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JASA ARTICLE

Fundamental frequency disturbances in female and male singers' pitch glides through long tube with varied resistances[a)]

Johan Sundberg,[1,b)] Filipa Lã,[2] and Svante Granqvist[3]
[1]*Department of Speech Music and Hearing, KTH (Royal Institute of Technology), Stockholm, Sweden*
[2]*Department of Didactics, School Organization and Special Didactics, Faculty of Education, The National Distance Education University (UNED), Madrid 28040, Spain*
[3]*Division of Speech and Language Pathology, Department of Clinical Science, Intervention and Technology, Karolinska Institutet, Stockholm, Sweden*

ABSTRACT:
Source-filter interaction can disturb vocal fold vibration frequency. Resonance frequency/bandwidth ratios (Q-values) may affect such interaction. Occurrences of fundamental frequency (f_o) disturbances were measured in ascending pitch glides produced by four female and five male singers phonating into a 70 cm long tube. Pitch glides were produced with varied resonance Q-values of the vocal tract + tube compound (VT + tube): (i) tube end open, (ii) tube end open with nasalization, and (iii) with a piece of cotton wool in the tube end (conditions Op, Ns, and Ct, respectively). Disturbances of f_o were identified by calculating the derivative of the low-pass filtered f_o curve. Resonance frequencies of the compound VT+tube system were determined from ringings and glottal aspiration noise observed in narrowband spectrograms. Disturbances of f_o tended to occur when a partial was close to a resonance of the compound VT+tube system. The number of such disturbances was significantly lower when the resonance Q-values were reduced (conditions Ns and Ct), particularly for the males. In some participants, resonance Q-values seemed less influential, suggesting little effect of source-filter interaction. The study sheds light on factors affecting source-filter interaction and f_o control and is, therefore, relevant to voice pedagogy and theory of voice production. https://doi.org/10.1121/10.0020569

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I. INTRODUCTION

Fundamental frequency of phonation (f_o) can be disturbed by source-filter interaction, causing unintended pitch jumps and voice breaks. Such disturbances are of great relevance, particularly in singing pedagogy.

Source-filter interaction has attracted much attention in voice research over almost half a century (Flanagan and Landgraf, 1968; Ishizaka and Flanagan, 1972; Rothenberg, 1981; Fant, 1986; Titze, 2004). It concerns the effects that vocal tract resonances can exert on glottal airflow and vocal fold vibration, effects referred to as level 1 and level 2 source-filter interaction, respectively. Level 2 interaction is generally assumed to depend on the frequency difference between a spectrum partial and a vocal tract resonance frequency. According to Titze (2008a,b), vocal fold vibration is facilitated when f_o is lower than the first vocal tract resonance, while vibratory instabilities or even cessation of vibration may occur when f_o is higher than the first vocal tract resonance frequency.

Almost a century ago, Weiss published an article on vocal registers and voice breaks (Weiss, 1932). He studied register breaks occurring at various f_o during phonation into 50 and 100 cm long glass tubes. Kågén and Trendelenburg (1937) adopted this experimental procedure, asking participants to produce, with and without nasalization, pitch glides into glass tubes of 50, 75, and 100 cm length. They noted that pitch jumps tended to occur at the resonance frequencies of the glass tubes. They further observed that when subjects attempted to avoid the jumps in pitch, "tremolo-like alterations" (p. 148) appeared; they also reported that "medium disturbances of tone disappear…where the tones are made nasel [*sic*]" (p. 148).

Later, phonation through a long tube was studied in terms of a two-mass model of the vocal folds coupled to a model of tube resonators of varied lengths (Hatzikirou *et al.*, 2006). The researchers systematically varied subglottal pressure, f_o, and the length and diameter of the tube, the aim being to explore the effects on voice instabilities. In agreement with the findings of Kågén and Trendelenburg (1937), they found that changes of tube length and f_o led to voice instabilities in regions where the frequencies of the tube resonances matched those of a voice source partial. Reduction of the tube diameter caused "bifurcations at the resonance between the second harmonic of the source and the lowest formant frequency of the tube" (Hatzikirou *et al.*, 2006, p. 473).

