in Figure 3 under the same condition of abdominal wall pressure pulsing.

Dependent Measures

Several physiologic and acoustic measures were used to obtain additional information about both laryngeal- and output-level vibrato characteristics.

Sound pressure level (SPL). The mean sound pressure level at 100 cm during the two-second sample was derived from the sound level meter signal.

Fundamental frequency (F0). The mean fundamental frequency during the two-second sample was derived from the Praat analysis of the microphone signal.

EGG AM extent. This measure is the average *variation* in the amplitude of the EGG speed quotient cycles. It was calculated by measuring the peak to trough height of each modulation cycle in the EGG AM trace, which was then averaged for all cycles within the two second sample. Thus, more modest modulations would result in a smaller value on this measure. A larger EGG AM extent indicates more variation in the ratio of the vocal folds' closing rate (upward peak in the EGG first derivative) to the opening rate (downward peak). This measure is reflective of the degree of AM at the level of the larynx, prior to any effects from the resonance-harmonics interaction in the vocal tract.

Results

SPL. The mean SPL (at 100 cm) for the 2 second vowel sample was 76.8 dB for soft, 81.6 dB for comfortable, and 84.4 dB for loud conditions.

F0. The mean F0 levels for the three pitch conditions were 388.7 Hz (G4), 586.9 Hz (D5), and 883.4 Hz (A5).

EGG AM extent. The mean extent (across singers) of EGG AM varied among the pitch and loudness conditions. These data are summarized in Table 2. Repeated measures analysis of variance revealed a significant change in EGG AM extent as a function of loudness condition ($F [2, 32] = 13.053$, $p < .001$) when the data were collapsed across the three pitches. Tests of within-subjects contrasts showed that the mean was higher in the soft phonation condition than for the comfortable ($F [1, 16] = 15.753$, $p=.001$) and loud ($F [1, 16] = 14.405$, $p=.002$) conditions, which did not differ from each other. Figure 4 shows this pattern in the pitch-collapsed data. The EGG AM extent was not statistically significantly influenced by pitch, although Figure 5 reveals a slight decrease with increasing pitch when the data were collapsed across loudness conditions.

The extent of EGG AM varied substantially between individual singers, as well as among each singer's 27 tokens. For example, Figure 6 illustrates the token during which the highest degree of EGG AM was present (0.881), while Figure 7 illustrates the token during which the lowest degree of EGG AM was present (0.027).

Discussion

The purpose of this study was to measure amplitude modulation during vibrato, and determine whether any AM might be occurring at the source (laryngeal) level in addition to the AM hypothesized to arise at the subsequent filter (vocal tract) level through the resonance-harmonics interaction (RHI). Modulations in amplitude detected by the EGG speed quotient were considered to be evidence of laryngeal-level AM.

Resonance-Harmonics Interaction

The RHI is considered the main source of amplitude modulation in vibrato (5,10). AM resulting from the RHI was present extensively in the vowels recorded in the present study. In instances where very little laryngeal-level AM was detected in the EGG speed quotient, output-level AM was present to a greater degree in the microphone trace, suggesting that additional AM was arising as a result of the RHI. This is particularly apparent in Figure 7.

In addition to the AM which occurs as a result of the RHI, the presence of EGG AM, or AM which has been detected by the EGG speed quotient, can be considered direct evidence of laryngeal-level AM. In Figures 2 and 3, which depict the consequences of abdominally-induced Psub fluctuations, corresponding laryngeal-level rhythmic changes to the vocal folds' closing to opening peak ratios in the differentiated EGG signal are also visible. These changes are evidence of periodic fluctuation in the intensity contour at the laryngeal level, which the EGG speed quotient can be seen to detect. In a case such as this, where Psub pulses were deliberately induced, it is not surprising to find AM at the laryngeal level.

