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Wagner's music is even better than it sounds: resonance tuning produced by matching vowels with pitch

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ABSTRACT

The vowels of European languages are primarily distinguished by the frequencies of the two lowest formants in the spectrum of the output sound, which are in turn produced by the frequencies ($R1$ and $R2$) of the first two resonances of the vocal tract [1]. Under some conditions, many singers use the strategy of resonance tuning; i.e. they tune a resonance to a harmonic of the fundamental frequency f_0. In particular, sopranos deliberately tune $R1$ to match f_0, ($R1$:f_0 tuning) once the fundamental frequency f_0 approaches or exceeds the value of $R1$ in normal speech [2]. According to simple models of oscillator-duct interactions [3], and the reports of singers, resonance tuning can increase the loudness, uniformity of timbre, stability and ease of singing, all of which are usually considered to be particularly advantageous in opera. There is, however, a reduction in intelligibility once $R1$ is varied from its value in normal speech. The amount of deliberate resonance tuning required by sopranos would be reduced if the pitch of the note written for a vowel corresponded with its usual range of $R1$. Analysis of soprano rôles in operas by different composers indicates that Wagner aided the acoustics of the soprano voice at high pitch when setting text to music. Some other composers show either no systematic correlation of vowel with pitch, or correlations that do not aid $R1$:f_0 resonance tuning. The paper will be illustrated with a collection of sound files.

INTRODUCTION

Vocal tract resonances in singing

The first resonance of the vocal tract, $R1$, has an important phonetic function. The first two or sometimes three resonances produce peaks in the spectral envelope of the voice, and thereby identify vowels in most Western languages [1]. In speech, $R1$ is varied between about 250 and 1000 Hz, chiefly by varying the opening of the mouth aperture.

This range of $R1$ coincides approximately with that of the fundamental frequency f_0 of the soprano voice, and overlaps the high range of other voice types. This overlap poses a performance problem for singers of nearly all voice types, but the problem is particularly important for sopranos. Consider a pitch-vowel combination for which f_0 exceeds the normal value of $R1$. If a singer maintains the normal value of $R1$, below f_0, then the singer loses the boost in radiated power that is associated with $R1$.

Sundberg [4], observing that sopranos increasingly lower the jaw or otherwise open the mouth as pitch increases, suggested that they were matching $R1$ to f_0,. By measuring $R1$, we showed that sopranos do indeed employ $R1$:f_0 tuning to match $R1$ to f_0, once the fundamental frequency f_0 approaches or exceeds the value of $R1$ in normal speech [5,6].

Resonance tuning allows the possibility of greater loudness and/or less effort, which in turn allows the singer to be heard over orchestral accompaniment in large halls, or allows a greater range for expression in less demanding situations. According to some models, it may also help 'drive' the vocal fold oscillations [*e.g.* 3]. Finally, it avoids the rapid changes in loudness or timbre that might occur as f_0 and $R1$ sometimes coincide.

In concert music and opera, the composer specifies the pitch to be sung and the lyricist or librettist specifies the vowel. Thus the composer imposes f_0 with high precision: ideally a percent or so. In contrast, while the librettist asks for a vowel that suggests $R1$ and $R2$, considerably greater variation is possible.

Phonetic consequences

For sopranos, however, the displacement of $R1$ required to effect this tuning can exceed an octave [5,6], which is much greater than the characteristic displacement in the ($R1$,$R2$) plane at which vowels begin to be confused [7].

Even without this complication, there are phonetic problems with the high voice. A periodic signal (like the voice) samples the frequency domain at the fundamental frequency, f_0 and integral multiples of it. In the range of say 100 Hz < f_0 < 300 Hz, which includes most of the conversational speaking range for both sexes, the peaks in the spectral envelope are determined with moderate precision. For higher voices, the frequency domain is less well sampled.

Singing poses a further problem for the high voice. In normal speech, the fundamental frequency varies continually. Many classes of singing, on the other hand, fix the pitch during a syllable. Many exceptions exist, of course, including styles with extensive glissandi, extreme vibrato or melisma. We consider here only fixed-pitch singing. Thus, in speaking a syllable, the harmonics of the voice sweep a range of frequency and thus convey more information about the spectral envelope than do the fixed frequency harmonics in fixed-pitch singing.

Losing the information in vowels is already an important information loss. Fortunately, languages are redundant and, with sufficient context, one can still understand text -v-n -n th- -bs-ns- -f v-w-ls. However, the variation in time of $R1$ and $R2$ also carries information important to identifying consonants [1].

Thus a number of reasons lead one to expect difficulties in comprehension of sopranos in the high range and such difficulties have been reported [8–10]. Indeed Berlioz, acknowledges this in his classic treatise on orchestration [11]. Sound files are available that illustrate the problem [12].

