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Comparisons of Pharynx, Source, Formant, and Pressure Characteristics in Operatic and Musical Theatre Singing

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Summary: Belting, a vocal technique typically cultivated in musical theatre singing, differs timbrally from operatic singing in many interesting respects. The underlying phonatory differences have not been previously investigated in detail. Yet, belting is frequently associated with disturbances of voice function. Articulatory and phonatory characteristics are investigated in a female subject who is a professional singer (co-author JL) trained in both the operatic and belting styles and in an intermediate vocal technique ("mixed"). This article presents data obtained from this subject by video-fiberoptic observation of the pharynx, inverse filtering of airflow, and measurement of subglottal pressure. The results reveal that belting was characterized by very high subglottal pressures and sound levels, and apparently also by a comparatively high degree of glottal adduction. Comparisons with other investigations of related aspects of belting and operatic singing support the assumption that the data obtained from our subject are representative for these vocal techniques. **Key Words:** Belting—Inverse filtering—Subglottal pressure—Formant frequencies—SPL—Operatic singing—Pharynx shape.

Most voice research in the past has focused on operatic singing, while the equally phonatorily interesting type of singing cultivated in the performance of popular songs and musicals has been largely neglected by voice scientists. As a consequence, the vocal techniques used in nonoperatic singing are poorly understood.

One type of singing that is commonly used in musical theatre is called belting. It has been described by Lawrence (1), who reviewed laryngological observations from 27 "belters." He found laryngeal and pathological similarities between belting and hyperfunctional speech. Estill et al. (2) studied belting, as well as five other modes of singing, with regard to spectrum, electromyography (EMG), and electroglottography. They showed that belting had very strong overtones and was produced with a relatively long closed phase and a high EMG activity in the geniohyoid muscle. Yanagisawa et al. (3) used fiberoptics to examine the aryepiglottic sphincter in a number of different singing styles. They found that the aryepiglottic area was constricted in both the operatic and the belting styles. A review of the research on belting was recently published by Miles and Hollien (4).

According to the general opinion among voice teachers and laryngologists, belting may be detrimental to the voice. Therefore, singing teachers have strived to find alternative types of voice production that are healthy and yet meet the demands raised in musical theatre singing. The purpose of the present investigation was to compare such an alternative singing style with both belting and the operatic style of singing. The alternative vocal technique was developed by co-author JL, who calls it mixed. According to her long-term pedagogical experience, it is appropriate for musical theatre singing and yet not harmful to the voice. It sounds somewhat sim-

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ilar to belting, but less hyperfunctional. (It should be observed that the term mixed does not mean to suggest any relationship with the so-called voix mixte, as described by, e.g., Vennard (5) and Reid (6).)

Our subject was co-author JL, who is active as a voice teacher of a nonoperatic singing style, but professionally trained in all three styles of singing. She can easily switch between these different styles, although she finds it difficult to change style after having sung in the belting style for a while. This ability actually served as a unique and fundamental condition for the entire experiment; our aim was to describe and explain the timbral and physiological characteristics of mixed, belting, and operatic styles as produced by one and the same subject. The basic strategy was to compare tones produced at identical pitches in each of these three singing styles.

The acoustic and phonatory characteristics of the three singing styles can be assumed to derive from both voice source and formant frequency characteristics. These are controlled by subglottal pressure, laryngeal adjustment, and vocal-tract shaping. Our investigation included, directly or indirectly, all these parameters. We carried out two different experiments, which we present separately in this article. Experiment I concerned the phonatory and acoustical aspects, while Experiment II tried to describe the pharyngeal shape by video-recording a fiberoptical inspection.

EXPERIMENT I

Method

Vowel sounds produced in the three singing styles were analyzed using inverse filtering and regular spectrogram analysis. In addition, we also determined subglottal pressure and sound level.

The subject sang comparable tones in the pitch range common to the three singing styles—the pitches G4, Ab4, and A4. She sang the vowel [æ:] at an intermediate degree of loudness—first in operatic style of singing, then in mixed, and finally in belting style. In addition, she sang excerpts of two songs—Gershwin's "Summertime" from "Porgy and Bess" and Giordani's "Caro mio ben"—in the same key in the three singing styles. Each sample was first produced in the operatic and then in the mixed styles. Thereafter, all samples sung in belting style were run in one sequence. In this way, a number of phonations comparable with regard to vowel and pitch were assembled.

