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Sundberg, J.

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The singer's formant revisited

Johan Sundberg

Abstract

The singer's formant is a high spectrum envelope peak near 3 kHz typically occurring in voiced sounds produced by male singers and altos in western operatic singing. Three aspects of the singer's formant are discussed. First, the contribution to this peak from the voice source is considered; it is concluded that there seems to be no reason to assume that this contribution is different from what applies to normal speech. Second, an examination is presented of the significance of the larynx tube to the formant frequency constellations which has been proposed as the main acoustic explanation of the singer's formant in the author's earlier investigations. Perturbation analysis of area functions derived from magnetic resonance images of the vocal tract for a singer's spoken and sung [i:] and [a:] reveal that F4 and F5 of the sung vowels are both highly, though not exclusively, dependent on the area function of the larynx tube. Third, a tentative method for measuring the level of the singer's formant is presented. The method is based on the difference L_{SF} between predicted and observed level of F3, whereby the prediction takes F1 and F2 into account and assumes a speech-like frequency distribution of F3, F4, and F5. When applied to a set of spectra of untrained speakers and professional operatic singers it turns out that L_{SF} is close to zero or negative for the speakers, while it is clearly positive for the male opera singers. For the sopranos, L_{SF} varied between singers and also with pitch and vowel.

Introduction

Sixty years ago Bartholomew published an article in the Journal of the Acoustical Society of America in which he presented spectra of vowels sung and spoken by a number of more or less experienced singers (Bartholomew, 1934). He found a prominent spectrum envelope peak in the frequency range 2.4 to 3.2 kHz in the spectra of singer's sung vowels. This peak was later called the singer's (or the singing) formant. Today, it is recognised as an important acoustic characteristic of male operatic singing (Winckel, 1953; Sundberg, 1974; Hollien, 1983; Bloothoof & Plomp, 1986; Sundberg, 1987). Thus, a major difference between untrained voices and operatic singing voices is the level near 3 kHz in the spectrum; if this level is exceptionally high in a voice, this voice is said to possess a singer's formant.

The singer's formant has been explained as a resonatory phenomenon arising from a clustering of F3, F4, and F5 (Sundberg, 1974). In this explanation, an important role was ascribed to the larynx tube. This tube is about 2 cm long, its bottom is constituted by the vocal folds, the anterior wall by the epiglottis and the posterior wall by the arytenoid cartilages. It inserts into the pharynx at an angle, some 2 cm above its bottom. If the cross-sectional area of its aperture is much narrower than that of the pharynx, an acoustical mismatch occurs. If the area ratio is smaller than 1:6, the larynx tube acts as a separate resonator, the resonance frequency of which is almost exclusively dependent on the shape of the larynx tube. The resonatory explanation of the singer's formant assumes that F4 is the resonance frequency of the larynx tube,

while its upper and lower neighbour formants are regular formants of the kind found in normal speaking voices.

The above does not imply that all questions regarding the singer's formant have been answered. First, the strong affiliation between F4 and the larynx tube in singing has been questioned. Second, data have been presented which apparently suggest that the singer's formant is sometimes associated with certain characteristics of the voice source, and hence is not a resonatory phenomenon. One aim of the present paper is to examine these alternative interpretations. Third, there is still no quantitative definition of the singer's formant; a voice is considered to possess it, if the spectrum level near 3 kHz is high. But no attempts have been made to define how high the level must be; a tentative solution to this problem is presented.

1. Contributions from the voice source

Estill and co-workers (1994) matched spectra of vowels sung with different vocal techniques with a formant model and compared the sound levels in the frequency region of the singer's formant observed in professional singers with those obtained from the formant model. They found good agreement for the vowel [a:] but not for the vowel [i:] and thus concluded that the singer's formant reflects voice source characteristics in certain cases.

The exact significance of this result is obscured by two factors. First, subglottal pressure was not taken into account. The source spectrum slope is reduced when subglottal pressure is increased. Therefore, if the vocal techniques differed with regard to subglottal pressure, a difference in the relative level of the singer's formant will result. Second, the higher-pole correction was included in the voice source. This correction compensates for formants which are not included as such in the formant model and is dependent on the vocal-tract length. If this length differed between the vocal techniques studied, e.g., because of a difference in the vertical positioning of the larynx, a small error will result. It seems that this experiment would be worthwhile to repeat, whereby subglottal pressure should be regarded as a systematically varied, independent variable.

2. Dependence of F4 on the larynx tube

Detweiler analysed singers' vocal tracts during singing of sustained vowels by means of magnetic resonance (MR) imaging (Detweiler 1994). She did not find any 1:6 vocal-tract cross-sectional area discontinuities near the larynx-tube opening. She limited her analysis to vocal-tract cross-sectional contours that were either parallel with or normal to the contour of the cervical vertebrae. As the larynx tube inserts into the pharynx at an angle, it seems likely that these two sections do not yield a sufficiently detailed representation (Fig. 1). Although F4 would still be mainly dependent of the larynx tube even when the area ratio is slightly smaller than 1:6, Detweiler recently suggested that F4 in singers depends on the vocal-tract length rather than on the larynx tube (Detweiler & Detweiler, 1995).