Maxfield *et al.* (2017) studied the effects on f_o when subjects produced pitch glides through tubes of lengths varying between 5 and 19 cm. Analyzing 144 pitch glides, they

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[b)]Also at: University College of Music Education Stockholm, Stockholm, Sweden. Electronic mail: jsu@kth.se

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found more than 600 f_o instabilities, which occurred when one of the first four harmonics crossed one of the three lowest resonances. Moreover, they noted that "maximum reinforcement is achieved by placing a harmonic slightly below a formant frequency" (p. 154). The frequencies of the resonances were measured in a vocal fry condition, which preceded the pitch glide. In addition, when a harmonic passed a formant, "the harmonic intensity did not grow and decay in a strictly symmetric fashion" (p. 154). They ascribed this asymmetry to non-linear source-filter interaction.

Wade *et al*. (2017) analyzed f_o instabilities in sopranos under different conditions: (i) constant f_o while varying formant frequencies; (ii) pitch glides on constant vowel with constrained lip and jaw openings as well as with unconstrained lip openings; and (iii) pitch glide into an infinite tube, i.e., a resonance-free vocal tract. For the unconstrained pitch glides, where the sopranos could adjust the first vocal tract resonance, thus, avoiding f_o crossover, no correlation was found between pitch instabilities and resonance frequencies, as might be expected from trained soprano singers. By contrast, pitch instabilities were frequent under the constrained condition. For the case of the resonance-free vocal tract, fewer instabilities occurred, except for pitches near the lower limit of the falsetto range. Similar results were observed by Echternach *et al.* (2021) in a study with professional singers of different classifications; consistent source-filter interactions were rarely found when a formant was crossing a partial.

It seems reasonable to assume that effects of source-filter interaction are strongly dependent on the ratio between the frequency and bandwidth (Q-value) of the filter resonances, as Q-values reflect the amplitude of the pressure oscillations at the glottal level. The assumption is supported by the results of the experiments with pitch glides into a quasi-endless tube, which eliminates sound reflection and, hence, resonance (Wade *et al*., 2017).

The Q-values of vocal tract resonances are clearly affected by nasalization as evidenced, e.g., by Fujimura and Lindqvist (1971). They measured the vocal tract response to sweep-tone excitations of nasalized and non-nasalized vowels and showed that nasalization attenuated the first formant (see Fig. 1). As illustrated in Fig. 1, nasalization attenuated the first formant, an effect also observed on three-dimensional (3D) models of vocal tracts coupled to a 3D model of the nasal tract (Havel *et al*., 2023). This phenomenon would explain the observation made by Kågén and Trendelenburg (1937), that the number of voice breaks was reduced when the singer nasalized the pitch glides.

The purpose of the current investigation was to test whether resonance Q-values affect the occurrence of f_o disturbances during the production of pitch glides. The study should shed additional light on singers' possibilities to avoid such disturbances.

II. METHOD

A. Experiment

Four females and five males agreed to participate (F1, F2, F3, F4 and M1, M2, M3, M4, M5, respectively), all choir singers and reportedly in good vocal health at the time of the recording. Of them, F3, F4, M3, and M5 had taken singing lessons. As age could be assumed to be irrelevant to voice breaks in a choir population, age data were not collected. Depending on time available, they performed three to five loud ascending pitch glides on the intended vowel /ae/ while holding the end of a 70 cm standard hard-walled plastic tube [inner diameter (ID) 3.6 cm] tightly against the mouth. They were instructed to extend the glides as widely as possible, from lowest to highest, under three conditions ordered as follows: (i) with the tube end open (condition Op); (ii) to repeat the task while nasalizing the intended vowel (condition Ns); and finally (iii) when a piece of loose fibrous cotton wool was inserted into the far end of the tube (condition Ct). The tube end was kept at least 70 cm from reflecting surfaces. The experiment yielded a total of 129 glides.

The glides were recorded in office rooms with short reverberation time at KTH (Stockholm, Sweden). They were picked up by an omnidirectional OM1 condenser microphone (Line Audio Design, Stockholm, Sweden) placed 12 cm from the tube end, and recorded via a Focusrite Scarlett 2i2 external sound card (Focusrite Engineering Ltd., High Wycombe, UK). All recordings were made using the custom-made software Sopran.[1]

The acoustic properties of the 70 cm long tube were analyzed using TombStone software.[2] It provided a sine-sweep to an earphone mounted in a plastic washer sealed to one tube end while the response was recorded by a microphone at the opposite end. Figure 2 shows the transfer functions of the tube with and without cotton in the far end.

Table I lists the frequencies, bandwidths, and Q-values of the five lowest resonances of the tube alone. As expected, the cotton caused a lowering of the resonance frequencies and Q-value differences varying between −4.5 and −10.5.