Examination of the figures reveals that the phase relationships between AM and FM were variable. Figure 3 shows the two traces from the microphone signal to be similar to each other in their phase. This would be consistent with the mechanism by which modulations were produced in this sample. Manually applied pressure pulses to the abdomen would be predicted to result in rhythmic Psub fluctuations. Because Psub is the main contributor to vocal amplitude changes, the AM trace followed this rhythmic trend. The accompanying FM would likely be due to passive F0 fluctuations resulting from changes in the amplitude of vocal fold excursions, which during increased loudness raise the vocal fold tension and thus the fundamental (17). The FM derived from the EGG (lowest panel in Figure 3) shows a slight lag. This is likely due to the computation of this trace, which relied on F0 extraction over several glottal cycles, whereas the Praat analysis which revealed the microphone modulations, operated on a shorter time window. Figure 7 shows the microphone AM trace to be far less regular in its pattern than the accompanying FM, which is consistent with previous accounts (18). This finding is also congruent with Horii's RHI model (5), which proposes that AM arises in many instances as a 'side effect' of FM. The near absence of EGG AM in this figure further supports the RHI model's applicability for this sample.

As measured by the EGG speed quotient, laryngeal-level AM was present in each of the 459 vibrato tokens, across singers and across pitch and loudness conditions. EGG AM extent was greatest in the three soft conditions. The D5 comfortable and loud conditions had, on average, the smallest mean EGG AM extents, approximately half the size of the greatest mean EGG AM extent, which was found in the soft D5 condition. Three-fourths of the tokens with the lowest EGG AM extents occurred at pitch A5, while almost all of the tokens with the highest EGG AM extents occurred at the soft D5 pitch. These findings suggest that modulation of amplitude as well as frequency is occurring at the laryngeal level, and to a greater extent during soft conditions.

It is possible that laryngeal-level AM may be driven by respiratory factors such as Psub; however, the present methodology did not include the necessary invasive procedures to determine with certainty whether respiratory forces may be directly generating laryngeal-level AM. Given the higher EGG AM extents associated with softer singing conditions, another possibility is that decreased vocal fold tension, associated with lower laryngeal resistance, may introduce more susceptibility to fluctuations in amplitude at the laryngeal level. As a consequence of CT activity during pitch fluctuations, tension in the vocal folds increases and decreases. It may follow that as tension in the vocal folds changes, the amplitude of vocal fold excursion may passively change accordingly. If the vocal folds are stretched tightly, vibratory amplitude will be smaller for a given level of respiratory drive, but when the vocal folds are looser, the amplitude of vibration may be greater. Thus, laryngeal level AM may be an indirect consequence of the FM that is presumably driven by fluctuations in the neural drive to the CT.

The singers in this study were relatively close in age, and shared similarities in the type of voice training (classical) they received. This was especially true for those admitted to the university voice program. However, their individual levels of EGG AM were unpredictable. There was no apparent association between a singer’s class, age, or duration/type of training, and the extent of EGG AM in her vibrato samples. Singers with differing levels of EGG AM were found across all levels of training and experience, and each singer had a range of EGG AM extents which varied under different conditions, rather than remaining at a relatively stable level across conditions. These findings suggest that EGG AM may be an unconsciously or passively occurring laryngeal phenomenon, subject to pitch and especially loudness demands, and dependent more on individual physiological makeup than on deliberate training or technique.

Within the classical style, there appear to be several ways to achieve pleasing vibrato. The presence of EGG AM across pitch and loudness conditions and among singers in fluctuating degrees is congruent with the notion of motor equivalence. According to this view, the different singers are most likely achieving vibrato through the execution of slightly different motoric patterns which in spite of their differences result in the desired perceptual features of vibrato extent, rate, and periodicity.

While it was not measured in the present study, Psub could potentially be a significant contributor to amplitude modulation, because it indirectly influences glottal configuration, resistance, and closure type and speed, which may also affect EGG speed quotient values. Rothenberg et al. (12) suggested that instances of abdominally-induced vibrato, which are driven by volitional Psub fluctuations, can be found even among Western classical singers who have been trained to use laryngeally-mediated vibrato, in which the CT is primarily responsible for FM, with AM derived from it. The use of an alternate means of generating AM, such as abdominally-induced Psub pressure fluctuations, should not be excluded as a possibility among classically-trained singers.

Directions for Future Research

More in-depth study is needed regarding the roles of not only Psub, but also of glottal configuration and resistance as potential contributors to AM during vibrato. Similarly, electromyography, a direct but invasive measure of muscular activity, was not possible in the present study, but would likely have revealed important details of laryngeal muscle activation.