DETWEILER'S MR DATA

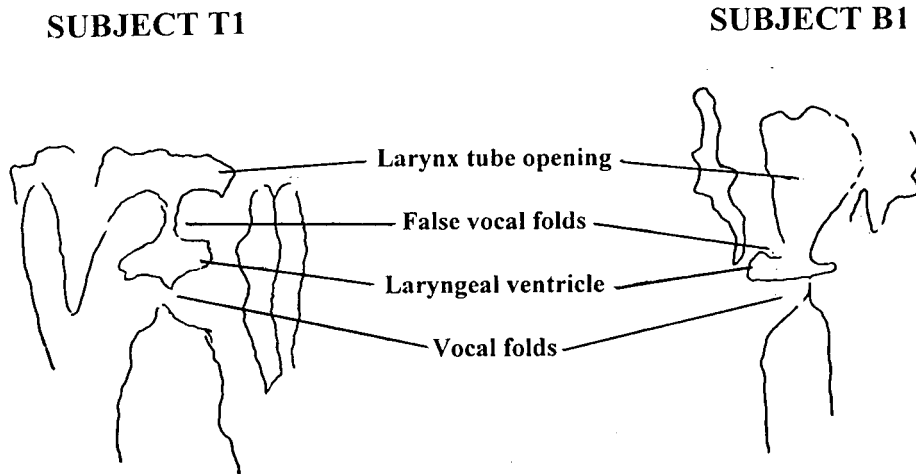


Figure 1. Vertical sections of the upper part of the larynx tube according to MR data published by Detweiler (1994).

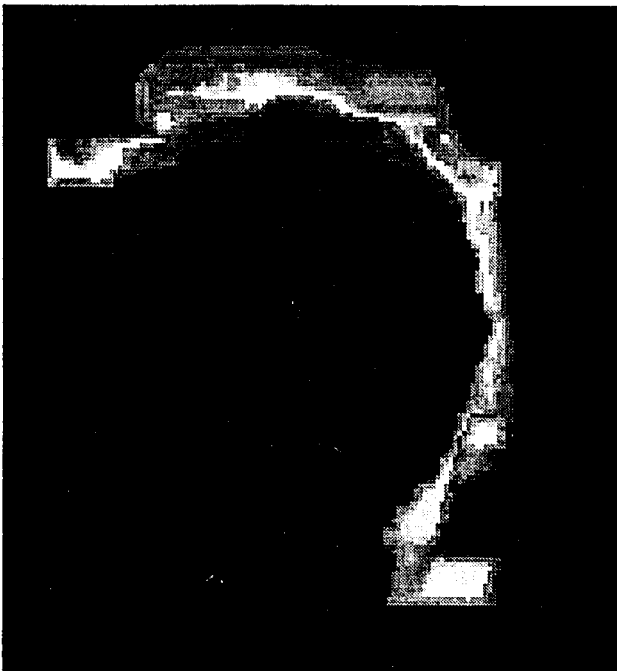


Figure 2. Lateral view of the MR image of the vocal tract for spoken vowel [a:].

Recently, some more information on the relevance of the larynx tube to the production of the singer's formant was collected in an experiment using MR technique. In co-operation with Ingo Titze and Brad Story of the Iowa University, MR images were taken of a sung and a spoken version of the vowels [i:] and [a:] as produced by a baritone singer. The total exposure time was about 400 sec; keeping articulation as constant as possible, the subject repeatedly sustained the same vowel for about 10 sec, whereby the imaging equipment was running. Figure 2 shows an example of the vocal tract profile.

From the resulting three-dimensional data, area functions were computed describing how the cross-sectional area varied along the length axis of the vocal tract (Fig. 3). The FORMFLEK computer program (Liljencrants & Fant, 1975; Sundberg et al., 1992) was used for calculating the formant frequencies of these area functions. This program assumes plane wave propagation, a requirement which is not fulfilled at high frequencies. Therefore, the formant frequencies were also measured in ACMOD, an

