Airflow Vibrato: Dependence on Pitch and Loudness

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Abstract: Objective. To describe the airflow vibrato characteristics at various pitches and loudness levels during vocal vibrato production.

Method. This descriptive case series research design included four subjects: 1 baritone, 1 tenor, and 2 sopranos. The extent and rate of airflow vibrato and fundamental frequency vibrato were measured by analyzing /pa:pa:pa:p/ strings with at least 3-4 cycles of vibrato during the vowels. Comparison was made within and between the subjects at different pitches and loudness levels.

Result. Airflow vibrato was quite evident for all subjects. Mean airflow vibrato extents were larger in female than male singers. Increase in airflow vibrato extent was observed with increase in pitch, and it was statistically significant when comparison was made within each subject, within males (for P2, M = 74.55 cc/s, S.D = 27.44 cc/s, $p < 0.01$), within females (for P2, M = 94.36 cc/s, S.D = 24.13 cc/s, $p < 0.01$), and between males & females (for P1 in females, M = 46.96 cc/s, S.D = 16.16 cc/s, $p < 0.003$; for P2 in females, M = 94.365 cc/c, S.D = 24.13 cc/s, $p < 0.02$). Statistically significant increase in airflow vibrato extent was observed between males and females only at the highest loudness level (for females, M = 81.77 cc/s, S.D = 23.80 cc/s, $p < 0.0001$). The range of phase difference between them was 34∘-197∘, and most of the time, airflow vibrato lead F0 vibrato. EGG values were also reported.

Conclusion. This study shows that the characteristics of airflow vibrato are similar to F0 vibrato; i.e., airflow vibrato also has extent, rate, regularity, and waveform complexity. However, airflow vibrato waveforms were seen to be more complex in waveshape than F0 vibrato waveforms. Studies on the sources of airflow vibrato are necessary.

Key Words: vibrato−aerodynamics−singing voice−EGG−airflow−frequency vibrato.

INTRODUCTION

Vocal vibrato production

Vibrato is commonly used in Western classical singing. Vibrato is primarily considered to be a relatively regular variation of fundamental frequency (f_o).[1] It is also considered as a musical effect that adds expression to vocal (and instrumental) music. A perceptually pleasant and acceptable professional vibrato in Western classical singing production is characterized by a f_o modulation rate of approximately 5−7 Hz with an extent of about ±1 semitone (ST).[2] Studies suggest that the production of vibrato involves primarily the cyclic contraction of the cricothyroid (CT) muscles to lengthen and shorten the vocal folds at the vibrato rate (thus changing the tension of the vocal fold tissue that alters the f_o),[3,4] cyclic pulsations of the subglottal pressure to also alter the vocal fold tissue tension,[4,5] and a peripheral reflexive negative feedback loop requiring a pair of agonist−antagonist muscles (like the CT *vs* vocalis (VOC) muscles) for vocal fold lengthening control and thus tension alteration.[6] Consistent with this latter statement from Hampala et al,[7] Shipp et al[3] emphasize that other muscles can contract synchronously with vibrato, including the lateral cricoarytenoid muscles especially.

The fluctuating f_o vibrato is accompanied by synchronous variations of intensity and loudness[7] due to altering the relation between the source harmonics and the vocal tract resonances during the vibrato cycle.[7,8] Rothenberg et al[9] measured the glottal airflow and subglottal pressure during vibrato produced by a bass-baritone singer, and observed synchronous oscillations in the sound pressure level, which was termed "amplitude vibrato." They indicated that the frequency vibrato was accompanied by synchronous variations in the waveshape of the glottal airflow pulse that might have a significant effect on perceived loudness.

The two most common measures of f_o vibrato are the *frequency extent* within the vibrato cycle (ie, the difference between the highest and lowest f_o value within the vibrato cycle, given in hertz, STs, or cents) and the number of vibrato cycles in 1 second, called the *vibrato rate*, given in hertz or cycles per second.[3,10−12] There has been reported an interaction between vibrato rate and extent, such that great extents appear in combination with slow rates and narrow extents are associated with faster vibrato rates[13]; however, Seidner et al[8] counter that assertion by showing data from Schultz Coulon and Battmer.[14] A third characteristic is the regularity of the vibrato rate, which has been less studied.[10,15]

In general, then, it can be summarized that vibrato is a physiological, aerodynamic, acoustic, and perceptual phenomenon.[7] As such, the vibrato cycle is a cycle of changing laryngeal behavior, and thus there can be an expectation of changing transglottal pressure, glottal adduction, glottal area, glottal airflow resistance, and corresponding glottal airflow.[16] The focus of the research presented here is the

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mean airflow variation during singing that accompanies frequency vibrato. The mean airflow variations are called *airflow vibrato* in this study.

It is hypothesized that airflow vibrato will have alternating airflow values that vary at the same rate as the f_o vibrato rate, and will also have a peak-to-peak airflow extent during the vibrato cycles as an important characteristic. This hypothesis comes from the assumption that the changing mean airflow may correspond to low-frequency variations in adduction (more airflow with less adduction), translaryngeal pressure (more airflow with greater translaryngeal pressure), or glottal area (more airflow with greater glottal area). It is possible that airflow vibrato may vary with changes in pitch and loudness, again due to variations in glottal configuration and air pressure.

The purpose of this study, then, was to explore the nature of airflow vibrato by measuring airflow vibrato characteristics at various pitches and loudness levels during vowel prolongations while singing in the classical Western style by professional performers. The results may reveal important physiological, aerodynamic, and pedagogical information about the production of vibrato.

Earlier studies of airflow vibrato

There are relatively few studies showing airflow vibrato and its relation to other production variables. Sundberg[17] shows "air flow pulsations" in two figures where there are distinct variations in the airflow. In that study, the authors conclude that the air flow pulsations "seem to be correlated with the amplitude [intensity] vibrato" (p. 53). Their examples show the airflow vibrato in phase with "amplitude vibrato" in some of the figures and nearly out of phase in another. Shipp et al[3] also show a figure of "air flow rate" variations with the audio signal. However, the signals are not quantified.

An important study on airflow vibrato was reported by Schultz Coulon and Battmer[14] who studied the relationship among vocal intensity, subglottal pressure, and airflow in singers while producing vibrato. In their Figure 4, the relationship between airflow vibrato and intensity vibrato for the male singer's middle pitch was such that airflow peaks led intensity peaks by approximately 113° (see below for the definition of phase calculations). For the highest pitch, airflow was nearly completely out of phase with both intensity and subglottal pressure. Schultz Coulon and Battmer's Figure 5 shows recordings for a female singing three loudness levels at the same fundamental frequency. For her middle loudness token, the airflow lagged intensity by approximately 72° for the last three cycles shown, and for the loudest production, all three signals were essentially in phase with each other. The authors' Figure 6 shows recordings for a female singing on a constant middle range pitch with a relatively strong vibrato in both the airflow and intensity signals, for three loudness levels. For the softest token, the airflow lagged intensity by approximately 58°, and for the middle loudness, airflow lagged intensity by a similar value of 55°. For the loudest token, however, airflow and intensity were nearly out of phase despite the singer using the same pitch, with airflow lagging intensity by approximately 152°. For both the middle and highest loudness levels, the subglottal pressure was nearly out of phase with the airflow. In addition to these phase relationships, the authors also showed that airflow vibrato extent increased for a soprano singer as her pitch increased while singing with at "'comfortable' intensity levels" (p. 53).

The results from the Scherer et al[18] study suggest that while singing, the vibrato-related oscillations of airflow, subglottal pressure, and intensity may have varying phase relationships with each other, an interesting but confusing finding from a mechanical−aerodynamic−acoustic orientation. In addition, the airflow signals in the figures of Scherer et al illustrate that airflow vibrato may not be a regularly oscillating signal, but may have a complex shape. These details of phase relationships and complexity of waveshape are explored in the current project.

Electroglottography and vocal vibrato

Electroglottography (EGG) is a noninvasive method for indirectly exploring phonation. The EGG signal magnitude appears to reflect the changes in vocal fold contact area during phonation.[19−23] Measures of the EGG waveform are sensitive to vocal register, vowel, the degree of vocal fold adduction, and the intensity of phonation.[24−30]

Scherer et al[28] studied the production of trillo, a baroque singing style that reiterates tone production over a range of rates below and above normal vibrato rates. Both the EGG signal height and pulse width (EGGW, defined below; Hicks and Teas[29]) of the signal varied with each trillo cycle, becoming taller and wider with greater adduction, and shorter and narrower with less adduction throughout the cycle, thus giving the impression that trillo for the singer subject was an adductory controlled phenomenon from the orientation of EGG waveform interpretations. Dromey et al[31] found no consistent, distinctive differences in the EGG waveforms with and without vibrato within different registers. However, the authors compared only waveform shapes, and no height and width measures were reported.

Horii[32] used their EGG speed quotient (the ratio of the magnitude of the peak rate of the EGG signal rise [peak rate of vocal fold contact] to the peak rate of EGG signal lowering [peak rate of vocal fold decontacting]) to indicate laryngeal-level changes associated with vibrato. The authors report the value of the EGG speed quotient extent within vibrato cycles, finding statistically significant larger values for the soft loudness levels compared to medium and higher loudness levels, but not statistically significantly different among the pitches used in the study. The authors show variations of the EGG speed quotient in response to externally pumping the respiratory system to cyclically vary the subglottal pressure (P_s), demonstrating that the EGG speed quotient tends to increase with cyclic increase in P_s. Similar findings were obtained by Laukkanen and Vilkman (1995).[15]

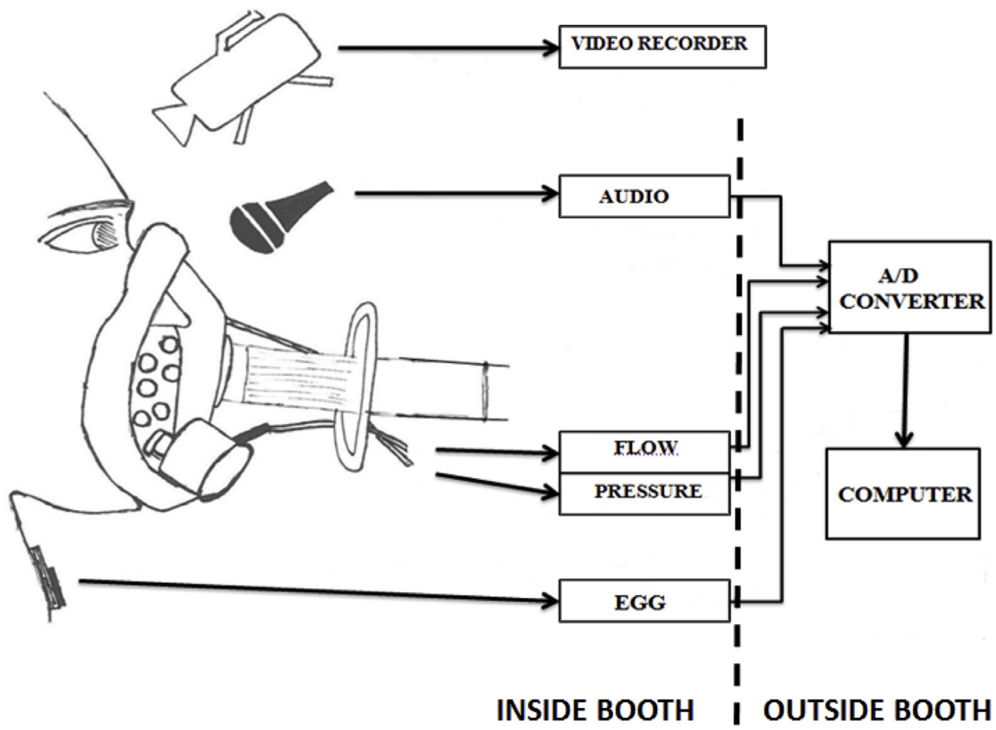

FIGURE 1. Experimental setup.

