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# Resonance Tuning in Three Girl Choristers

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**Summary: Objective.** The phenomenon of resonance tuning, whereby a singer modifies the shape of their vocal tract to increase the acoustic power output, is commonly exploited across large pitch ranges by professional sopranos and has been observed to a lesser degree in nonexpert adult singers.

This study considers the employment of two common resonance tuning techniques in experienced child singers; tuning the first vocal tract resonance to the fundamental ($R_1$: $f_o$) and tuning the second resonance to the second harmonic ($R_2$:2 $f_o$).

**Methods.** Wide-band excitation at the subject's mouth during singing was used to measure the vocal tract resonances of three girl choristers, and vowel formant values in speech were extracted from samples of spoken text.

Measured resonance values were cross-referenced with first and second harmonics for sung vowels across the subjects' ranges to identify the resonance tuning techniques employed, and these results were compared with those previously observed by others in professional adult classical singers.

**Results and Conclusions.** There was clear evidence that the subjects employed resonance tuning techniques comparable with the strategies used by adult singers. The protocol and results presented here pave the way for further studies exploring the development of resonance tuning techniques in young soprano voices, with the potential to impact on approaches to classical singing training in the future.

**Key Words:** Formant–Resonance–Tuning–Chorister–Singing.

## INTRODUCTION

Voiced sounds are produced when the harmonic signal produced by the larynx is passed through the vocal tract. The resonances of the vocal tract ($R_i$) give rise to broad peaks in the spectrum of the acoustic output of the voice, which are generally known as "formants" ($F_i$). For adult soprano singers, the first and second formants in speech typically lie between 310 and 860 Hz and 920 and 2790 Hz (D#4 and A5, and A#5 and F7), respectively.[1] At the upper end of the soprano range, therefore, where the fundamental frequency can exceed 1000 Hz, it is not only possible but highly likely that the fundamental frequency will fall above the first and possibly the second formant.

If all the harmonics of the voice source fall above the resonances of the vocal tract, there will be little or no acoustic energy in the frequency range of the resonances. This implies that not only will the production of sound be much less efficient, as some resonances of the vocal tract are not being utilized to their full potential, but it is likely that the vowel will be harder to identify,[2] as there is little or no spectral energy at the resonant frequencies.

Both male and female children have similar vocal ranges to adult females[3]; therefore, it could be assumed that similar difficulties in both the production and the perception of singing at high fundamental frequencies will be observed in children's singing as in that of adult sopranos.

Resonance tuning is a technique known to be used by adult sopranos,[4–7] whereby singers modify the shape of their vocal tracts to change its resonant frequencies[8]; "tuning" a vocal tract resonance to just above a harmonic enhances the amplitude of that harmonic, allowing the singer to produce more acoustic power without requiring an increased airflow, thus improving the acoustic efficiency of the voice.[9] Since children have shorter vocal tracts than adult females, their vocal tract resonances are higher by approximately 20%[10,11]; however, because children are also generally able to sing at a higher range of pitches, they can be expected to encounter similar effects as adult female singers as there will be a part of their range when the fundamental frequencies become higher than the first (and possibly also second) resonance.

Evidence of $R_1$:$f_o$ and $R_2$:2$f_o$ tuning has been observed in the upper part of the adult soprano range, as shown in Figure 1.[4,5] These tuning techniques were found to be employed extensively by professional singers, and also by advanced amateur singers, and to some extent by nonexpert singers (one had trained but had not sung for 7 years, the other three had experience in choirs and two of them had received some singing lessons).

The detection of resonance tuning in nonexpert singers, who all employed $R_1$:$f_o$ tuning over some part of their range, raises the question of whether resonance tuning is a technique unique to adult singers and learned with singing training and experience, or one which is also employed by young singers.

Previous work on developmental changes in children's voices has identified changes in the long-term average spectra of children's singing voices with age; Sergeant and Welch[12] found that children developed more acoustic energy in their voices below 5.75 kHz with age. They also found that the pitch range of children increases as they grew older. Howard and Graham[13] found that the relationship between the closed quotient of the vocal folds and the fundamental frequency changed as female choristers developed their singing, and there was a small increase in amplitude and dynamic range.

This experiment investigates how the use of resonance tuning manifests in young singers, by measuring the vocal tract resonances of highly experienced female choristers, and how their practices compare with those of adult singers.