Two recordings were made. Recording 1 was made in a sound-treated booth that was approximately 4 × 2 × 3 m, while recording 2 was made in an ordinary room using a pressure gradient microphone mounted in a flow mask ad modum Rothenberg (7). The microphone recorded the pressure drop across an acoustic resistance, represented by a screen with fine mesh covering a number of holes in the mask. In this way, the oral sounds could be captured in terms of the air-flow signal.

Subglottal pressure was recorded as the oral pressure during the occlusion for the consonant /p/. The pressure was captured by using a small plastic tube with an inner diameter of ~2 mm. This tube was mounted in the flow mask in such a way that the subject had it in the corner of her mouth. In recording 1, sound pressure level (SPL) was calibrated by recording a set of reference vowels produced by one of the experimenters at constant SPL values, as measured by means of a B&K sound level meter (model 2215), which was held just near the tape recorder microphone. During recording 2, the DC output signal from the sound level meter was used for measuring the SPL.

The recording was made on a TEAC (Tokyo, Japan) multitrack FM tape recorder. The following signals were stored: (1) flow mask output, (2) SPL as picked up by the sound level meter, and (3) subglottal pressure.

The voice-source analysis was realized using a Glottal Enterprises' inverse filter containing two filters, one for the first and one for the second formant. Using a transient recorder (BT-1; Glottal Enterprises, Syracuse, NY, U.S.A.), a selected portion of the signal was repeated and fed to the inverse filter. The output from the filter could be observed on an oscilloscope.

Inverse filtering results in so-called flow glottograms showing transglottal airflow versus time. In the analysis, the inverse filter settings were adjusted until an oscillation-free quasi-closed phase was obtained. However, as expected, it turned out to be extremely difficult to find a unique setting of the inverse filters that gave a nonoscillating quasi-closed phase. Rather, several different settings seemed possible, and it was difficult to decide which one was correct.

In such cases, independent estimates of the formant frequencies were needed. These were obtained from glide tones, approximately one fifth wide, performed by the subject. These glide tones were analyzed by means of a Kay Elemetrics spectrograph (Pine Brook, NJ, U.S.A.). As the amplitude of a spectrum partial increases when it transverses a formant, estimates could be made of the two lowest formant frequencies from the spectrograms. Using these more precise estimates of the two lowest formant frequencies, an inverse filter setting was again tried. It turned out that, with minor adjustments, these formant-frequency values resulted in convincing glottograms. This indicated that the subject reproduced the formant frequencies rather accurately in repeated renderings.

Results

Figure 1 shows two sets of spectra of the same vowels sung at identical pitches. These vowel sounds were taken from the songs as sung in each of the three styles. Several observations can be made. First, there are differences in the relative amplitudes of the two lowest spectrum partials. In operatic singing, the fundamental tends to be strong, while in belting it is weak. Indeed, in belting the fundamental disappeared almost entirely in the spectrogram of the first vowel in "Summertime." This may reflect both voice-source and formant-frequency differences.

The amplitudes of the partials in the upper part of the spectrum, i.e., in the region of the singer's formant, were higher in operatic and mixed singing styles than in belting. In addition, the strongest partial in this region appeared at a lower frequency in the operatic than in the mixed styles.

Figure 2 shows SPL at 0.5 m for two performances of the first phrases of one of the songs in operatic and mixed singing. It can be seen that the SPL varied only by small amounts between the renderings. Thus, the SPL seemed reasonably reproducible.

Figure 3 compares SPL in one of the performances of the same phrases in the three singing styles. The figure shows that SPL was quite similar in operatic and mixed styles, while it was at least 10 dB louder in belting.

Figure 4 shows the relationship between subglottal pressure and SPL at 0.5 m in the sustained phonations on the pitches G4, Ab4, and A4. It can be seen that operatic and mixed styles were produced with lower subglottal pressures than belting, and that the SPL values were accordingly lower. In fact, for these tones the SPL seemed to be a linear function of the log of the subglottal pressure. In other words, it seems fair to assume that the SPL in belting is louder because the subglottal pressure is higher.

Figure 5 shows flow glottograms for sustained tones sung at the same three pitches in the three styles. The results are quite consistent within and neatly separated between the styles. For all pitches, operatic style gave the highest peak amplitudes, and mixed style gave the smallest. The very high peak amplitude implies that the source-spectrum fundamental is strongest in operatic singing. Furthermore, the closed phase is clearly longest in belting.