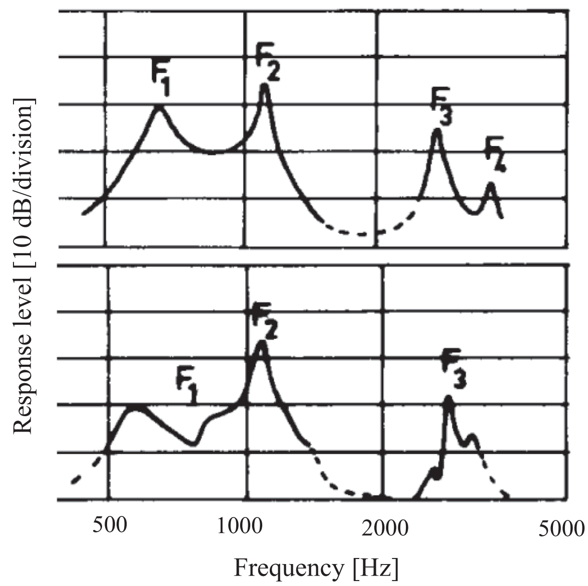

FIG. 1. Vocal tract response to sweep-tone excitation of a non-nasalized and nasalized vowel (upper and lower panels, respectively). Adapted from Fant, STL-QPSR **3**, 1–2 (1962). Copyright 1962 Royal Institute of Technology (Fant, 1962).

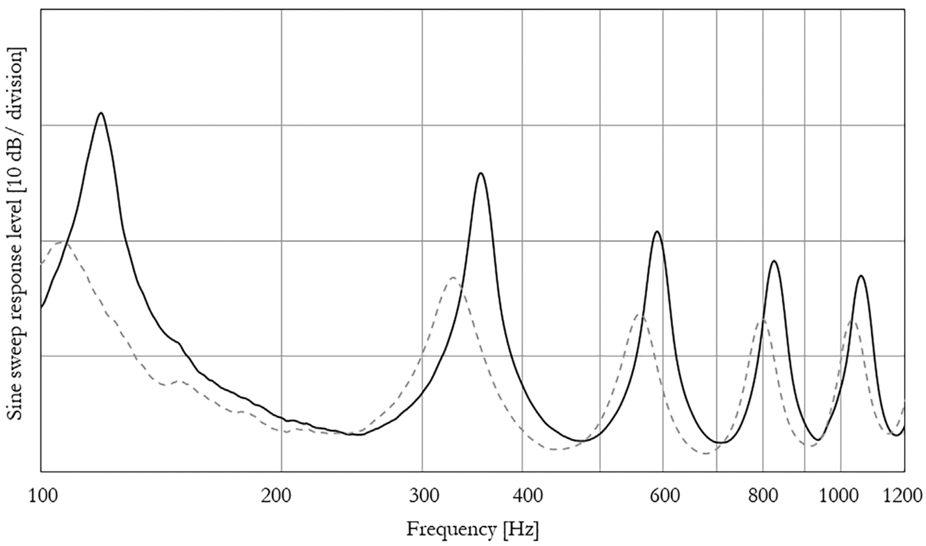

FIG. 2. Sine-sweep response of the 70 cm tube, without and with a piece of cotton wool in the far end (solid and dashed curves, respectively).

The narrowband spectrogram in Fig. 3 shows examples of pitch glides produced by female participant 2 under the Op condition. Ringings appeared as horizontal tails when a partial excited resonances of the compound vocal tract + tube (VT+tube). In some participants, glottal noise produced horizontal stripes in the spectrograms. The resonances were measured for each participant in terms of such ringings and noise traces, observed in narrowband spectrograms of the Op condition.

Table II lists the resonance frequencies measured for each participant. As indicated by the standard deviations, the frequencies were similar for all participants but tended to be somewhat lower for the males, as expected. It might be mentioned that the second resonance happened to fall into the typical frequency range of the modal/falsetto register transition.

The sound level at the tube end was, on average across participants, 2 dB weaker in the Ct and Ns conditions than in the Op condition.

B. Analysis

f_o was manually marked and automatically measured by means of the Correlogram module of the Sopran software. The f_o curve was (i) converted from Hz to semitones and (ii) low-pass filtered at 50 Hz, and then (iii) its derivative was calculated. Maxima of the resulting signal that exceeded a threshold value of +40 semitones/s (alarms) were then identified and collected, together with the f_o value and the time coordinate (see Fig. 4).

