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Source-Vocal Tract Interaction in Female Operatic Singing and Theater Belting

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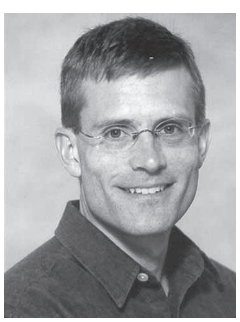

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INTRODUCTION

High pitched singing seems to follow two techniques that are clearly differentiated by the operatic style and the music theater style. Both styles (and hence the techniques) grew out of the need to produce intense unamplified vocal sound to large audiences and over considerable large background instrumental accompaniments. The styles have been cultivated over time, even though amplification is now part of some performances in both styles.

Several authors have described differences between operatic productions and music theater productions. Sundberg, Gramming, and LoVetri studied a female singer who could produce both styles and concluded that theater belting is characterized by a higher subglottal pressure, by a higher degree of glottal adduction, and a higher larynx position with a concomitant higher first formant frequency on comparable vowels.[1] Schutte and Miller pointed out that the second harmonic was characteristically strong in belting and went on record to suggest that, acoustically, the strength of the second harmonic was the defining element of belting.[2]

Bestebreustje and Schutte studied the strengthening of individual harmonics by formants on several vowels produced in the belt style.[3] Vowels with considerable mouth opening, such as / ɑ / and / ɔ /, needed less modification than the vowels with less mouth opening, like / i / and / u /, to reinforce several harmonics with formants. Stone et al. confirmed several of the conclusions reached by Sundberg et al., namely that belting had a higher subglottal pressure, a stronger second harmonic, a longer glottal closure phase, higher overall formant frequencies, and a long term average spectrum that was skewed to higher frequency partials (all in comparison to the operatic style).[4] The amount of vocal fold adduction (pressedness) used by singers in different styles was studied by Sundberg et al.[5] The classical style had the least amount of pressedness, followed by pop, jazz, and blues.

Björkner included a critical measurement in her comparison of music theater style and opera style.[6] For the same lung pressure, music theater production had a greater maximum flow declination rate (MFDR) than opera production. This begins to address source-vocal tract interaction, because

MFDR is highly dependent on skewing of the glottal flow pulse, which is produced by vocal tract inertance.[7]

Titze and Worley described source-vocal tract interaction in male singing at high pitches in the above mentioned styles of production, *operatic* versus jazz or theater *belt*.[8] The two styles were differentiated acoustically mainly by the way the second harmonic was reinforced by vocal tract inertance. For belt production, the first formant frequency of the vocal tract (F1) was kept above the second harmonic of the source (2F0) by a high larynx position and extreme mouth opening, whereas in operatic production the first formant was lowered by pharyngeal throat widening, larynx lowering, and lesser mouth opening to allow the second harmonic to be well above the first formant. The corresponding supraglottal vocal tracts for these formant-harmonic interactions were identified as a *megaphone* mouth shape for belt and an *inverted megaphone* mouth shape for operatic production in a comparable frequency range (around A_4).

It was also pointed out that, historically, a revolution took place around 1830 in male operatic singing. The French tenor Gilbert Duprez introduced a high C (C_5 = 523 Hz) in chest voice on the opera stage, which some critics thought was anything but appealing.[9] It was loud and had a raw quality. In the *bel canto* era of Rossini, Bellini, and Donizetti (leading up to Duprez's time), tenors sang high notes with a much lighter production. Stark contrasts between so-called *chest voice* and *falsetto voice* were avoided in favor of a blended or mixed register production. Later composers such as Verdi, Puccini, and Wagner preferred the robust tenor and baritone sound that contained more of the modal (male speaking) register at high pitches.[10] Subsequent to this revolution in male high voice production, the adjustment from opera to theater or jazz belt appears to have been mainly one of a brighter timbre and more of a speech-like quality for males.

In our opinion, the equivalent of the male singing voice revolution brought about by Duprez in 1831 occurred for females about a century later. Music theater singers like Ethyl Merman were searching for a non-operatic (more speech-like) voice quality that would fill a large house without amplification. The quality should also be a better match to jazz instruments (primarily brasses, woodwinds, and percussion) than the heavily string-dominated ensembles and symphony orchestras used to accompany classical singing. Perhaps the voice quality was also to reflect the emancipation of women in the portrayal of stronger and self-determined characters. Traditionally, the adult female speaking voice is a linear extension of the girl voice to a lower pitch, without a dramatic change at puberty to another register that prolongs the closed phase in vocal fold vibration and thereby increases second harmonic energy.[11] Research cited above has shown, however, that in high effort and high pitched singing, phonation with a longer closed phase (shorter duty ratio) becomes the belt when properly reinforced with vocal tract interaction.

The purpose of this paper is to explain the female opera-belt contrast in terms of source-vocal tract interaction. We give no proof, but show a strong likelihood that specific vocal tract shapes are sought out by singers to reinforce the sound source for the chosen style. It will be shown that selected harmonics are likely to be reinforced by vocal tract acoustic reactance, which peaks near a formant but not exactly at the formant frequency. It is known that supraglottal inertive reactance and subglottal compliant reactance both lower the phonation threshold pressure, thereby producing a larger amplitude of vocal fold vibration (and greater rate of change of glottal flow) than would be predicted by linear source-filter theory.[12] The technique of singing high notes at high intensity is then based on finding the most favorable reactance regions for a collection of harmonics. The primary question is: with the mouth shapes observed in the two styles on publicly available video recordings, what choice of vocal tract shape is best for overall strengthening of the dominant harmonics?