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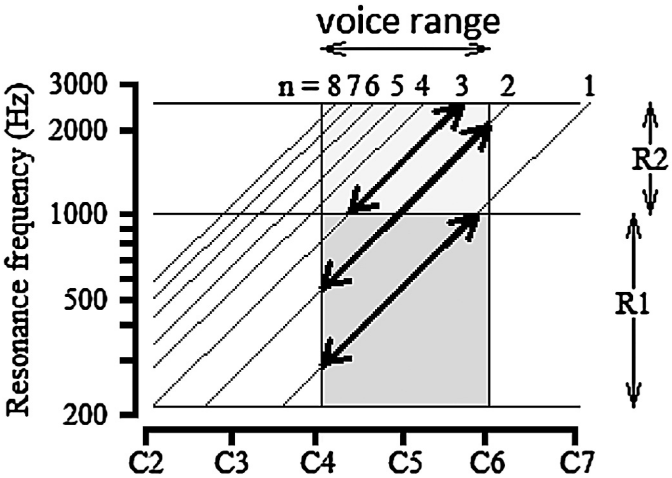



**FIGURE 1.** The possible resonance tuning strategies for soprano voice ranges on a log-log plot. Typical ranges of the vocal tract resonances $R_1$ and $R_2$ are shown in *dark* and *light grey*, respectively, and the *narrow diagonal lines* indicate when a resonance frequency coincides with the nth harmonic ($nf_o$) of the sung pitch ($f_o$), for the first eight harmonics, as identified at the top of the figure. The vertical lines indicate the typical soprano singing range. The *thick double-headed diagonal arrows* indicate possible tuning strategies, including those that have been measured or proposed (after[5]).

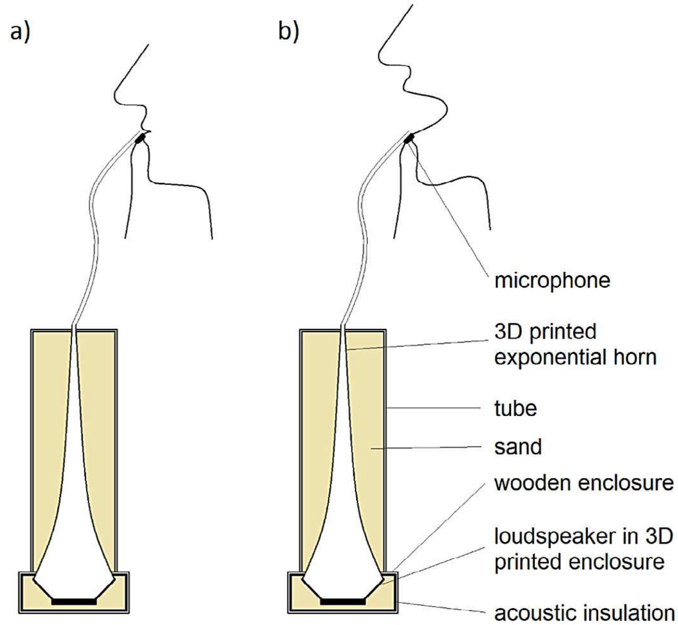



**FIGURE 2.** The equipment used to simultaneously play and record a signal at the subject's mouth using a 3D-printed impedance-matching horn and a microphone. The impedance-matching horn is enclosed in a wooden enclosure filled with sand. The flexible tubing allows the subject to position the acoustic source and microphone on their bottom lip.

## METHOD

### Subjects

The subjects chosen were two choristers from York Minster and one chorister from a well-respected local church choir. All three have singing lessons and perform regularly; the Minster choristers, 6 days per week; the Church chorister, at least twice per week. Details of the choristers are summarized in Table 1. Older choristers were chosen (York Minster choristers are aged 7–13 years) so that the effects of experience and training were most likely to be observed, based on the current understanding of increased resonance tuning with singing experience in adults.[4] Female subjects were chosen so that any resonance strategies employed could be compared with those of their adult counterparts. The subjects chosen all had ranges up to around A5.

### Resonance detection

The method used to determine the resonances of the vocal tract, initially developed by Epps et al,[14] and used by others including Garnier et al,[4] Henrich et al,[5] and Joliveau et al,[6] involved exciting the vocal tract at the mouth with a synthesized broadband signal, and recording the response with a lavalier microphone also placed at the subject's mouth (see Figure 2). The experimental setup for this study is shown in Figure 2.

