The tuning of vocal resonances and the upper limit to the high soprano range

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ABSTRACT

The upper limit of the useful range for many sopranos is around C6 or 'high C'. Others can extend their range well above this. This study investigated how sopranos use the resonances of their vocal tracts in the high and very high ranges. Twelve sopranos (4 non experts, 4 advanced, 4 professionals) produced *glissandi* up to their highest note (from 1000 to 2300 Hz). Later, they sustained pitches on [a] vowels, from A4 (~440 Hz) to their highest sustainable note, while the frequencies ($R1$ and $R2$) of the first two vocal tract resonances were measured by broadband excitation at the mouth. Adjustment of $R1$ near to f_0 ($R1$:f_0 tuning) was observed below C6 for both expert and non-expert singers. Experts began this tuning at lower pitches. Some singers also exhibited $R2$:2f_0 adjustment over the lower part of the $R1$:f_0 tuning range. In the very high range (above C6), the singers used one of two strategies. Some extended the $R1$:f_0 tuning as far as E6 or F#6. Others adjusted $R2$ near f_0 over the highest pitch range (up to D7). The limit of the sustainable range corresponded to the end of these resonance tunings. This suggests that the upper limit of their useful singing range may be determined by the upper limit of a resonance tuning mechanism. Further, it seems likely that, for some sopranos, learning $R2$:f_0 tuning might extend the practical upper range.

INTRODUCTION

The normal soprano voice range approximately coincides with the range of the first resonance of the vocal tract and sopranos often tune this resonance to the note sung [12]. What happens in the range above, in the territory above high C? With the assistance of a panel of subjects specialised in the high range, we measured their resonance techniques and articulation.

Singing range and registers

A minimum range for a chorus soprano is C4 to G5. Many sopranos – and many solo soprano roles and music parts – sing up to about C6, the 'high C' for sopranos. The range of coloratura sopranos extends substantially higher. The Queen of the Night in Mozart's *The Magic Flute* has several brief notes on F6. Some jazz and pop singers (including Georgia Brown and Mariah Carey) routinely sing well above C6.

Singers often refer to chest, head and whistle or flageolet registers. The 'chest' to 'head' register transition corresponds to the transition from laryngeal mechanism M1 to M2. In mechanism M1, a larger fraction of the mass of the vocal folds is involved in the vibration than in M2. In M1 but not M2, the vibrating mass includes parts of the vocalis muscle. The transition from M1 to M2, in both men and women, can occur over a range from about G3 to G4 and is often varied substantially by singers to avoid awkward transitions with a musical phrase [1-7].

Relatively little is known about the mechanism associated with the whistle register, perhaps because relatively few singers are able to sing in the very high range with which it is associated.

Resonances and resonance tuning

The upper vocal tract, from the vocal folds to the lips, has several resonances ($R1$, $R2$, … Ri) which, in normal speech, produce spectral peaks. Values of the frequencies of the first two or three of these are associated with different vowels [8,9]. $R1$ typically has values from about 200 to 1000 Hz and $R2$ from about 800 to 2200 Hz.

The range of $R1$ corresponds approximately with the high range of the soprano voice. Classically trained sopranos usually increase the size of the mouth opening as notes increase in pitch over a range that extends from below C5 to about C6 [10,11]. This allows them to tune $R1$ to the note sung over this range [12,13]. As well as enhancing the output power of the voice, models suggest that this tuning may have the further advantage that standing waves in the tract may aid or stabilise the vocal fold vibration [14,15].

Figure 1 shows the typical ranges of $R1$ and $R2$ against the range of the fundamental f_0 and second harmonic 2f_0 for the soprano range. Over the range up to about C6, $R1$ may be tuned to f_0. ($R1$ may alternatively be tuned to 2f_0, and this is practised in some women's singing styles at lower pitches than studied here [16, 17].)