While it is uncertain that an optimal level of AM, either at the source or filter level, would in itself be consistently perceptible to audiences, researchers have previously emphasized the crucial role that AM plays in the perception of vibrato beauty and richness (9), encouraging further direct study of how it is produced. It is unclear whether AM, because it appears to be mostly a passive by-product in the Western classical style, is a vocal attribute that could be directly trained or manipulated to the same degree as other more volitional aspects of vibrato quality.

Reference List

1. Seashore C. In search of beauty in music. New York: The Ronald Press; 1947.
2. Leydon C, Bauer JJ, Larson CR. The role of auditory feedback in sustaining vocal vibrato. J Acoust.Soc.Am. 2003;114(3):1575-81.
3. Laukkanen A, Vilkman E, Unto K. Aspects of the physiological sources of vocal vibrato: A study of fundamental-period-synchronous changes in electroglottographic signals obtained from one singer and two excised human larynges. Scan J Log Phon 1992;17:87-93.
4. Sundberg J. Acoustic and psychoacoustic aspects of vocal vibrato. In: Dejonckere P, Hirano M, Sundberg J, editors. Vibrato. San Diego: Singular Publishing Group; 1995. p. 35-62.
5. Horii Y. Acoustic analysis of vocal vibrato: A theoretical interpretation of data. J Voice 1989;3(1):36-43.

6. Titze IR, Story B, Smith M, Long R. A reflex resonance model of vocal vibrato. J Acoust Soc Am 2002;111(5 Pt 1):2272-82.

7. Titze IR, Solomon NP, Luschei ES, Hirano M. Interference between normal vibrato and artificial stimulation of laryngeal muscles at near-vibrato rates. J Voice 1994;8(3):215-23.

8. Vennard W. Singing: The mechanism and the technic. New York: Carl Fischer; 1967.

9. Arroabarren I, Zivanovic M, Bretos J, Ezcurra A, Carlosena A. Measurement of vibrato in lyric singers. Proceedings of the IEEE instrumentation and measurement technology conference, Hungary 2001;3:1529-34.

10. Horii Y, Hata K. A note on phase relationships between frequency and amplitude modulations in vocal vibrato. Folia Phoniatr 1988;40:303-11.

11. King JB, Horii Y. Vocal matching of frequency modulation in synthesized vowels. J Voice 1993;7(2):151-9.

12. Rothenberg M, Miller D, Molitor R. Aerodynamic investigation of sources of vibrato. Folia Phoniatr.(Basel) 1988;40(5):244-60.

13. Ladefoged P. Respiration, laryngeal activity and linguistics. In: Wyke B, editor. Ventilatory and phonatory control systems. New York: Oxford University Press; 1974. p. 299-314.

14. Shipp T, Doherty E, Haglund S. Physiologic factors in vocal vibrato. J Voice 1990;4:300-4.

15. Dromey C, Stathopoulos ET, Sapienza CM. Glottal airflow and electroglottographic measures of vocal function at multiple intensities. J Voice 1992;6:44-54.

16. Henrich N, d'Alessandro C, Doval B, Castellengo M. On the use of the derivative of electroglottographic signals for characterization of nonpathological phonation. J Acoust Soc Am 2004;115(3):1321-32.

17. Titze IR. On the relation between subglottal pressure and fundamental frequency in phonation. J Acoust Soc Am 1989;85(2):901-6.

18. Dromey C, Carter N, Hopkin A. Vibrato rate adjustment. J Voice 2003;17:168-78.

Table(s)

Table 1. Singers' vocal training

Singer	Age	University level	Years of training	Type of vocal training/lessons	Age of first vibrato
1	27	graduate	9	private classical and group choral	13
2	23	junior	9	choral group training	14
3	24	graduate	7	weekly private classical	15
4	23	senior	8	weekly private classical	15
5	18	freshman	9	private classical and group choral	6
6	20	sophomore	6	private classical and group choral	8
7	23	graduate	9	weekly private classical	16
8	25	senior	9	weekly private classical	16
9	20	junior	8	weekly private classical	11
10	23	graduate	5	weekly private classical	14
11	27	graduate	9	private classical and group choral	11
12	21	senior	8	weekly private classical	12
13	21	junior	9	weekly private classical	12
14	22	theater company	8	private classical and group choral	8
15	21	sophomore	13	weekly private classical	7
16	20	theater company	0.5	weekly private classical	14
17	19	theater company	0.6	private classical and jazz	14
M	22.2		7.5		12.1
SD	2.6		3.1		3.2