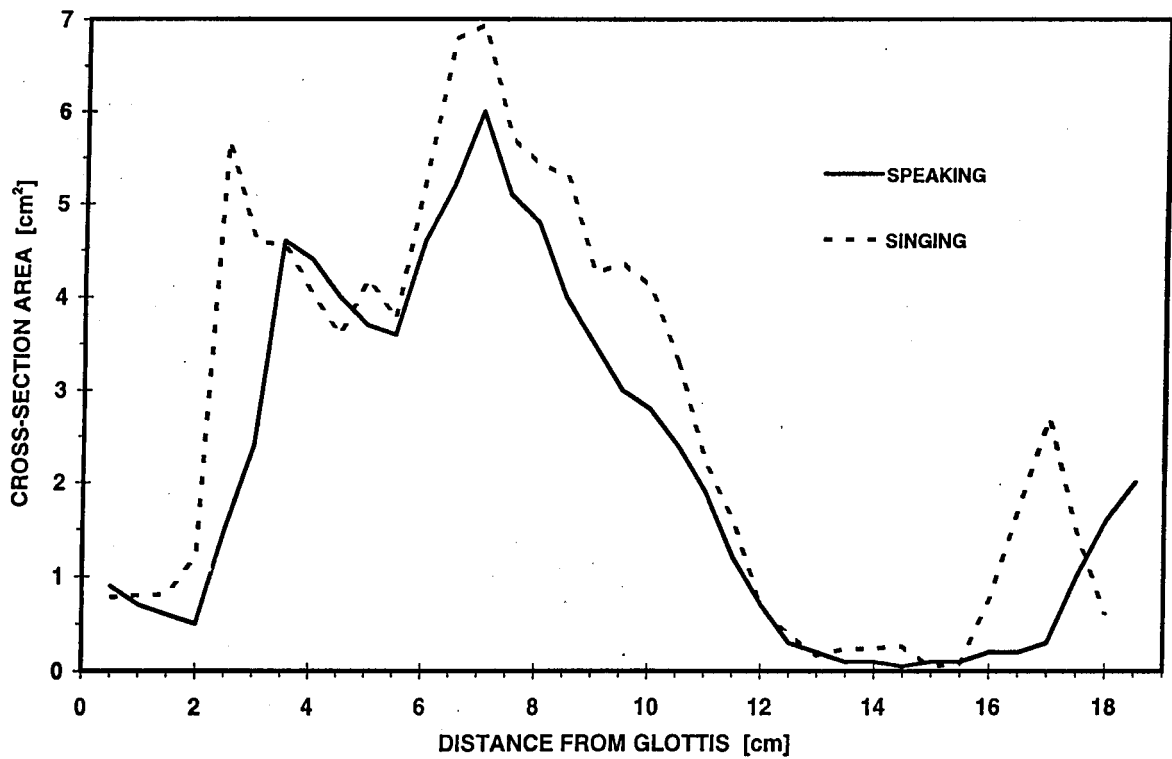
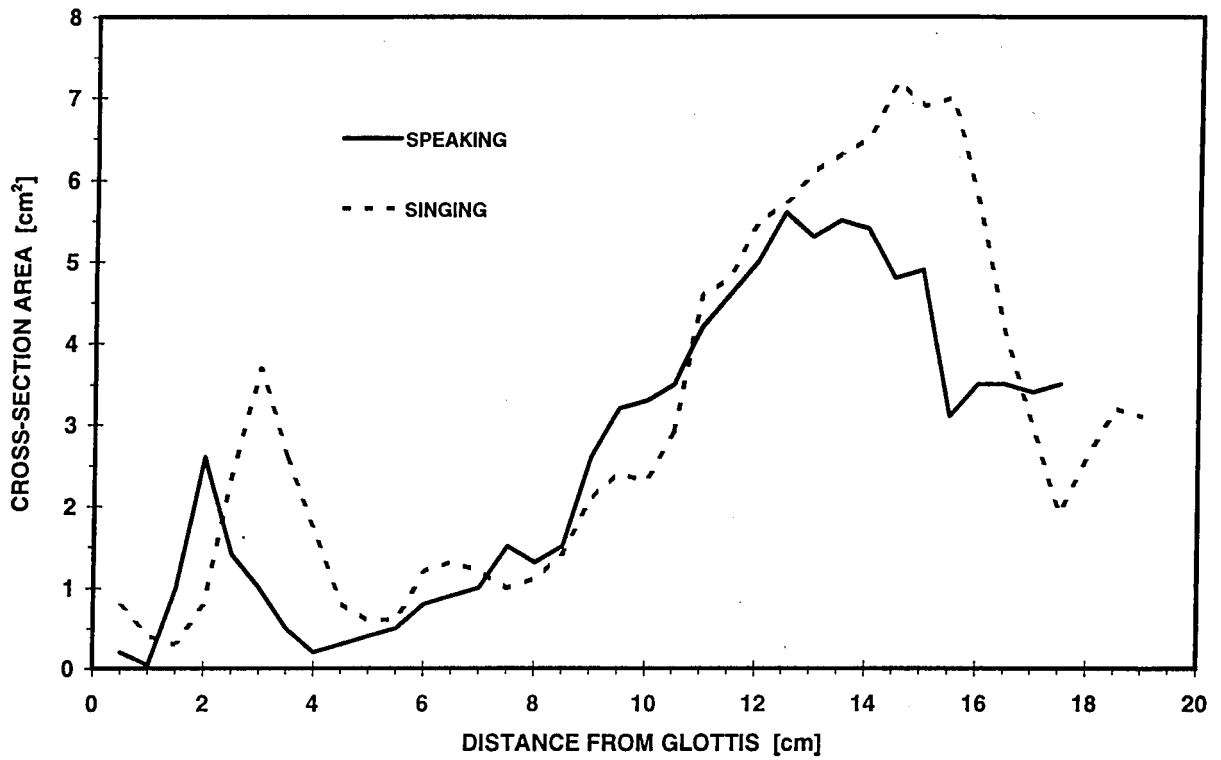


Figure 3. Area functions derived from MR images for the vowels [a:] (above) and [i:] (below).

acoustical model of the vocal tract. It consists of a pile of washers, each 0.5 cm thick and provided with center holes of various cross-sectional areas. The area functions were quantized according to the cross-sectional areas used by Fant (1960) as illustrated in Figure 4. These quantized area functions were excited with a sine sweep obtained from the STL Ionophone, a small sound source generated by a modulated discharge across two minute electrodes (Fransson & Jansson, 1971). Comparisons revealed that for identical area functions the FORMFLEK program produced errors of up to 19.9% at 3200 Hz. Hence, the ACMOD seemed preferable for analysing formant frequencies associated with the singer's formant.