METHODOLOGY

Subjects

Four professional singers volunteered for this study. All subjects were currently active Western classical singers and teachers of singing with over 15 years of professional performance experience in regional, national, or international opera and recital venues. The subjects were two sopranos (37 and 57 years old), a tenor (62 years old), and a baritone (37 years old). All singers signed a consent form that explained the purpose, procedures, risks, and benefits of the study. They were also given a health and voice history form to fill out. All subjects were healthy at the time of recording, and had no history of voice problems or other related health issues within the last month.

Instrumentation

Figure 1 shows a schematic of the instrumentation setup. The microphone (model 33-3013, RadioShack Corporation, Fort Worth, TX), aerodynamic system with a circumferentially vented flow mask (model MSIF-2 S/N 2049S, Glottal Enterprises, Syracuse, NY), electroglottograph (Kay Elemetrics, Lincoln Park, NJ), sound level meter (Precision Integrating, Bruel & Kjaer 2230, Denmark), and one of two video cameras were set up inside an IAC (Industrial Acoustics Company) acoustics is the name of the company sound-treated booth. The rest of the equipment was situated outside the booth and included the signal acquisition system with digital oscilloscope (model DI-720, DATAQ Instruments, Inc., Akron, OH, with WinDaq software), Dell computer (OptiPlex 780, Round Rock, TX), and a second video camera that recorded the activity in the booth through the booth window. The pneumotachograph flow mask and oral air pressure transducer were calibrated based on standard procedures over a wide range of constant airflows (with the use of a separate calibrated pneumotachograph, calibrated using standard rotameter flowmeters) and constant pressures (with the use of a U-tube manometer), with uncertainty within approximately ±3%.

Recording procedures

The experiment took place at the Voice Physiology Laboratory, Bowling Green State University. The microphone and sound level meter were placed at a constant distance from the subject's mouth (approximately 6 inches). The subject held the vented pneumotachograph mask tightly against her or his own face such that it could be removed easily by the subject at any time. Included in the vented mask was a small sterilized tube attached to a pressure transducer. The lip occlusion method for obtaining estimates of subglottal pressure from oral air pressure was used for a set of utterances. Pressures are reported in cm H_2O (where 1 cm $H_2O = 0.09804$ kPa) and airflows are reported in cm^3/s (where $1\ cm^3/s = 10^{-6}\ m^3/s = 10^{-3}$ L/s).

The electroglottograph was used to obtain waveforms of the assumed changes in vocal fold contact area. The device includes two small plates that were placed on the skin over the right and left thyroid laminae. The signal obtained is a demodulated variation of the impedance (high frequency, low amperage) through the neck as the vocal folds vibrate. The airflow, oral air pressure, EGG signal, and microphone

TABLE 1.
Frequencies of the Three Pitches Sung by the Singers

Voice Classification	P1	P2	P3
Tenor	D3 (147 Hz)	D4 (294 Hz)	G4 (392 Hz)
Baritone	A2 (110 Hz)	A3 (220 Hz)	F4 (349 Hz)
Soprano-1	C4 (261 Hz)	A4 (440 Hz)	G5 (784 Hz)
Soprano-2	C4 (261 Hz)	A4 (440 Hz)	G5 (784 Hz)

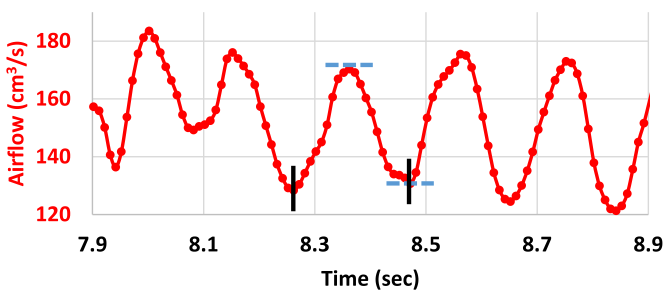

FIGURE 2. Airflow vibrato for Soprano-1 singing her lowest pitch (P1) and soft level of loudness (L1). The short vertical bars indicate local minima to demarcate periods, and the two blue dashed bars indicate a peak-to-peak measure of airflow extent. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

signals were recorded into separate channels of the 14-bit DATAQ A/D converter using a sampling rate of 20,000 Hz/channel and DATAQ's WinDaq software. The airflow signal was smoothed using a seven-point smoothing technique (within custom software using Matlab), a process that does not alter the time alignment between the original signal and the smoothed signal. The smoothed signal was then down sampled so that there were airflow values given every 10 ms. In Praat, the interval for reporting the f_o values was also

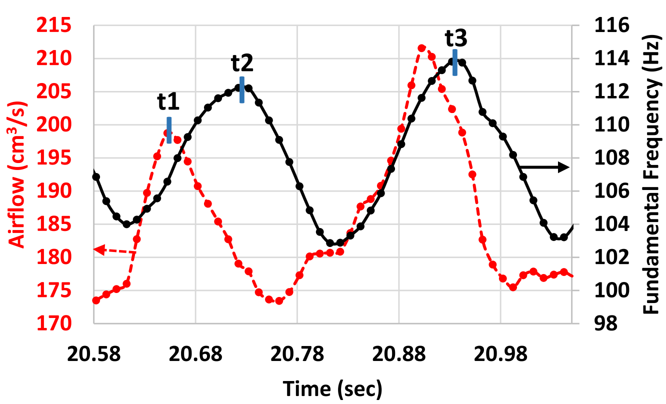

FIGURE 3. Maximum peaks on the airflow (dashed line) and f_o vibrato (solid line) waveforms used to measure the phase between airflow and f_o vibrato. Here the airflow vibrato leads the f_o vibrato by approximately 75°. The short horizontal arrows indicate the correct axis for the signal. See the text for measures related to *t*1, *t*2, and *t*3.

10 ms. The distance between the airflow screen and the headband microphone created negligible time delay (*ca.* 0.44 ms) relative to the periods of the vibrato rates (140−200 ms). Thus, the various signals were sufficiently time-aligned for both display and for establishing phase relationships between the f_o and airflow vibrato signals.

Tasks

The subjects performed sustained singing of the syllable string /p:a: p:a: p:a: p:a: p:a:/, produced in a smooth legato manner, with at least four or five vibrato cycles between /p/ productions. Three pitches were used. For male singers (Tenor "T" and Baritone "B"), lower modal (P1), higher modal (P2), and head (not falsetto; P3) registers were used; and for female singers (two sopranos, "S1" or "Soprano-1" and "S2" or "Soprano-2"), modal (P1), middle (P2), and head (not falsetto nor whistle; P3) registers were used. Three loudness levels, piano (L1), mezzo forte (L2), and forte (L3) were produced on each pitch. The three pitches used by the singers depended on his or her vocal classification and range (Table 1). Thus, there were nine conditions, namely, P1L1, P1L2, P1L3, P2L1, P2L2, P2L3, P3L1, P3L2, and P3L3.

Measures and procedures

Figure 2 is an example of airflow vibrato for Soprano-1 singing her lowest pitch (P1) and softest loudness (L1). The figure shows airflow vibrato with a rate of about 5.5 Hz. The interval between consecutive black vertical lines indicates one vibrato cycle. The dashed horizontal lines designate the peak and valley, respectively, of an airflow vibrato cycle. The difference between airflow values for the peak and the valley gives the airflow extent for that vibrato cycle.

Figure 3 is an example illustrating a phase relationship between airflow vibrato and f_o vibrato. The phase between the airflow vibrato and f_o vibrato in this example was measured to be approximately +75°, where the airflow is leading. This was determined by using the formula: $\square = (t2 - t1)/(t3 - t2) \times 360^{\circ}$, where *t*1 is the time of the peak of the airflow vibrato cycle, *t*2 is the time of the peak of the first f_o vibrato cycle, and *t*3 is the time of the peak of the next f_o vibrato cycle. Positive values indicate that the airflow vibrato cycle leads the f_o vibrato cycle, and negative values indicate that the airflow vibrato cycle lags the f_o vibrato cycle. The typical and curious finding in this study is that airflow vibrato leads f_o vibrato.