Table(s)

Table 2. Mean and standard deviation of EGG AM extent across pitch and loudness conditions for all 17 singers

	low (G4)	sd	mid (D5)	sd	high (A5)	sd
soft	0.42	0.17	0.52	0.27	0.39	0.19
comfortable	0.35	0.20	0.26	0.18	0.27	0.20
loud	0.31	0.14	0.24	0.14	0.30	0.23

Figure(s)

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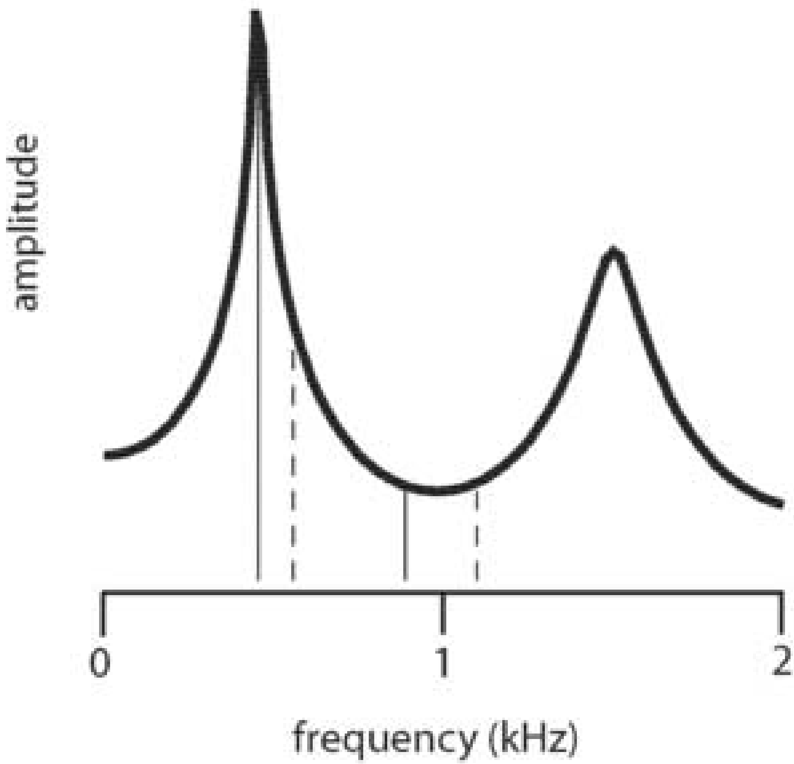