MRI RESULTS FROM A SOPRANO

Figure 1 shows a set of six vowel configurations for a female singer (left panel) and corresponding inertograms (right panel, to be discussed below). The singer was accomplished in both classical and jazz styles, but did not belt extremely high notes. Her vocal tract was previously described by Story.[13] The vocal tract area functions were obtained with three dimensional magnetic resonance imaging (MRI) and represent spoken and classically sung versions of three vowels, /i/, /ɑ/, and /u/. The image sets were collected while the subject lay supine, with hearing protection, in an MR scanner and produced

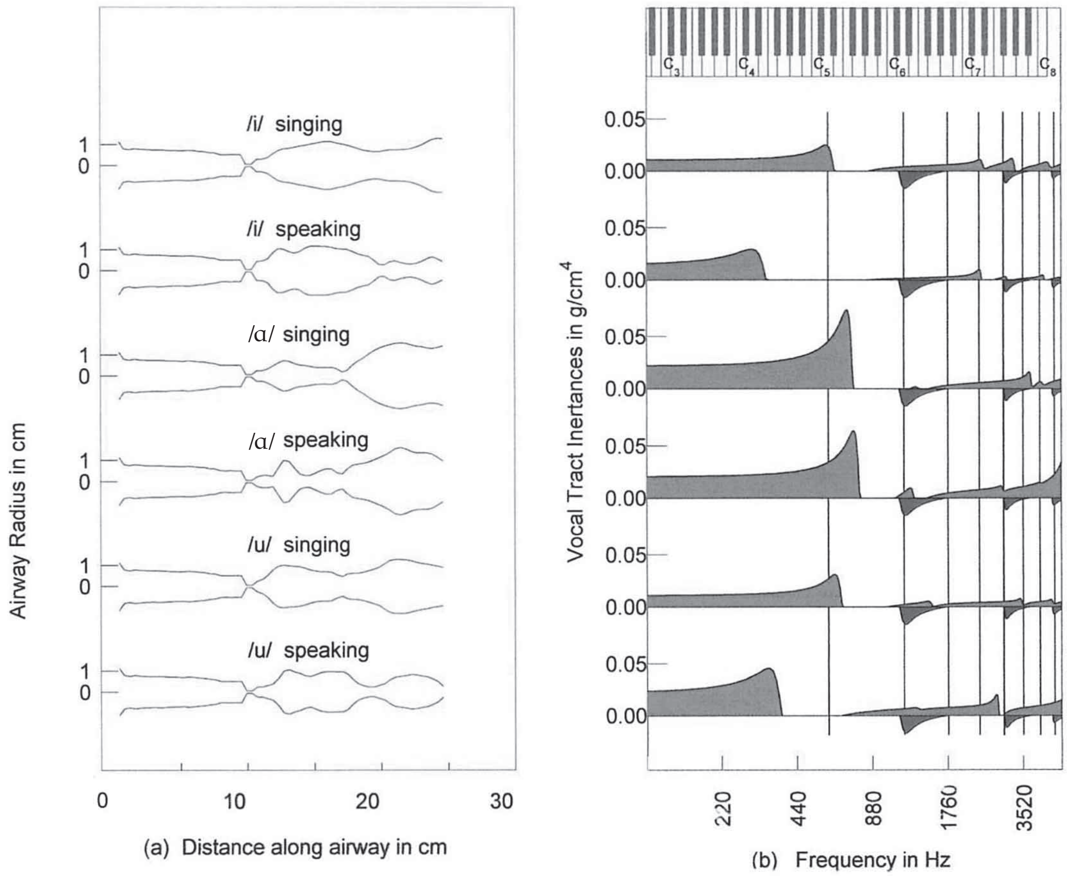

Figure 1. Magnetic resonance-derived area functions (left) of a female soprano for singing and speaking vowels, with corresponding computer-generated inertograms (right).

a given vowel with either speaking or singing quality. The target fundamental frequency was prescribed simply as "conversational" for the speech-like vowels and 587 Hz (D_5) for the singing vowels. The 3D image sets were analyzed such that the vocal tract was segmented from the surrounding tissue. The cross-sectional area variation of the resulting airspace was then measured as a function of distance from the glottis, producing the *area function*.

Audio recordings of each vowel were obtained the day prior to image collection. The intense sound produced by the MR scanner and the hard-walled environment prevent high-quality recordings to be made while scanning. Spectra of both the spoken and sung vowels are shown in Figure 2. These are averaged over a stable portion of vowel production approximately 1.5 seconds in duration and displayed as relative amplitude in dB. The speech spectra for the three vowels, shown in the left column of the figure, all have nearly the same fundamental (184 or 185 Hz) and demonstrate the usual enhanced spectral regions due to the influence of the formant frequencies. Although the target fundamental for the three singing vowels was 587 Hz (D_5), each of the corresponding spectra indicate a fundamental that deviated slightly upward (sharp) from the target (closer to 600 Hz). The spectra will be discussed below.

Returning to Figure 1, the subglottal and supraglottal vocal tract airways (from bronchial bifurcation to lips) are about 25 cm long, compared to about 33 cm in a typical male airway.[14] This raises both subglottal and supraglottal formant frequencies by about 20–30%, or about 3–5 semitones, above those of males. But because females are often scripted (musically) to sing an octave higher (12 semitones) than males, the harmonic-formant relationships are not simply scaled up from males.