The airflow vibrato rate (the number of primary airflow undulations per second during vibrato production) and the airflow vibrato extent (the difference between the peak [maximum] and valley [minimum] airflow values during each airflow vibrato production) were measured and compared to simultaneous f_o vibrato productions. Thus, the dependent variables were rate and extent of airflow vibrato and f_o vibrato, and the phase difference between airflow vibrato and f_o vibrato. The independent variables were pitch (P1, P2, and P3) and loudness levels (L1, L2, and L3). A three-way

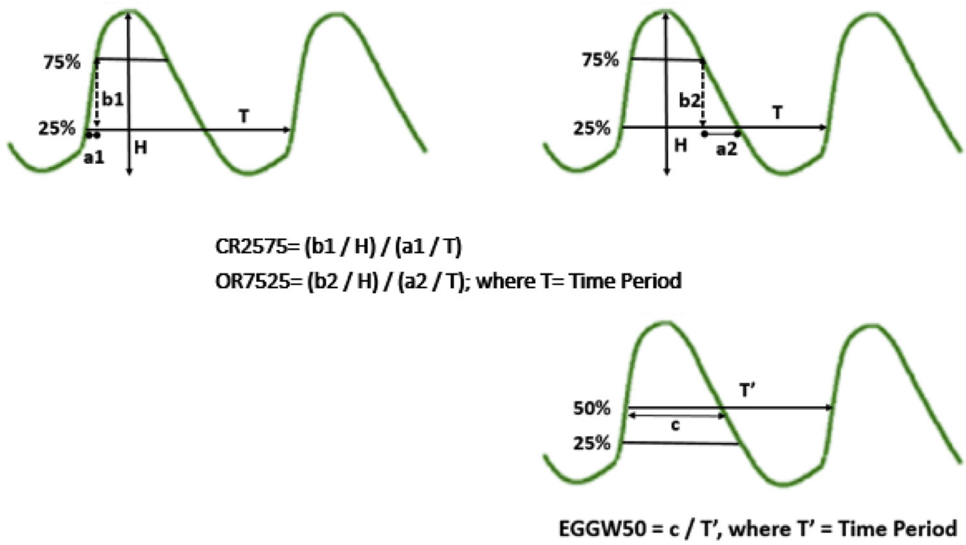

FIGURE 4. Two EGG waveforms—one shows 25–75 closing ratio and the other one shows 75–25 opening ratio. The horizontal black discrete line at 50% shows the width of EGG waveform to measure EGGW50.

ANOVA was performed with a 3 × 2 × 2 three-factor design in order to compare the mean differences of f_o vibrato extent and airflow vibrato extent. The Pearson product-moment correlation coefficient was obtained to see the strength of the relationship between airflow and f_o vibrato rates. Phase values will be reported without statistical analysis. The regularity and consistency of the airflow waveforms were interpreted subjectively depending on the presence or absence of multiple peaks, the shape of the waveform (quasi-sinusoidal), and its relation to f_o vibrato. The average oral air pressures for the nine conditions were obtained by taking the average of the pressures during the lip occlusion of the stop consonant /p:/ productions. The average intensity values were obtained using Praat for all nine conditions as well.

The EGG signal was usable for only two of the subjects (the Tenor and Soprano-2). EGGW50[29] (pulse width) and normalized rate quotient (NRQ) were measured for the subjects. EGGW50 is the relative pulse width of the EGG waveform at the 50% height location, and is associated with laryngeal adduction (Figure 4).[29]

The NRQ, a measure similar to the EGG speed quotient of Chen et al.,[26] was obtained as the ratio of CR2575 divided by OR7525 (Figure 4), *viz*, NRQ = CR2575/OR7525. The closing slope ratio, CR2575, is defined as the normalized rise ($b1/H$) divided by the normalized run ($a1/T$), where $b1$ is the EGG waveform height corresponding to the segment between 25% and 75% of the peak-to-peak amplitude H, $a1$ is the time segment corresponding to $b1$, and T is the cycle period. The opening slope ratio, OR7525, is defined by the normalized rise ($b2/H$) divided by the normalized run ($a2/T$), where $b2$ is the EGG waveform height corresponding to the segment between 75% and 25% of H, and $a2$ represents the time for the signal to drop from the 75% to the 25% level.[33] It is noted that $b1 = b2$, and when the NRQ expression is simplified, NRQ = $a2/a1$, the ratio of the duration to lower the EGG signal from 75% to 25% of the height on the right-hand side to the duration to raise the EGG signal from 25% to 75% of the height on the left-hand side of the EGG cycle. NRQ is a negative quantity because it is the ratio of a positive slope (left-hand side) and a negative slope (right-hand side). The closing and opening slope measures depend upon the speed and manner of vocal fold movement during contact. A larger negative NRQ value means that the medial vocal fold surfaces come together faster or separate slower. The two measures (EGGW and NRQ) were obtained for a sequence of about 3–4 cycles at both the peaks and the valleys of the airflow vibrato cycles. The values were averaged at the peaks and averaged at the valleys to give representative EGGW and NRQ values for each utterance.

RESULTS

Airflow vibrato complexity and phase

Figure 5a–d illustrates the range of complexity of airflow vibrato waveshapes, from regular and consistent airflow vibrato cycles to inconsistent cycles with multiple peaks. This range suggests that there is a more complex and different genesis for airflow vibrato than for f_o vibrato. Figure 5c, for example, shows airflow vibrato having a complex form since there are approximately 2–3 airflow cycles for each f_o cycle. Because the shape of the airflow vibrato waveform apparently does not need to follow the shape of the f_o vibrato waveform, nor does the airflow vibrato waveform need to be in phase with the f_o vibrato (Figure 5a–d illustrates a range of 54.5°–130° with airflow vibrato leading f_o vibrato for each), the question of degree of interdependence between the two phenomena is raised. The complex waveshape of the airflow vibrato in Figure 5c suggests that it is possible to have one, two, or three variations of airflow within one cycle of f_o vibrato. Figure 5d suggests that there can be a wide range of adjacent airflow vibrato cycle extents as well as portions of the airflow vibrato cycle that are

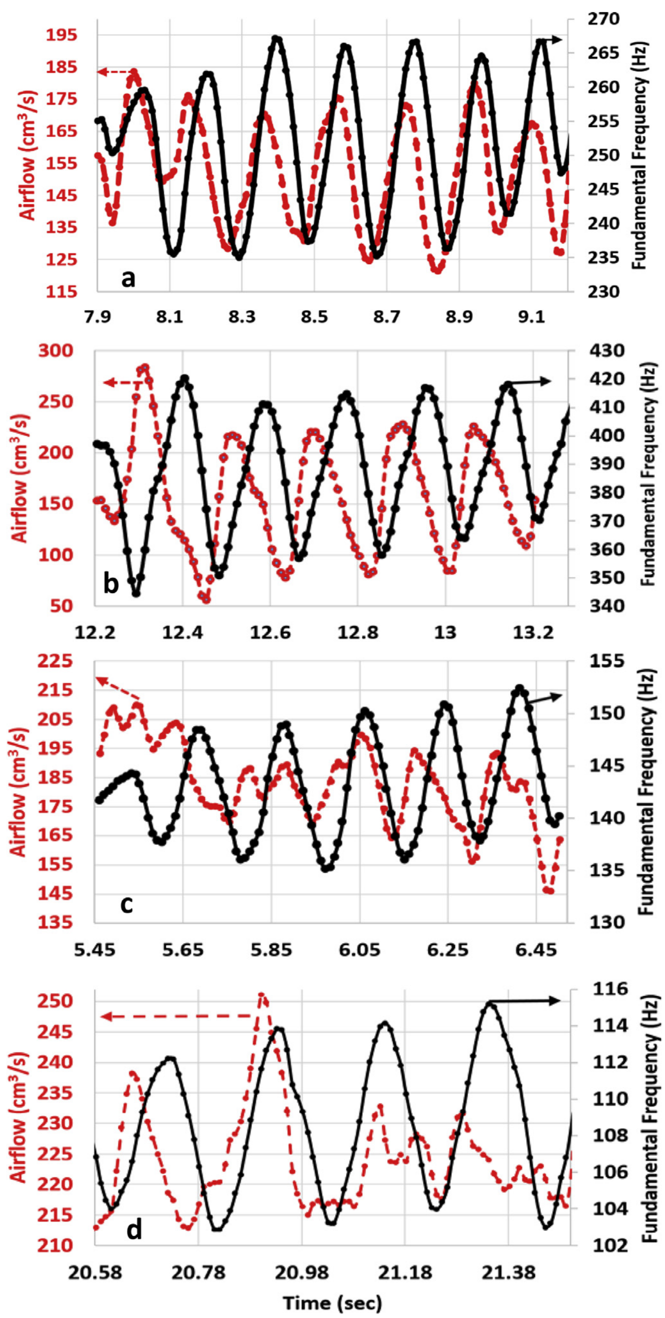

FIGURE 5. Examples of complexity of the airflow vibrato waveforms. (**a**) A relatively consistent airflow vibrato leading f_o vibrato by 54.5°. The condition is Soprano-1 singing the pitch P1 with loudness L1. (**b**) A relatively consistent airflow vibrato, somewhat less sinusoidal appearing than in (**a**), leading f_o vibrato by 130°. The condition is Soprano-2 singing the pitch P3 with loudness L2. (**c**) Inconsistent undulations in airflow vibrato leading f_o vibrato (considering the first peak of each cycle), by an average of 105°. The condition is the Tenor singing the pitch P1 with loudness L1. (**d**) Irregular and inconsistent airflow vibrato cycles that indicate high level of complexity. The airflow vibrato appears to lead f_o vibrato by about 75°. The condition is the Baritone singing the pitch P1 with loudness L3.

relatively flat, meaning essentially no change in airflow. Table 2 shows the phase difference between airflow and f_o vibrato for all nine conditions.

Rate of airflow vibrato and its relation to rate of f_o vibrato

The rate of airflow vibrato was measured and compared with the rate of f_o vibrato. Figure 6 shows the rates for both for all conditions (4 singers × 3 pitches × 3 loudness levels). The relationship was seen to be moderately strong ($R^2 = 0.7456$). This suggests that similar mechanisms govern the rate of both types of vibrato (such as synchronized muscle activity separately governing f_o and airflow modulation, or perhaps a single cause for both such as pulmonary pressure alterations, concepts to be explored in a subsequent study). It would seem likely that both vibrato types should have exactly the same rates. This is most likely more realistic than what Figure 6 indicates. That is, because only 4–5 cycles were used to obtain vibrato rates, which is a relatively small number of cycles, and furthermore the airflow vibrato waveforms were often complex in shape (nonsinusoidal), the calculation for airflow vibrato rate was more variable than for the f_o vibrato rate. Figure 7 shows a condition (data point circled and labeled #1 in Figure 6) where the airflow and f_o vibrato rates were most dissimilar—the rate of f_o vibrato (5.26 Hz) is seen to be faster than the approximate rate of airflow vibrato (4.84 Hz), assuming the secondary oscillations are within single cycles. Figure 5a is a reasonable example of matching vibrato rates between airflow and f_o.