The excitation signal used here consisted of harmonics spaced 5.38 Hz apart, from 250 Hz to 3500 Hz, and phases adjusted to improve the signal-to-noise ratio.[15] The device was held by the subject, touching their bottom lip.

Using software developed by Henrich et al,[5] a calibration procedure was first carried out, which involved measuring the pressure response at the mouth with the subject's mouth closed ($P_{closed}$), and adjusting the amplitudes of the frequency components so that the signal strength of the microphone at the subject's mouth was independent of frequency. (The amplitudes of each frequency component in the input signal were adjusted so that

**TABLE 1.**
**Details of the Choristers' Ages and Singing Experience**

| Chorister | Age (Years) | Choir | Years as Chorister | Singing Lessons (Years) | ABRSM Exams* |
|---|---|---|---|---|---|
| 1 | 14 | York Minster | 6 | 3.5 | Grade 5 Singing |
| 2 | 15 | St Olave's Church, York | 9 | 3 | Grade 5 Singing, Grade 5 Clarinet, Grade 5 Piano |
| 3 | 13 | York Minster | 5 | 1.5 | Grade 4 Singing, Grade 3 Clarinet, Grade 2 Piano |

* The Associated Board of the Royal Schools of Music (ABRSM) is an examinations board and registered charity based in London, UK, which provides examinations in music at centers around the world. According to the UK Qualifications and Credit Framework, grades 4 and 5 are equivalent to a General Certificate of Secondary Education (GCSE), whereas grades 6–8 are equivalent to an advanced level (A level). (http://gb.abrsm.org/en/home).

the amplitude of each frequency component recorded with the subject's mouth closed became equal.)

This "calibrated" signal was then used as the excitation signal for the measurements taken while the subject sang the required note ($P_{open}$). Because the source approximates an ideal current source,[14] the ratio $P_{open} / P_{closed}$ measures the ratio of the impedance of the vocal tract to that of the radiation field (see Henrich et al[5]). The spectrum of the signal recorded at the subject's mouth therefore shows the harmonics of the voice source superimposed on the approximate transfer function of the vocal tract. In addition to being reliable for measuring vocal tract resonances, an advantage of this method is that it allows the subject to sing normally while the measurement is being taken. The average amplitude of the excitation signal was 95.9 dB, which introduced sufficient acoustic energy to get a reliable resonance measurement, but was low enough to allow the subject to hear themselves, to cause minimal interference.

Because the fundamental frequencies in speech are significantly lower than for most of the sung notes investigated in this experiment, it was possible to calculate the frequencies of the formants in speech (which are assumed to be equivalent to the vocal tract resonances) by analyzing a spectrum of the spoken voice for each vowel sound.

This allowed the vocal tract resonances in sung vowels to be compared with the average values in speech, and the harmonics of the voice, to find evidence of resonance tuning in sung vowels at high pitches and to determine if similar resonance tuning techniques were used by female choristers as by professional adult classical singers.

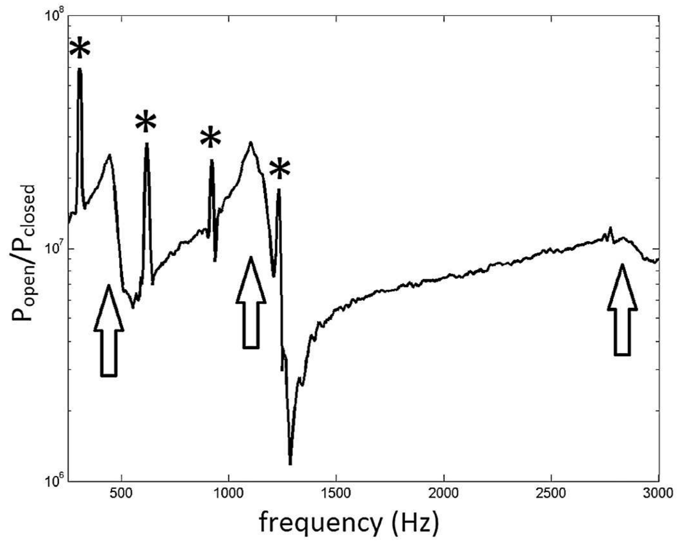



**FIGURE 3.** A plot of $P_{open} / P_{closed}$ against frequency for an /u/ vowel. The first four harmonics are marked with *asterisks*, and the resonances are marked with *arrows*.