A high glottogram peak amplitude can result both from a high subglottal pressure combined with a comparatively high degree of glottal adduction, and from a lower subglottal pressure combined with a lesser degree of glottal adduction. Therefore, it is interesting to examine the relationship between the peak amplitude of the flow glottogram and the subglottal pressure. This comparison can be made in Fig. 6. It can be seen that operatic and mixed styles both were generated with moderate subglottal pressure, but operatic style results in considerably higher peak amplitudes of the glottogram. This suggests that glottal adduction is lower in operatic than in mixed style. Belting was produced with high subglottal pressure, but this does not lead to particularly high peak amplitudes. This suggests that glottal adduction was comparatively high in belting, and it seems relevant to examine the ratio between these amplitudes and pressures. As glottal adduction obviously has a great influence over phonation, it is not surprising that an acoustic analysis of phonation can reveal the degree of glottal adduction. Sundberg et al. (8) recently demonstrated that the ratio between the peak amplitude of the flow glottogram and the subglottal pressure seems to vary consistently with the mode of phonation. Sundberg and Rothenberg (9) called this ratio peak glottal permittance.

Peak glottal permittance is shown in terms of a correlogram in Fig. 7. It can be seen that this permittance was much higher in operatic than in belting and mixed singing. This suggests that glottal adduction was weaker in operatic style than in mixed style and belting.

Figure 8 shows the formant-frequency values obtained from inverse filtering. It can be observed that the three singing styles were also well separated with respect to formant frequencies. In the sustained vowel shown, the first and second formants were lowest in operatic style. In mixed style and belting, both the first and second formants were much higher, and the second was highest in mixed.

EXPERIMENT II

The aim of this experiment was to examine the typical pharyngeal shapes characterizing operatic,