Extent of airflow vibrato

Table 3 provides airflow vibrato information for each subject across the pitch and loudness conditions. The Baritone's range of airflow vibrato extent across all conditions was 4.5–188.8 cm^3/s, with an average airflow vibrato extent of 53 cm^3/s, and an average rate of airflow vibrato of 4.93 Hz. The Tenor produced a range of airflow vibrato extent of 4.8–113.12 cm^3/s, an average airflow vibrato extent of 62.8 cm^3/s, and an average rate of airflow vibrato of 5.64 Hz. Soprano-1 had a range of airflow vibrato extent of 31.4–171.4 cm^3/s, an average airflow vibrato extent of 68.3 cm^3/s, and an average rate of airflow vibrato of 5.3 Hz. Finally, Soprano-2 had a range of airflow vibrato extent of 21.6–146.7 cm^3/s, an average airflow vibrato extent of 66.3 cm^3/s, and an average rate of airflow vibrato of 5.6 Hz. Thus, across the four subjects and across the pitch–loudness conditions, the extent of the airflow vibrato could be quite narrow (near 5 cm^3/s) to quite wide (near 190 cm^3/s). The average airflow vibrato extent across the subjects, however, was confined to a relatively narrow range, between 53 and 68 cm^3/s, and the average airflow vibrato rates, 4.9–5.6 Hz, were within acceptable rates reported for f_o vibrato rates.

TABLE 2.
Phase Difference Between Airflow Vibrato and f_o Vibrato for All Conditions for the Four Subjects. There Were 2–5 Sung Tokens per Each Condition for Which the Phase Difference Was Calculated (Positive Values Indicate Airflow Vibrato Leading f_o Vibrato and Negative Values Indicate Airflow Vibrato Lagging f_o Vibrato)

Subjects	P1L1	P1L2	P1L3	P2L1	P2L2	P2L3
Soprano-1	94.7, 56.8, 37.9, 37.9, 45	37.9, 37.9, 40, 20	75.8, 113.7, 151.6, 40, 127.1	108, 108, 108, 114	94.7, 114, 126, 108, 133	120, 120, 68.6, 140
Soprano-2	154.3, 144, 137.1	205.7, 180, 140	−113.7, −240, −216, −220	162, 171, 125, 180	162, 126, 126, 160	137, 120, 126, 152
Tenor	120, 133, 20, 148	84.7, 160, 160, 158	148, 191, 169, 113	40, 106, 120, 148	140, 140, −21.2	140, 80, 60.9, 44.5
Baritone	−72, −85.7	103, 51.4	137, 51.4, 36	72, 103, 108, 152	144, 103, 115	85.7, 137, 98.2, 152

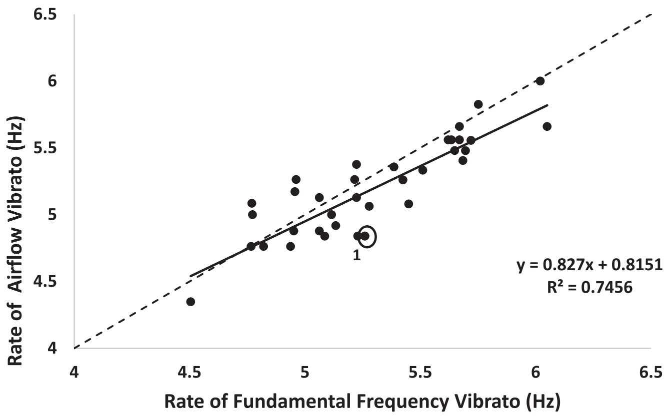

FIGURE 6. Rate of airflow vibrato *vs* rate of f_o vibrato for all conditions and subjects. The regression suggests that f_o vibrato tends to be slightly faster than airflow vibrato. The dashed line is the 1-1 line.

For comparison with the airflow vibrato characteristics, Table 4 gives information on the f_o vibrato for all subjects in all conditions. The table shows that the Baritone had an average f_o vibrato extent of 1.56 ST, and his

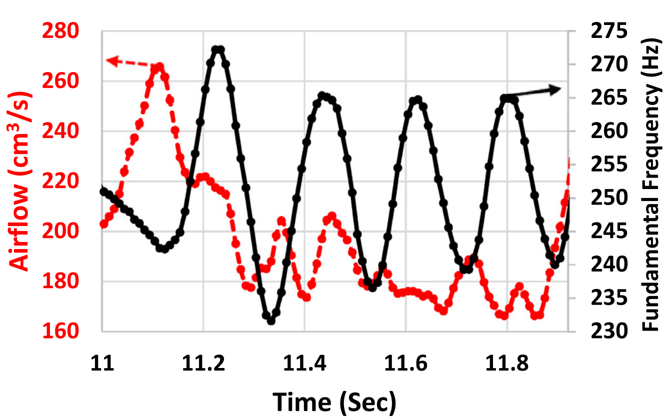

FIGURE 7. Airflow and f_o vibrato waveforms corresponding to circle #1 in Figure 6, a case where the airflow vibrato rate is different from the f_o vibrato rate, and also with different waveshape. The condition is Soprano-2 singing the pitch P1 with loudness L2.

average rate was 4.9 Hz. The Tenor had an average f_o vibrato extent of 1.4 ST and an average f_o vibrato rate of 5.7 Hz. Soprano-1 produced an average f_o vibrato extent of 2.2 ST, and her average rate was 5.7 Hz. Soprano-2 had an average f_o vibrato extent of 2.3 ST, and an average rate of 5.33 Hz. These general results indicate that the men had less f_o vibrato extent than the women, and the Baritone had the slowest rate. It is also evident that the f_o vibrato characteristics were more consistent over relatively narrower ranges than similar measures for the airflow vibrato.

A three-way ANOVA was performed to compare the mean differences between gender, two lower pitches, and three loudness levels. A summary of results is presented in Table 5. Main effect results revealed that airflow vibrato extent was significantly different between the two lower pitches, $F(1, 97) = 98.86$, $P < 0.000$. Airflow vibrato extents were also significantly different when compared between male and female participants, $F(1, 97) = 14.37$, $P < 0.0002$. But it was not significantly different when compared among the three loudness levels, $F(2, 97) = 0.533$, $P < 0.59$.

Figure 8 shows the relation of airflow vibrato extent for each subject relative to loudness levels (collapsing data for the two lower pitches). The lack of any significant difference as loudness increased, which should be and was accompanied by an increase of subglottal pressure (Table 7), suggests an essential lack of influence of subglottal pressure (alone) to govern vibrato airflow extent across the three loudness levels for each singer.

Figure 9 shows the mean airflow vibrato extents compared within each subject relative to the two lower pitches. For each of the singers, the higher pitch had greater mean airflow vibrato extent values than for the lower pitch. Figure 10 shows the comparison of mean airflow vibrato extent values between the male and female singers between the two pitches, where significant increases were found for the high pitch. Thus, in this study, pitch is an important factor relative to airflow vibrato extent, the higher pitch yielding larger airflow vibrato extents.

TABLE 3.
Airflow Vibrato Information for the Baritone, Tenor, Soprano-1, and Soprano-2 Subjects for All Conditions of Pitch and Loudness

Pitch and Loudness Level	Range of Vibrato Airflow Extent (cm^3/s)	Average Vibrato Airflow Extent (cm^3/s)	Average Airflow (cm^3/s)	(Range of Airflow Extent)/(Average Airflow)	Average Rate of Airflow Vibrato (Hz)
B-P1L1	14.3–23.0	17.1	245.4	0.05–0.09	4.35
B-P2L1	4.5–21.2	15.8	231.5	0.02–0.09	5
B-P3L1	9.2–34.8	18.1	185.2	0.05–0.19	4.8
B-P1L2	39.6–91.6	64	319.6	0.12–0.29	5.3
B-P2L2	30.5–75.8	57.6	237.9	0.13–0.32	4.8
B-P3L2	27.3–85.6	53	160.2	0.2–0.53	5.1
B-P1L3	66.5–188.8	112	330.2	0.2–0.6	4.9
B-P2L3	61.2–103.5	83	304.4	0.2–0.34	4.9
B-P3L3	35.2–78.5	53.2	92.4	0.38–0.85	5.2
T-P1L1	4.8–41.3	24.1	140.2	0.03–0.3	5.6
T-P2L1	13.4–66.3	45.2	168.7	0.08–0.4	6
T-P3L1	25.5–89.8	58	185.6	0.14–0.5	5.7
T-P1L2	60.9–113.1	91.2	109.8	0.85–1.03	5.83
T-P2L2	86.7–104.5	96.1	90.7	0.96–1.09	5.6
T-P2L3		Mask rim leak			5.1
T-P1L3	26.0–83.2	57.6	180	0.15–0.46	5.7
S1-P1L1	44.1–51.1	46	111.7	0.40–0.46	5.1
S1-P2L1	31.4–64.4	52	98	0.32–0.7	5.33
S1-P3L1	47.3–62.8	59.3	88.6	0.53–0.8	5.5
S1-P1L2	50.4–74.7	59.1	120.3	0.42–0.62	5
S1-P2L2	71.2–171.4	102	150.3	0.50–1.14	5.3
S1-P3L2	69.5–111.0	92	208.9	0.3–0.53	5.4
S1-P1L3	47.3–71	59.3	88	0.54–0.81	5.48
S1-P2L3	69.5–111	92	208.3	0.33–0.53	5.36
S2-P1L1	28.7–88.0	57	197	0.15–0.45	4.8
S2-P2L1	24.9–42.6	34	150.3	0.2–0.3	4.6
S2-P3L1	21.6–34.4	27.1	103.8	0.2–0.33	4.84
S2-P1L2	75.6–146.7	101.1	125.7	0.6–0.9	4.84
S2-P2L2	73.2–99.4	77.2	167.4	0.4–0.6	4.92
S2-P3L2	88.5–116.1	102	228.1	0.40–0.51	4.84
S2-P1L3	24–47.2	34.5	104	0.23–0.45	4.84
S2-P2L3	88.5–116.3	102	229	0.39–0.51	4.84

Table 6 gives the summary of results for a three-way ANOVA conducted to compare the mean differences of f_o vibrato extents among all the conditions. Main effect results revealed that f_o vibrato extent was not significantly different when compared among the loudness levels, $F(2, 106) = 0.846$, $P < 0.432$, but was significantly different among the three pitches, $F(1, 106) = 76.83$, $P < .0001$. The f_o vibrato extent was also significantly different between gender, $F(1, 106) = 112.89$, $P < 0.0001$. Figure 11 shows the mean f_o vibrato extent in STs for each of the three loudness levels where there was lack of significant differences across loudness levels. Figure 12 shows the mean f_o vibrato extent in STs for three pitches between males and females, indicating a significant difference in extent, with the two sopranos having a wider f_o extent than for the Tenor and Baritone together.

