Resonance strategies used in Bulgarian women's singing style: a pilot study.

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Running title:

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Abstract:

Are the characteristic timbre and loudness of Bulgarian women's singing related to tuning of resonances of the vocal tract? We studied an Australian female singer, who practises and teaches Bulgarian singing technique. Two different vocal qualities of this style were studied. The louder *teshka* is characterised by a sonorous voice production. The less loud *leka* has a smoother timbre that is closer to that of the head voice register. Six vowels in each of *teshka*, *leka* and the subject's 'normal' (i.e. Western rather than Bulgarian) style were studied. The acoustic resonances of the singer's vocal tract were measured directly during singing by injecting a synthesised, broad band acoustic current. This singer does not use resonance tuning consistently in her classical Western style. However, in both *teshka* and *leka,* she tunes the first tract resonance close to the second harmonic of the voice for most vowels. This tuning boosts the power output in the radiation field for that harmonic. This tuning also contributes to the very strong second harmonic which is a characteristic of the timbre identified as the Bulgarian style.

Key words: Bulgarian singing, resonance tuning, vocal qualities

INTRODUCTION

In traditional Bulgarian music, the singers are predominantly women and the instrumentalists are predominantly men. Bulgarian women's songs traditionally come from work, seasonal rituals and festivities, which were essentially outdoor activities. The songs and singing styles vary among seven major ethnographic regions, but share characteristics across the nation. The characteristic singing voice features two different vocal qualities, sometimes referred to as *teshka* (meaning heavy) and *leka* (meaning light), which are utilised by women across most of Bulgaria, with minor regional variations. These qualities are the subject of the current study. *Teshka* corresponds to a loud, projected sound, and it tends to be used more in slower, sadder songs. *Leka* corresponds to a gentler, more lyrical sound, and to some extent, it shares timbral similarities with the classical female head voice used in Western European singing.

Many traditional Bulgarian songs have a limited pitch range. The typical tessitura for songs sung by groups in unison is only about a fifth (typically D4 to A4). The melodies of some traditional solo songs can have a pitch range of an octave or more, with a typical tessitura of C4 (262 Hz) to C5 (524 Hz) for a high (soprano) voice and A3 (220 Hz) to A4 (440 Hz) for a low (alto voice). (Since the 1950s, modern choral arrangements of folk songs for up to 6 female voices, using the authentic traditional vocal quality, have increased the overall pitch range of the songs, including all parts, to two octaves or more, with a typical group tessitura of D3 (147 Hz) to D5 (587 Hz).)

To unaccustomed ears, Bulgarian women's songs are surprisingly loud. Messner (1980) reported that a characteristic feature of the singing of women in the Bistritsa region was that the amplitude of the second harmonic usually exceeded that of the fundamental in pressure spectra. This feature may have an effect on the perceived timbre. However, an increase in the power ratio of the second harmonic to the first does not directly explain the loudness. This is because, for most of the range of the female voice, the sensitivity of the human ear is not very much greater at the frequencies of the second harmonic than it is at the frequencies of the fundamental (Robinson and Dadson, 1956).

What causes the unexpected strength of the second harmonic and the overall loudness? Although the source-filter model (Fant, 1960) is perhaps somewhat too simple for the subtleties of singing, it is helpful to ask whether the effect could result from the source spectrum of the vocal folds, the frequency response of the filter (i.e. the vocal tract), or a combination of the two. In a recent study (Joliveau et al., 2004a,b), we showed that, over the upper part of their range, classically trained Western sopranos tune the lowest resonance of the vocal tract to match closely the frequency of the fundamental of the note being sung, as had been hypothesised by Sundberg (Sundberg, 1975; Sundberg and Skoog, 1997). We have also reported that tenors and altos, singers whose fundamental frequency is in general lower than that of sopranos, sometimes tune the first resonance of the tract to match the second harmonic of the note sung, over part of their range (Wolfe et al., 2004).
Is it possible that Bulgarian women singers tune the lowest vocal tract resonance to the second (or another) harmonic of the note sung? Do they, like the singers we studied previously, vary the vocal tract geometry according to the pitch so that the vocal tract is a highly efficient impedance matcher for a low harmonic of the note sung?