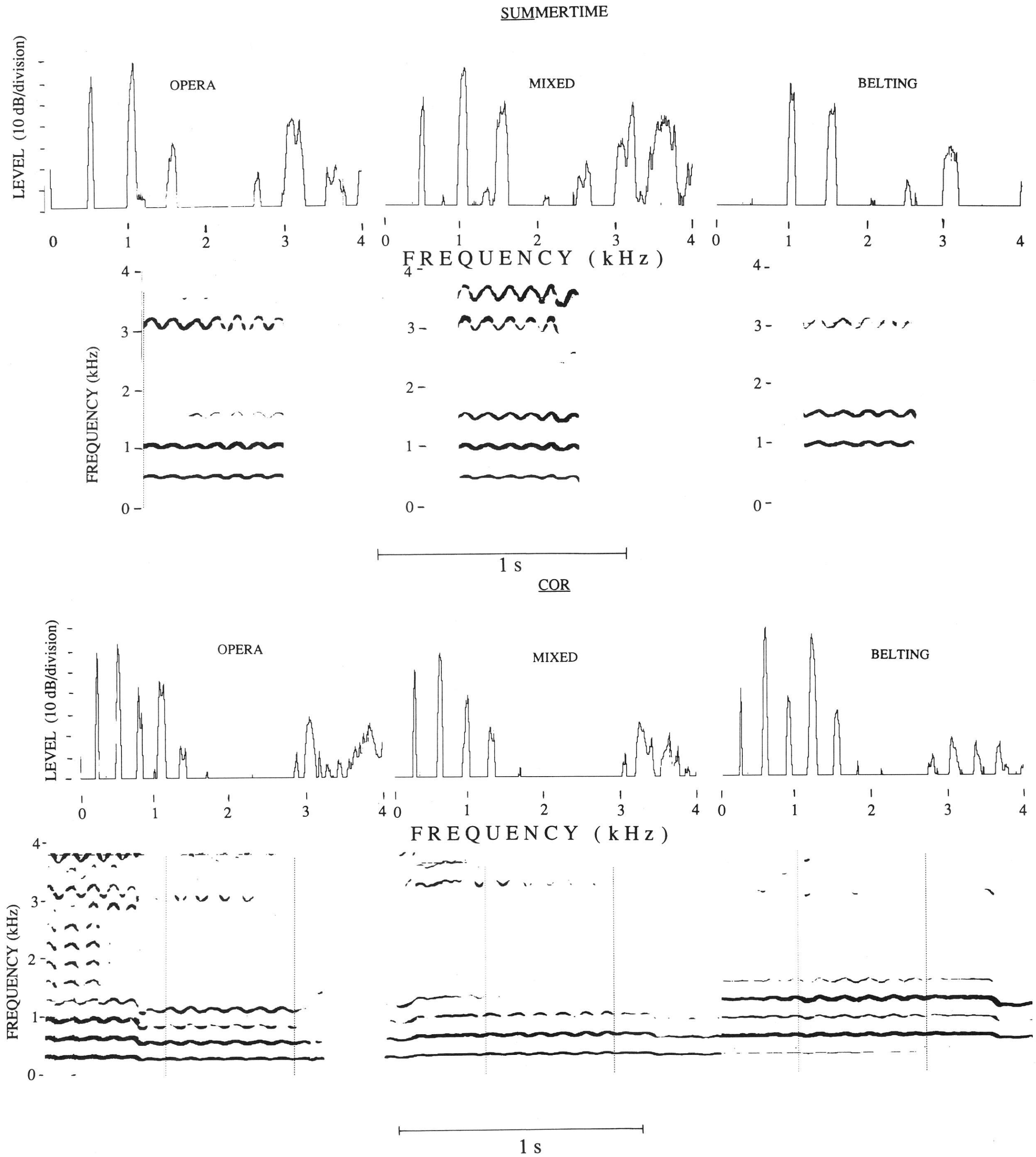

FIG. 1. Spectrograms and spectrum sections from a Kay Elemetrics Sona Graph of indicated vowels sung at identical pitches in operatic, mixed, and belting style.

mixed, and belting singing styles using fiberoptics. This allowed us to find out if the acoustic characteristics found for the different singing styles in Experiment I were consistent with the pharyngeal characteristics. Many previous investigations of belting have also used fiberoptics. This allowed us also to compare our single subject's belting behavior with behaviors described in other investigations of belting.

Method

An Olympus fiberscope (Tokyo, Japan) was introduced paranasally into our subject, who preferred to refrain from using topical anaesthesia. The

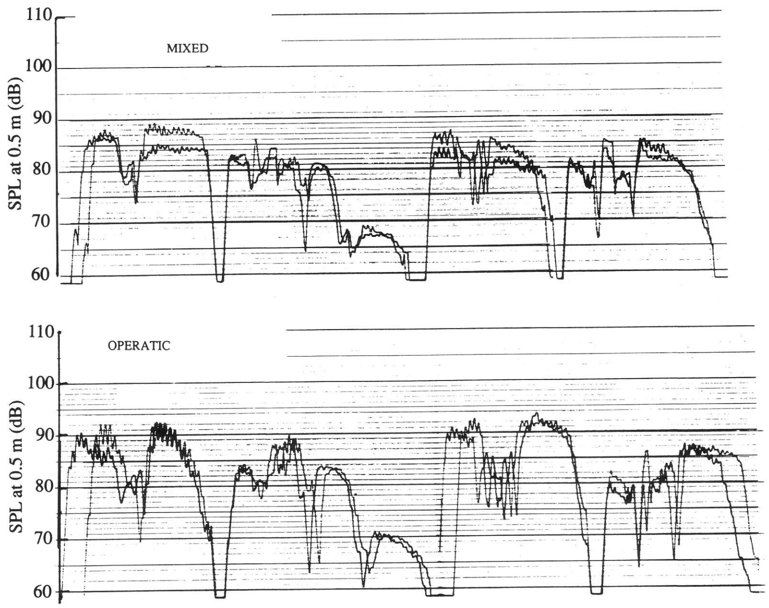

FIG. 2. Sound pressure level (SPL) at 0.5 m for two performances of the first phrases of one of the songs in operatic and mixed styles.

image was recorded on a video-cassette recorder. The monitor was placed so that both the investigator and the subject could watch the image. Pitch references were provided by means of a simple Yamaha synthesizer.

Wherever possible, the subject sang the entire program in operatic, mixed, and belting styles. The program consisted of sustained vowels in the pitch range A3 to E5 and the first line of the same songs sung in the same key, as in Experiment I. In addition, the subject also demonstrated a very special kind of phonation that she called "chipmunk," which appeared phonatorily interesting, as it seemed to represent a phonatory extreme.

Data processing

The pharyngeal landscapes seemed to differ in several respects between the operatic, mixed, and belting styles. Within each of the three styles, however, there was a considerable variability depending on the vowel and the pitch. Therefore, in comparing the three singing styles, it is necessary to select the same vowel and pitch. A 3.5-min edited copy was made of the video recording to facilitate comparison. In the tape, the same vowel sung at the same pitch in all three singing styles was copied in sequence on the tape. At the highest pitches, no samples from belting were available, since the subject preferred not to produce these pitches in that singing style.