TABLE I. Frequencies (f_R), bandwidths (B), and Q-values (Q) of the five lowest resonances (R) of the tube without and with cotton in its far end. The Q-value differences (ΔQ) are listed in the rightmost column.

	Without cotton			With cotton			
R	f_R (Hz)	B (Hz)	Q	f_R (Hz)	B (Hz)	Q	ΔQ
1	120	7	17.1	106	16	6.6	−10.5
2	358	17	21.1	330	30	11.0	−10.1
3	587	26	22.6	563	42	13.4	−9.2
4	824	42	19.6	804	57	14.1	−5.5
5	1060	51	20.8	1040	64	16.3	−4.5

As illustrated by the figure, some alarms appeared in sequences (marked by arrows in the figure). Only those separated by a more than 50 ms long disturbance-free part were accepted as disturbances (vertical marks). This time threshold was selected based on the typical duration of the f_o disturbances observed in the spectrograms. Henceforth, we refer to events causing alarms as f_o disturbances. The f_o of the disturbances was measured at the start of each accepted alarm. The number of disturbances was counted for each condition. As data were not normally distributed, the difference between condition Op and the two other conditions was compared using a Mann–Whitney U test (SPSS, version 27, IBM, Armonk, NY).

III. RESULTS

To examine the reliability of the data, the effect of training was analyzed by comparing the values observed in the first and last takes of the pitch glides under condition Op (empty tube end). All singers had between zero and six more f_o disturbances in the final than in the first take, except singers 1 and 3, who had one and two fewer breaks in the final take, respectively (see Table III). Thus, it seemed reasonable to assume that no training effect reduced the reliability of the data.

Figure 5 provides an overview of the total number of occurrences of f_o disturbances per condition for the female and the male singers pooled. In the 43 pitch glides analyzed in each condition, condition Op caused a clearly higher number of f_o disturbances, a total of 143 (49% of all cases). Of these, 63 happened in the female voices and 80 in the male voices. For condition Ns, a total of 84 (29% of all cases) were observed, 41 for females and 43 for males, whereas for condition Ct, a total of 65 were observed (22% of all cases), 37 for females and 28 for males. The difference between conditions Op and Ct was significant ($Z = -2.371$;

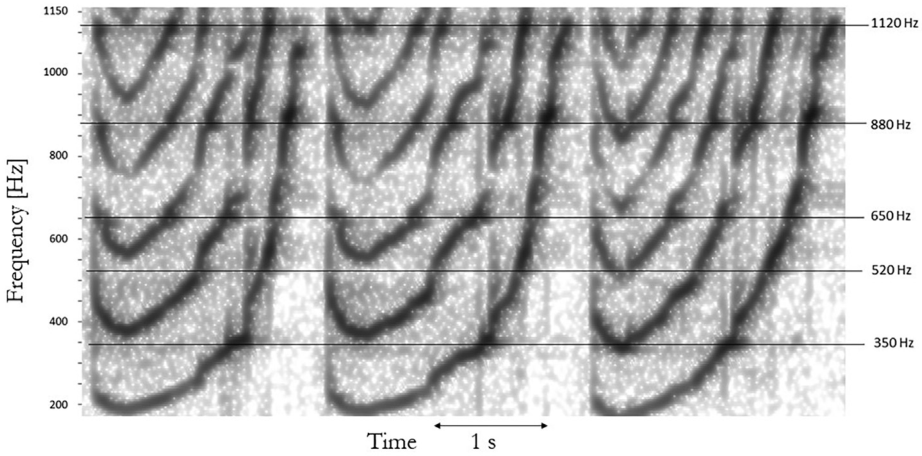

FIG. 3. Narrowband spectrogram of three pitch glides performed by participant F2 into the compound VT+tube system recorded in the Op condition. The thin lines mark the ringings caused when a partial crossed a resonance.

TABLE II. Participants' six lowest resonances frequencies of the compound VT+tube system in the Op condition, evidenced by narrowband spectrograms in terms of ringings appearing when a partial passed a resonance (*R*) and, in some participants, also as gray stripes produced by glottal noise.