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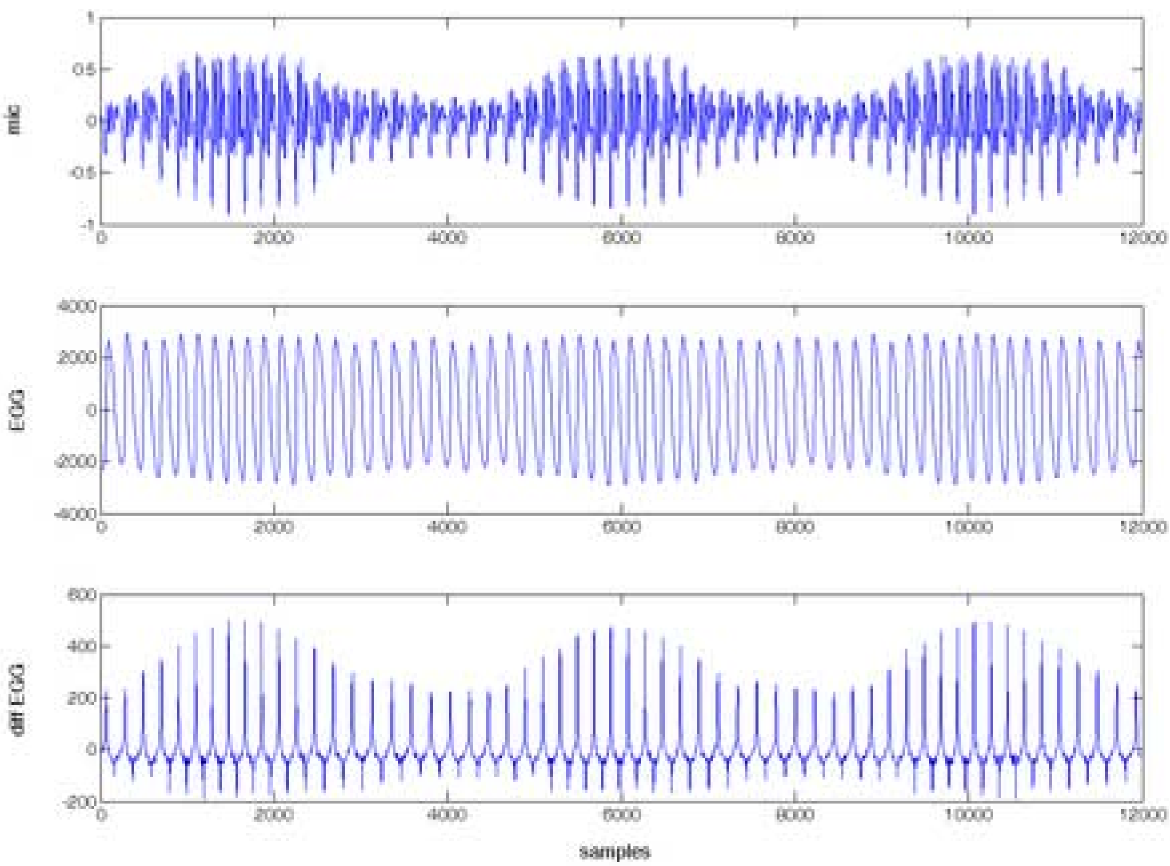

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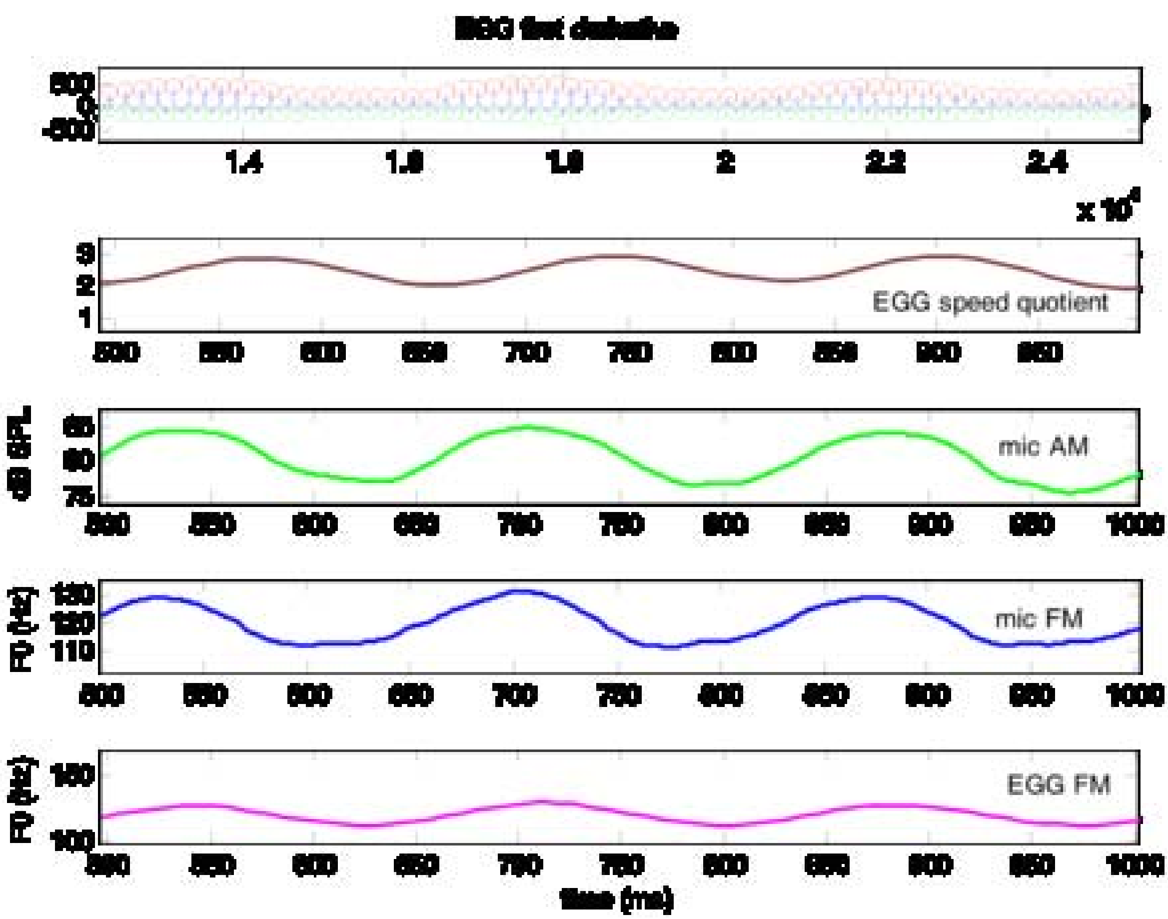