**TABLE 2.**
**The Percentages (and Number) of Measurements Omitted for Each Resonance, for Each Vowel**

| Vowel | /ɑ/ | /i/ | /u/ |
|---|---|---|---|
| $R_1$ | 10.8% (9) | 14.5% (11) | 9.7% (7) |
| $R_2$ | 2.4% (2) | 27.6% (11) | 0% (0) |

### Experimental procedure

Subjects were asked to answer a short questionnaire about their singing experience, read an information sheet explaining the nature of the experiment, and sign a consent form. The subjects in this study were also accompanied by a parent/guardian at all times.

In the fully anechoic chamber at the University of York, the subjects were fitted with a head-mounted microphone (DPA 4066, DPA microphones) (approximately 4 cm from the lips), which was used to record the speaking task to find the formant values in speech. A second microphone (Earthworks M30, Earthworks microphones) was placed approximately 1 m from the subject, and this was used to record the entire experiment for later reference. These signals were recorded simultaneously during the entire experiment.

The first task was for the subject to read a short text in their normal speaking voice, and the subjects were given a "practice" attempt to familiarize themselves with the text. For the second task, the subject was asked to sing individual notes, each on one breath, in an ascending chromatic sequence (12 notes per octave) from C4 to the top of their range, on three vowel sounds (/ɑ/, /i/, and /u/), singing into the wide-band vocal tract measuring device. They were played each note on an electric piano in the anechoic chamber before it was sung and required to hold each note for approximately 6 seconds. The subjects were asked to sing in their "normal singing voice, as if you were singing a solo with your choir," keeping their mouth shape constant and at a medium volume. They were reminded if necessary during the tasks. Notes were only repeated if the measurement was insufficient or if the subject failed to maintain the note until the end of the measurement.

Data collected consisted of (1) answers to a questionnaire to determine the subject's level of singing, and their training, (2) their acoustic speech and singing recordings, and (3) recordings made by the broad-band vocal tract measuring device.

Prior ethical approval was gained from the Physical Sciences Ethics Committee at the University of York.

## RESULTS

### Data analysis

As in previous works,[4,5] the frequencies of the vocal tract resonances were measured manually from the plot of $P_{open} / P_{closed}$ against frequency by one author, and then checked by another researcher. An example plot of $P_{open} / P_{closed}$ against frequency is shown in Figure 3. In some cases, especially for closed vowels or when the subject did not remain completely still while singing,[a] it was not possible to accurately identify the vocal tract resonances. In these cases, the data were omitted from the results. The percentages and numbers of measurements omitted for $R_1$ and $R_2$ for each vowel are shown in Table 2.

[a]In some cases, this could be identified by observing the subject; however, movement of the subject also produced a characteristic error in the measurement, which allowed the movement to be detected.