	Female singers (Hz)						Male singers (Hz)						
	Ringing frequencies						Ringing frequencies						
R	1	2	3	4	M[a]	SD[b]	1	2	3	4	5	M	SD
1	200	—	—	198	—	—	200	—	214	209	—	—	—
2	385	358	349	345	359	18	324	297	—	353	293	317	34
3	560	491	565	—	539	41	510	453	446	597	450	491	74
4	690	660	603	673	657	38	667	637	686	701	657	670	29
5	884	897	896	871	887	12	888	860	920	858	902	886	31
6	1130	1108	1130	1120	1122	10	1123	1094	1128	1106	1111	1112	14

[a]Mean (M).
[b]Standard deviation (SD).

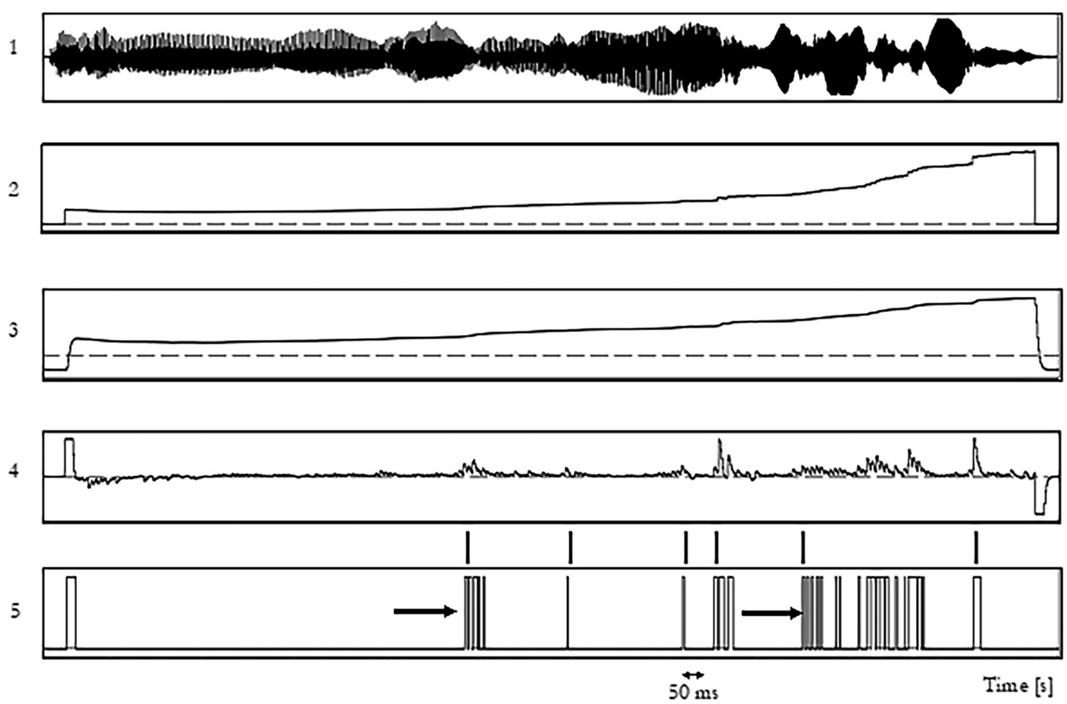

FIG. 4. Method used for detecting f_o disturbances. From top to bottom, the panels show audio, f_o before and after smoothing, the derivative of the smooth version of f_o, and resulting alarms, in which the arrows mark two groups of alarms spaced by less than 50 ms; vertical lines mark accepted f_o disturbances.

TABLE III. Number of f_o disturbances in first and last take of the pitch glides sung under the Op condition (far tube end open).

Singer	First pitch glide	Last pitch glide	Difference
Females			
1	3	2	1
2	6	7	−1
3	4	2	2
4	8	14	−6
Males			
1	0	1	−1
2	5	8	−3
3	0	1	−1
4	2	2	0
5	2	5	−3

$p = 0.018$) and accounted for 70% of the data variability ($\eta^2 = 0.70$), whereas the difference between conditions Op and Ns did not quite reach significance ($Z = -1.899$; $p = 0.058$).

Another relevant aspect is how close a harmonic was to a resonance when an f_o disturbance occurred. We analyzed the narrowest frequency distance between each of the six lowest resonances of the VT+tube compound system and each of the 13 lowest partials for males and the lowest six partials for females. Figure 6 shows histograms of the smallest frequency distance between a partial and a resonance for which an f_o disturbance happened, presented for each condition and sex. As expected, very narrow distances occurred for the Op condition, for both females and males, and for the females also in the vicinity of 4%. For the conditions Ns and Ct, the narrowest difference varied considerably for the females but was still close to low values. For the males, condition Ct, distances near 0% were most frequent.