The main difference between the sung and spoken vowels for this singer was a more open mouth for all sung

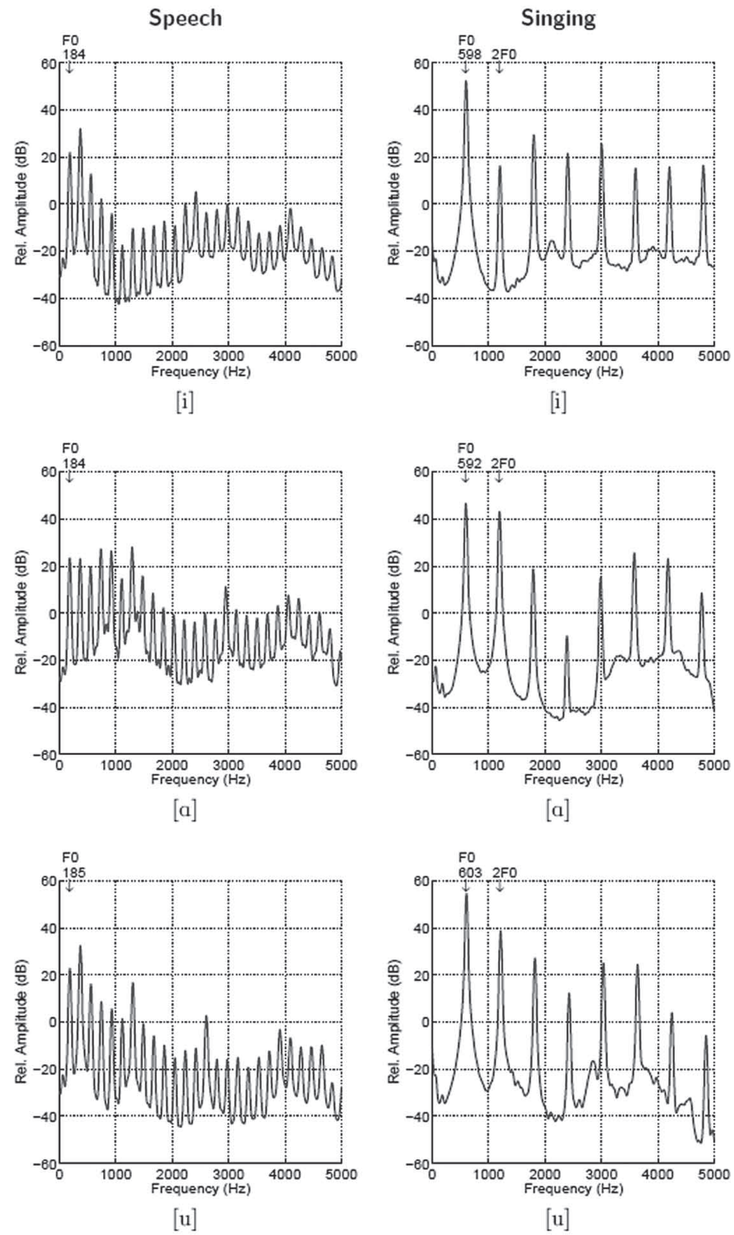

Figure 2. Frequency spectra of speaking vowels (left) and singing vowels (right) from the soprano for whom vocal tract shapes are shown in Figure 1.

vowels. There is also a slight widening in the pharynx for singing, but not uniform across vowels. The narrowest tract section is more forward for the sung /ɑ/ and more backward for the sung /u/, compared to the speaking vowels.

In the right panel of Figure 1, we show *inertograms* for the vocal tract shapes.[15] Inertograms display the amount of inertance the vocal tract offers at any frequency. This inertance is important because it helps the vocal folds sustain their vibration and thereby increases the acoustic energy at the sound source. Supraglottal inertance is shown above the horizontal zero reference line in filled horizontal bars. Subglottal compliance (which also helps vocal fold vibration) is shown below the zero reference line as smaller "tear drops" for each shape. These inertances and compliances were obtained from the shapes on the left by computing the acoustic *input impedance* of the vocal tract (a pressure/flow ratio). Inertance is expressed in units of g/cm^4.

The supraglottal formants are located where the inertance suddenly collapses to zero and the subglottal formant frequencies are where the compliance begins its downward thrust from zero. For example, for the singing /i/ vowel on top, the first formant frequency (F1) is at 640 Hz (D_5) and for the singing /ɑ/ it is at about 800 Hz (G_5). Higher formant frequencies are identified where similar sudden drops in inertance from positive to zero take place. Note that the only major "dead spot" in inertance is directly above the first formant frequency for all configurations.