As fiberoptic observations are difficult to quantify, the edited copy was presented to a panel of six expert observers, five phoniatricians, and one laryngologist. They were given a copy of the cassette that they could watch and listen to repeatedly. Their task was to describe, on the basis of what

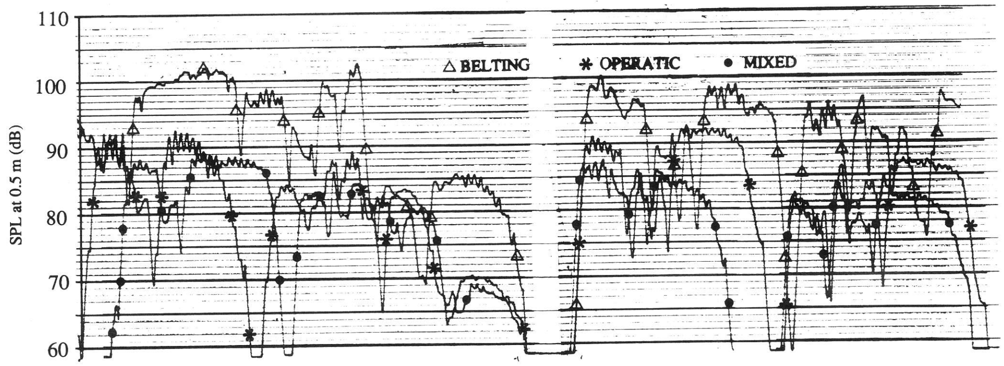

FIG. 3. Sound pressure level in one of the performances of the same phrases in operatic, mixed, and belting styles.

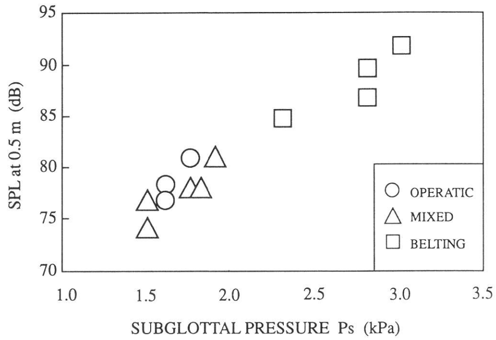

FIG. 4. Sound pressure level at 0.5 m as function of subglottal pressure in sustained phonations of the vowel [æ:] sung on the indicated pitches in operatic, mixed, and belting styles.

they saw, what they believed was typical for the four singing styles. No restrictions were imposed regarding terminology.

Results

The answers from our panel have been combined in Table 1. In their descriptions, the panel referred to 11 different structures or features. In Table 1, synonymous terms have been changed so as to increase uniformity. There were no instances of conflicting observations among the panel members. Some variables were mentioned by most members, while other variables were mentioned only by one or two members. These were the pharyngeal side walls, the sinus piriformes, the larynx height, and the vocal folds. Our panel found that in belting, the side walls of our subject were clearly advanced, thus constricting the pharynx; the constriction was less in mixed and nil in operatic style. The sinus piriformes seemed wide in operatic style, medium in mixed, and narrow in belting.

The interpretation of the fiberscope view with respect to larynx height was facilitated by one transition from mixed to operatic style, and during phonation, when the subject firmly pinched the fiberscope tube with her velum so that the vertical position of the fiberscope tip remained constant. This facilitated the interpretation of the video recording. The larynx was low in operatic style, high in belting, and in an intermediate position in mixed style. The visibility of the vocal folds was best in operatic and mixed styles, and less in belting. These differences were probably caused by changes in the larynx tube and also in the position of the ventricular folds.

GENERAL DISCUSSION

By and large, the typical pharyngeal characteristics for the different singing styles were consistent with the acoustic characteristics found in Experi-