Table IV shows, for each singer, the average of the absolute value of the minimum distance between the one of the 6 and 13 lowest partials that were closest to a resonance and the frequency of that resonance. The values are given in percent relative to the frequency of the resonance. For each of the three conditions Op, Ns, and Ct, averages for the female singers were higher than those for the male singers. Regarding conditions, the average across singers was higher in condition Op than in conditions Ns and Ct. Taking into account the limited accuracy of the measurement of the resonance frequencies, it seems fair to hypothesize that all disturbances happened when a partial crossed one of the resonances.

The number of disturbances varied greatly, not only between conditions, but also between singers. This is illustrated in Fig. 7. For condition Op, singers F2 and M5 had the highest number of f_o disturbances, 25 and 34, respectively, while singers F3 and M3 showed the fewest, 6 and 4, respectively. Furthermore, the effects of the conditions varied substantially between the singers. Singer F2 showed almost the same number of disturbances for Op, Ns, and Ct conditions, 25, 22, and 24, respectively. Also, singer M1 appeared to be almost insensitive to resonance Q-values, having a low and similar number of occurrences for the three conditions, 6, 4, and 7, respectively. By contrast, singers F4 and M5 were quite affected by the resonator properties, having 19, 10, and 10 and 34, 2, and 5 disturbance occurrences for conditions Op, Ns, and Ct, respectively.

IV. DISCUSSION

The current investigation tested the effect on singers' pitch control of varying the attenuation in a tube resonator that substantially added to the length of the vocal tract. The results showed a number of f_o disturbances that were all associated with a spectrum partial crossing a resonance in the compound VT+tube system, as illustrated in Fig. 3. Attenuating the tube resonance either by nasalizing or by placing a piece of loose fibrous cotton in the far tube end dramatically reduced the number of disturbances in two singers and reduced it slightly in some singers. This effect was

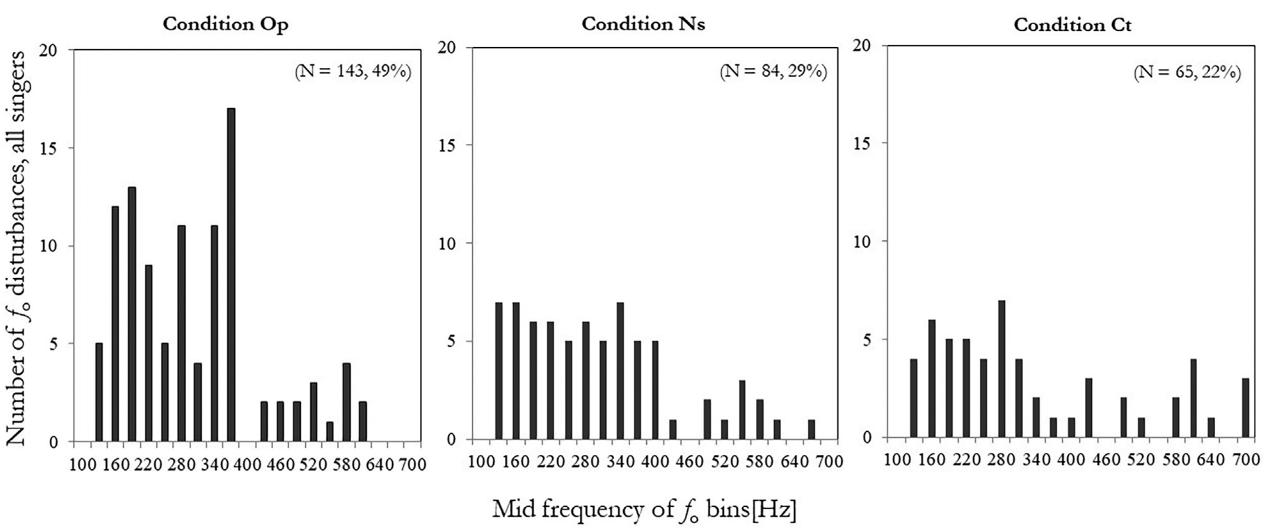

FIG. 5. Histograms showing the distribution of f_o disturbances along the f_o continuum in the indicated conditions for the female and male singers pooled. N, number of disturbances.