Relation between intensity and airflow in vibrato

To determine how airflow vibrato compared to intensity variation of the audio signal, the intensity was also obtained every 10 ms using the Praat software. It is noted that the decibel values reported here are relative only within an utterance and do not correspond to SPL- sound pressure level.

Figure 13 provides an example of airflow vibrato compared to both intensity variation of the audio signal (Figure 13a) and f_o vibrato (Figure 13b) for Soprano-1 singing pitch P2 with loudness L2. The figure indicates that the intensity vibrato waveform is more complex than either the airflow vibrato waveform or the f_o vibrato waveform in this case and leads the airflow, whereas the f_o lags the airflow (by about 115°). The airflow and intensity were approximately completely out of phase for the last few cycles seen in Figure 13a. The intensity range was approximately 3.5 dB for this utterance.

TABLE 4.
The f_o Vibrato Information for the Baritone, Tenor, Soprano-1, and Soprano-2 Subjects for All Conditions of Pitch and Loudness

Pitch and Loudness Level	Range of Extent (Hz)	Range of Extent (ST)	Average Extent (ST)	Rate (Hz)	Average Rate (Hz)
B-P1L1	6.17–9.55	0.99–1.53	1.22	4.0–5.0	4.51
B-P2L1	6.03–9.44	0.97–1.52	1.32	4.55–5.0	4.80
B-P3L1	8.2–11.1	1.31–1.75	1.62	4.55–5.0	4.80
B-P1L2	10.1–25.3	0.84–2.1	1.50	4.55–5.26	5.0
B-P2L2	19.0–24.6	1.6–2.01	1.73	4.76–5.0	4.80
B-P3L2	17.1–26.5	1.43–2.21	1.80	4.35–5.0	4.80
B-P1L3	8.2–31.9	0.4–1.6	1.22	4.8–5.26	5.10
B-P2L3	27.6–34.0	1.4–1.73	1.61	4.54–5.26	5.0
B-P3L3	35.5–47.0	1.77–2.35	2.03	4.76–5.26	5.0
T-P1L1	9.9–14.6	1.2–1.77	1.60	5.26–5.88	5.63
T-P2L1	5.5–16.9	0.66–2.02	1.64	5.26–7.14	6.02
T-P3L1	8.91–17.9	1.05–2.15	1.70	5.55–6.66	6.10
T-P1L2	15.4–30.3	0.92–1.81	1.51	5.56–5.88	5.80
T-P2L2	23.9–36.7	1.43–2.22	1.90	5.56–5.88	5.72
T-P3L2	18.5–35.6	1.11–2.14	1.72	5.56–5.88	5.70
T-P1L3	9.3–20.1	0.42–0.92	0.60	5.0–6.25	5.70
T-P2L3	12.6–13.9	0.57–0.67	0.63	5.0–5.88	5.43
T-P3L3	11.5–17.5	0.52–0.74	0.70	5.0–5.56	5.22
S1-P1L1	25.23–31.9	1.84–2.20	2.0	5.0–7.14	5.70
S1-P2L1	22.7–33.6	1.54–2.33	1.94	5.26–5.88	5.51
S1-P3L1	20.1–31.2	1.35–2.15	1.80	5.26–6.7	5.70
S1-P1L2	35.3–52.9	1.4–2.12	1.90	4.76–5.6	5.12
S1-P2L2	50.1–57.6	2.0–2.28	2.20	5.0–5.6	5.22
S1-P3L2	41.2–65.9	1.61–2.63	2.30	5.0–5.6	5.40
S1-P1L3	74.3–127.6	1.64–2.83	2.40	5.0–5.6	5.22
S1-P2L3	90.2–122.6	1.97–2.73	2.51	4.8–5.6	5.10
S1P3L3	91.6–114.9	2.07–2.54	2.40	5.0–5.88	5.30
S2-P1L1	21.12–29.9	1.43–2.02	1.80	4.35–5.6	4.94
S2-P2L1	24.9–42.6	1.74–2.31	2.0	4.76–5.88	5.23
S2-P3L1	21.7–34.4	1.55–2.2	1.90	5.0–5.88	5.50
S2-P1L2	75.6–146.7	1.83–2.92	2.41	5.0–5.6	5.23
S2-P2L2	73.2–99.6	1.9–2.92	2.40	4.76–5.88	5.13
S2-P3L2	88.5–116.1	1.72–2.72	2.30	4.76–5.88	5.1
S2-P1L3	115.0–166.3	2.79–3.8	3.30	5.26–5.88	5.70
S2-P2L3	130.7–155.2	2.5–2.74	2.72	5.26–5.88	5.50
S2P3L3	37.4–52.1	1.64–2.3	2.0	5.6–5.88	5.62

Figure 14 is another example of a comparison of airflow vibrato with intensity variation (Figure 14a) and f_o vibrato (Figure 14b), this time for the Tenor singing pitch P1 with loudness L3. The f_o vibrato shows greatest simplicity (a quasi-sinusoidal waveshape), whereas both the airflow vibrato and intensity variation are more complex. Airflow leads f_o by about 75°. For the first few vibrato cycles, intensity appears to be nearly out of phase with the airflow and nearly in phase with f_o, but then there is a strong shift of phase for the last cycle and a half. Intensity varied by approximately 2.5 dB.

For a third example, shown in Figure 15, the Baritone sang his first pitch P1 with loudness L3. Airflow vibrato was highly irregular, and the intensity waveform demonstrated double peaks to airflow and f_o vibrato single peaks (suggesting that a lower harmonic of the f_o vibrato was passing above and then below the first formant during one vibrato cycle, although the decibel range of change was only about 1.2 dB).

The final example of the relationship among airflow vibrato, intensity variation, and f_o vibrato is shown in Figure 16. Here the Baritone sang his first pitch P1 with loudness L1. The f_o vibrato is somewhat irregular, and both airflow vibrato and intensity variation are quite irregular, with a relatively wide range of intensity (*ca.* 5 dB from the beginning of the utterance and *ca.* 2 dB during most of it, Figure 16a). The variation of airflow does not appear to have a discernable relation with intensity variation. The airflow vibrato appears to have a varying relation with the f_o vibrato—gross variation related to each f_o vibrato cycle,

TABLE 5.
Three-Way ANOVA Summary Table for Airflow Vibrato Extent

Source	Sum of Squares	*df*	Mean Squares	*F*	*P*
Pitch	53,389	1	53,389	98.861	0.0000*
Loudness	576	2	288	0.533	0.5885
Gender	7758	1	7758	14.366	0.0002*
Pitch × loudness	633	2	317	0.586	0.5582
Loudness × gender	431	2	216	0.399	0.6718
Pitch × gender	6	1	6	0.010	0.9193
Residuals	52,384	97	540		

and minor triplet variations within each f_o cycle. Average oral air pressure and intensity values are reported in Tables 7 and 8, respectively, for all nine conditions.

EGG width measurement and airflow vibrato

Airflow vibrato may reasonably be caused by changes in adduction, less adducted for higher airflows within the vibrato cycle, and greater adduction for lower airflows within the cycle. To test this, EGGW50 was measured at the peaks and valleys of the airflow vibrato cycles. It is noted that EGGW50 is related to membranous vocal fold contact[29] and should reflect changes in anterior glottal activity (dynamic membranous vocal fold behavior) rather than posterior glottal activity.

Two to three consecutive glottal cycles of the EGG waveform were analyzed at all primary peaks and valleys of the airflow vibrato waveforms under all conditions for the Soprano-1 and the Tenor (the EGG signal could not be obtained from Soprano-2 and the Baritone; for Soprano-2, the EGG signals were too small, and the Baritone was not comfortable wearing the EGG device). The *t* tests for EGGW50 values between

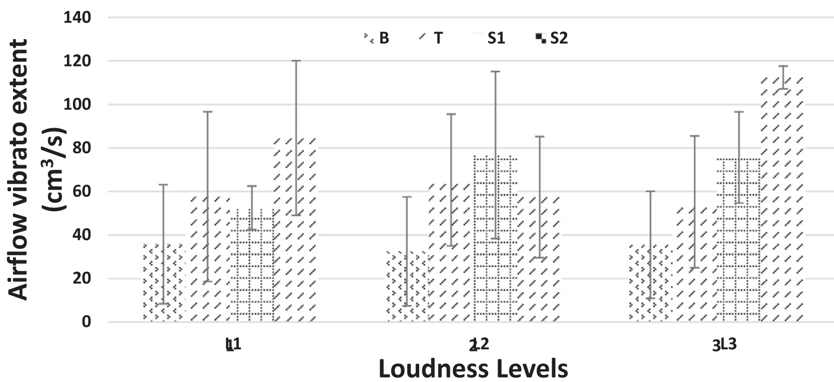

FIGURE 8. Mean and standard error values of *airflow vibrato extent* for each of the singers (B, T, S1, and S2) for the three loudness levels (L1, L2, and L3) collapsed across the two lower pitches (P1 + P2).

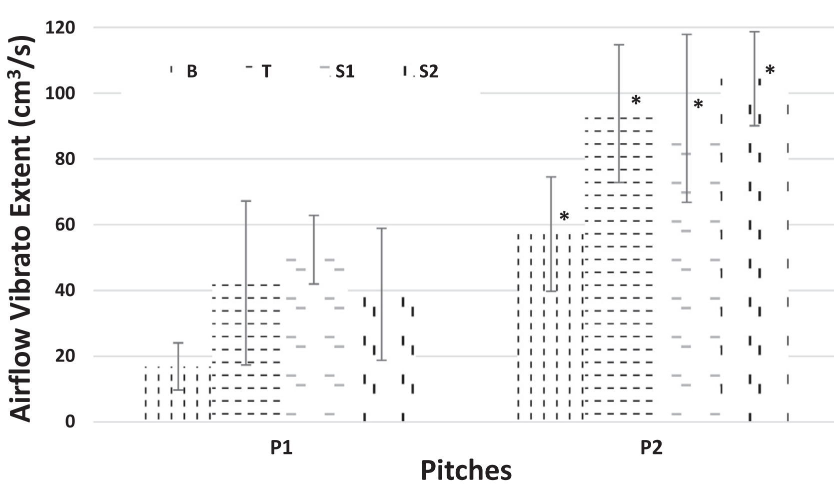

FIGURE 9. Mean values and standard errors of *airflow vibrato extent* between the two lower pitches for each of the singers (B, T, S1, and S2) collapsed across the three loudness levels (L1 + L2 + L3). All comparisons were statistically significantly different.