Display of a musical keyboard above the inertance curves makes it possible to predict the amount of help that a set of source harmonics receives from the vocal tract for a given note. At the bottom of the graphs, tic marks for the frequencies of five octaves above A_2 (110 Hz) are shown. Vertical lines indicate harmonics of the sung note D_5. Note that the fundamental frequency (left-most vertical line) is in inertive territory for all sung vowels. The second harmonic (second line from left) is above the first formant, however, suggesting that the fundamental is predicted to carry most of the energy. This is borne out by the measured harmonic spectra of Figure 2. For the singing /i/ vowel (top right), the amplitude of the first harmonic (F0) was 36 dB higher than for the second harmonic, presumably because it resides in the peak of the inertance curve in Figure 1. In contrast, the first harmonic amplitude in the sung /ɑ/ vowel (middle row) was only 3 dB higher than the second harmonic amplitude, presumably because inertance in Figure 1 was not at its peak. For the sung /u/ vowel, the first harmonic amplitude was 15 dB greater than the second harmonic amplitude. The first harmonic was also not quite at peak inertance in Figure 1. If speech vowels were used for /u/ and /i/ at this pitch (around D_5, or about 600 Hz), the fundamental would get no reinforcement from vocal tract inertance. It would be in the "dead spot." This is significant, suggesting that larger mouth opening for singing may have the purpose of raising the first formant to keep the fundamental in inertive territory.

For singing or speaking an octave lower, everything we have said about the fundamental now applies to second harmonic. In other words, imagine the left-most vertical line in Figure 1 to be the second harmonic. (The fundamental would be around D_4 if it were shown.) Thus, with the given shapes, the female maintains the second harmonic below the first formant for all configurations except the spoken /i/ and /u/. For these two speech configurations, the second harmonic gets no inertive vocal tract reinforcement for this octave lower pitch. It is likely that most females develop a strategy in speech to avoid sudden loss of second harmonic energy for /u/ and /i/ by blending the modal register (which demands a strong second harmonic) into a mixture of modal and falsetto register across vowels.

For open-mouth vowels like /ɑ/ on a lower (speech-like) pitches, both the fundamental and the second harmonic can benefit simultaneously from inertive reactance, so that a more male-like modal register can be produced up to about 400 Hz. Much beyond that, however, the /ɑ/ vowel also requires the second harmonic to be lifted over the first formant, into the "dead" region. Belters avoid this lifting of second harmonic over the first formant by wide mouth opening and larynx raising. Physiological constraints, however, ultimately limit the pitch range for belting.

MOUTH SHAPES FROM WELL KNOWN SINGERS

Mouth shapes from the following music theater artists producing belt productions were analyzed for modeling purposes.

1. Eden Espinosa: F_5 on /ae/ from "No Good Deed," *Wicked*; YouTube recording—Audio from 1:55 to 2:05 of video; Spectrum from 7.003 of cropped audio, image from 2:02 of video.[17]
2. Idina Menzel: C#$_5$ ($D\flat_5$) on /ae/ from "Defying Gravity," *Wicked*; YouTube recording—Audio from 3:55 to 4:05 of video; Spectrum from 3.474 of cropped audio, image from 3:58 of video.[18]
3. Ethel Merman: C#$_5$ on /a/ from "I've Got Rhythm" medley as performed with Mary Martin from the 1953 television special celebrating the Ford Motor Company's 50th anniversary. YouTube recording—Audio from 0:25 to 0:35 of video; Spectrum from 4.947 of cropped audio, image from 0:30 of video.[19]

Mouth shapes were also extracted from three classical singers performing similar pitches:

1. Natalie Dessay: E_5 on /a/ from "Ah, non giunge," Bellini's *La sonnambula*; YouTube recording—audio from 4:45 to 4:55 of video; spectrum from 4.372 of cropped audio, image from 4:39 of video.[20]

TABLE 1. Estimated mouth areas at the lips of seven artists for different singing styles.

Artist	Style	Note	Freq.	Mouth/head Ratio	Mouth Area (cm^2)	Figure
Espinsosa	Belt	F_5	693	0.0856	21	5
Menzel	Belt	$C^{\#}_5$	545	0.1237	31	5
Merman	Belt	$C^{\#}_5$	547	0.0477	12	5
Dessay	Classical	E_5	660	0.0282	7	3
Fleming	Classical	D_5	589	0.0382	10	3
Sutherland	Classical	E_5	667	0.0272	7	3
Dessay	Classical	$D^{\flat}_6$	1273	0.0694	17	7
Fleming	Classical	$C^{\#}_6$	1106	0.0599	15	7
Sutherland	Classical	$C^{\#}_6$	1117	0.0389	10	7
Robin	Classical	$B^{\flat}_6$	1915	0.1074	27	9
Dessay	Classical	F_6	1419	0.0601	15	9

2. Renee Fleming: D_5 on /a/ from "The willow song," Verdi's *Otello*, YouTube recording; audio from 3:05 to 3:15 of video; spectrum from 5.238 of cropped audio, image from 3:10 of video.[21]
3. Joan Sutherland: E_5 on /o/ from "Teneste la promessa/ Addio del passato," Verdi's *La traviata*, taken from 1983 concert in Sydney, Australia; audio from 13:10 to 13:20 of video; spectrum from 6.375 of cropped audio, image from 13:16 of video.[22]

Mouth shapes were also extracted from the same three classical female singers on pitches approximately an octave higher.

1. Natalie Dessay: $D^{\#}_6$ on /ae/ from "Ah, non giunge," Bellini's *La sonnambula*; YouTube recording; Audio from 7:40 to 7:50 of video; Spectrum from 6.404 of cropped audio, image from 7:47 of video (actually close the end of 7:46, but the video time counter is crude).[23]
2. Renee Fleming: $C^{\#}_6$ on /a/ from "Tacea la notte placida," Verdi's *Il trovatore*; YouTube recording; Audio from 4:40 to 4:50 of video; Spectrum from 5.086 of cropped audio, image from 4:45 of video.[24]
3. Joan Sutherland: $C^{\#}_6$ on /a/ from "A vos jeux, mes amis," Thomas' *Hamlet*; taken from 1983 concert in Sydney, Australia; Audio from 59:15 to 59:25 of video; Spectrum from 4.414 of cropped audio, image from 59:19 of video.[25]

Finally, the mouth shapes of two classical singers producing very high pitches were analyzed.