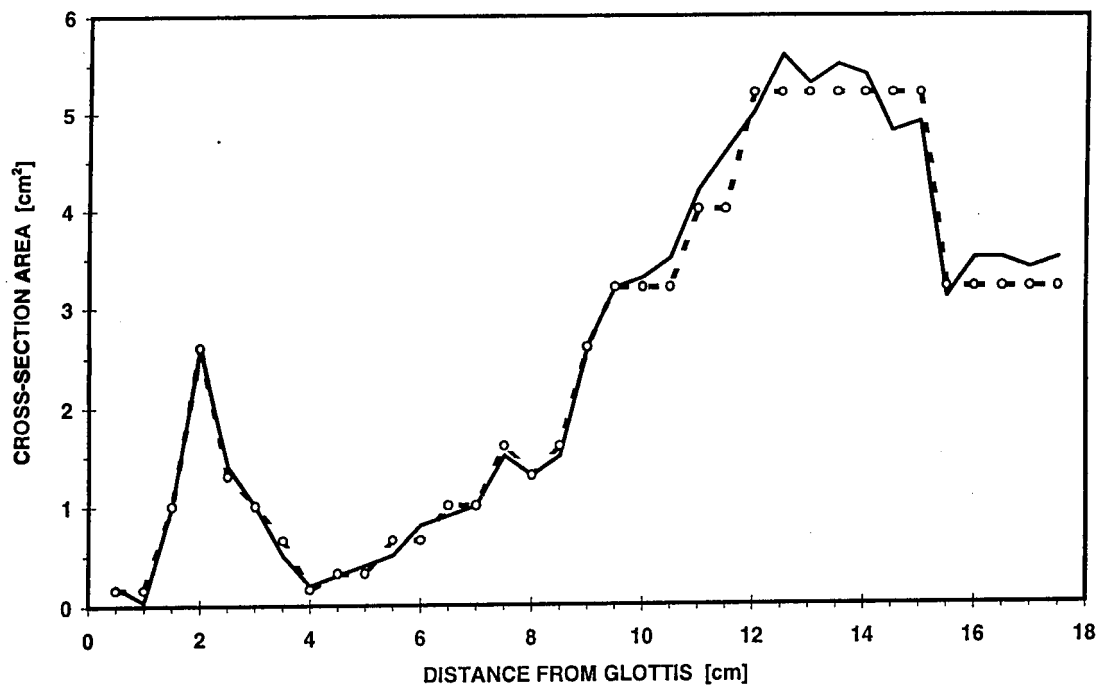
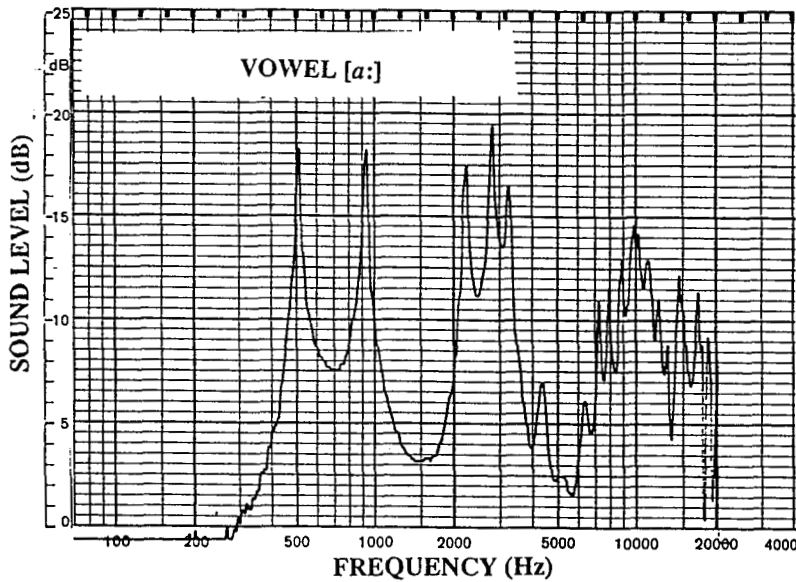


Figure 4. Original area function of the vowel [a:] pronounced in a speech mode and derived by MR imaging and the approximation used for the formant frequency measurements on ACMOD (solid and dashed curves).

Figure 5 shows frequency sweep responses of the area functions for sung [a:] and [i:] as derived from ACMOD. It can be seen that the frequency separation of F5 and F3 is approximately 1000 Hz, i. e., F3, F4 and F5 appear as a cluster. This corroborates the assumption that the singer's formant reflects resonatory phenomena.

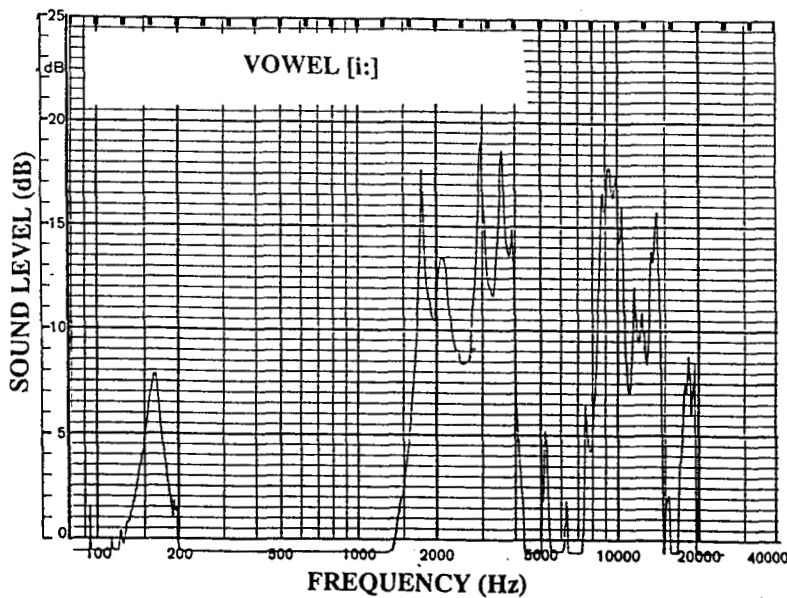
The validity of the assumption that F4 is strongly dependent on the larynx tube was tested by measuring the formant frequency changes due to a doubling of the cross-sectional area at each 0.5 cm interval along the vocal tract length axis. Thus, using the ACMOD, the area function was repeatedly modified according to this principle at each 0.5 cm portion of the length axis, and the formant frequencies were measured for each perturbation.

TRANSFER FUNCTIONS FOR SUNG VOWELS
AREA FUNCTIONS FROM MR DATA



FORMANT FREQUENCIES DAT
ACCORDING TO

ACMOD (Hz)	FORMFLEK (Hz)	DIFF %
519	534	2.9
944	973	3.0
2283	2362	3.5
2818	3250	15.3
3262	3913	19.9



	174	
1838	1805	-1.8
2212	2235	1.0
3106	2820	-9.2
3757	3871	3.0

Figure 5. Frequency sweep responses of ACMOD area functions for sung [a:] and [i:] derived from MR images of a baritone singer. The table to the left compares the formant frequencies measured for identical area functions on the ACMOD and with the FORMFLEK computer program.

The results for F3, F4, and F5 of the sung vowels are shown in Figure 6. It can be seen that F4 in particular, but also F5, was very sensitive to the details of the area function in the larynx tube. However, also other parts of the area function influenced these formant frequencies. This is in accordance with the fact that the area mismatch was only about 4.5:1 between the exit of the larynx tube and the pharynx. These results support the assumption that F4 is strongly, though not entirely, affiliated with the larynx tube.