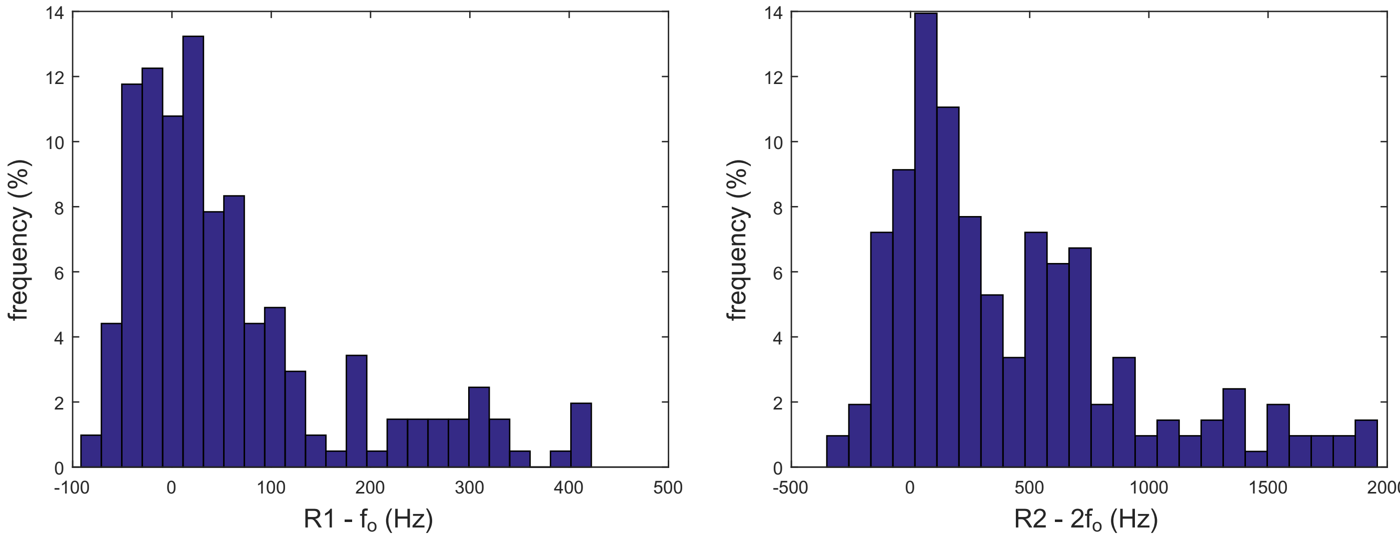



**FIGURE 4.** Histograms showing the distribution of the difference between the measured values of $R_1$ and $f_o$ (left), and between $R_2$ and $2f_o$ (right).

## Speech formant measurements

The values of the speech formants were calculated from the recordings of the choristers reading a short text. The average reading rates of the choristers were 234, 242, and 174 words/minute. Samples including the relevant vowels were extracted from the audio signal by hand: the samples chosen were from the middle of the vowel, where the formant values remained approximately constant across the entire sample. These samples were then analyzed using *Praat*,[16] and then collated using *Microsoft Excel* (Microsoft). Between two and six values were obtained for each formant measurement, and the average and standard deviation of these were calculated and shown on the left sides of Figure 6a–c.

## Resonance measurements

Henrich et al[5] identified resonance tuning in adult voices by plotting a histogram of $R_1 - f_0$. In their study, a peak approximately 50 Hz wide was found centered on 0 Hz, so resonance tuning was assumed when $R_1$ was within 25 Hz of $f_o$. A similar technique was adopted in this study, and Figure 4 shows the difference between $R_1$ and $f_o$ for all measurements of $R_1$, and the difference between $R_2$ and $2f_o$ for all measurements of $R_2$. It can be seen that there is a much broader peak in $R_1$ measurements around $f_o$ than those in Henrich et al,[5] and that this is approximately 140 Hz wide. In this experiment, therefore, resonance tuning will be assumed when $R_1$ is within 70 Hz of $f_o$, whether the resonance falls above or below the fundamental (or harmonic for $R_2$).

For illustration, the extent of resonance tuning is shown in Figure 5, using parameters for resonance tuning from this study (Figure 5a), and the parameters used in Henrich et al[5] (Figure 5b).

The frequencies of the vocal tract resonances for all three choristers were then plotted against frequency (separately for each vowel) and can be seen on the right of Figure 6a–c. The first and second harmonics are represented as solid and dashed lines, respectively. The vocal tract resonances of the first chorister are represented by circles, the resonances of the second by squares, and the resonances of the third by triangles.

The frequency ranges for resonance tuning are summarized in Figure 5. This figure indicates that all three choristers employ both $R_1$:$f_o$ and $R_2$:$2f_o$ tuning over a wide range of fundamental frequencies and that the pattern of resonance tuning is highly dependent on the vowel sung.

For the /ɑ/ vowel, the subjects began tuning $R_1$:$f_o$ when $f_o$ was between 4 and 2.5 tones below $R_1$, and continued this to the upper limit of their ranges (with the exception of one note for subject 3). $R_2$:$2f_o$ tuning was less consistent, beginning when $R_2$ was 1–4 tones[b] below $2f_o$, and extending over a range of 3 tones for subjects 1 and 2, but continuing to the top of her range for subject 3.