This question cannot be investigated by examining the spectrum of the output sound alone. The spectrum of the voice for any one pitch has frequency components at the first harmonic H1 (i.e. the fundamental f_0) and integral multiples of it (i.e. the other harmonics: H2 = 2H1 etc). This gives only very widely spaced sampling in the frequency domain: the resonance frequency can only be estimated with a precision of the order of H1/2. For women singers, this gives an error about 100 Hz in the low range, and rather more at higher pitches. Much more detail on the frequency response of the vocal tract can be measured by injecting a synthetic broad band signal into the tract during singing (Joliveau et al, 2004a,b). The response of the tract to the injected signal can then be measured simultaneously with the harmonics of the voice. This technique can determine resonance frequencies to about 11 Hz.

Here we report the use of the injected sound technique to study the resonance strategies of a singer trained in the traditional and modern techniques of Bulgarian singing.

MATERIALS AND METHODS

Measurements of vocal tract resonances

The resonances of the tract were measured directly, during sustained sung notes, using a technique described previously (Epps et al., 1997; Dowd et al., 1998; Joliveau et al., 2004b). A small source of acoustic current and a microphone, connected side by side on a flexible mounting, were positioned just below the subject's mouth, where they gently touched the bottom lip throughout the experiment. A broad band signal with frequencies spaced at 5.38 Hz over the range 0.2—4.5 kHz was synthesised on a computer (Mac IIci with analogue interface card—National Instruments NB-A2100) and passed via amplifier, loudspeaker and horn to the current source. The microphone at the mouth measured simultaneously the harmonics of the voice and also the sound produced when the synthesised sound interacts with the vocal tract. This acoustic current acts on $Z_{//}$, the parallel combination of the acoustical impedance of the vocal tract Z_t and that of the radiation field Z_r outside the mouth. The value of Z_r is low but it increases with frequency. In a calibration stage, Z_r was measured on the subject with her mouth closed, and the frequency components of the acoustic current were adjusted so that the measured pressure spectrum p_{closed} was independent of frequency. The ratio $\gamma = Z_{//}/Z_r$ was then measured. The spectrum of γ shows peaks at the resonance frequencies of the tract (Dowd et al., 1998). The output impedance of the sound source is very much higher than that of the load. Consequently, a plot of the ratio of the broad band components measured during singing (p_{open}) to those measured during calibration (p_{closed}) shows peaks corresponding to the vocal tract resonances. The frequencies of the resonances may be measured to about ±11 Hz. The measured spectrum also shows the harmonics of the voice, superimposed over the broad band signal.

The subject for vocal tract studies

The subject sings and teaches Bulgarian singing technique. She is Australian, but has

learned from Bulgarian singing experts in Australia and Bulgaria. She has been singing Bulgarian songs (authentic traditional group and solo songs as well as choral arrangements of traditional songs) for the past 23 years. She has been training a choir of Australian singers in this singing technique for the past 16 years.
The six common vowel sounds in Bulgarian language were chosen: (/a/, /e/, /o/, /u/, /i/ and /œ/). The subject then sustained a note for about 4 s. All measurements were made without vibrato, which is used sparingly in this style of singing. Beginning at the low end of the comfortable range of the singer (at which the characteristic timbre was strongest), notes over an ascending diatonic scale were investigated for each vowel, in each case stopping near the comfortable upper limit. The corresponding pitches were F4, G4, A4 and B4 for *teshka*, F4, G4 and A4 for *leka*, and F4, G4, A4, B4 and C5 for head voice. A note was played on a glockenspiel to give the subject the desired pitch. The measurements were made in a room treated to reduce reverberance and sound transmission from outside.
For comparison, samples of spoken vowels were also investigated using the same technique.

RESULTS

[insert Figure 1]

Figure 1 shows two sound spectra for the vowel [e] on the note A4 sung first in the *head voice* and then in *leka* quality. The harmonics of the voice are clearly seen above the broad band signal of the simultaneous acoustical measurement. The peaks in the broad band signal identify resonances of the vocal tract. In the case of *leka* phonation, R1 coincides with H2 and contributes to the unexpectedly high relative level of that harmonic.