TABLE 6.
Three-Way ANOVA Summary Table for f_o Vibrato Extent

Source	Sum of Squares	*df*	Mean Squares	*F*	*P*
Pitch	5218	1	5218	76.826	0.0000*
Loudness	115	2	57	0.846	0.432
Gender	7667	1	7667	112.885	0.0000*
Pitch × loudness	84	2	42	0.619	0.54
Loudness × gender	0	2	0	0.003	0.997
Pitch × gender	1	1	1	0.012	0.912
Residuals	7199	106	68		

* indicates statistically significant difference

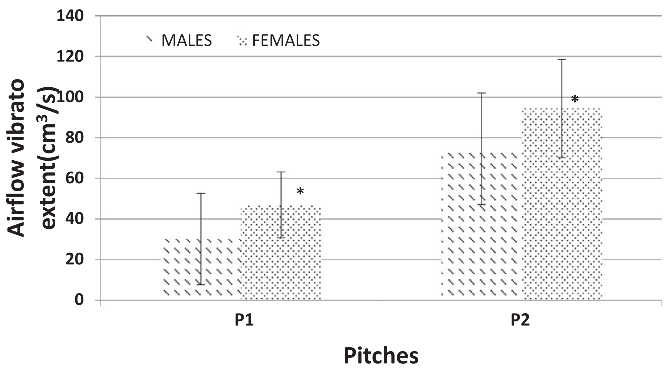

FIGURE 10. Comparison of mean values of *airflow vibrato extent* between the male (B + T) and the female (S1 + S2) singers for the two lower pitches (P1 and P2) collapsed across the three loudness levels (L1 + L2 + L3).

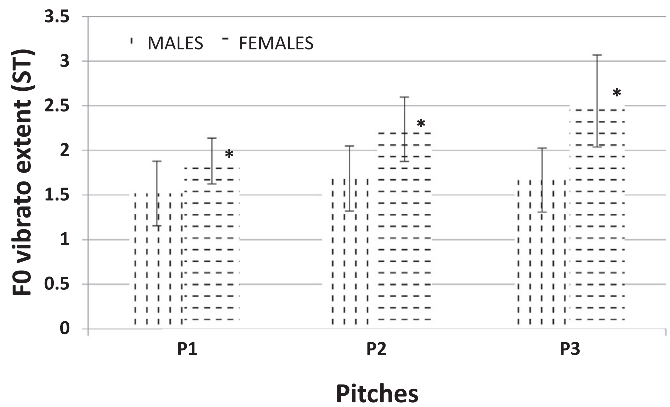

FIGURE 12. Comparison of mean values of f_o *vibrato extent* between male (B + T) and female (S1 + S2) singers for each pitch (P1, P2, and P3) collapsed across the three loudness levels (L1 + L2 + L3). Each comparison was significant with $P < 0.001$.

peaks and valleys indicated no significant differences. Figure 17 provides two examples: one for Soprano-1 (Figure 17a) and one for the Tenor (Figure 17b). In Figure 17a, the EGGW50 values at the peak of the airflow vibrato are shown to be 0.30 and 0.32, and at the valleys 0.31 and 0.33, indicating that there was no difference in EGGW50 between the two extremes. Similar nondifferences are shown in Figure 17b. Therefore, the causes of the airflow vibrato

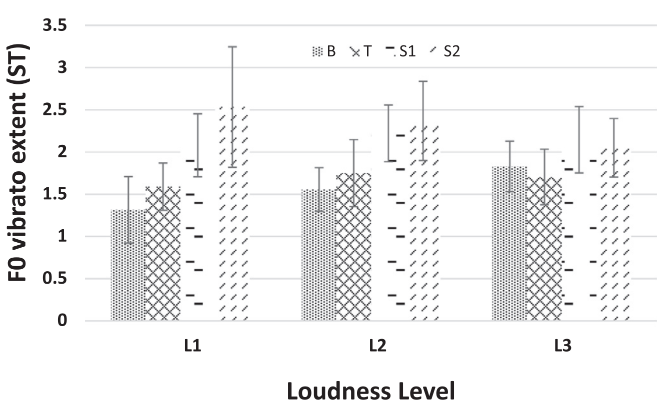

FIGURE 11. Mean values of f_o *vibrato extent* for each singer (B, T, S1, and S2) for the three loudness levels (L1, L2, and L3) collapsed across the three pitches (P1 + P2 + P3).

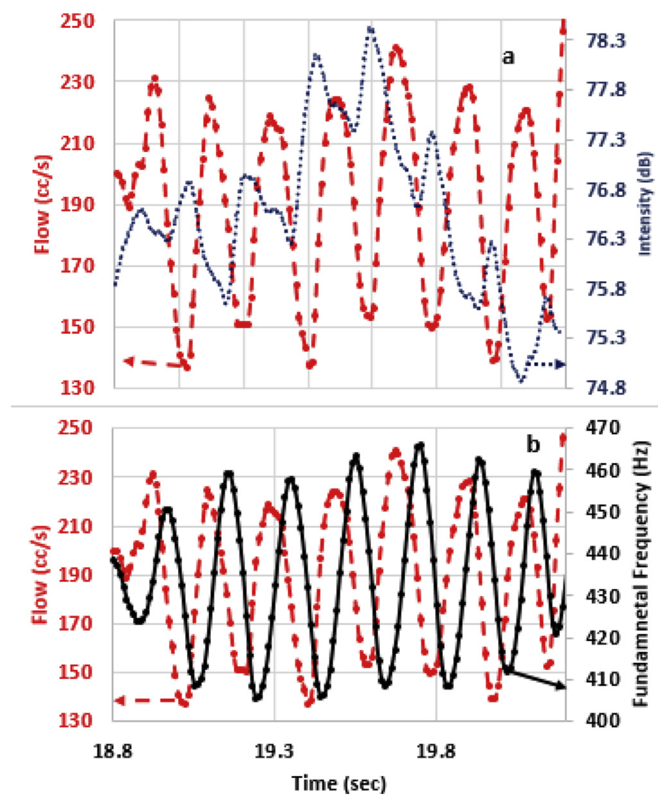

FIGURE 13. Airflow vibrato compared with intensity variation (**a**) and f_o vibrato (**b**) for Soprano-1 singing her middle pitch (P2) with loudness (L2).

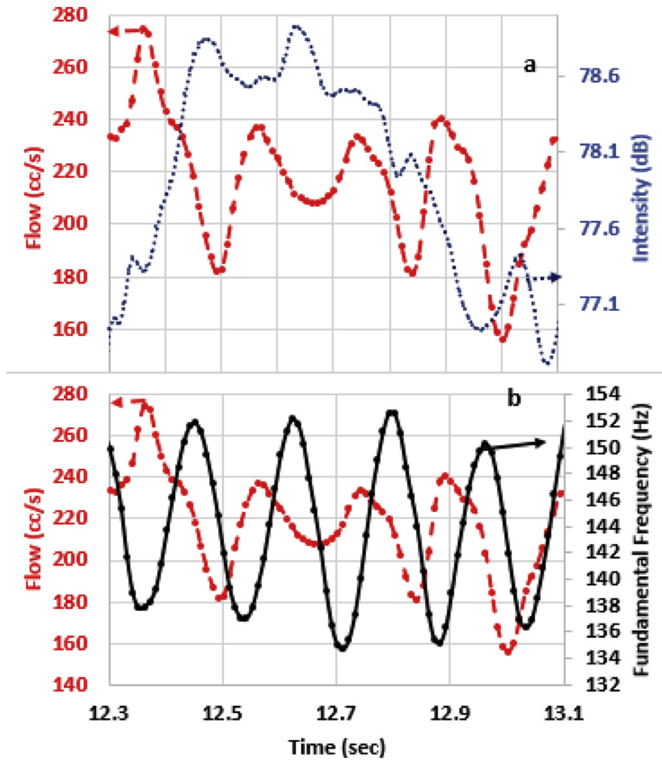

FIGURE 14. Airflow vibrato compared with intensity variation (**a**) and f_o vibrato (**b**) for the Tenor singing at his lowest pitch (P1) with loudest level (L3).

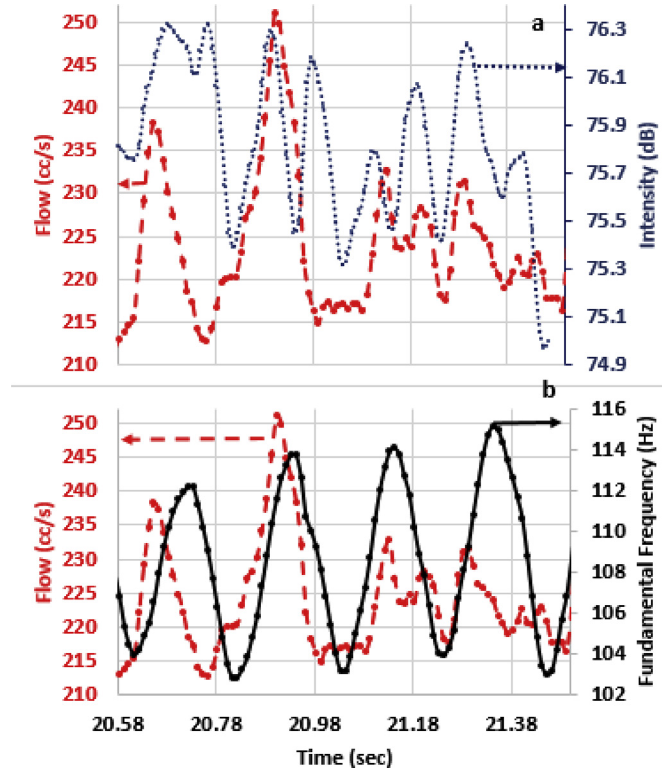

FIGURE 15. Airflow vibrato compared with intensity variation (**a**) and f_o vibrato (**b**) for the Baritone singing at his lowest pitch (P1) and loudest level (L3).