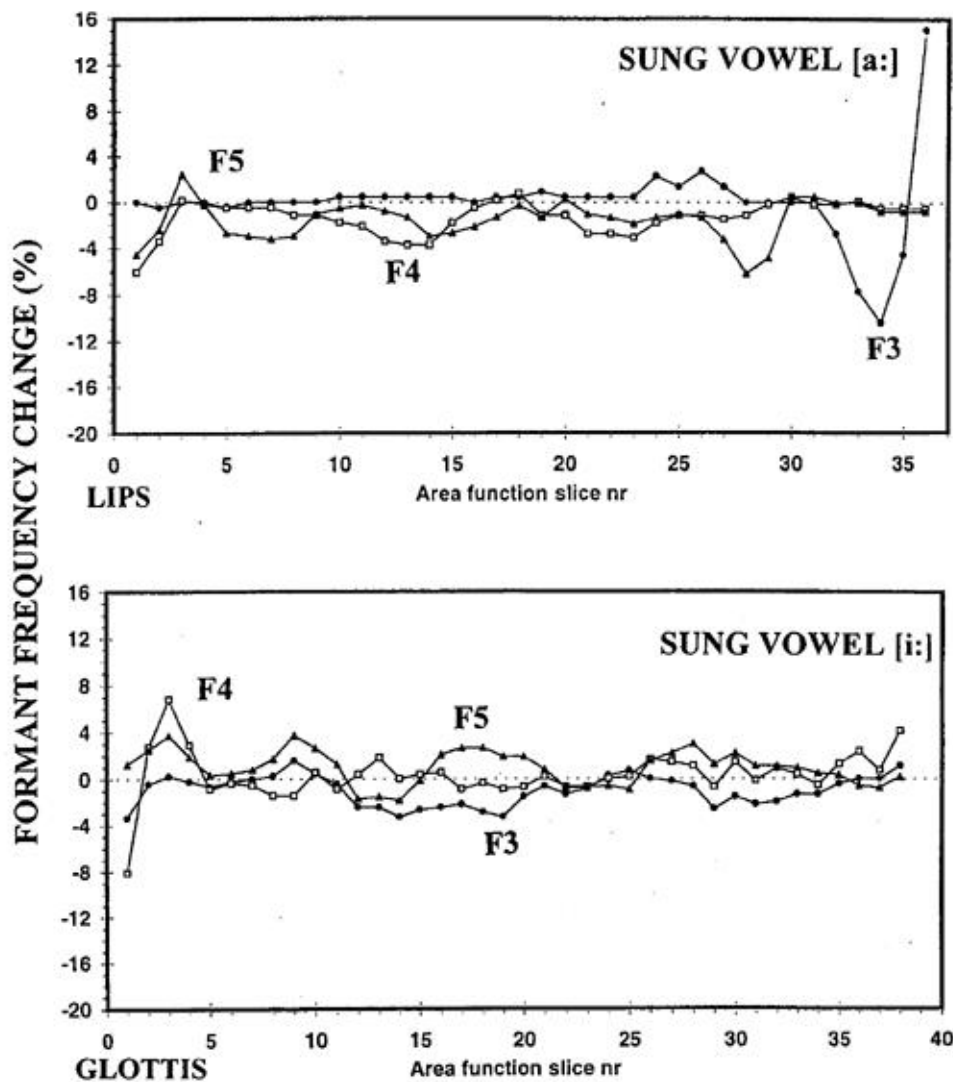


Figure 6. Changes in F3, F4, and F5 for a doubling of the cross-sectional area in each 0.5 cm long slice of area functions shown in Figure 3. The left end of the x-axis corresponds to the glottis, and the upper and lower panels refer to the sung vowels [a:] and [i:].

To produce a clear singer's formant, F3, F4, and F5 have to be clustered somewhat narrower than indicated in Figure 5. On the other hand, small area function errors can have great effects on these formant frequencies. Furthermore, potentially important differences may exist between real vocal tracts and their realisations on the axisymmetrical ACMOD representation. For example, the sinus piriformes make the glottal end of the vocal tract far from axisymmetrical in reality. For a more accurate assessment of the interpretation of the singer's formant as the result of a clustering of F3, F4, and F5, we have to await sweep-frequency measurements of high fidelity, three dimensional models of the vocal tract.

3. What is an exceptionally high spectrum level?

All vowel sounds contain sound energy near 3 kHz, since the third and/or fourth formants typically reside in this frequency region. Even in cases where no partials are generated at these frequencies, the formants may be excited by and thus contain noise generated in the glottis. Thus, if the singer's formant is defined as the spectrum envelope peak near 3 kHz with no further qualifications, nearly all vowel sounds will possess a singer's formant. This would make the singer's formant a meaningless concept.

Thus, to define the singer's formant its *level* is crucial. The level in a frequency band of a spectrum depends on several factors. One is the *overall vocal loudness*. To compensate for some of this dependence, the level of the singer's formant, henceforth L_{SF} , is generally measured in relation to the level of F1, henceforth L1 (Schultz Coulon & al., 1979; Hollien, 1983; Miller & Schutte, 1983; Schutte & Miller, 1984; Cleveland & Sundberg, 1985; Bloothoof & Plomp, 1986; Schutte & Miller, 1985 a and b; Seidner & al., 1983). Unfortunately, this normalisation only solves part of the problem. When vocal loudness is increased the spectrum balance is typically changed, as the levels of the higher spectrum partials tend to gain more in sound level than those of the lower spectrum partials. The reason for this is the behaviour of the voice source. Thus, if the singer's formant is defined as the difference between L1 and a peak near 3 kHz, vowels produced at a high degree of vocal loudness will be regarded as possessing a stronger singer's formant than vowels sung more softly.