[insert Figure 2]

[insert Figure 3]

Figures 2 and 3 show the vocal-tract resonance frequencies R1 and R2 for the *teshka* and *leka* qualities respectively. A graph for each vowel plots R1 and R2 against the fundamental frequency H1. The dotted lines show the frequency of each of the harmonics of the voice, i.e. the lines H1 = H1, H2 = 2H1, H3 = 3H1 etc. The two horizontal lines drawn on each plot show R1 and R2 measured for that vowel in normal speech. We should expect that the formants (i.e. the broad peaks in the spectral envelope) for speech would lie close to these resonances.
We are particularly interested in the behaviour of the first resonance, R1, the resonance that is most strongly associated with vowel height (Fant, 1960; Sundberg, 1975). In both *teshka* and *leka*, R1 increases smoothly with increasing pitch for all vowels studied. The values are also similar, except for the vowel [u], where R1 is higher in *teshka* than in *leka*. Further, R1 is located close to H2 for the vowels [a], [e], [o] and [œ] and close to H1 for the vowel [i]. In the case of the vowel [u], the R1 for *leka* is located close to H1 (like [i]) whereas for *teshka* R1 falls midway between H1 and H2, but still

increases with increasing pitch. In no case is R1 found below H1.

[insert Figure 4]

The results for this subject singing in her normal Western classical voice show no systematic tuning of resonances to harmonics (see Figure 4), except for [u] and [i].

DISCUSSION

The vocal range studied here was the part of the subject's range at which the characteristic timbre was strongest. This corresponded to the upper part of the subject's comfortable singing range for Bulgarian songs. The results clearly show that resonance tuning is used in both *teshka* and *leka*. In contrast to the resonance tuning we have reported for classically trained (Western) sopranos (Joliveau et al, 2004a,b), the tuning here usually involves the second harmonic, rather than the first. This is probably determined largely by the tessitura involved. The sopranos in that study tuned R1 when H1 was above about 400 or 600 Hz (above about G4 or D5), depending on the vowel. The range for Bulgarian women's singing (and the comfortable *teshka* and *leka* range for this subject) rarely exceeds 600 Hz (D5).

For most of the vowels, R1 for speech falls somewhere near H2 for some part of the singing range, so tuning of H2 is practicable, especially given the modest range of traditional songs.
For both *teshka* and *leka*, the first resonance is tuned close to the second harmonic for the vowels [a], [e], [o] and [œ], which have high R1 in speech (and which are classified phonetically as 'mid' or 'low' vowels). For [u] and [i], which have a low R1 in speech ('high' vowels), R1 is found closer to H1. The data also suggest that R1 might be tuned to H1 for [u] and [i] in *leka*, and also the head voice. For [u] in *teshka*, while R1 rises with increasing H1, it is not tuned.
In a few cases, R2 rises with increasing H1 (for the vowels [a], [o], [u] in *teshka a*nd [u] in *leka*), but does not simply tune to one of the harmonics. This may be an incidental effect of tuning R1 (see Joliveau et al. 2004b where a similar effect was seen for sopranos). The higher resonances show no strong or consistent dependence on pitch.

The tuning of R1 to H2 for most vowels offers an explanation for the observation by Messner (1980) and Kiek (2005) that Bulgarian women's singing is characterised by a second harmonic that is usually substantially stronger than the fundamental. The enhanced output power of H2 due to resonance tuning would increase the power ratio of H2 to H1.

The upper vocal tract (from glottis to mouth) may be considered as a variable waveguide connecting the vocal source at the glottis to the radiation field outside the mouth. Because of the geometry and size, the acoustic impedance at the glottis is much higher than that of the radiation field. Under appropriate conditions, the upper vocal tract may act as an

impedance matcher between the two, serving to increase the radiated power (Fant, 1960). It does this most effectively near its resonances. Consequently, tuning R1 to H2 may increase very considerably the output power of that harmonic.
This enhanced power in H2 not only contributes to the unusual timbre of the Bulgarian singing voice, but it also increases the total radiated power, in a frequency range where the human ear is sensitive and therefore also contributes to the overall loudness of the voice.
The differences between *teshka* and *leka* do not result from differences in resonance strategy (except for [u]), but may result from different behaviour of the glottis.
The speed of closure of the glottis is known to affect both the sound pressure level and the spectrum of the voice: the quicker the closure, the higher the sound level and the greater the power in high frequencies. It is possible that *teshka* may be produced with a more rapid closure and a longer closed phase than in the case of *leka*, while the latter may share glottal behaviour similarities with the head voice. The contribution of glottal behaviour to the characteristic timbre is under study.