1. Mado Robin: $B^{\flat}_6$ on /a/ from "Spargi d'amaro pianto," Donizetti's *Lucia di Lammermoor*; YouTube recording; Audio from 2:45 to 2:55 of video; Spectrum from 3.048 of cropped audio, image from 2:48 of video.[26]
2. Natalie Dessay: F_5 on /a/ from "Air des clochettes," Delibes' *Lakme*; YouTube recording; Audio from 1:25 to 1:35 of video; Spectrum from 1.773 of cropped audio, image from 1:27 of video.[27]

The choice of each video clip was based on availability of close-up video images of mouth shapes and corresponding audio that was free of background accompaniment. As in our previous publication on male singers,[28] the ratio of mouth area to projected head area in the coronal plane was measured (look ahead to Figures 3, 5, 7, and 9). Table 1 shows the measurement results. The intended sung vowel was generally an /ɑ/, but since vowel perception is based on the existence of energy in the first two formants, vowel identity at these pitches is typically ambiguous.

The projected head area (in the coronal plane) was estimated to be 250 cm^2 from standard anatomic measures on female head size.[29] The absolute mouth areas at the lips were then estimated as shown in Table 1 (second column from right). We acknowledge that these areas lack accuracy because the head areas were not individualized, but the standard deviation of head areas as reported in the above reference is small in comparison to the mouth variation across singing styles.

Note that the mouth areas for belting were categorically the largest (top three rows of Table 1), followed by classical singing at extremely high pitches (bottom two rows), followed by classical singing at around C_6 (rows 3–5 from bottom), followed by classical singing around

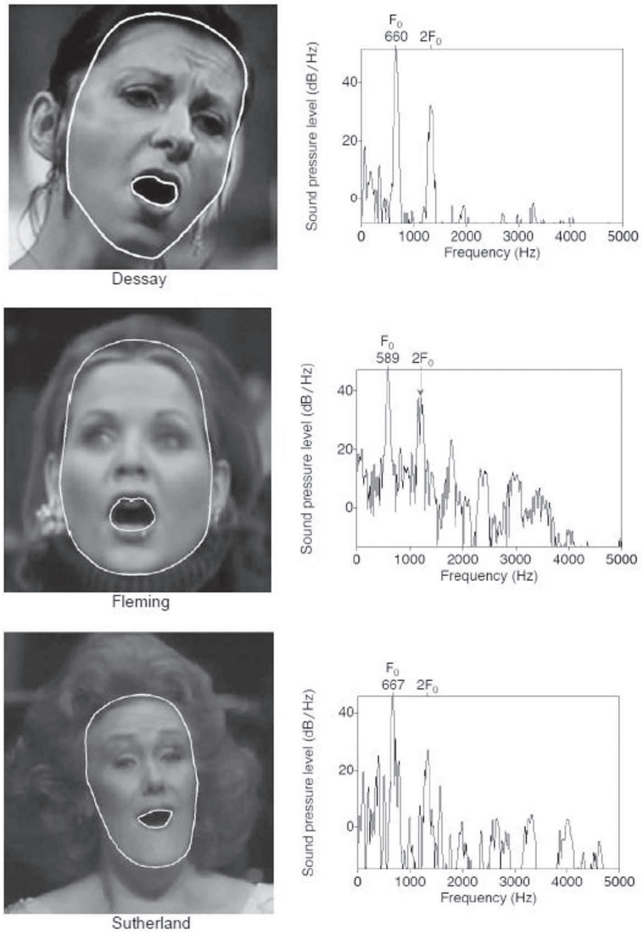

Figure 3. **Mouth shapes for sopranos Dessay, Fleming, and Sutherland (left) and corresponding frequency spectra (right). Fundamental and second harmonic frequencies arindicated on the spectra.**

C_5 (rows 4, 5, 6). The most interesting comparison is between classical singers and belters in the common pitch range C_5–E_5 (top half of Table 1). Classical singers reduce their mouth area around this pitch, in sharp contrast to the belters. But the same classical singers open up as they progress toward C_6 and above. We will now provide some insights that may explain this dichotomy.

VOCAL TRACT MODELING OF WELL KNOWN SINGERS

Based on our female singer's MRI-derived vocal tract area functions, modified shapes were developed to accommodate the mouth areas in Table 1. The new vocal tract area functions were generated by performing a Principal Component Analysis (PCA) on the sung versions of the