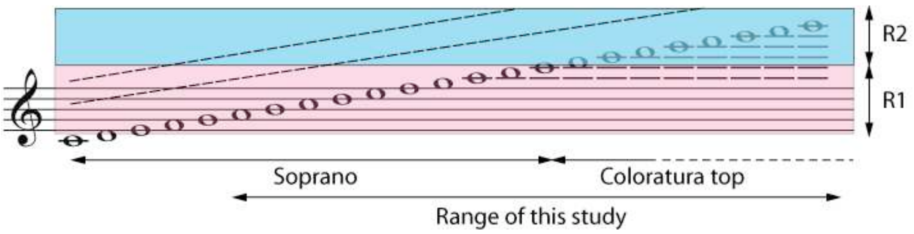

Figure 1. Ranges over which resonance tuning by sopranos is possible. The two shaded boxes show the approximate ranges of the first two vocal tract resonances, $R1$ and $R2$. The dashed lines show the second and third harmonic to which, in principle, $R1$ or $R2$ might be tuned. The range expected of a soprano soloist is indicated: from C4 to C6 (sopranos' 'high C'). The coloratura top range extends this by a variable amount. The range above F6 (the high note demanded of Mozart's *Queen of the Night*) is shown with a dashed line. This study commenced on A4, avoiding the low range to allow for a concentrated study on the high range. The upper limit of D7 was that of the subject who could produce the highest note.

What happens above C6, that is, above about 1 kHz? Can sopranos tune $R1$ above 1 kHz (and thus to wavelengths less than 340 mm)? Or do they use $R2$? In either case, what articulations do they use to achieve these tunings? Are the limits of singing range related to the possible range of resonance tuning? These were the questions that inspired the current study.

MATERIALS AND METHODS

Subjects

Twelve sopranos who could sing C6 or above volunteered as subjects for the study. Four were young professionals, with 7-13 years of training and 1-4 years of professional experience. They are identified as PR1 to PR4 below. Four were advanced students (AD1 to AD4), with 6-10 years of training. Of four classed as non-expert (NE1 to NE4), one had trained but had not sung for 7 years, the other three had experience in choirs and two of them some singing lessons.

Techniques

Each singer first sang a *glissando* on the vowel [a], gliding smoothly upwards to the limit of her range. This was followed by a descending glide. These were repeated twice or more. The *glissandi* gave a measure of the highest note that could be (briefly) produced. In seven cases, this upper limit was above the highest note that could be sustained. Discontinuities in the *glissandi* can indicate transitions between mechanisms.

After the glissandi, each singer sang a series of single notes on the vowel [a]. Each note was sustained for 4 s, with no change in loudness or pitch and limited vibrato. They began on A4 and continued upwards, diatonically, to the highest note that they could produce.

The vocal tract resonances were measured using broad band excitation at the mouth [13,18]. A flexible tube of inner diameter 6 mm provided a source of acoustic current. The tube and a microphone (Brüel and Kjær 4944-A) were placed on a stand positioned so that both the end of the tube and the microphone rested against the singer's lower lip. The microphone signal was pre-amplified (Brüel and Kjær Nexus 2690) and digitised using a Firewire interface (MOTU 828). The flexible tube was connected via a horn to a loudspeaker that was driven with a synthesised broadband signal. The broad band signal consisted of a sum of sine waves between 200 and 3000 Hz, spaced at 10.77 Hz (= 44.1 kHz/2^{12}). In a calibration measurement with the singer's mouth closed, the amplitudes of the components are adjusted so that the microphone signal is independent of frequency. The same signal is then used for all measurements. Because the tube approximates an ideal current source, the ratio of the pressure components measured with mouth open to that with mouth closed measures the ratio of the impedance of the vocal tract, seen from the mouth, in parallel with that of the radiation field, to that of the radiation field. We call this impedance ratio γ. The spectrum of a microphone recording includes the narrow harmonics of the voice signal superimposed on the broad band signal result from the interaction of the injected acoustic current with the vocal tract and radiation impedance. Peaks in γ were identified visually and used as measurements of the resonances of the tract.

A second microphone, similar to that described above, was placed 300 mm in front of the singer. Its signal was similarly amplified and digitised.

A camera in front of the singers recorded video images of each experiment at 25 images per second. To calibrate pixel measurements in these images, an image of a measured grid was also made in each experiment. Because of the tube resting on the lip, forward and backward movement of the singers was limited. Some such movement did occur, however, and thus introduced a small possible error into these measurements. The inner contour of the lips was used to obtain the lip opening area.

RESULTS AND DISCUSSION

Figure 2 shows experimental results in which the broad band excitation shows different examples of resonance tuning. The first, Figure 2(a), shows a measurement made as a singer sang 'ah' at B4, a note near the middle of the standard soprano range, with no relation between the harmonics f_0, $2f_0$, $3f_0$ etc and the resonances $R1$ and $R2$: in other words, no tuning. In (b), the singer has $R1 = f_0$, exhibiting the standard tuning that sopranos use over most of their high range, and occasionally over the upper part of their bottom octave.

