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COMPARISONS OF PHARYNX, SOURCE, FORMANT AND PRESSURE CHARACTERISTICS IN OPERATIC AND MUSICAL THEATRE SINGING

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Abstract

Musical theatre singing, as typically cultivated in "Broadway musicals", differs timbrally from operatic singing in many interesting respects. It is quite widespread, and is reportedly often associated with disturbances of voice function. The present investigation compares phonatory and articulatory characteristics of operatic and musical theatre singing as produced by a professional singer experienced in both these styles of singing. The properties of the glottal voice source are analyzed by means of inverse filtering, and the associated subglottal pressures are measured in terms of oral pressure during p-occlusion. Typical differences are found that seem to reflect differences in vocal fold adduction. Vocal tract shape is studied by means of fiberoptics revealing typical differences, e.g., in larynx height and pharyngeal side walls. By comparing the findings with those obtained in previous investigations, it is concluded that the subject offered typical examples of the different styles of singing.

INTRODUCTION

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

One type of singing which is commonly used in musical theatre singing is called *belting*. It has been described by Lawrence (1979) who reviewed laryngological observations from 27 "belters". He found laryngeal and pathological similarities between belting and hyperfunctional speech. Estill, Baer, Honda, & Harris (1985) studied belting as well as five other modes of singing with regard to spectrum, 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, Estill, Kmucha, & Leder (1989) 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 & Hollien (1990).

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 operatic style of singing. Such an alternative vocal technique was developed by co-author JL, who calls it *mixed*. (It should be observed that the term mixed does not mean to suggest any relationship with the so-called *voix mixte*.) According to her long-term pedagogical experience, it is appropriate for musical theatre singing and yet not harmful to the voice. It sounds somewhat similar to belting but less hyperfunctional.

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. Her ability to shift between these vocal techniques actually served as a unique and funda-

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mental condition for the entire experiment; our aim was to describe and explain the timbral and physiological characteristics of mixed, belting, and operatic 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 aimed at describing 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 (440 Hz). She sang the vowel [æ:] at an intermediate degree of loudness, first in operatic style of singing, then in mixed, and finally in belting. Also, 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. Samples in operatic and mixed were interleaved while those in belting 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, 4x2x3 m approximately, while recording 2 was made in an ordinary room using a pressure gradient microphone mounted in a flow mask ad modum Rothenberg (1973). The microphone records the pressure drop across an acoustic resistance represented by a screen with fine meshes 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 means of a small plastic tube, ID, approximately 2 mm. This tube was mounted in the flow mask such that the subject had it in her mouth corner.

In recording 1, 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 multitrack FM tape recorder. The following signals were stored: (1) the flow mask output, (2) the SPL as picked up by the sound level meter, and (3) the 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. By means of a transient recorder (Glottal Enterprises, BT-1), 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 which gave a non-oscillating 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 a fifth wide, performed by the subject. These glide tones were analyzed by means of a Key Elemetrics spectrograph. 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 indicates that the subject reproduced the formant frequencies rather accurately in repeated renderings.

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

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, 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 than in belting. Also the strongest partial in this region appeared at a lower frequency in operatic than in mixed.

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

Fig. 2. SPL at 0.5 m for two performances of the first phrases of one of the songs in operatic and mixed.

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 while in belting, it was mostly at least 10 dB louder.

Figure 4 shows the relation between subglottal pressure and SPL at 0.5 m in the sustained phonations on the pitches of G4, Ab4, and A4. It can be seen that operatic and mixed 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.

Fig. 3. SPL in one of the performances of the same phrases in operatic, mixed, and belting.

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 the smallest. The very high peak amplitude implies that the source-spectrum fundamental is strongest in operatic. Further, the closed phase is clearly longest in belting.

Fig. 4. SPL 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.

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 relation 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 both were generated with moderate subglottal pressures, but operatic results in considerably higher peak amplitudes of the glottogram. This sug-

gests that glottal adduction is lower in operatic than in mixed. 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, Scherer, & Titze (1991) have recently demonstrated that the ratio between the peak amplitude of the flow glottogram and the subglottal pressure seems to vary consistently with mode of phonation. Sundberg & Rothenberg (1986) 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. This suggests that glottal adduction was weaker in operatic than in mixed and belting.

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

EXPERIMENT II

Introduction

The aim of this experiment was to examine by means of a fiberoptic investigation the typical pharyngeal shapes characterizing operatic, mixed, and belting. 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.

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

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

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

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

Method

An OLYMPUS fiberscope was introduced paranasally into our subject who preferred to refrain from using topical anaesthesia. The 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. It consisted of sustained vowels in the pitch range A3 to E5 and also the first line of the same songs as in Experiment I sung in the same key. In addition, the subject also demonstrated a very special kind of phonation, that she called "Chipmonk", 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 also on 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 sang at the same pitches in all three styles of singing were copied in sequence on the tape. At the highest pitches no samples from belting was available, since the subject preferred not to produce these pitches in that style of singing.

As fiberoptic observations are difficult to quantify, the edited copy was presented to a panel of six expert observers, five phoniaticians 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 they saw, what they felt was typical for the four singing styles. No restrictions were imposed regarding terminology.

Results

The answers from our panel have been combined in Table I. In their descriptions, the panel referred to 11 different structures or features. In the Table, 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, less so in mixed and nil in operatic. The sinus piriformes seemed wide in operatic, 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 opera, and during phonation, 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 and high in belting, with an intermediate position in mixed. The visibility of the vocal folds was best in operatic and mixed 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 Experiment 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 sidewalls, sinus piriformes, and larynx height agree with these acoustic differences.