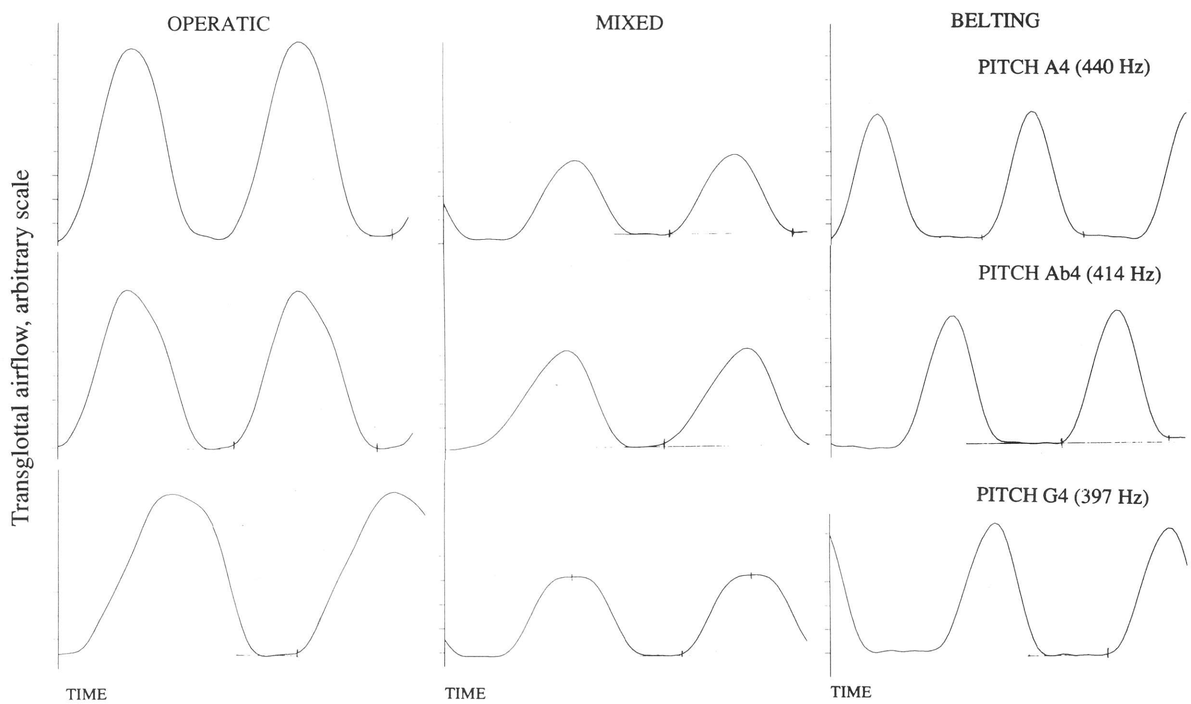

FIG. 5. Flow glottograms for sustained tones sung on the vowel [æ:] sung at the indicated pitches in operatic, mixed, and belting styles.

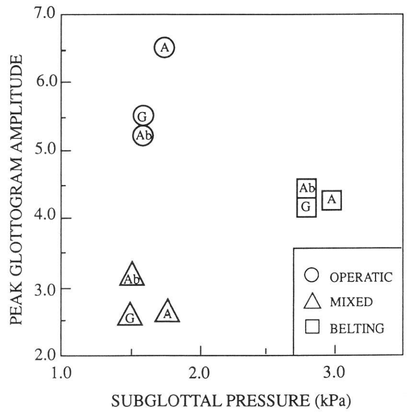

FIG. 6. Flow glottogram peak amplitude versus subglottal pressure for the vowel [æ:] sung at the indicated pitches in operatic, mixed, and belting styles.

ment I. The main acoustic differences were that in belting, subglottal pressure and SPL were high, while glottal permittance was low. These characteristics seem to suggest a hyperfunctional type of voice use. In addition, formant frequency differences were found. Now we can ask if the pharyngeal characteristics observed in lateral pharyngeal walls, sinus piriformes, and larynx height agree with these acoustic differences.

Unfortunately, the relationships between pharynx shape and acoustic voice characteristics are not understood in detail; we do not know explicitly which pharyngeal landscapes are associated with specific types of phonation. However, it is generally assumed that a constricted pharynx is typically

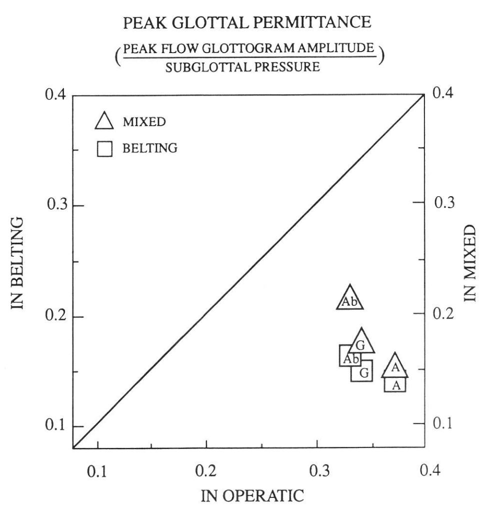

FIG. 7. Correlogram of peak glottal permittance values observed in mixed and belting styles for the same vowel [æ:] sung at the indicated pitches; the values are plotted as function of the corresponding values in operatic style.