Another factor affecting the level in a spectrum band is the constellation of *formant frequencies*. According to acoustic theory of voice production, the frequency distance between formants affect their level relations; if the frequency separation between two formants is decreased by one octave, both gain 6 dB and the spectrum valley between them gains 12 dB, other things being equal (Fant, 1960). This implies that the spectrum level near 3 kHz is much lower in the vowel [u:], which has low F2, than in the vowel [i:], which has much higher F2. Thus again, if the singer's formant is defined as the spectrum envelope peak near 3 kHz, the vowel [i:] will possess a stronger singer's formant than the vowel [u:] for purely acoustical reasons.

These examples indicate the possibility to define the singer's formant as an *exceptionally* high spectrum envelope peak near 3 kHz. For this a prediction of expected spectrum level is needed, thus allowing comparison between observed and predicted spectrum levels in this frequency range. A voice could be said to possess a singer's formant when the difference between observed and predicted levels exceeds a minimum. An attempt to construct a procedure for such comparisons will next be presented. (A preliminary version was presented at the Annual Symposium Care of the Professional Voice, Philadelphia, 1989).

The overall strategy was to predict the level of the third formant, L3, taking into consideration the frequencies of the two lowest formants, and then to compare this predicted L3 with the observed L3. This procedure takes care of the influence of the formant frequencies on the formant levels, but does not take into account the effect of vocal loudness.

Fant's (1970) equations for predicting formant levels were used for calculating expected values of L3, given the values of F1 and F2. Figure 7 shows the result assuming a voice source spectrum rolloff of -12 dB/octave and the indicated values of F3. It was further assumed that, normally, $F_4=3.5$ kHz and $F_5=4.5$ kHz, but in all cases the differences $F_3-F_2 \geq 0.5$ kHz, $F_4-F_3 \geq 1$ kHz, and $F_5-F_4 \geq 1$ kHz. Thus, a certain minimum distance was always assumed between adjacent formants. These conditions are realistic for most spoken vowels, except for rounded front vowels such as [y:]. Thus, for most vowels recorded in an anechoic chamber the curves in Figure 7 apply, provided a -12 dB/octave source spectrum slope and a distribution of F3, F4, and F5 typical for speech.

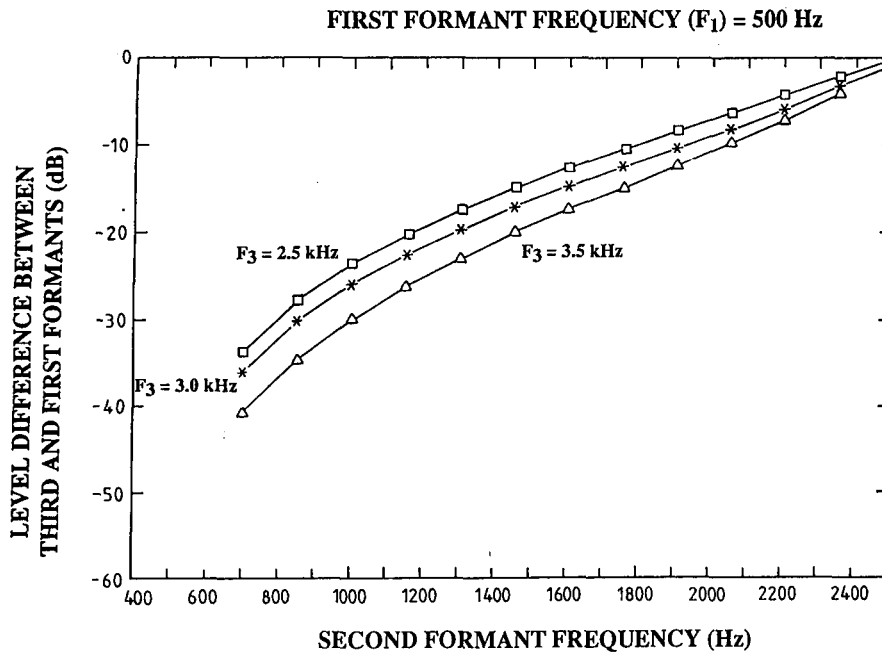


Figure 7. Difference between L3 and L1 as function F2 for $F_1=.5$ kHz and the indicated values of F3. For $F_3=2.5$ and $F_3=3$ kHz $F_4=3.5$ kHz, while for $F_3=3.5$ kHz $F_4=4.5$ kHz. The voice source spectrum roll-off is -12 dB/octave.

The figure shows that the influence of the third formant is mostly rather small, particularly when $F_3 \leq 3$ kHz, the variation being less than 6 dB. This suggests the possibility of representing these curves by one single curve, using the F1 rather than F3 as the parameter. This has been done in Figure 8 where the curves show the L3 as function of F2, F1 being the parameter.

Figure 8 shows that, in the absence of a singer's formant, an F1 at .5 kHz and an F2 at 1 kHz induces a 30 dB difference between L1 and L3. If $F_2=1.8$ kHz, this level difference is more than halved. If F_5-F_3 is smaller than assumed, L3 will be higher, thus suggesting the presence of a singer's formant.

The values shown in Figure 8 can be used to predict a neutral value for L3, provided speech-like values of F3, F4, and F5. Such values are shown for some vowels in Figure 9. The relative L3 varies widely, from -45 in [u:] to +20 dB in [i:]. Thus, the vowel influence on the relative L3 is substantial.