Making it easier

Much of the difficulties facing both singer and listener could, however, be removed if f_0 and $R1$ were not varied independently. In principle, the librettist and composer might collaborate so that the vowels with high $R1$ occurred at high pitch and conversely. This would mean that $R1$ would need less adjustment by the singer to be tuned to f_0, which would not only make life easier for an accomplished singer, but might actually help a learner acquire the technique of resonance tuning. By giving the listener a spectral peak in the sound relatively close to the appropriate value of $R1$, it might also be expected to aid comprehensibility.

Would such a collaboration be more likely to be found when the composer set text already written by the librettist? Would the composer's 'mind's ear' create melodies to enhance tuning? Or would it be more likely for a sensitive librettist to match words to a melody already composed? Or should one look to a composer-librettist who might create and adjust music and text together?

METHODS

The phoneme and fundamental (pitch) frequency f_0 were recorded using pencil and paper for each note sung in the chosen rôles in using the published scores for each opera studied. Any obvious ornamentation, grace notes, trills, and mordants were not included as they carry no textual information. The resonances of speech are quite broad and consequently we could assume that A4 = 440 Hz throughout. See [13] for more details.

RESULTS

The first requirement is to associate a range of values of $R1$ with each vowel. To simplify presentation, the 12 vowels of German were grouped into the four standard categories according to their jaw height in the vocoid or Cardinal Vowel space – see Figure 1. The range of $R1$ we assumed to be associated with each category was: *closed* 250–400 Hz, *close–mid* (or *half-close*) 400–550 Hz, *open–mid* (or *half-open*) 550–750 Hz, and *open* 750–1000 Hz. For Italian and Russian the vowels were grouped into *closed*, *mid* and *open*.

Of course the values of $R1$ vary with language, dialect, accent, etc. Furthermore it is possible that listeners may learn to use a different formant 'map' for sopranos (i.e. a different categorisation of the vowel plane), in much the same way that we use different maps for men, women and children. Ultimately, we can only make an informed guess at the vowel sound imagined by the composer-librettist. Although there might be uncertainty about the range of resonance frequencies in each category, the important feature for this study is that their order with increasing frequency is known.

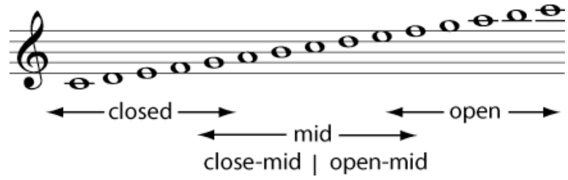

Figure 1. Approximate frequency range of $R1$ for the four standard categories of jaw height in the vocoid or Cardinal Vowel space.

Figure 2 shows the distribution of vowels for the rôle of Brünnhilde in *Der Ring des Nibelungen* by Wagner. The upper figure shows there is a reasonably smooth distribution of vowels with pitch, although some preference for keys harmonically close to C major is evident. In the lower figure the vowels have been grouped into the four categories for jaw height and thus $R1$. It is immediately apparent that the vowel distribution does vary with frequency, and in a fashion that helps match $R1$ to f_0. Thus as f_0 increases above 700 Hz, the open vowels with high $R1$ bcome inceasingly common compared with the closed and close-mid vowels that have low $R1$. Conversely, the fraction of open-mid and open vowels starts to decrease at low pitch.

The open vowels are, of course, preferred at high pitch, whereas the comprehensibility of other vowels would be seriously reduced by resonance tuning. However, open vowels are also used across the whole pitch range. The unmodified $R1$ for these vowels is sufficiently high that, for almost the whole of the soprano range, the vocal tract load at the glottis is inertive. Further, for notes in the low soprano range, $R1$ may be excited by a second harmonic [6]. So the open vowels are least likely to be distorted by resonance tuning.

Does this degree of favourable vowel-pitch matching exist in operas by other composers? Figure 3 shows the results for the soprano rôle of Sophie in *Der Rosenkavalier* by Richard Strauss. Although Richard Strauss was a very experienced operatic composer with a long-term collaboration with the librettist of this opera, Hugo von Hoffmannsthal, there is no evidence of a favourable distribution of vowels with pitch, Indeed the closed vowels are less common at low pitch.

Figure 4 shows the results for the rôle of Katerina in *Lady Macbeth of the Mtsensk District* by Shostakovich. Although there is not the systematic increase in open vowels at high increasing pitch shown in figure 2 for Brünnhilde, there is a marked increase in the use of open vowels at pitches Ab5 and A5 that would facilitate resonance tuning.