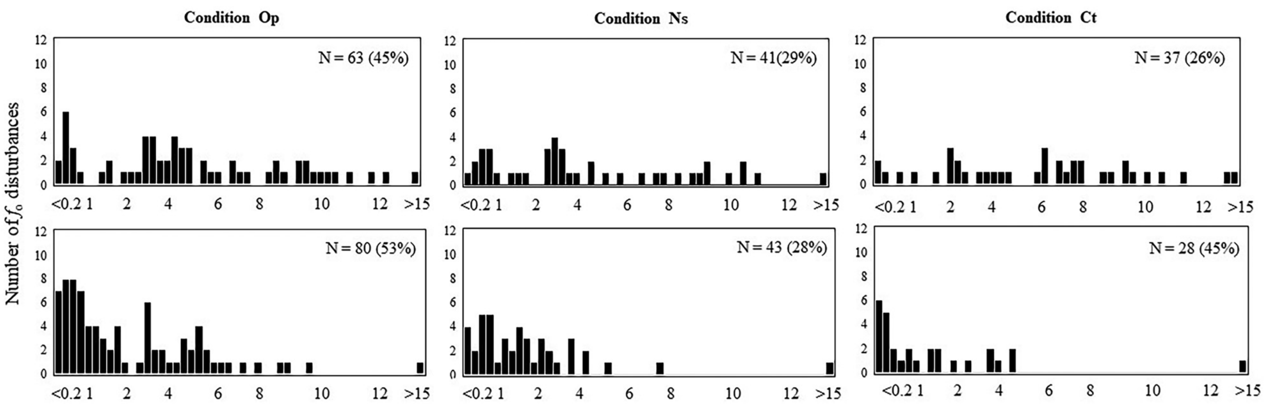

FIG. 6. Histograms showing the lowest percent difference between resonance frequency and f_o observed at f_o disturbances. The upper and lower panels refer to the female and male singers, respectively.

particularly enhanced for the greatest attenuation of the resonance, i.e., the cotton condition, but in female singer 2 and male singer 1, it had almost no effect (Fig. 7).

One may argue that the repetition of pitch glides might have caused a training effect, resulting in an overall tendency to fewer f_o disturbances in the later than in the earlier takes in each condition. However, no such tendency was found, thus, supporting the assumption that the differences in occurrences of f_o disturbances were caused by the differences in conditions.

The total number of f_o disturbances, but not their frequencies, turned out to be similar in condition Op for our male and female singers, 45% and 53%, respectively. Thus, the control of f_o seems equally sensitive to source-filter interaction in female and male voices. However, it should be noted that, in condition Op, the total number of disturbances varied dramatically between singers, the maximum and minimum amounting to 69 and 8, respectively. Also interesting is that, for the same condition, the singers with few disturbances (e.g., female singer 3 and male singer 4) tended to have a larger mean ΔH-R. These observations suggest that the sensitivity to source-filter interaction varied between the singers.

In the Op condition and for male voices, more than half of the f_o disturbances (48 of 80) occurred when a partial was closer than 2% from one of the six lowest resonances. For the female voices, only 13 of 63 f_o disturbances occurred under the same condition (Fig. 6). It is tempting to speculate that this difference was associated with sex-related differences in glottal configuration, formant bandwidth, or mechanical properties of the vocal folds (Fujimura and Lindqvist, 1971; Fant, 1972). For the other two conditions, the resonances were attenuated, and the f_o disturbances were considerably fewer. Particularly for females, they were also more widely distributed along the f_o continuum, thus, suggesting that factors other than source-filter interaction may cause f_o disturbances. Pedagogical implications of such sex-related differences need to be further explored.

For most singers, the number of f_o disturbances was higher for conditions Op than for conditions Ns and Ct (Fig. 7). However, this difference was small for female singer 2, who had similar numbers of occurrences for all three conditions, and for male singers 1 and 3, the difference was reversed. This suggests that in these voices, the disturbances were caused by vocal fold properties rather than by VT+tube resonances. This suggestion is supported by the slight concentration of disturbances near 350 Hz (Fig. 5, left panel), a typical register transition range.

We measured the resonances of the VT + tube in terms of ringing frequencies caused by a partial crossing a resonance and, in some voices, also glottal noise bands. Obviously, these resonance frequencies were dependent not only on the tube but also, to some extent, on the singers' vocal tract shape. Although singers were instructed to perform pitch glides on an intended vowel /ae/, they may have varied their vocal tract shape. Presumably, the ringing near 450 Hz instead of at 520 Hz in the middle glide in Fig. 3 is an example.