How high can $R1{:}f_0$ tuning be taken? Figure 2(c) shows $R1{:}f_0$ tuning with one of the highest values of $R1$ that we have ever measured. In this example, this singer sang E6 with $R1$ at 1.3 kHz. At this frequency, the wavelength is 260 mm. A simple closed-open pipe having a first resonance at this frequency would have a length of about 65 mm, an open cone would have a length of 130 mm. Few vocal tracts are this short. Of course, the vocal tract is not a simple geometric figure. But these values do prompt the question: what to do above the range of $R1{:}f_0$ tuning?

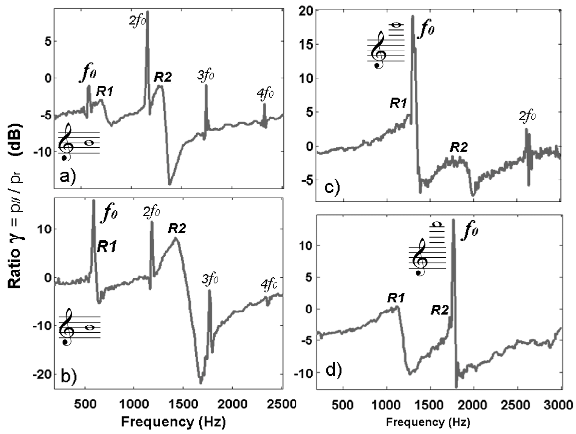

Figure 2. Four examples of resonance measure-ments using broad band excitation at the mouth. In (a), there is no simple relation between the resonances Ri and the harmonics nf_0. In (b), a singer sings the same note (B4) but tunes $R1$ to f_0. (c) shows a soprano at the top of her range (E6). She is still tuning $R1$ to f_0., with a value close to the highest we have ever measured for $R1$. In (d), the note (A6) is too high for $R1$:f_0 tuning. Here, a different soprano has tuned the *second* tract resonance, $R2$, to f_0.

Figure 2(d) shows one response. This singer sings A6 and has tuned $R2$ to f_0. Even in speech, $R2$ for women can go well beyond 2 kHz [20], in principle offering a range of $R2$:f_0 that would extend above C7 – more than an octave above 'top C'.

In a very limited analogy, we could compare this to playing a woodwind instrument. Using the first mode of vibration of the duct ($R1 = f_0$), the player ascends the first register by successively shortening the resonator (increasing $R1$). When there are no more keys to open (and no resonator key, let's insist) the player increases the natural frequency of the reed/air jet still further until it is driven by the second mode of vibration in the duct. The player then ascends the second register.

The analogy is limited, of course: in woodwinds, a standing wave in the resonator usually 'drives' the reed/air jet whereas, in low voices, the Ri and f_0 may be varied almost independently (the vowel and pitch are independent) [21]. In the high soprano voice, where the ranges of $R1$ and f_0 are similar, the independence of the two is not obvious: models [19] indicate the possibility of driving the valve near a duct resonance. Further, $R1$:f_0 tuning is not limited to trained singers, but is practised by sopranos with no formal training as well [20]. In the highest range, where singers find it most difficult to sustain aero-acoustic vibration at the glottis, perhaps it is necessary, or at least very helpful, to tune a resonance to the fundamental frequency. What were the limits of tuning ranges in this study?

*R*1:*f*₀ tuning

Figure 3 shows, for each singer, the ranges used for resonance tuning. It also shows the upper limit of the range achieved on both sustained notes (solid lines) and *glissandi* (dashed lines). The data $R1(f_0)$ and $R2(f_0)$ are shown for each singer in Figure 4.

For two of the non-expert singers, $R1$ lies near f_0 only for a few notes: all others practised $R1$:f_0 tuning over a substantial range. All singers used this tuning near C6, but the advanced students and professionals began the tuning (for this vowel) at lower pitches (B4 to D5). That two inexperienced singers used the tuning is interesting, as it shows that $R1$:f_0 tuning is not necessarily a technique acquired after advanced training.