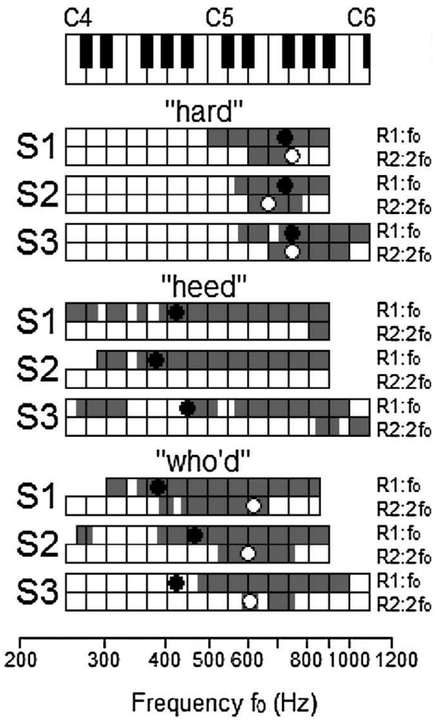
For the /i/ vowel, all the subjects tuned $R_1$:$f_o$ over almost the entire range of fundamental frequencies investigated (although subject 2 had a gap of around 3 tones around F4); however, only a small amount of $R_2$:$2f_o$ tuning was seen at the upper limit of the range investigated for subjects 1 and 3, and none for subject 2. For this vowel, the normal value of $R_2/2$ in speech did not fall within the range of $f_o$s investigated for any of the subjects.

For the /u/ vowel, again all the subjects tuned $R_1$:$f_o$ over a wide range of the fundamental frequencies investigated. In addition to this, $R_2$:$2f_o$ tuning was employed by all three choristers to some extent; from a range of 4 tones for the first subject to 1.5 tones for the third subject.

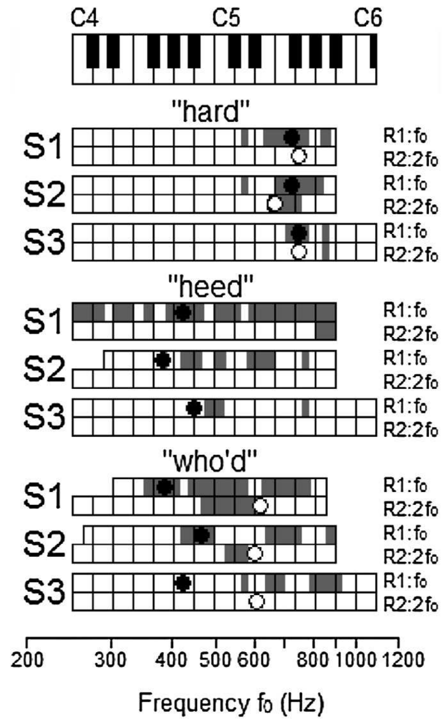
# DISCUSSION

Figure 6 shows a distinct pattern in the resonance measurements for all three vowels, and Figure 5 shows clear evidence of $R_1$ tuning in all three of the choristers for all the vowels. Evidence of $R_2$ tuning was seen in the /ɑ/ and /u/ vowels, but very little in the /i/ vowel, suggesting that the extent to which the different resonance tuning techniques were used was highly vowel specific.

[b] A "tone" here is defined as 2 semitones, where there are 12 semitones in an octave.




(a) Resonance tuning within 70 Hz




(b) Resonance tuning within 25 Hz

**FIGURE 5.** The frequency ranges for resonance tuning for female singers measured for three different vowels. For each singer the *upper shaded boxes* indicate $R_1$:$f_o$ tuning, and the *lower shaded boxes* indicate $R_2$:2$f_o$ tuning. The *filled* and *open circles* indicate the values for $R_1$ and $R_2$/2, respectively, measured for that singer in speech (see left side of Figure 6a–c). The range of boxes indicates the range of fundamental frequencies produced by each subject.

For the /ɑ/ vowel (seen in Figure 6a), the use of resonance tuning was largely as expected. All three choristers maintained approximately constant values of both $R_1$ and $R_2$ until they became close in frequency to $f_o$ and 2$f_o$, respectively (within 1–2 tones). $R_1$ and $R_2$ were then tuned to the relevant harmonic and continued to rise until near the tops of their ranges. It can be seen that at a certain frequency for each subject, they appeared to stop tuning $R_2$, and this then remained fairly constant, and consequently fell below 2$f_o$.