Space does not permit presentation of the complete data for the ten operas studied. Accordingly we introduce γ, a parameter that indicates whether the distribution within a pitch range is favourable or unfavourable for resonance tuning. The parameter γ is defined as follows: For all notes lying in a frequency band whose frequency corresponds to the resonances associated with a particular jaw height, let g be the average fraction of notes whose vowel corresponds to that jaw height. Let h be the average fraction of notes at all other frequencies having those vowels. The parameter $\gamma = g/h - 1$ then indicates the preference for the appropriate vowel-pitch combinations. Positive and negative values indicate favourable or unfavourable pitch-resonance matching respectively.

Figure 5 shows the values of γ calculated for the vowels in different pitch ranges in ten operas. The operas of Wagner are seen to offer significantly more favourable vowel-pitch matching of the open vowels at high pitch then the other composers. Possible reasons for this have been discussed elsewhere [13,14].

CONCLUSIONS

The authors are unaware of any written evidence on the composers' intentions nor if they were advised on this topic by sopranos, with whom they sometimes had quite close relationships. However it does appear that Wagner, and perhaps Shostakovich, did consider the acoustics of the soprano voice when setting text to music at high pitch. This was perhaps facilitated by both composers also being librettists.

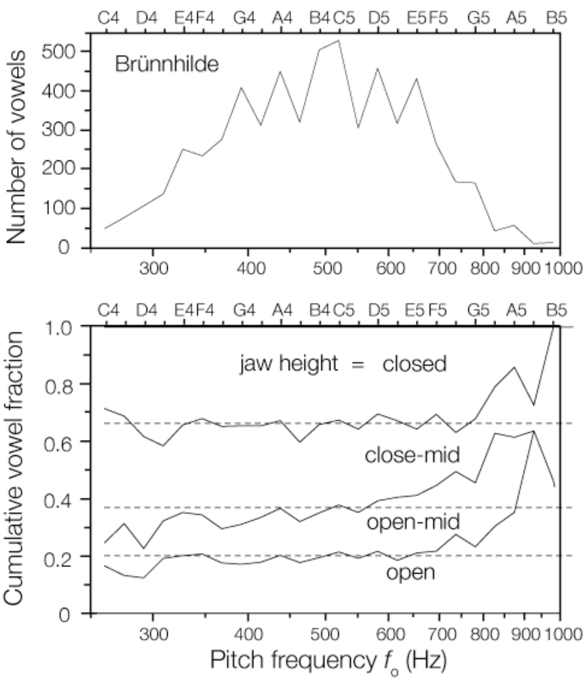

Figure 2. Semi-logarithmic plots of the number of vowels (upper) and the cumulative vowel fraction (lower) as a function of written pitch frequency f_0 for the rôle of Brünnhilde in *Der Ring des Nibelungen* by Wagner (5747 notes). Here the data from *Die Walküre*, *Siegfried* and *Götterdämmerung* have been combined. On the lower figure, the open vowels lie between the axis and the lowest continuous line, open-mid between the two lowest continuous lines, etc. The dashed lines show the null hypothesis: equal distribution of vowels across pitch.

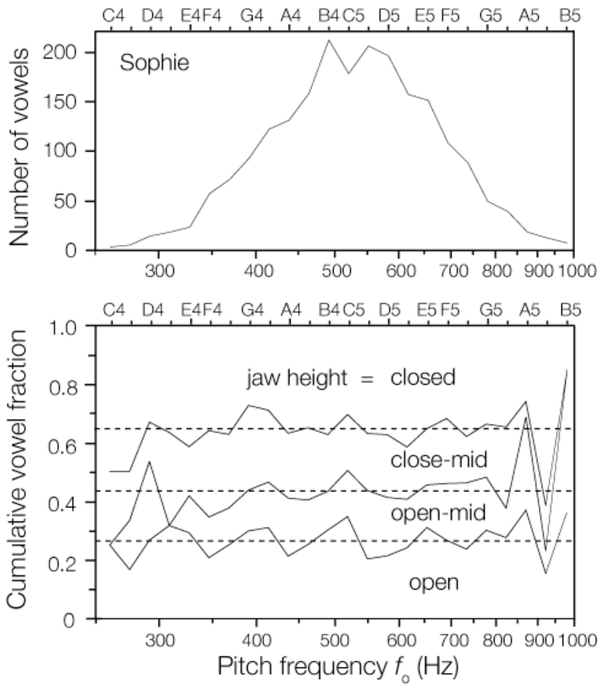

Fig. 3. Semi-logarithmic plots of the number of vowels (upper) and the cumulative vowel fraction (lower) as function of written pitch frequency f_0 for the rôle of Sophie in *Der Rosenkavalier* by Richard Strauss (2140 notes).