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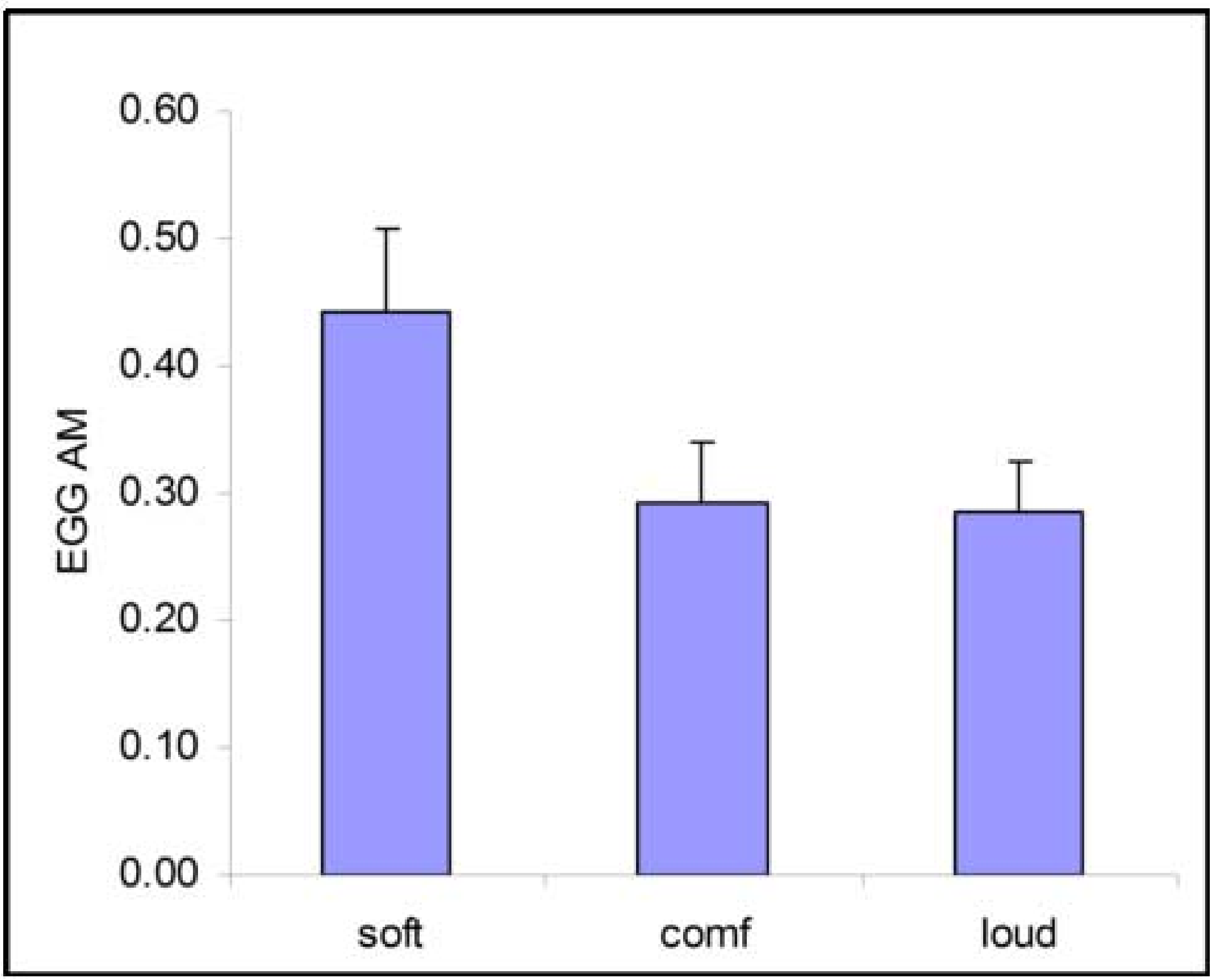