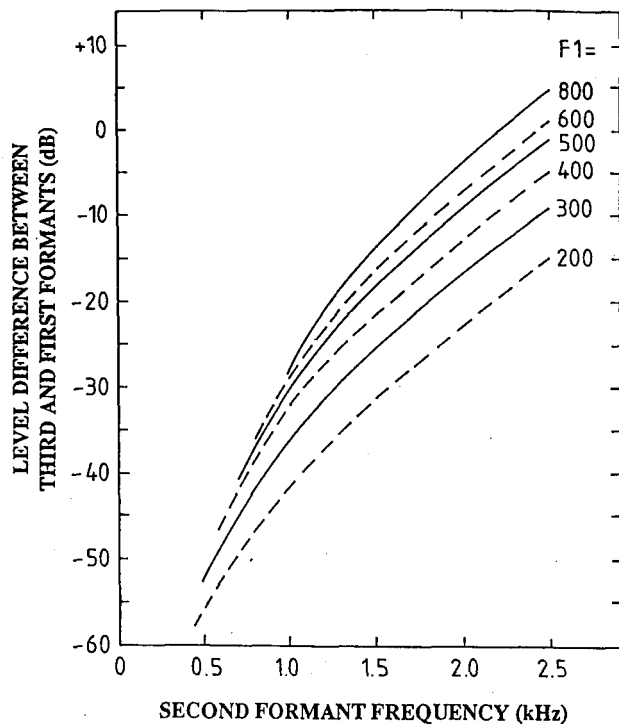


Figure 8. Difference between L_3 and L_1 as function F_2 , for the indicated F_1 values. $F_3=2.5$ kHz, $F_4=3.5$ kHz and $F_5=4.5$ kHz, but always $F_3-F_2 \geq 5$ kHz, $F_4-F_3 \geq 1$ kHz, and $F_4-F_3 \geq 1$ kHz.

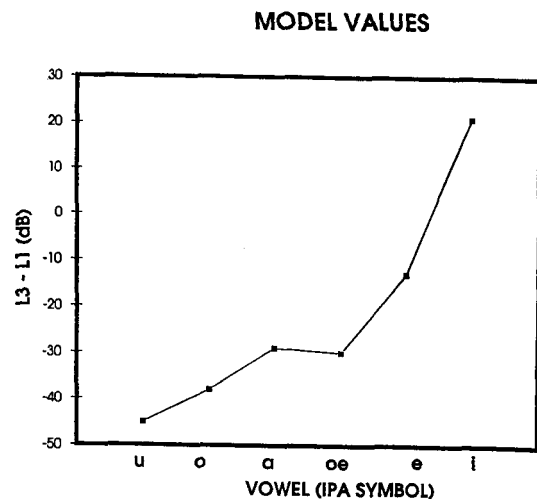


Figure 9. Difference between L_3 and L_1 for ideal vowel spectra produced in accordance with acoustic theory of vowel production, and assuming a voice source spectrum roll-off of -12 dB/octave.

These predictions can now be compared with observations from real voices. Such observations were collected from three sets of recordings. In one, three speakers read a standard text in a sound-treated booth. In the second set, 4 tenors and 4 baritones or basses, all professional opera singers, sang a vowel sequence with the consonant [v] interspersed between the vowels. These recordings were made in an anechoic room. In the third set, three sopranos sang the solo part of Felix Mendelsohn's motet "Hear my prayer". During these recordings, also made in an anechoic room, the sound of the accompanying choir and piano was presented in earphones to the singers together with their own voices, captured by a microphone in front of the mouth.

We can now determine the difference between observed and theoretically predicted L_3 values. These differences, henceforth L_{SF} , can be regarded as a quantitative estimate of the singer's formant. Figure 10 shows these data for three male speakers, eight professional singers, and three professional soprano singers.

One speaker (filled triangles) matched the expected values of the third formant rather closely. Hence, the L_{SF} is close to zero, so he can be said to lack a singer's formant. Another subject (open circles), showed negative values of L_{SF} , so also this speaker lacked a singer's formant. The third subject, the trained singer (open squares), had a L_{SF} of 4 dB, approximately, for most vowels.