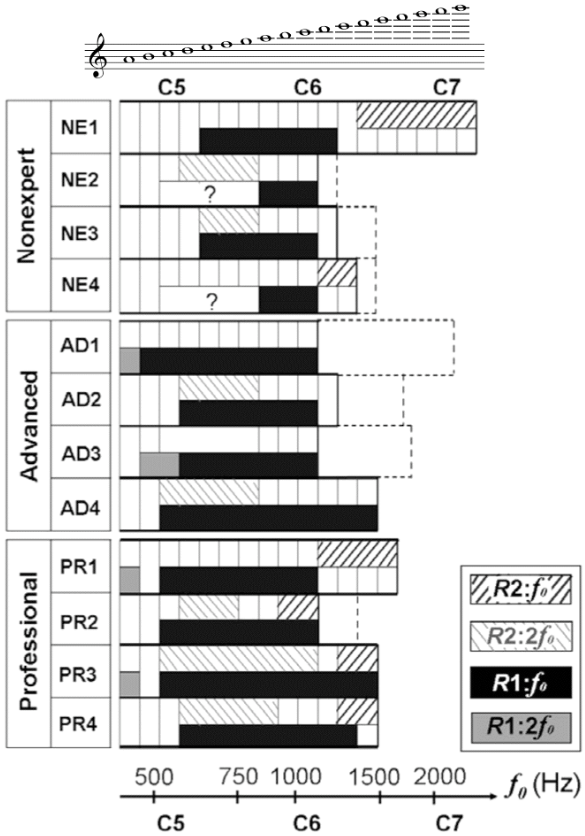

Figure 3. Over the range of this experiment (A4 to D7), this figure summarise the resonance tuning strategies of all singers. Solid lines show notes that can be sustained, dashed lines indicate the limit of pitches achieved only briefly in a *glissando*. For each singer, the upper and lower rows show respectively the tuning of $R1(f_0)$ and $R2$. For these singers, these resonances are tuned to the fundamental f_0, to the second harmonic $2f_0$, or to neither. Note that, with one exception, the singers who can sing above D6 use $R2$:f_0 tuning either sometimes (PR3) or always (NE1, PR3, PR4) for their highest notes. The exception is AD4, who extends $R1$:f_0 tuning to 1400 Hz.

How closely are resonances tuned to one of the harmonics?

One important consideration is whether a resonance is tuned higher or lower in frequency than the nearest harmonic, as this will can make the acoustic load on the vocal folds caused by the vocal tract to be inertive or compliant respectively. Models [15,19] suggest that this has implications for the amplitude and stability of vocal fold vibration.

Figure 5 shows a histogram of $R1 - f_0$, the difference in frequency between the first resonance and the fundamental frequency. It is apparent that the resonances in these experiments are most commonly tuned to within ±2.5 Hz of the fundamental frequency. In this data set there were 87 measurements with $R1 > f_0$ and 103 measurements with $R1 < f_0$. Averaging over the population, $R1 - f_0$ was slightly negative, but the difference was smaller than the precision we claim for $R1$ measurements (about 11 Hz). It would only require a small systematic error in our estimates of the resonance frequencies to shift the distribution.