In the Bulgarian language, R2 is arguably more important than R1 in vowel distinction. The six vowels come in 3 pairs, with each pair having a characteristic level of fronting. This phonetic parameter corresponds predominantly to differences in R2. The distinction within each pair is by vowel height, which corresponds predominantly to differences in R1. Although formal speech distinguishes the vowels within each pair, this distinction is substantially reduced in dialects of Eastern Bulgaria, especially in informal speech. Further, in a language with 33 phonemes, of which only 6 are vowels, the loss of this distinction within pairs could be argued to be less serious than in some other languages. Consequently, tuning R1 loses relatively little information and so there is little perceptual cost to be offset by the considerable gain in radiated power.

CONCLUSION

Resonance tuning is used by our subject in both the *teshka* and *leka* qualities of Bulgarian women's singing. It is used over all of the limited range of the songs usually sung in this style, i.e. between F4 and B4 in the present case. In contrast to the resonance tuning previously reported for classical sopranos, Bulgarian singing technique usually tunes the first resonance (R1) to the second harmonic (H2) for most vowels. This is probably determined largely by the tessitura involved. The development of resonance tuning in this singing style may be related to the relatively low importance of vowel height in some dialects of Bulgarian. Tuning of the vocal tract resonance contributes to the predominance of the second harmonic in Bulgarian women's singing in these styles, to its characteristic timbre and to the high sound levels achieved.

ACKNOWLEDGMENTS

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FIGURES

Figure 1: Spectrum of γ measured for singing with a head voice phonation (top panel) and a leka quality (bottom panel) for vowel [e] and pitch A4. Harmonics (H1 = f_0, H2 = $2f_0$, H3 = $3f_0$ ...) are measured simultaneously with (and so appear superimposed over) the response to the broad band signal. Vertical arrows indicate the frequencies of the vocal tract resonances (R1 to R3). Bottom panel illustrates R1 being tuned to H2 in the leka quality with a consequent increase in relative magnitude of H2 with respect to H1.

Figure 2: Resonance frequencies measured in the case of phonation with a teshka quality for the six vowels and the four pitches (F4, G4, A4, and B4). Horizontal lines indicate the frequencies R1 and R2 for normal speech. Harmonic lines ($f = n*f_0$, where n is an integer) are indicated with dotted lines.

Figure 3: Resonance frequencies measured in the case of phonation with leka quality for the six vowels and three pitches (F4, G4, and A4). Horizontal lines indicate the frequencies R1 and R2 for normal speech. Harmonic lines ($f = n*f_0$, where n is an integer) are indicated with dotted lines.

Figure 4: Resonance frequencies measured in the case of head voice phonation for the six vowels and five pitches (F4, G4, A4, B4, and C5). Horizontal lines indicate the frequencies R1 and R2 for normal speech. Harmonic lines ($f = nf_0$, where n is an integer) are indicated with dotted lines.