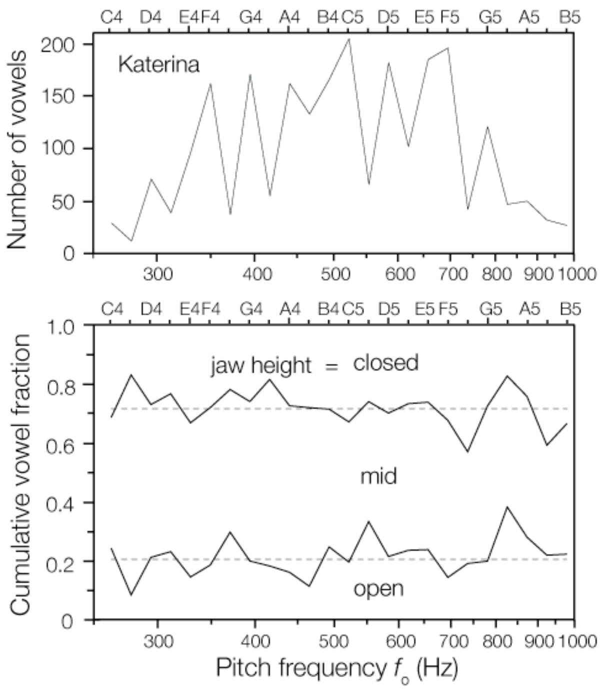

Figure 4. Semi-logarithmic plots of the number of vowels (upper) and the cumulative vowel fraction (lower) as a function of written pitch frequency f_0 for the rôle of Katerina in *Lady Macbeth of the Mtsensk District* by Shostakovich (2392 notes).

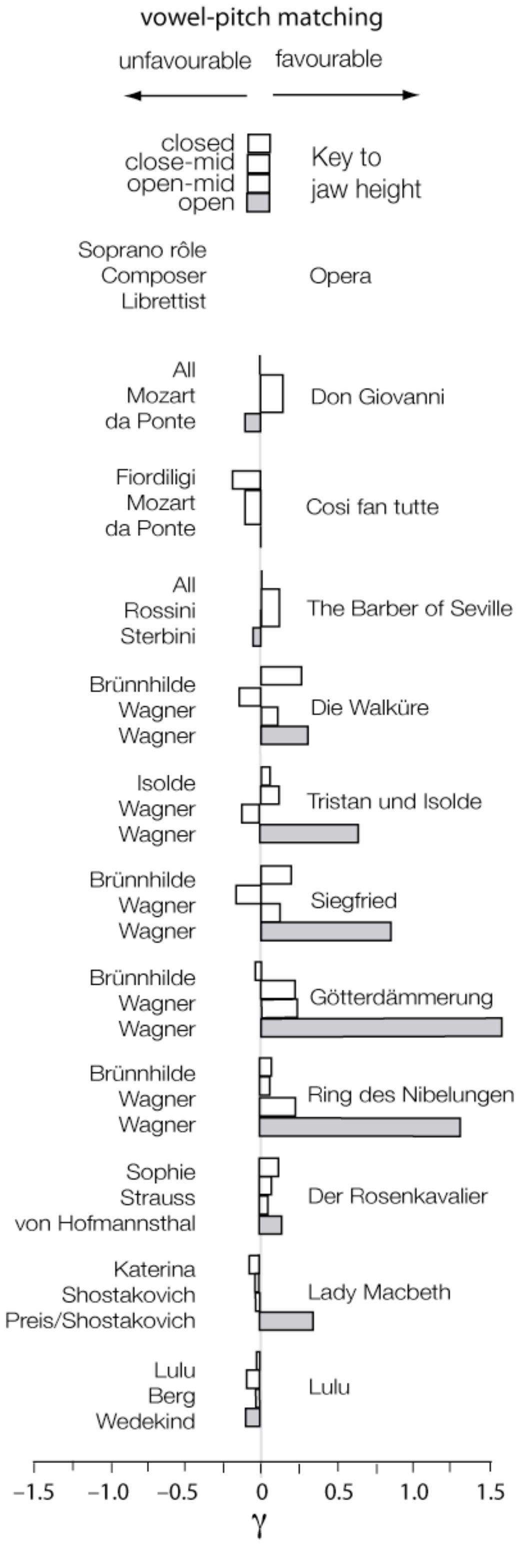

Figure 5. The extent of pitch-resonance matching for soprano rôles in the ten operas studied. The degree of matching for the pitch ranges corresponding to different jaw height is indicated by γ, a parameter that indicates the preference for the appropriate vowel-pitch combinations (see text). Positive and negative values of γ indicate favourable or unfavourable pitch-resonance matching respectively. Values associated with open vowels (high $R1$) are indicated by shading. The operas are shown in order of composition from top to bottom.

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