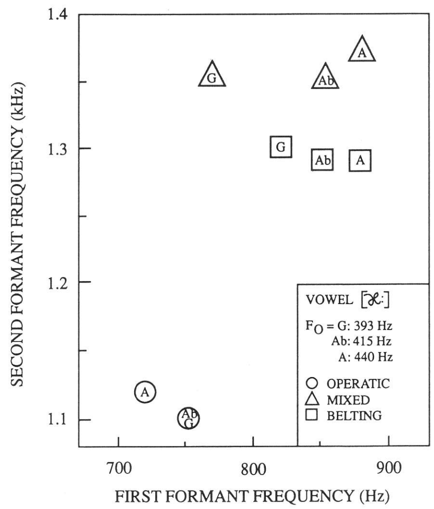

FIG. 8. Formant frequency values obtained from inverse filtering of the vowel [æ:] sung at the indicated pitches in operatic, mixed, and belting styles.

associated with phonatory strain, which would correspond to a high larynx position, a high degree of glottal adduction, and a relatively high subglottal pressure. In this qualitative sense, the observations made from our fiberscope investigation agree with those of the acoustic analysis.

The first formant frequencies in particular, but also the second, were found to be higher in belting and mixed than in operatic styles. A raised larynx has been shown to increase the frequencies of these formants considerably in the vowel [æ:] (10,11). Thus, the acoustic observations seem to be consistent with the observations of pharynx shape. In this investigation only one single subject was used. Therefore, it is particularly interesting to find out to what extent her voice behavior was similar to that of other singer subjects that have been analyzed in previous investigations.

Using fiberlaryngoscopy and acoustic analysis, Yanagisawa et al. (3) studied aryepiglottic constriction in the vowel /i:/, as sung by five subjects in a number of different singing styles, including belting and operatic. The investigators found similarities in this respect between these two styles. However, none of our observers mentioned this parameter. It is possible that this difference is typical only for the vowel /i/; a number of different vowels were included in Experiment II, so a difference that appeared only in the vowel /i/ may have escaped the panel.

Other observations collected from the panel in Experiment II were in agreement with those re-

TABLE 1. *Summary of the characteristics of the four singing styles shown on the video recording*[a]

Parameter	Observer	Opera	Mixed	Belting	Chipmunk
Sidewall (16)	1	Passive	Some active	Active	
	2	Nil		Pressed	Narrow
	3	Vibrato	Vibrato	Less vibrato	
	4	Separated	Constricted	Very constricted	Extra narrow
	5		At low pitch:wide	Very constricted	Constricted
	6	Separated	Slightly constricted	Constricted	Narrow
Summary:		*Separated*	*Medium*	*Constricted*	
Sinus piriformes (14)	1	Wide	Less visible	Narrow	
	2	Nil		Smaller	Narrow
	4	Wide			Narrow
	5	Wide, pitch dependent	Rather wide	Deep	Very narrow
			Pitch dependent	Constricted	
	6	Wide	Wide	Wide?	
Summary:		*Wide*	*Medium*	*Narrow*	
Larynx height (11)	1	Low	Higher	High	
	2	Low	Lower?	High	
	5		Varied	Raised	
	6	Low	Medium	Elevated	High
Summary:		*Low*	*Medium*	*High*	
Vocal fold (9)	1	Visible	Visible	Slightly visible, vowel dependent	
	2				Stretched
	3				Stretched
	4	Visible	Visible	Less visible	
	5				Stretched, thin
	6	Visible			
Summary:		*Visible*	*Visible*	*Less visible*	
Ventricular fold (8)	2	Open	Compressed	Compressed	Narrow
	5		Slightly adducted	Very adducted	
	6	Passive	Slightly active	Adducted	Compressed
Summary:		*Separated*	*Medium*	*Adducted*	
Arytenoid (7)	1				Adducted
	3				Top tight
	4	Top split	Top split	Top split	Top tight
				Slightly tilted	Tilted
	5			Top split	
	6	Adducted		Compressed	Compressed
Summary:		*Top split*	*Top split*	*Top split*	
				Tilted	
Larynx tube (6)	1	Passive	Not fully open	Slightly narrow	
	4	Wide		Constricted	Narrow
	5	Stable	Slightly narrow		Very constricted
Summary:		*Wide*	*Medium*	*Constricted*	
Epiglottis (5)	2	Straight		Tilted	
	3	Vibrato	Vibrato	Close to arytenoids	
Glottis (5)	2	Wide		Narrow	
	3	Incomplete closure	Posterior chink	No chink	
Esophagus entrance (3)	2	Nil	Compressed	Compressed	Narrow
Aditus (3)	3		Wider than operatic	Narrow	Very narrow
	5				Very constricted
	6		Slightly constricted		