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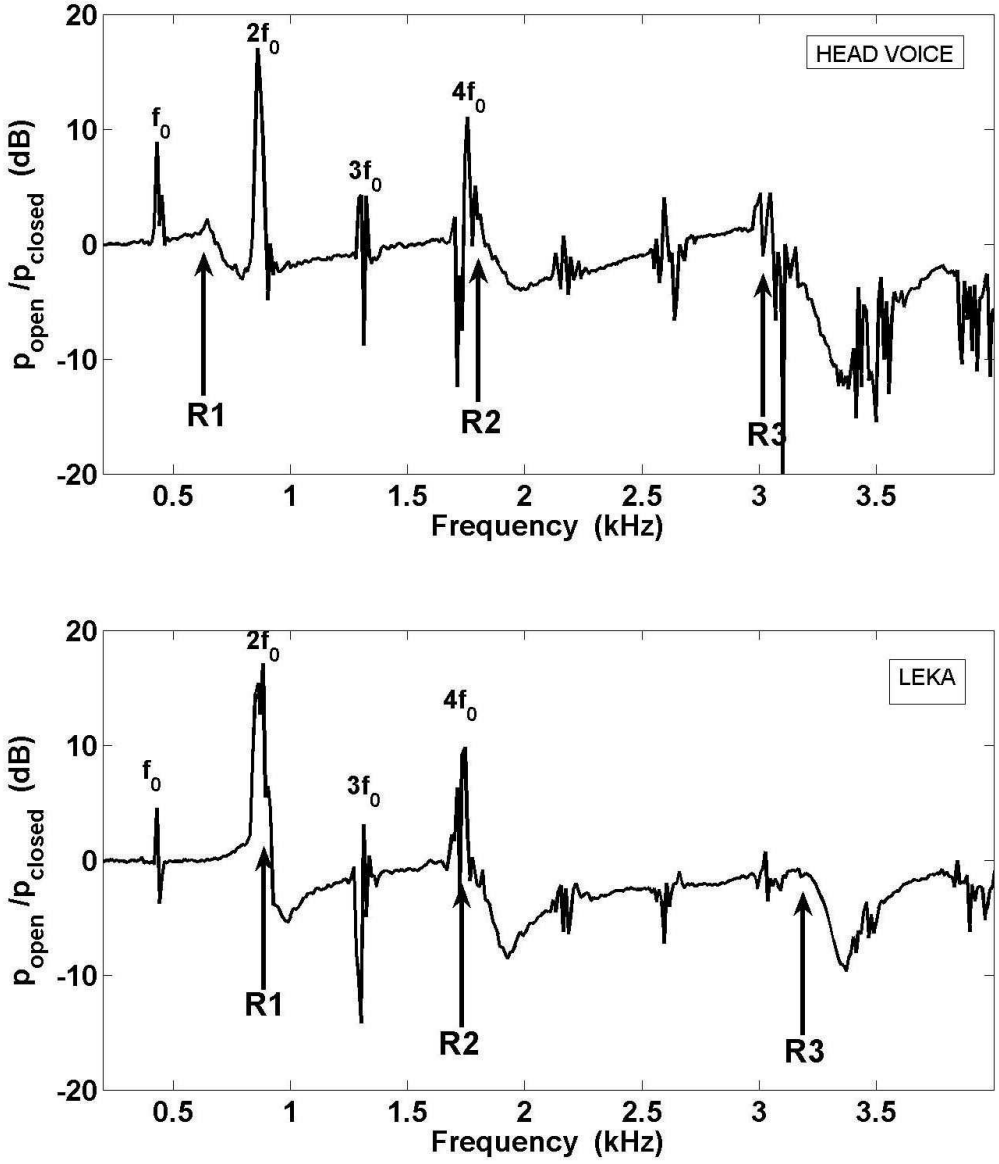