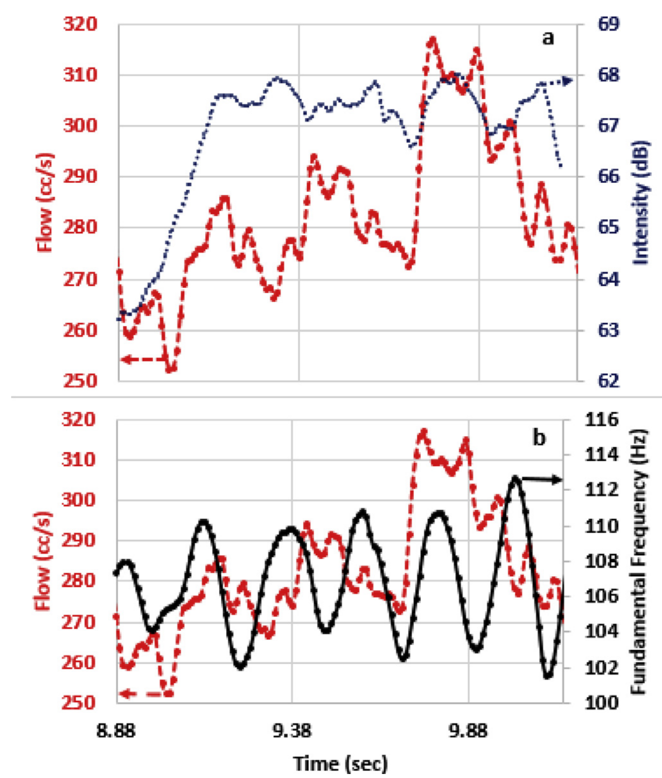

FIGURE 16. Airflow vibrato compared with intensity variation (**a**) and f_o vibrato (**b**) for the Baritone singing at his lowest pitch (P1) and lowest loudness level (L1).

peaks and valleys are not reflected in the EGGW50 measure. This suggests that the change in airflow during the vibrato cycle may be related more to a posterior glottal area variation than adduction variation of the true vocal folds. If there were a wider vocal process gap (greater glottal area) when the airflow vibrato reaches a peak, a higher subglottal pressure may compensate the relative closed time of the cycle as well, keeping the EGGW50 value about the same. This needs further investigation.

NRQ and airflow vibrato

Because the NRQ measure is the normalized EGG rise slope divided by the normalized fall slope (between the 25% and 75% height regions), the more negative the value, the faster the initial contact between the two vocal folds compared to the separation of the two vocal folds. This measure was also made at the peaks and valleys of the airflow vibrato. If the measure differed between the peaks and valleys, it would indicate a mechanical and physiological differentiation between the two regions.

NRQ values for two peaks and valleys from all nine conditions of pitch and loudness for Soprano-1 and the Tenor were obtained and averaged. Figure 18 shows the results. With one exception (condition 2), the airflow vibrato peaks and valleys had similar NRQ values for each of the singers. This finding again suggests that the EGG waveform did not help to explain the cause of the peak *vs* valley airflows within the airflow vibrato.

TABLE 7.
Average Oral Air Pressure Values (cm H_2O) for All Four Subjects for All Nine Conditions

Subjects	P1L1	P1L2	P1L3	P2L1	P2L2	P2L3	P3L1	P3L2	P3L3
Soprano-1	4.99	7.26	9.32	7.67	10.79	12.73	13.75	18.63	25.58
Soprano-2	6.82	10.59	11.45	12.31	15.55	19.07	22.02	29.75	36.45
Baritone	5.01	6.77	10.77	13.45	15.48	20.55	19.09	26.37	29.45
Tenor	4.96	6.46	11.60	11.34	18.03	23.90	20.24	21.04	28.87

TABLE 8.
Average Intensity Values (dB) for All Four Subjects for All Nine Conditions Obtained From the Praat Display. It Is Noted That the Values Are not SPL Values *Per Se*, and the Values Between Subjects Cannot Be Compared Because the Microphone–Mouth Distance Might not Be the Same, but That dB Values Across Conditions for Each Subject Are Relevant. The Average Difference Between Loudness Levels Was 4.4 dB

Subjects	P1L1	P1L2	P1L3	P2L1	P2L2	P2L3	P3L1	P3L2	P3L3
Soprano-1	66.9	74.6	78.2	71.6	76.9	80.9	71.4	78.9	83.3
Soprano-2	68.0	73.5	78.3	73.7	77.3	80.4	72.2	75.3	78.9
Baritone	67.5	72.4	77.2	73.9	76.6	79.2	76.3	79.8	80.5
Tenor	64.2	72.3	76.3	67.3	76.0	79.4	70.5	76.5	79.8

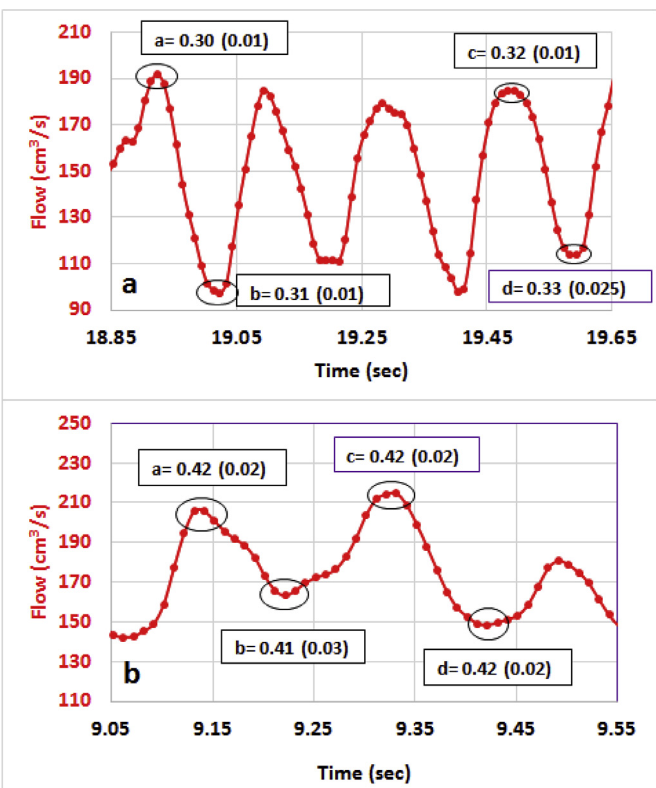

FIGURE 17. EGGW50 means and standard errors at peaks and valleys of airflow vibrato for (**a**) the Soprano-1 singing her middle pitch (P2) and middle loudness (L2), and (**b**) the Tenor singing his lowest pitch (P1) and middle loudness (L2). Within the figures, "a" and "c" indicate the EGGW50 values at the airflow vibrato peaks, and "b" and "d" indicate the EGGW50 values at the airflow vibrato valleys.

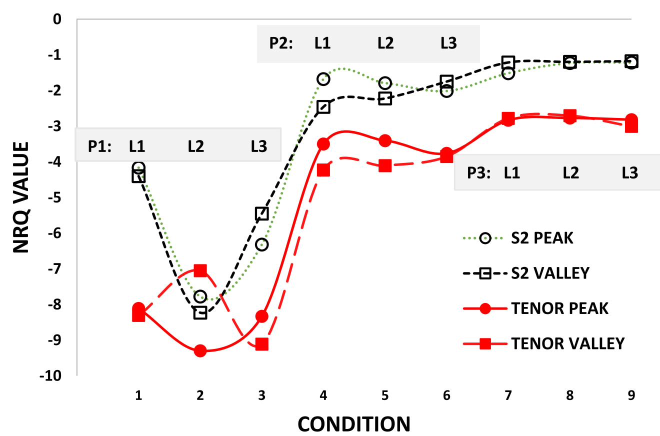

FIGURE 18. NRQ values for Soprano-2 and the Tenor for all nine conditions of pitch and loudness.

In general, the NRQ values were less negative for Soprano-1 than for the Tenor, but the pattern of change across conditions was similar for both singers. The greatest negative NRQ values corresponded to the lower pitch P1, suggesting that the increase in vocal fold contact area during medial surface closure was relatively faster than the decrease in vocal fold contact area later during vocal fold decontact, compared to the other two pitches used. The largest negative value was approximately −9, indicating nine times faster increase than decrease in contact area. In comparison, for the highest pitch P3, Soprano-1 had NRQ values close to −1, indicating approximately the same rate of increase and decrease on either side of the EGG waveform (suggesting a relatively sinusoidal waveform).

DISCUSSION

General comments

The purpose of this study was to gain a more complete understanding of the production mechanism for vibrato that should then lead to a fuller understanding of laryngeal mechanics and pedagogical underpinnings in singing, as well as a deeper understanding of laryngeal aerodynamic modulation in general. This study is descriptive relative to understanding the phenomenon of airflow vibrato.

The study provides characteristics of airflow vibrato produced by four professional singers singing three pitches and three loudness levels. Results indicate that airflow vibrato is a real phenomenon, with strong correspondence to fundamental frequency (f_o) vibrato. However, airflow vibrato waveforms are more complex than f_o vibrato waveforms.

Causative factors are most likely quite different between airflow vibrato and f_o vibrato. Fundamental frequency vibrato should be dependent on vocal fold effective stiffness, length, and mass changes throughout the vibrato cycle, whereas airflow vibrato should be most sensitive to changes in the laryngeal airflow resistance (more airflow with less resistance due to greater glottal area) and subglottal pressure (more airflow with greater subglottal pressure). Both f_o vibrato and airflow vibrato may be dependent on vocal fold length change, however, suggesting that a subtle length change should raise the f_o value as well as increase glottal area, raising the airflow value, and thus f_o vibrato and airflow vibrato may be in phase with each other. The figures in this report strongly indicate that indeed airflow vibrato is synchronized with f_o vibrato, but typically airflow vibrato leads f_o vibrato (a yet to be understood phenomenon).

When one examines the extent of airflow change within an airflow vibrato cycle, however, it would appear that simple and subtle vocal fold lengthening should not result in airflow vibrato extents averaging about 60 cm^3/s and ranging up to over 100 cm^3/s (A high rate of particle velocity of 50 cm/s passing through the glottis to yield 100 cm^3/s would require a membranous glottal opening of 2 cm^2, suggesting a glottis of very large size: if the vocal process gap were 0.4 cm, the glottal length would have to be 10 cm, using a triangular shape for the membranous glottis. Thus, changes of airflow up to 100 cm^3/s cannot be explained by a change of glottal length alone.). This size of airflow extent suggests change in glottal adduction and/or change in subglottal pressure to account for much of the airflow vibrato extent. The EGGW50 measure was used as an indicator of glottal adduction, but its values were not statistically different between the peaks and valleys of the airflow vibrato waveform. That would tend to discount gross glottal adduction, and leave subglottal pressure variation as a primary cause. However, airflow vibrato extent did not vary systematically with increases in loudness, which should be governed by relatively large increases in subglottal pressure (Table 7 that shows increasing estimated subglottal pressures as loudness increased for all subjects), and thus airflow vibrato may not be highly dependent on mean subglottal pressure. It is noted that this study did not investigate changing subglottal pressure during the vibrato cycle, which might play a primary role in creating the airflow vibrato modulations.