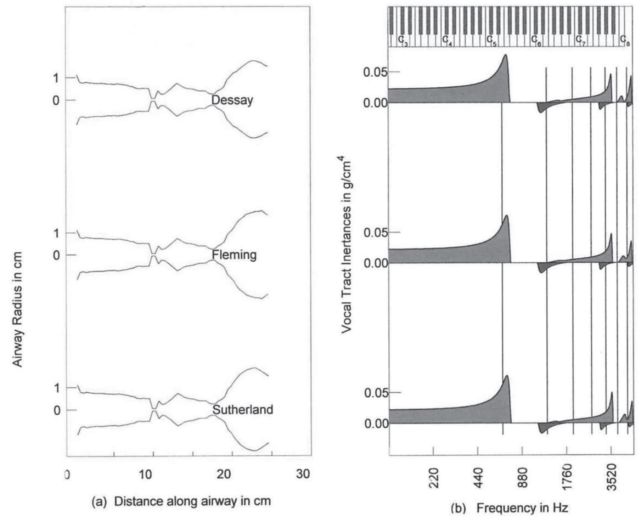

Figure 4. **(Left) Predicted vocal tract area functions for Dessay, Fleming, and Sutherland on the basis of mouth shapes from Figure 3 and the measured MRI vocal tract of another singer, (right) the corresponding inertograms.**

/ɑ/, /i/, and /u/ vowels shown previously in Figure 1. In essence, the front portion of the vocal tract (the mouth portion) was morphed such that geometric continuity and physiologic plausibility existed between the pharynx and the lips.[30] Figure 3 (left side) shows the mouth shapes of classical singers Dessay, Fleming, and Sutherland singing pitches similar to those sung by our experimental soprano. To the right in Figure 3 are measured frequency spectra. The corresponding predicted area functions and inertograms are shown in Figure 4. The fundamental frequency (left-most vertical line) was in positive inertance territory below the first formant, which accounts for the strength of this fundamental in the three measured spectra of Figure 3.

Figure 5 shows mouth shapes and spectra for three belt productions by singers Espinosa, Menzel, and Merman. Pitches were similar to those for the classical singers. In sharp contrast to the spectra of the classical singers, however, the dominant feature in the spectra of these belters is the strong second harmonic (labeled as 2F0). How is this achieved? Figure 6 shows predicted vocal tract area functions and corresponding inertograms for the modeled belt productions. By terminating the vocal tract with the large mouth openings, all three shapes developed into megaphone mouth shapes. Menzel showed the widest mouth opening, followed by Espinosa and

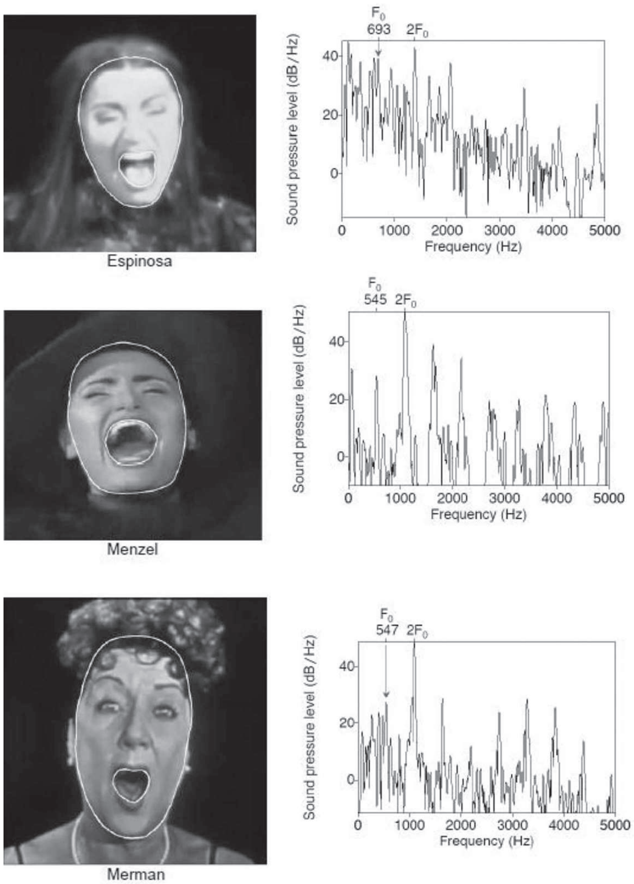

Figure 5. Mouth shapes from theatre singers Espinosa, Menzel, and Merman (left) and corresponding frequency spectra (right). Fundamental and second harmonic frequencies are indicated on the spectra.

then Merman. In estimating the vocal tract area functions, a higher larynx position was realized with a shortening of the pharyngeal portion of the supraglottal vocal tract. The inertograms of the three belters (Figure 6) show that for pitches up to around C_5, both the first and second harmonics can be reinforced by vocal tract inertance (two leftmost vertical lines), but the second harmonic is predicted to be much stronger than the fundamental because it is near the peak of the inertance bar. As noted above, the strength of the second harmonic (2F0) is evident in the measured spectra in Figure 5. Thus, the combination of a shortened vocal tract and an extremely wide mouth caused the first formant to be raised to 1200 Hz (about D_6 on the keyboard) for Espinosa and Menzel and to 1100 Hz for Merman. The inertograms predict that pitches up to about E_5 can be sustained with a strong second harmonic, which is the top note for many belters.