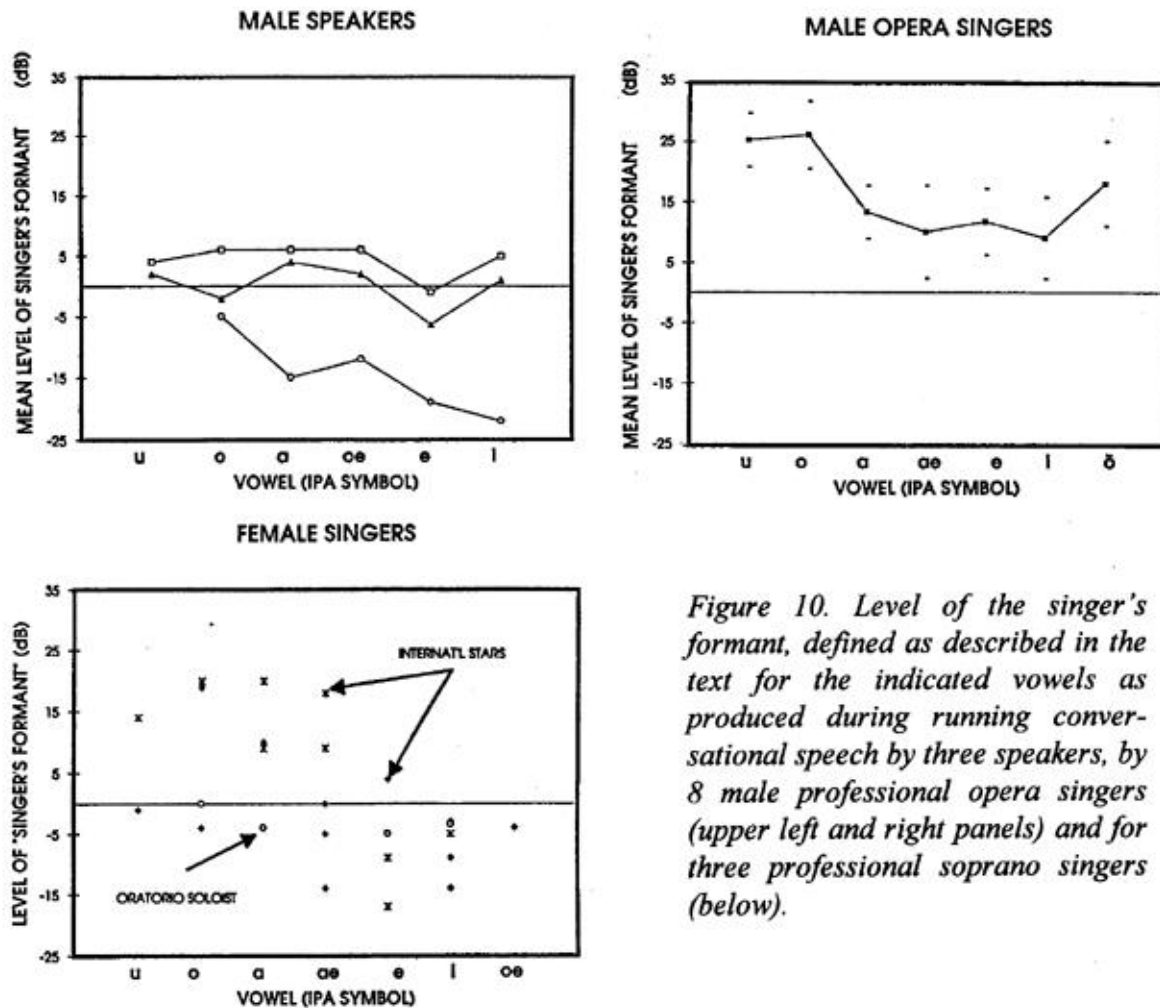


Figure 10. Level of the singer's formant, defined as described in the text for the indicated vowels as produced during running conversational speech by three speakers, by 8 male professional opera singers (upper left and right panels) and for three professional soprano singers (below).

For the professional male singers, the group mean is shown plus minus one standard deviation. The mean L_{SF} is strongest for the vowels [u:] and [o:], which has a low value of L_3 in speech, and weakest for the vowels [i:] and [e:], which has a high value of L_3 in speech. This reflects the observation just made, that the singers reduced the vowel-dependence of L_{SF} .

The female singers exhibited a great variability both between and within vowels. Thus, in some cases, L_{SF} was about 15 dB while in other cases it was negative. It is interesting that the oratorio soloist (open circles) showed low values for all vowels, suggesting that she was singing without a singer's formant. By contrast, the international stars (stars and filled diamonds), exhibited quite high values in many cases, particularly for the back vowels [u:], [o:], and [a:]. The great variability within vowels would reflect the strong pitch and loudness dependence of the singer's formant at high pitches.

The procedure proposed above can be used for comparing observed and expected values of L_3 , whereby the expected values are based on F_1 and F_2 . Such comparison allows us to decide when L_3 is exceptionally high and, thus, to determine whether or not a voice possesses a singer's formant. It is only a matter of convention to decide how large the difference between the observed and expected L_3 must be in order to say that the voice has a singer's formant. On the basis of the present material, a minimum

excess level of 6 dB can be tentatively proposed. Thus, we suggest that a voice be said to possess a singer's formant, if L3 is at least 6 dB higher than what could be expected from the values of F1 and F2. In other words, a vowel can be said to possess a singer's formant provided that $L_{SF} \geq 6$ dB.

However, our attempt to formulate a definition of the singer's formant measure is limited in two important respects. One is that it considers the level difference between ideal formant levels and the levels of spectrum partials. These measures are comparable only as long as fundamental frequency is low, but at higher pitches, such as in the soprano range, the exact distance between the formant peak and the partial closest to this peak will be relevant, so the ideal levels of formants cannot be accurately determined. The scatter of the soprano data observed in the last figure reflects this effect.

The other limitation is that the method proposed does not take vocal loudness into account. Gauffin and Sundberg (1989) found that a 10 dB increase of the overall sound level of a vowel was accompanied by a 15 dB increase of L3 in a singer subject. This implies that, according to our definition, the L_{SF} will increase with vocal loudness. To avoid this, a normalisation with regard to vocal loudness is required. This normalisation should be based on systematic measurements on vowel sounds produced at different degrees of vocal loudness.

The fact that these two effects were disregarded leads to the consequence that the L_{SF} varies depending on loudness and, at high pitches, also on pitch. Systematic experiments should be carried out to analyse these dependencies. Thereby, also the effect of assuming a constant frequency of the third formant for all vowels and subjects should be examined.

In spite of these limitations it is likely that the proposed method of measuring the singer's formant corresponds quite well with auditory perception. This possibility should be tested in listening experiments.

This attempt to find a new way of defining the singer's formant seem encouraging. The singer's formant was found to be much stronger in vowels in which L3 is normally low than in vowel with a high L3. In this manner, the singer reduces the timbral difference between front and back vowels. This equalisation of vowel timbre in the high-frequency range of the spectrum is probably quite important from a musical point of view. In music performance, contrasts in timbre are often used for marking boundaries in the musical structure, e.g. phrase boundaries (Dowling & Harwood, 1986).

Our data should enable us to answer the question who possesses a singer's formant? For a general answer, a greater material is obviously needed. If we limit the perspective to the voices used as examples in the present investigation, the following result would emerge. Among the speakers, the two untrained voices and also the trained voice, lacked a singer's formant. All male singers, by contrast, showed a clear singer's formant. For the sopranos, the results were varied. In some cases, a given vowel showed a strong singer's formant and in other cases the singer's formant was absent. This would reflect the limitation of the method mentioned above, that it does

not work for high F0. Also, the material analysed was vowels extracted from a song for the sopranos and vowel sequences for the males.

Conclusions

On the basis of the evidence reviewed here there seems to be no reason to abandon the assumption that the singer's formant is a resonatory phenomenon arising as a consequence of a clustering of F3, F4, and F5. Further, it seems reasonable to assume that F4 and also F5 are strongly, though not exclusively, dependent on the larynx tube. It also seems reasonable to assume that the singer's formant cannot be explained if only plane wave propagation in the vocal tract is taken into account. The method of measuring the level difference between observed and expected L3 values seems promising. A difference of 6 dB may be useful as a necessary minimum requirement for the possession of a singer's formant.

Acknowledgements

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