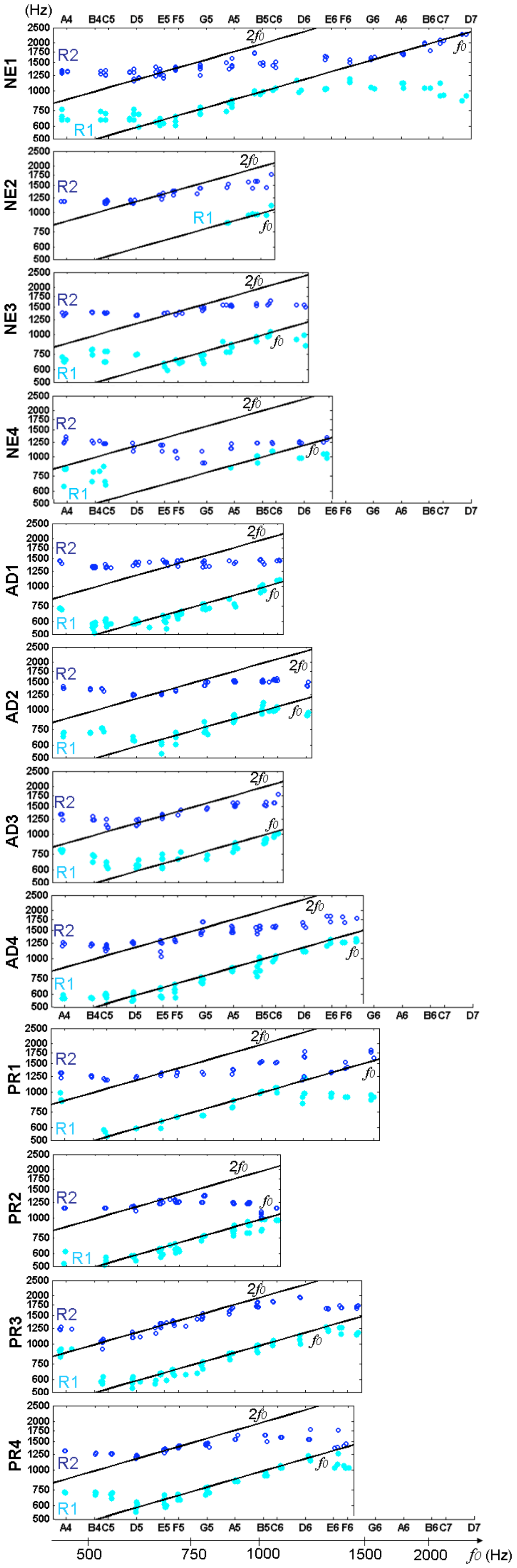

Figure 4. The resonances $R1$ and $R2$ as functions of frequency for each subject on a log-log graph. The diagonal lines indicate the relationships $R1 = f_0$ and $R2 = 2f_0$.

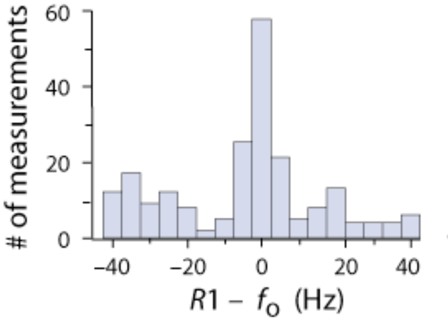

Figure 5. A histogram of the difference in frequency between the first resonance and the fundamental frequency over the range ±40 Hz. The data have been combined from all 12 singers.

R2:f_0 tuning

Six of the singers used $R2$:f_0 tuning, that is, at very high pitches, they tuned the second vocal tract resonance to the fundamental of the note sung. This group included all the professionals and also all of the singers who could sustain notes above D6.

Only one singer who could sustain notes higher than D6 did not use $R2$:f_0 tuning. That singer (advanced student AD4) could sing to F6 using $R1$:f_0 tuning. This involved raising $R1$ to 1400 Hz. Two other subjects could raise $R1$ to 1300 Hz.

Articulation in the high range

What articulation do singers use to achieve resonance tuning? This question is particularly interesting for those singers who could tune $R1$ to 1300 Hz or above. An obvious way to increase the resonance of a duct that is open at the mouth is to increase the mouth opening but there are limits to the possible extent of opening (see [20] for some measurements). Constricting the opposite end of the tract would also be expected to raise $R1$.

The principal articulation usually associated with $R1$:f_0 tuning is mouth opening [10,11]. Figure 6 shows $R1$ plotted as a function of mouth area measured from the video images for two singers. Ten of the singers showed a similar correlation between $R1$ and area that was significant at the 0.1% level or better. The equation of best fit to the combined data from these 10 singers (370 measurements) was

$$(R1/\text{Hz}) = 510\ (\pm 20) + 500\ (\pm 30) \times (\text{area/mm}^2).$$

However, it is immediately apparent that R1 is determined by more than simply the open mouth area. For example figure 6 shows that singer PR4 was able to vary $R1$ from 700 to 1050 Hz while keeping the area constant around 700 mm^2. Some singers appeared to be able to vary $R1$ independently of mouth area. – see Fig 7 where singer AD3 adjusted $R1$ over a wide range while keeping the area below 500 mm^2. Figure 7 provides a different example where $R1$ was maintained constant while the area almost doubled.

These singers must have used a different articulation, perhaps raising $R1$ by constricting the lower tract. These different articulation strategies may be responsible for the different timbres in the cases of singers who were able to produce different voice qualities over the lower range of $R1$:f_0 tuning [20].