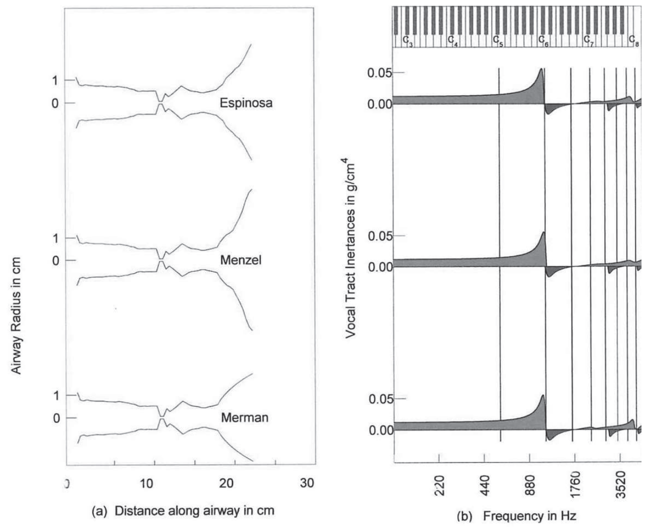

Figure 6. (Left) Predicted vocal tract area functions for Espinosa, Menzel, and Merman on the basis of mouth shapes from Figure 5 and the measured MRI vocal tract of another singer, (right) the corresponding inertograms.

As the classical singers progress upward in pitch from C_5 to C_6, they also open their mouths widely, but to maintain the first formant above the fundamental only. With the mouth shapes of Figure 7, the predicted area functions and inertograms in Figure 8 show the possibility of keeping the first formant slightly above the fundamental. The second harmonic is predicted to be weak, which is confirmed in the measured spectra of Figure 7.

Finally, some extremely high-pitched productions of classical singers Robin (B^b_6, 1915 Hz) and Dessay (F_6, 1419 Hz) involve complete "lifting" of all harmonics over the first formant. The mouth shapes are shown in Figure 9, and the predicted area functions with the inertograms are shown in Figure 10. It appears that no harmonic reinforcement is obtained from the first formant.

DISCUSSION AND CONCLUSIONS

The hypothesis that singers have cultivated singing styles (and associated techniques) to build on source-vocal tract interaction cannot be rejected with data from this study. But the hypothesis needs much more support. Unfortunately, three-dimensional MRI data on singers are still difficult to obtain, inertances of the vocal tract are not measureable in live humans, and decoupling the vocal tract from the source is possible only with models. Hence, conclusions are tentative at this point. A large

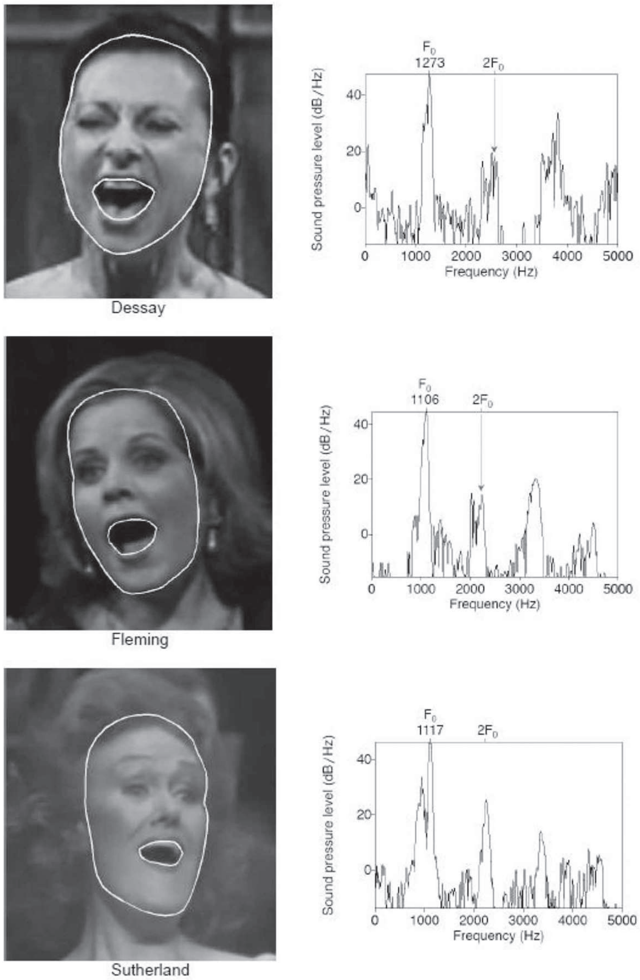

Figure 7. **Mouth shapes for sopranos Dessay, Fleming, and Sutherland (left) and corresponding frequency spectra (right). Fundamental and second harmonic frequencies are indicated on the spectra.**

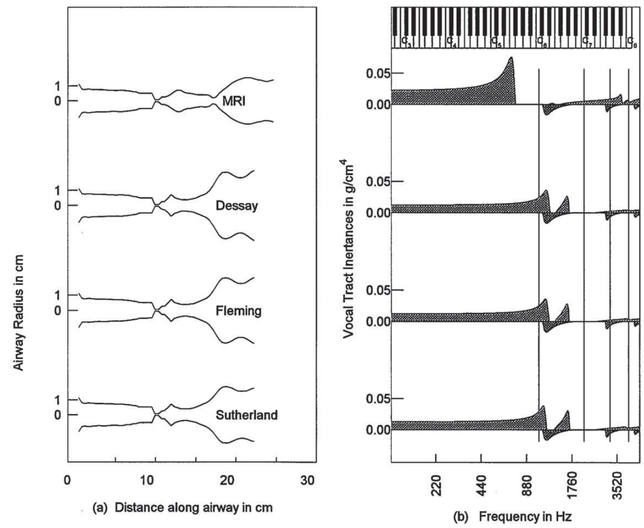

Figure 8. **(Left) Predicted vocal tract area functions for Dessay, Fleming, and Sutherland on the basis of mouth shapes from Figure 7 and measured MRI vocal tract shape of another singer shown on top, (right) the corresponding inertograms.**