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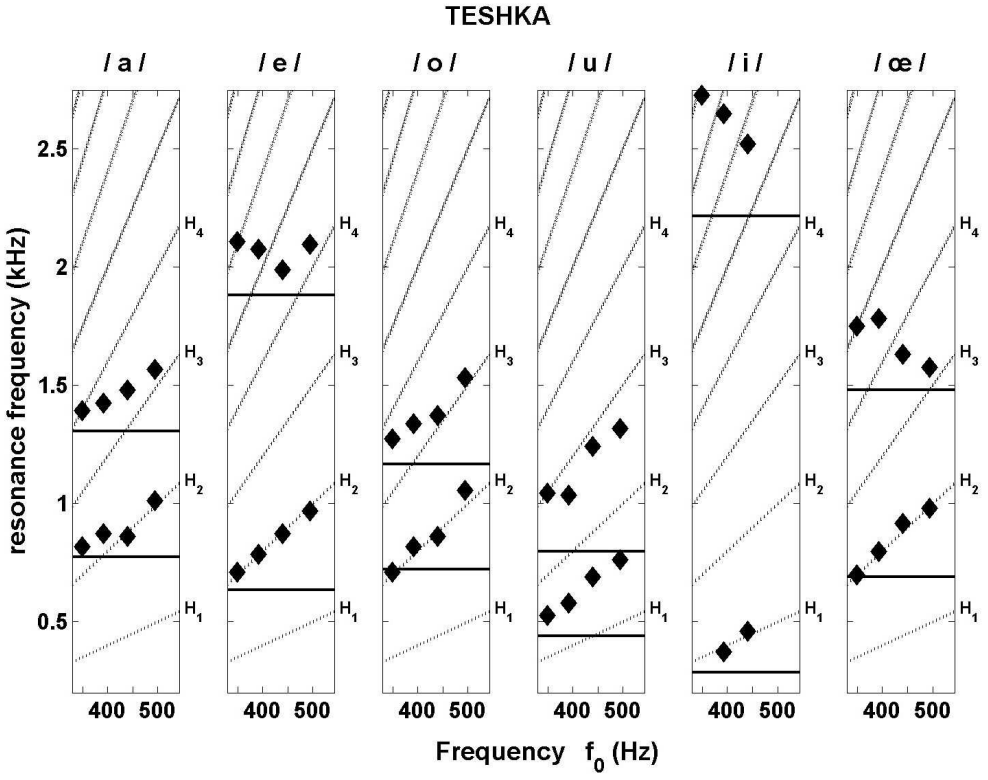

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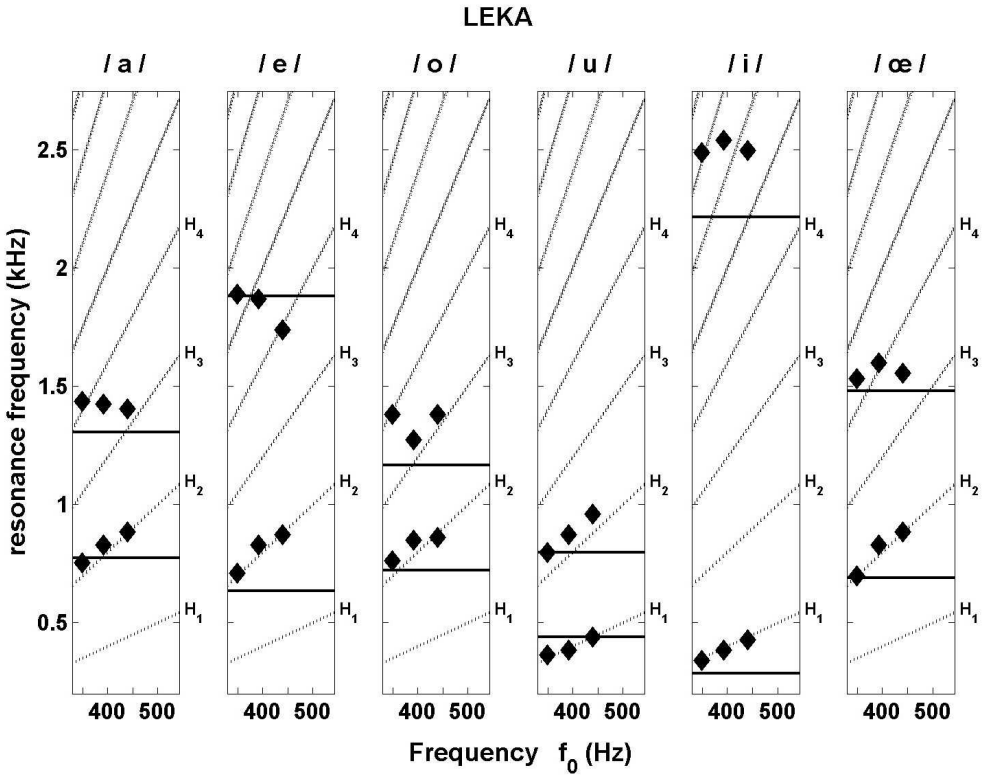

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