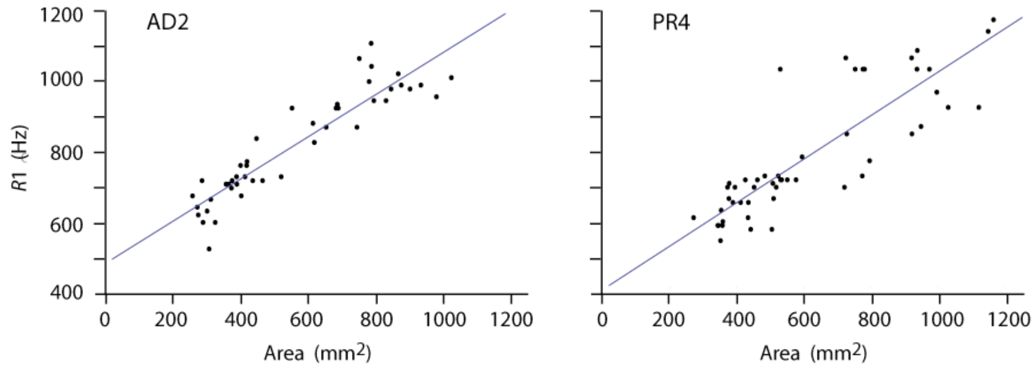

Figure 6. $R1$ as a function of measured mouth area for two singers. The diagonal lines indicate the line of best fit to the data for that singer.

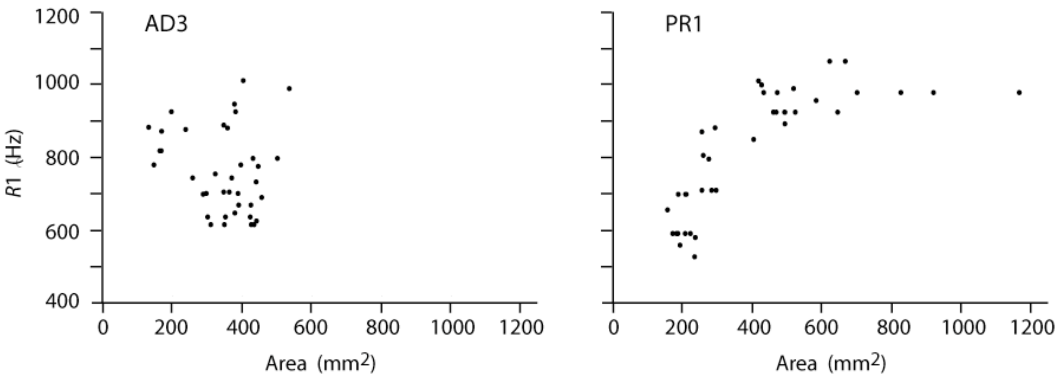

Figure 7. $R1$ as a function of mouth area for two singers for whom $R1$ did not depend simply upon the measured mouth area.

The $R1$:f_0 to $R2$:f_0 transition

For three professionals (PR1, PR2 and PR4) and one inexperienced singer (NE4), the transition from $R1$:f_0 to $R2$:f_0 tuning occurred on successive diatonic notes. For these singers, we could almost use the 'woodwind register key' analogy mentioned above: once they could no longer increase $R1$, they switched abruptly to $R2$.

Non-expert NE1, however, sang one or two diatonic notes between the ranges of $R1$:f_0 and $R2$:f_0 tuning. These notes had sound levels several dB lower than those in the tuning regimes above and below.

$R1$:f_0 and $R2$:f_0 tuning are not exclusive in the high range: Figure 4 shows that PR3 and PR4 are able to use either mechanism for notes D6 and/or E6, notes at the limit of their range.

Two of the non-experts and all of the advanced students did not use the $R2$:f_0 tuning. Let us consider the high range limit of this group, but omit AD4, who was capable of $R1$:f_0 tuning up to F6. The other five (NE2-3, AD1-3) all ceased $R1$:f_0 tuning at C6. The highest note that they could sustain was either C6 or D6, although all could briefly produce higher notes in a *glissando*, in some cases several notes higher. It is tempting to speculate that, if these singers were to learn $R2$:f_0 tuning, they might be able to use it to stabilise vocal production in the range above C6.

CONCLUSIONS

Of these twelve singers, ten tuned $R1$ to f_0 over parts of their upper range. These included two inexperienced singers. The professionals commenced $R1$:f_0 tuning at lower pitch. Over the tuning range, there was no systematic displacement of $R1$ from f_0. Some could continue $R1$:f_0 tuning a few notes above C6 ('high C'), one tuning $R1$ as high as 1400 Hz.

Of those who could sustain notes above D6, all could tune $R2$ to f_0, one continuing this $R2$:f_0 tuning to D7. The professionals were able to switch from $R1$:f_0 to $R2$:f_0 tuning from one diatonic note to the next.

ACKNOWLEDGEMENTS

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