part of singing training deals with selecting the best vowel for a given pitch.[31] This suggests that there may be source-vocal tract interaction. Females seem to face a minefield of pitch–vowel interaction because they sing at pitches where the most dominant harmonics overlap with formants. It is known that belters avoid low first formant vowels, modifying /i/ towards /ɛ/ and /u/ towards /ɔ/. Belting is sometimes trained by first having the singer produce a bright call, such as "hey." This is the speech version of a belt. Alternately, the singers can first produce a twang (the sound of a plucked guitar string). A twang narrows the pharyngeal part of the vocal tract which raises the overall inertance.[32] Thus, a wide open mouth with a raised larynx and a narrow pharynx maintains a high first formant, so that both the fundamental and the second harmonic can possibly be reinforced with the vocal tract.

Female belters do not compromise the second harmonic by lifting it over the first formant. We agree with Schutte and Miller that a strong second harmonic is the defining characteristic of the belt production.[33] Belters raise the first formant as high as possible with the megaphone mouth shape, and they limit their pitch range to avoid loss of second harmonic energy. Assuming that larynx raising, pharynx opening, jaw lowering, and lip spreading collectively can raise the first formant as high as 1300 Hz, our predictions have been that belting is possible to about 600 Hz (around D_5–E_5) if the second harmonic is to be kept in inertance territory.

As with male singers, the modal register is used by females in belting. Belters who attempt to sing higher than about E_5 usually are forced to make an abrupt register change, singing in a lighter register from F_5–C_6. It was shown that this region is not a problem for females who sing in operatic style because the second harmonic is not dominant in the classical female registration. The fundamental frequency can be taken as close as possible to the first formant, allowing for another octave in pitch range without having to deal with a stark register shift.

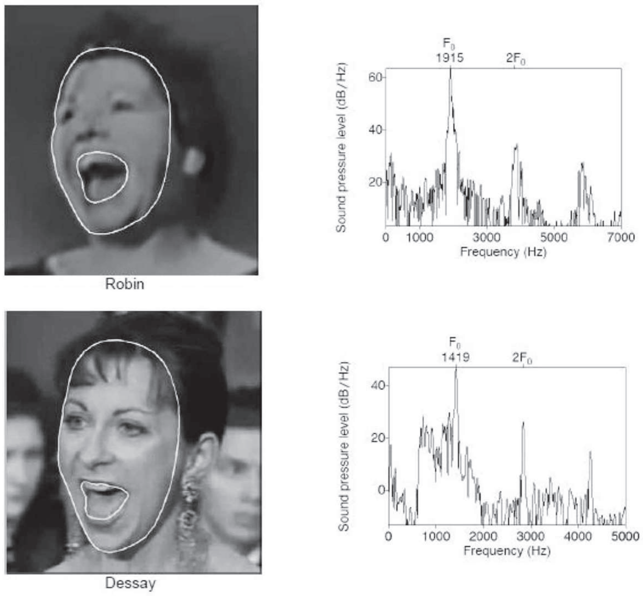

Figure 9. Mouth shapes for sopranos Robin and Dessay (left) and corresponding frequency spectra (right). Fundamental and second harmonic frequencies are indicated on the spectra.

Classically trained mezzo sopranos, altos, and (to a lesser extent) lyric sopranos, do use a male-like modal register for occasional masculine sounding low notes, but this registration is not used for high notes.

For extremely high pitches, operatic sopranos resort to the same megaphone shape that belters resort to, showing a wide open mouth.[34] The difference is that the fundamental alone (rather than the fundamental and second harmonic) is reinforced by inertance below the first formant. For this reason, the pitches can be a whole octave higher than for belting.

In future investigations, more clarity needs to be brought into the picture of how the pharyngeal and epilaryngeal portions of the vocal tract change across the two contrasting productions. Here we have explored vocal tract adjustments in the oral cavity only, but we suspect that enhancement of various harmonics are also facilitated by optimal adjustments in the epilarynx tube and the pharyngeal cavity.

ACKNOWLEDGEMENT

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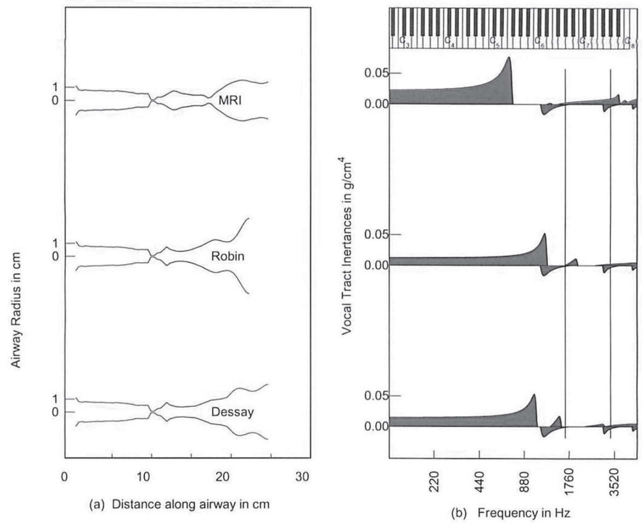

Figure 10. (Left) Predicted vocal tract area functions for Robin and Dessay on the basis of mouth shapes from Figure 9 and measured MRI vocal tract shape of another singer shown on top, (right) the corresponding inertograms.

NOTES

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