For the /i/ vowel, it can be seen from Figure 6b that all three choristers employed $R_1$:$f_o$ tuning over a very wide range of the fundamental frequencies investigated, whereas there was little evidence of any $R_2$:2$f_o$ tuning at all. For all the choristers $R_2$ continued to fall as $f_o$ increased. Only one chorister was able to sing at a fundamental frequency above 900 Hz, and some evidence of $R_2$:2$f_o$ tuning is seen here, suggesting that had the other choristers been able to reach higher fundamental frequencies, they might also have employed $R_2$:2$f_o$ tuning at these very high pitches. Since the frequencies of $R_2$ in speech fell between 2404 and 2880 Hz for this vowel, for $f_o$ to reach $R_2$, it would need to be approximately 1400 Hz, which would be unlikely for any chorister.

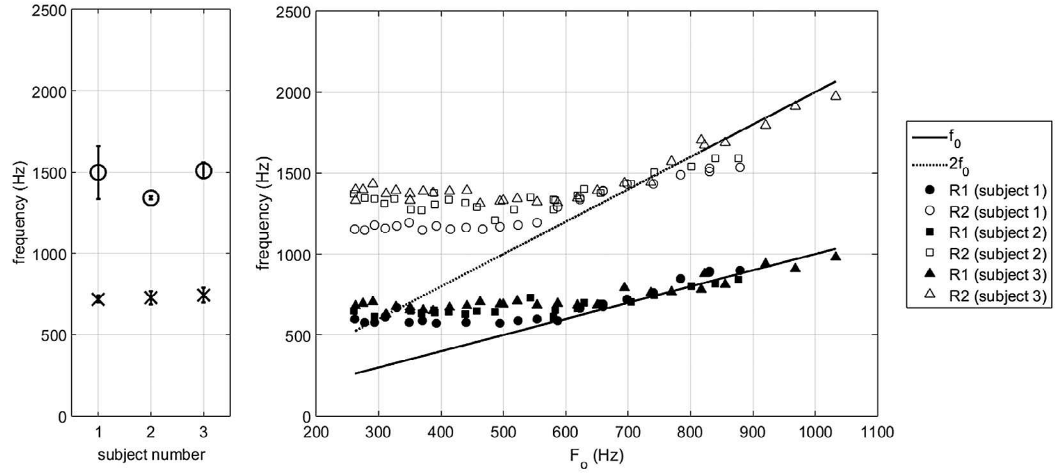
For the /u/ vowel (Figure 6c), the use of first resonance tuning was slightly wider than for the /ɑ/ vowel, with subjects 1 and 3 starting to tune $R_1$ a couple of tones before $f_o$, but subject 3 only starting once $R_1$ had exceeded $f_o$. The range of $R_2$ tuning varied a great deal between subjects, with subject 1 employing second resonance tuning over a range of 4 tones, but subject 3 over only 1.5 tones.

This difference in tuning techniques between vowels was also seen in the study by Henrich et al,[5] which investigated four vowel sounds: /ɑ/, /ɜ/, /ɔ/, and /u/. As in this study, the sopranos showed a similar range of $R_1$ tuning, but a greater range of $R_2$ tuning for the /u/ vowel than for the /ɑ/ vowel.

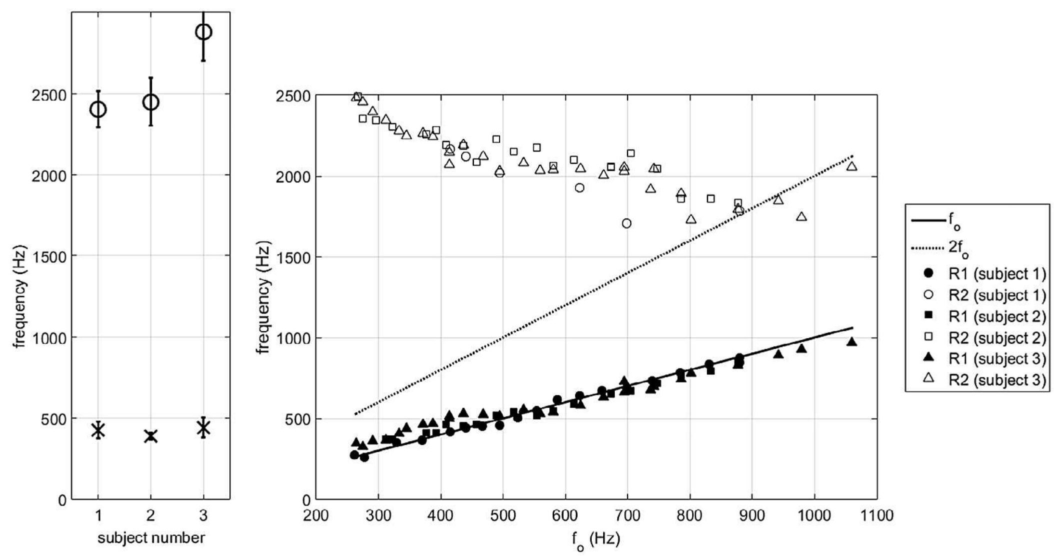
Using the same criteria (to within 25 Hz), the frequency range over which resonance tuning was employed on an /ɑ/ vowel was approximately the same as the nonexpert singers in the studies by Garnier et al[4] for subjects 1 and 2, although subject 3 employed the same techniques over a slightly smaller range.