PARAMETER	s	OPERA	MIXED	BELTING	CHIPMONK
Sidewall	1	PASSIVE	SOME ACTIVE	ACTIVE	
(16)	2	NIL	-	PRESSED	NARROW
	3	VIBRATO	VIBRATO	LESS VIBR	
	4	SEPARATED	CONSTR.	VERY CONSTR.	EXTR. NARROW
	5		L F0:WIDE	VERY CONSTR.	CONSTR.
	6	SEPARATED	SL CONSTR	CONSTRUCT	NARROW
SUMMARY:		SEPARATED	MEDIUM	CONSTRUCTED	
SinPir	1	WIDE	LESS VIS.	NARROW	
(14)	2	NIL	-	SMALLER	NARROW
	4	WIDE			NARROW
	5	WIDE, F0 DPT	RATHER WIDE	DEEP,	VERY NARROW
			F0 DPT	CONSTR	
	6	WIDE	WIDE	WIDE?	
SUMMARY:		WIDE	MEDIUM	NARROW	
Lar heigth	1	LOW	HIGHER	HIGH	
(11)	2	LOW	LOWER?	HIGH	
	5		VARIED	RAISED	
	6	LOW	MEDIUM	ELEVATED	HIGH
SUMMARY:		LOW	MEDIUM	HIGH	
Voc Fold	1	VISIBLE	VISIBLE	SL VISIBLE	VOWEL DPT
(9)	2				STRETCHED
	3				STRETCHED
	4	VISIBLE	VISIBLE	LESS VISIBLE	
	5				STRETCHED, THIN
	6	VISIBLE			
SUMMARY:		VISIBLE	VISIBLE	LESS VISIBLE	
Vent Fold	2	OPEN	COMPRS	COMPRESSED	NARROW,
(8)	5		SL ADDUCTED	VERY ADDUCT	
	6	PASSIVE	SL ACTIVE	ADDUCTED	COMPRESSED
SUMMARY:		SEPARATED	MEDIUM	ADDUCTED	
Aryten	1				ADDUCTED
(7)	3				TOP TIGHT
	4	TOP SPLIT	TOP SPLIT	TOP SPLIT	TOP TIGHT
				SL TILTED	TILTED
	5			TOP SPLIT	
	6	ADDUCTED		COMPRESSED	COMPRESSED
SUMMARY:		TOP SPLIT	TOP SPLIT	TOP SPLIT	
				TILTED	
Lx Tube	1	PASSIVE	NOT FULLY OPEN	SL NARROW	
(6)	4	WIDE		CONSTRUCTED	NARROW
	5	STABLE	SL NARROW		VERY CONSTR
SUMMARY:		WIDE	MEDIUM	CONSTRUCTED	
Epigl	2	STRAIGHT	-	TILTED	
(5)	3	VIBRATO	VIBRATO	CLOSE TO ARYT	
Glottis	2	WIDE	-	NARROW	
(5)	3	INCOMPL CLS	POST CHINK	NO CHINK	
Es Entr (3)	2	NIL	COMPR	COMPRESSED	NARROW
Aditus	3	-	WIDE RE A	NARROW	VERY NARROW
(3)	5				VERY CONSTR
	6		SL CONSTR		

Table I. Summary of six expert observers' descriptions of the characteristics of the four singing styles shown on the video recording indicates how many of the six observers in the expert panel who mentioned the trait in their description.

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 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.

Particularly the first, but also the second, formant frequencies were found to be higher in belting and mixed than in operatic. A raised larynx has been shown to increase the frequencies of these formants considerably in the vowel [æ:] (Fant 1975; Nordström & Sundberg, 1983). 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 fiberoptic laryngoscopy and acoustic analysis, Yanagisawa & al. (1989) studied aryepiglottic constriction in the vowel /i:/ as sung in a number of different singing styles, including belting and operatic, by five singer subjects. They 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 for the vowel /i/ only; in Experiment II a number of different vowels was included 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 good agreement with those reported 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 (Estill, 1988; Lawrence, 1979; Yanagisawa & al., 1989). Also, Estill (1988) found that the EMG signal from the middle constrictor was greater in belting than in opera; this would lead to advanced side walls in belting, which were observed in the present investigation.

Using electroglottography, Estill (1988) found belting to be typically associated with a long closed phase while operatic had a short closed phase. 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 and different associates (Estill, Baer, Honda, & Harris, 1985). Their subject was able to demonstrate belting and operatic 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 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 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 & al. (1985).

Estill & al. also studied the glottal voice source by means of 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 as compared with operatic. This is in agreement with our flow glottogram findings. The agreement supports the above conclusion that our subject's behaviors in operatic and belting was similar to those studied by Estill & al.

Summarizing, these instances of agreement suggest that our subject offered typical examples of belting. Thus, although our investigation concerned one single subject only, it apparently yielded representative results. Also, the results of the acoustic analyses and the fiberoptic examination of the larynx produced results that appear compatible.

We derived 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. 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, in the songs no corresponding consistency in the formant values could be observed. This suggests that in singing sustained, isolated vowels, our singer subject used a stable and neutral set of formant frequencies while in performing songs, she used formant frequencies, i.e., vowel coloring, for the purpose of musical expression. 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 through 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 styles of singing. As a result, we obtained a rather complete description of how she used her voice in the three styles of singing.

CONCLUSIONS

Belting and operatic differed with respect to subglottal pressure, glottal adjustment, and articulation. *Operatic* 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* 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. Also, 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. Probably due to the greater adductive forces in belting, the amplitude of the voice-source fundamental was higher in operatic than in belting and mixed. As our subject seemed to produce typical examples of belting and operatic, we conclude that this is a representative description of belting.

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