[a] Data are descriptions of six expert observers. The numbers within parentheses indicate the total number of times that the parameter was mentioned in the judges' characterizations of opera, mixed, and belting.

ported in previous investigations. The most frequent observations mentioned by our panel concerned side walls, sinus piriformes, and larynx height. Precisely these structures have been mentioned in all previous investigations of belting (1,3, 12). In addition, Estill (12) found that the EMG signal from the middle constrictor was greater in belting than in operatic style; this would lead to advanced side walls in belting, which were observed in the present investigation. Using electroglottography, Estill found belting to be typically associated with a long closed phase, while operatic singing had a short closed phase (12). Our inverse-filtering analysis showed a clear difference of this kind between our subject's operatic and belting styles.

Belting and operatic singing on the vowel /i/ have been analyzed acoustically and physiologically by Estill et al. (2) and Yanagisawa et al. (3). Their subject was able to demonstrate belting and operatic singing within a wider range than our subject. Still, the acoustic characteristics were similar to those found in the present investigation. They found that the mean spectrum envelope of operatic singing was dominated by the fundamental, while that of belting had a weak fundamental and relatively strong overtones; the spectrum level difference between operatic and belting styles was no less than 35 dB at 3 kHz for the fundamental of this vowel. Although we found a somewhat smaller difference for the vowel /a/, qualitatively similar spectrum differences were found. This suggests that our subject's phonatory behavior in belting was similar to that studied by Estill et al. (2) and Yanagisawa et al. (3).

Estill et al. (2) also studied the glottal voice source by using electroglottography. This offers another opportunity to compare our results with those of a different subject. The waveforms indicated that the closed phase was longer in their subject's belting compared with operatic singing. This agrees with our flow glottogram findings. The agreement supports the aforementioned conclusion that our subject's behaviors in operatic and belting style were similar to those studied by Estill et al. (2) and Yanagisawa et al. (3).

These instances of agreement suggest that our subject offered typical examples of belting. Thus, although our investigation concerned only one subject, it apparently yielded representative results. In addition, the acoustic analyses and the fiberoptic examination of the larynx produced results that appear to be compatible.

We determined the peak glottal permittance, i.e., the ratio between the peak glottal airflow and the underlying mean subglottal pressure. The result showed that the permittance was clearly highest in operatic and lower and approximately the same in belting and mixed styles. Peak glottal permittance must depend on glottal adduction. However, the similarity in the permittance does not necessarily imply that glottal adduction was the same in this case. The great difference in subglottal pressure may have entailed differences in vocal fold length, which may reduce the comparability of this measure. More theoretical work is needed before such a conclusion can be drawn.

The formant frequencies of the sustained vowels sung at identical pitches in the three singing styles were very similar within style. On the other hand, no corresponding consistency in the formant values could be observed in the songs. This suggests that in singing sustained, isolated vowels, our subject used a stable and neutral set of formant frequencies, whereas in performing songs, she used formant frequencies for musical expression, i.e., vowel coloring. The variability of formant frequencies in sung performances is an interesting question for future investigation.

It is interesting that during the inverse-filtering experiment all data were clearly stratified; Figs. 4–8 indicated that the three singing styles were consistently differentiated with regard to several phonatory parameters: subglottal pressure, SPL, peak glottal permittance, and formant frequencies. This means that our subject used her voice both consistently and differently in the three singing styles. As a result, we obtained a rather complete description of how she used her voice in the three singing styles.

CONCLUSIONS

Belting and operatic styles differed with respect to subglottal pressure, glottal adjustment, and articulation. Operatic singing seemed characterized by moderate subglottal pressures and glottal adductive forces, and the formant frequencies suggested a moderate degree of jaw opening and a lowered larynx. Belting was produced with high subglottal pressures and greater glottal adductive forces, and the formant frequencies suggest a wide jaw opening and an elevated larynx. Mixed singing seemed characterized by moderate subglottal pressures, moderate glottal adductive forces, and by formant frequencies, suggesting a wide jaw opening and a raised larynx. Although the pharyngeal landscape varied considerably with vowel and pitch, belting as compared to operatic style seemed characterized by a high larynx position. In addition, the side walls were advanced and the sinus piriformes were small in many vowels in belting. The subglottal pressure differences seemed to result in considerably higher SPL in belting than in mixed and operatic singing. The amplitude of the voice-source fundamental was higher in operatic than in belting and mixed styles, probably because of the greater adductive forces in belting. As our subject seemed to produce typical examples of belting and operatic singing, we concluded that this was a representative description of belting.

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