However, it is important to realize that the criteria for determining resonance tuning are different in this study, and using the definition of resonance tuning definition of within 70 Hz (the left part of Figure 5), then a wide range of resonance tuning is seen. It seems therefore reasonable to conclude that although the choristers are employing resonance tuning techniques over a similar range to the adult singers in the Garnier et al study, they are not tuning their resonances as *closely* as the adults to the relevant harmonic.

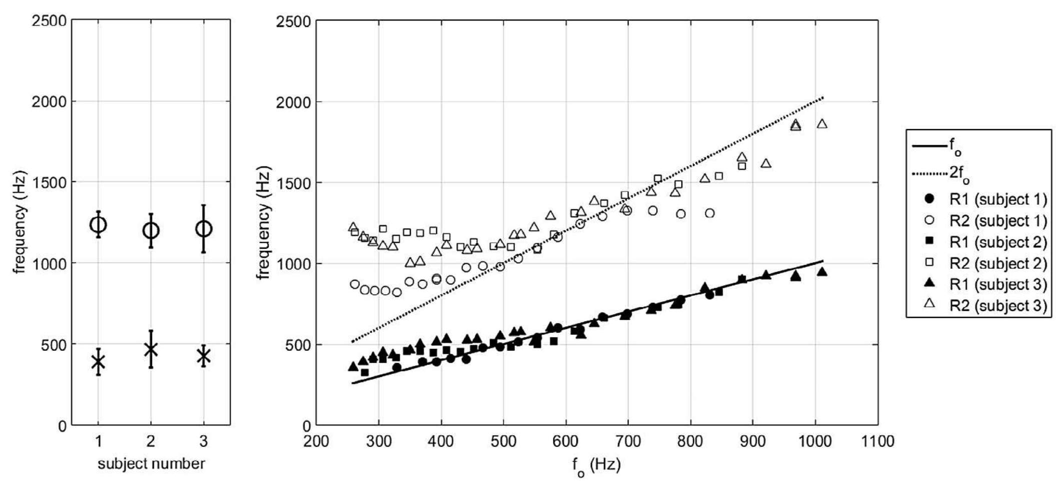
All three subjects in this experiment showed similar use of resonance tuning techniques, perhaps reflecting the particular timbre expected from choristers in the Church of England, and training techniques used to encourage this. Further investigation considering different genres would be valuable.




(a) /ɑ/ vowel




(b) /i/ vowel




(c) /u/ vowel

**FIGURE 6.** The first (*crosses*) and second (*circles*) formants in speech for each subject are shown in on the left side, and the resonances against fundamental frequency for all the subjects singing three different vowels (the *solid line* represents $f_o$, and the *dashed line* represents $2f_o$) are shown on the right side.

## CONCLUSION

It is clear from these results that the choristers in this experiment used both $R_1$:$f_o$ and $R_2$:$2f_o$ resonance tuning techniques to some extent, over the range of fundamental frequencies investigated. This was as expected, considering the relationship between the fundamental frequency and the first two harmonics in this range, and was comparable with the resonance tuning techniques used by nonexpert adult singers, although the subjects in this study did not tune their resonances as close to the relevant harmonic as the adults. The results of this study indicate that this protocol is a valid method for analyzing tuning resonance behavior in young singers and that the techniques used by individual choristers are reasonably similar. Further investigation with more subjects at different stages of training would allow investigation into what point these strategies are employed, and the extent of the effect of training.

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