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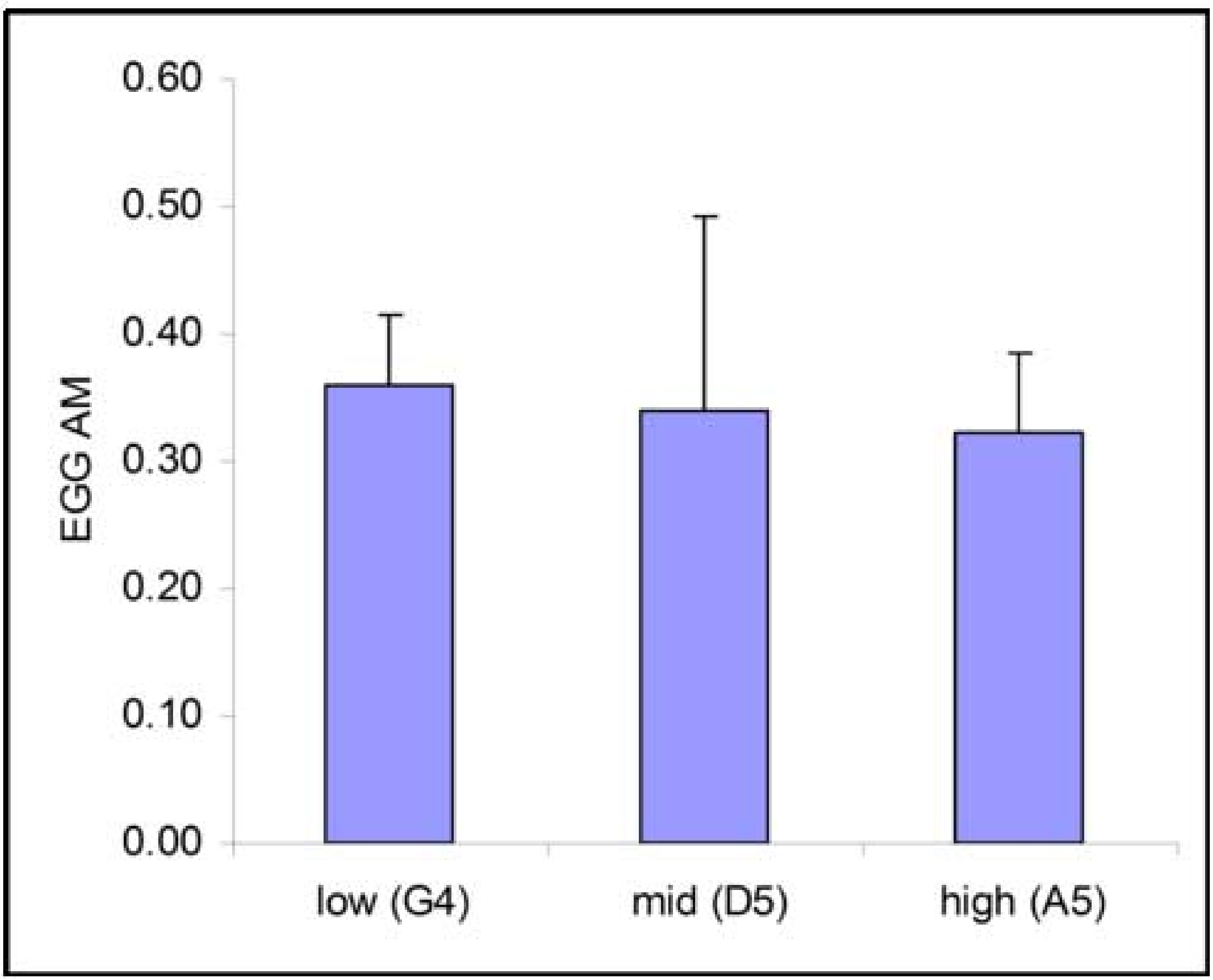