One aspect of laryngeal airflow resistance of interest in this study then, is the dependence, the airflow has on the posterior glottal area. The flow through the posterior glottis was not measured in this study, but it makes sense as a causative factor in airflow vibrato. That is, if a singer wishes to preserve the sound quality produced by the larynx, it is rather doubtful that the singer would choose to alter the anterior glottal adduction a great deal, unless the person is intentionally producing an ornament such as trillo in which glottal adduction appears to be the dominant factor (typically a singing student attempts to get rid of this “bleat” vibrato behavior as he or she is developing a “smooth” vibrato).[28] Thus, it is hypothesized that the posterior glottal area varies in such a manner that it is a primary causative factor for airflow vibrato. Because airflow vibrato and f_o vibrato are often synchronized with each other, it is further hypothesized that as the CT and VOC muscle contraction levels alter to govern vocal fold tissue tension to change the fundamental frequency, the interarytenoid muscles are also changing in a synchronized manner with the CT and VOC for the subjects of this study. The phase delays between airflow vibrato and f_o vibrato constitute another area of needed explanation, but may relate to the phasing between the vocal fold lengthening mechanism (CT and VOC) and the posterior adductory system (the interarytenoid muscles).

Another factor that may accompany the airflow vibrato as a causative influence is the rise and fall of the larynx during the vibrato cycle. A laryngeal rise would increase the output airflow and a laryngeal fall would decrease the output airflow. This possibility would not necessarily disturb the glottal adduction, and thus would be consistent with the EGG measures used in this study (where the results of those methods did not infer adductory changes at the peak and valleys of the airflow vibrato cycles). Unfortunately, the amount of airflow change with this cause is quite limited, perhaps maximally in the range of 10−20 cm^3/s (by rough calculation).

Some other interesting findings also need valid explanations. (1) What explains the alterations within the airflow vibrato cycle? How can an airflow vibrato cycle have triple peaks, greatly changing airflow across a few contiguous cycles, or have a flat portion (while f_o vibrato continues without a constant f_o); are these governed by a subtle adductory (at the vocal processes) mechanism? (2) The airflow vibrato extent tended to be greater for the female singers than the male singers, by about 25 cm^3/s on average. Is this due to more cycles per second and a relatively larger posterior glottal opening for the females? (3) Airflow vibrato extent was greater for the middle pitch (P2) than for the lowest pitch (P1) across the singers and loudness levels. Do longer vocal folds (greater glottal area on average) and higher subglottal pressure variations for the higher pitch generate the difference in the airflow vibrato extent?

Comparison to other studies

Scherer et al[18] found that the rate of airflow vibrato was similar to f_o vibrato, with a range of 4.0−6.5 Hz, similar to the new study reported here. Scherer et al presented figures whereby waveforms for airflow and intensity could be compared. Airflow could either lead or lag the intensity signal, whereas in the present study the intensity tended to lead the airflow vibrato if a lead or lag was discernible (Figures 13−15).

In the Horii[32] study, the difference between the EGG speed quotient at the highest and lowest portions of the vibrato cycle was greatest for their softest productions but not related to pitch, whereas in the current study the difference for the comparable measure, NRQ, did not appear to be significant for either loudness or pitch (across subjects). Thus, this aspect of vocal fold dynamics does not appear to be a discerning feature of the peaks and valleys of the airflow vibrato.

CONCLUSION

Airflow vibrato complements fundamental frequency vibrato and acoustic intensity variation during vibrato production by being an aerodynamic factor (airflow) that should deepen the understanding of this important singing phenomenon. The results from studying four professional singers suggest that airflow vibrato varies in an overall manner with f_o vibrato, usually leading f_o vibrato, but can be much more complex in waveshape, and therefore also seemingly not a factor that is consciously controlled by the singer. Because airflow in general is related strongly to airflow resistance, it might be assumed that airflow vibrato is strongly related to glottal adduction and subglottal pressure. In this study, however, adduction (suggested by the EGGW measure) and mean subglottal pressure did not have obvious causative relations with airflow vibrato. Airflow vibrato did have a strong relation with pitch, however, having a wider airflow vibrato extent with higher pitch. In addition, the two female singers tended to have greater vibrato extent than the two male singers. Further research should attempt to determine changes in glottal area (especially the posterior glottis) and transglottal pressure as airflow vibrato changes, and devise ways to determine what causes airflow vibrato waveshape complexities such as triple peaks and unchanging airflow portions. Further insight into the nature of airflow vibrato also would come from inverse filtering the wideband airflow to examine how basic glottal flow waveform characteristics vary with the vibrato modulation.

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REFERENCES

1. Sundberg J. Acoustic and psychoacoustic aspects of vocal vibrato. *STL-QPSR*. 1995;35:045–068.
2. Hirano M, Hibi S, Hagino S. Physiological aspects of vibrato. In: Dejonckere P, Hirano M, Sundberg J, eds. *Vibrato*. San Diego, CA: Singular Publishing Group, Inc.; 1995:9–33.
3. Shipp T, Doherty ET, Hagland S. Physiological factors in vocal vibrato production. *J Voice*. 1990;4:300–304.
4. Titze IR. On the relation between subglottal pressure and fundamental frequency in phonation. *J Acoust Soc Am*. 1989;85:901–906.
5. Titze IR, Story B, Smith M, et al. A reflex resonance model of vocal vibrato. *J Acous Soc Am*. 2002;111:2272–2282.
6. Seashore CE. *The Vibrato*. Iowa City, IA: University of Iowa Press; 1932:30–37.
7. Hampala V, Garcia M, Švec JG, et al. Relationship between the electroglottographic signal and vocal fold contact area. *J Voice*. 2015;30:161–171.
8. Seidner, S., Nawka, T., & Cebulla, M. "Dependence of the vibrato on pitch, musical intensity, and vowel in different voice classes." In: P. Dejonckere, M. Hirano & J. Sundberg, eds. *Vibrato* San Diego, CA: Singular Publishing Group, Inc., 63−82.
9. Rothenberg M, Miller D, Molitor R. Aerodynamic investigation of sources of vibrato. *Folia Phoniatr Logop*. 1988;40:244–260.
10. Sundberg J. Perceptual aspects of singing. *J Voice*. 1994;8:106–122.
11. Prame, E. "Measurement of the vibrato rate of ten singers." In: P. Dejonckere, M. Hirano & J. Sundberg, eds. *Vibrato*. San Diego, CA: Singular Publishing Group, Inc., 121−139.
12. Keidar A, Titze I, Timberlake C. Vibrato characteristics of tenors singing high C's. In: Lawrence V, ed. *Transcripts of the 13th Symposium Care of the Professional Voice Part I*. 105–110.
13. Sundberg J, Titze I, Scherer RC. Phonatory control in male singing: a study of the effects of subglottal pressure, fundamental frequency, and mode of phonation on the voice source. *J Voice*. 1993;7:15–29.
14. Schultz Coulon S, Battmer R. Die quantitative Bewerung des Sangervibratos. *Folia Phoniatr*. 1981;33:1–14. mentioned in Sundberg, J. (1995b).
15. Laukkanen A, Vilkman E. Tremor in the light of sound production with excised human larynges. In: Dejonckere P, Hirano M, Sundberg J, eds. *Vibrato*. San Diego, CA: Singular Publishing Group, Inc.; 1995:93–110.
16. Rubin HJ, LeCover M, Vennard W. Vocal intensity, subglottic pressure and air flow relationships in singers. *Folia Phoniatr Logop*. 1967;19:393–413.
17. Sundberg J. Synthesis of singing by rule. In: Mathews M, Pierce J, eds. *Current Directions in Computer Music Research*. Cambridge, MA: The MIT Press; 1989:45–55. 401−403.
18. Scherer RC, Druker DG, Titze IR. Electroglottography and direct measurement of vocal fold contact area. In: Fujimura O, ed. *Vocal Fold Physiology*. Vol. 2, Raven Press; 1988:279–291.
19. Orlikoff RF. Vocal stability and vocal tract configuration: an acoustic and electroglottographic investigation. *J Voice*. 1995;9:173–181.
20. Fourcin AJ. Laryngographic assessment of phonatory function. In: Ludlow CL, Hart MO, eds. *Proceedings of the Conference of the Assessment of Vocal Pathology, Rockville, MD, December 1981*. Vol. 11, Rockville, MD: American Speech-Language-Hearing Association; 1981:116–127.
21. Large J, Iwata S. Aerodynamic study of vibrato and voluntary 'straight tone' pairs in singing. *Folia Phoniatr Logop*. 1971;23:50–65.
22. Henrich N, Roubeau B, Castellengo M. On the use of electroglottography for characterisation of the laryngeal mechanisms. *Stockholm Music Acoustics Conference*. Stockholm, Sweden.
23. Fisher KV, Scherer RC, Guo CG, et al. Longitudinal phonatory characteristics after botulinum toxin type A injection. *J Speech Lang Hear Res*. 1996;39:968–980.
24. Orlikoff RF. Assessment of the dynamics of vocal fold contact from the electroglottogram: data from normal male subjects. *J Speech Hear Res*. 1991;2:5–19.
25. Higgins MB, Netsell R, Schulte L. Vowel-related differences in laryngeal articulatory and phonatory function. *J Speech Lang Hear Res*. 1998;41:712–724.

26. Chen Y, Robb MP, Gilbert HR. Electroglottographic evaluation of gender and vowel effects during modal and vocal fry phonation. *J Speech Lang Hear Res*. 2002;45:821–829.
27. Brown LR, Scherer RC. Laryngeal adduction in trillo. *J Voice*. 1992;6:27–35.
28. Scherer RC, Vail VJ, Rockwell B. Examination of the laryngeal adduction measure EGGW. *Producing Speech: Contemporary Issues: for Katherine Safford Harris.* 1995;269–290.
29. Hicks DM, Teas E. An electroglottographic study of vocal vibrato. *J Voice*. 1987;1:142–147.
30. Childers DG, Larar JN. Electroglottography for laryngeal function assessment and speech analysis. *IEEE Trans Biomed Eng*. 1984;31:12.
31. Dromey C, Reese L, Hopkin JA. Laryngeal-level amplitude modulation in vibrato. *J Voice*. 2009;23:156–163.
32. Horii Y. Acoustic analysis of vocal vibrato: a theoretical interpretation of data. *J Voice*. 1989;3:36–43.
33. Sundberg J. Acoustic and psychoacoustic aspects of vocal vibrato. In: Dejonckere P, Hirano M, Sundberg J, eds. *Vibrato*. San Diego, CA: Singular Publishing Group, Inc.; 1995:35–62.