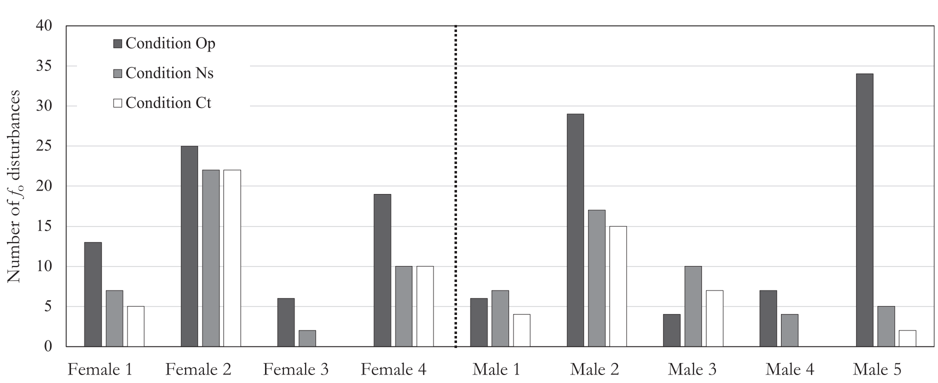

FIG. 7. Individual singers' occurrences of f_o disturbances observed for the indicated conditions.

TABLE IV. Average minimum distance ($\Delta H\text{-}R$) between the partial closest to a resonance and the frequency of that resonance, expressed in percent, for all singers and conditions.

Singer	Condition Op (%)	Condition Ns (%)	Condition Ct (%)
Females			
1	6.4	3.4	7.7
2	4.8	5.0	6.5
3	7.5	1.9	—
4	4.6	6.0	5.5
Males			
1	1.3	1.2	1.2
2	3.1	2.1	2.8
3	2.9	3.1	0.7
4	3.0	2.2	—
5	3.1	3.0	0.5

It cannot be excluded that room reverberation contributed to the durations of some ringings. However, the frequencies, not the durations of the ringings, were of interest in the present investigation. Also, contribution from room reverberation is quite unlikely, given the short reverberation time in the recording rooms and the short distance between the tube end and the microphone.

The results showed that the number of f_o disturbances was greatly reduced when the singers produced pitch glides while nasalizing. Nasalization attenuates the first vocal tract resonance, as shown by the Fujimura and Lindqvist (1971) sweep-tone measurements of vocal tracts as well as by the corresponding measurements on 3D vocal tract models connected by means of coupling tubes of varied sizes to a 3D nose model (Havel *et al.*, 2023). A narrow velopharyngeal opening was also observed to boost spectral partials above 2 kHz in singers' vowel sequences produced at different pitches (Gill *et al.*, 2020). This speaks to a pedagogical relevance of our results; a velopharyngeal opening may not only boost the high frequency partials, but also reduce the risk of register breaks, two major goals in voice training.

It should be recalled that our results were derived from no more than nine subjects, all singers. Singers are particularly good subjects in voice research in the sense that they have acquired an accurate and consistent control of f_o. At the same time, they have also learned to avoid f_o disturbances at register transitions. It would be worthwhile to repeat the present experiment with untrained voices.

V. CONCLUSIONS

This investigation analyzed the effect on source-filter interaction of varying the attenuation of the filter resonances. Nine subjects produced pitch glides into a 70 cm long, hard-walled cylindrical tube. The results support the following conclusions. First, source-filter interaction is strongly dependent on the Q-values of the filter resonances; disturbances happened more frequently when resonance Q-values are high. Second, sensitivity to source-filter interaction differed substantially between individuals; for the unattenuated tube condition, the number of disturbances varied between 25 and 6 for the females and between 34 and 4 for the males. Furthermore, female participants showed fewer disturbances than male participants, possibly due to lower Q-values of vocal tract resonances in females than in males. Also, disturbances were more widely distributed along the f_o continuum for females than for males; it is possible that sex-related differences, such as glottal configuration and morphological properties of the vocal folds, also account for disturbances. Factors accounting for interindividual differences in the sensitivity to source-filter interaction remain an open question.

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[1]Available at https://www.tolvan.com.
[2]Available at https://www.tolvan.com.

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