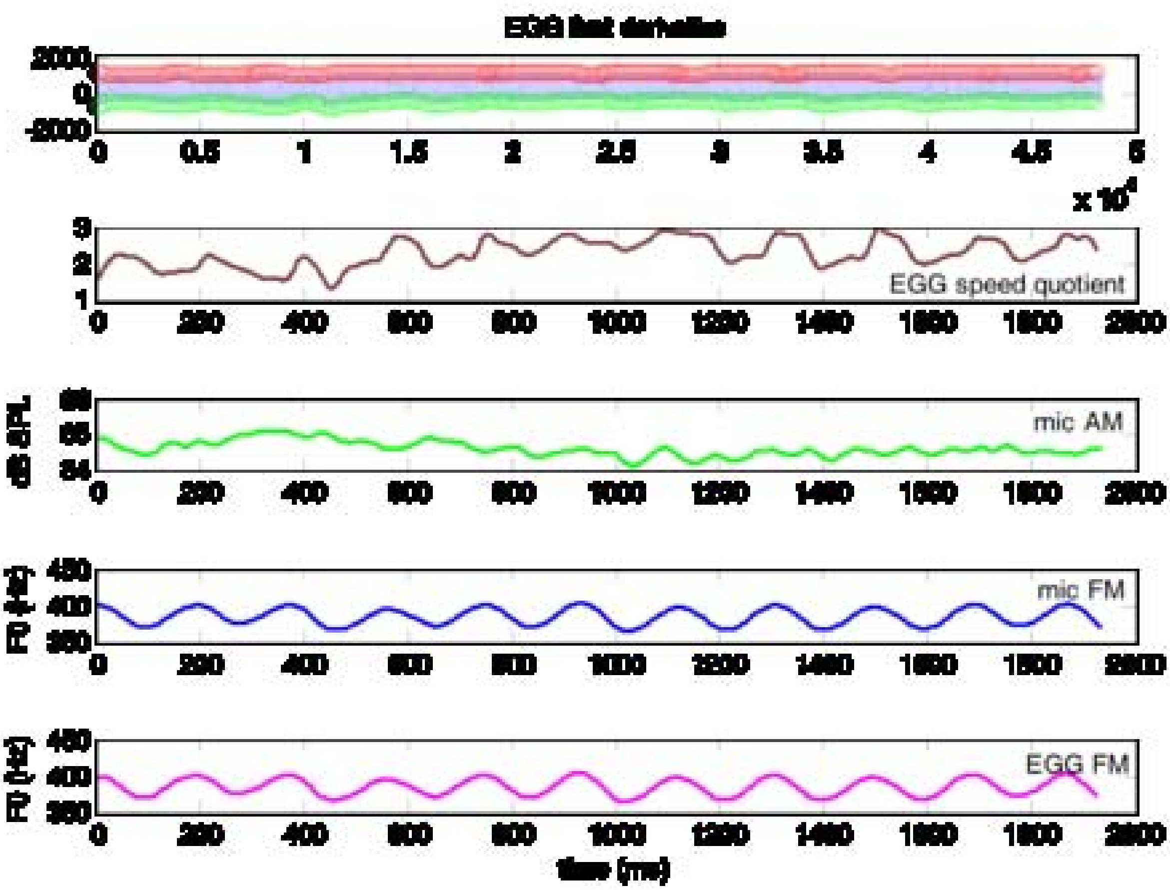
EGG speed quotient
mic AM
mic FM
EGG FM

Figure(s)

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