Logopedics Phoniatrics Vocology, 2010; 35: 51–58

informa
healthcare

ORIGINAL ARTICLE

Voice characteristics of amateur female tenors are comparable with those of male tenors

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Abstract
In order to explore the suitability of adding female voices to the tenor sections of amateur choirs, six male and six female tenors were screened for voice characteristics. Audio signals and signals from an electroglottograph were analyzed by means of VoceVista computer software. All subjects produced closed quotients of 60% or higher in singing with a loud chest voice. There was more variance between the individuals than between groups of male and female singers. Long-time average spectra showed a general trend in the presence of a high-intensity peak between 4 and 5 kHz. The results revealed no significant differences in the most important voice characteristics between female and male tenor voices.

Key words: *Closed quotients, electroglottograph, female tenors, singer's formant, VoceVista, voice characteristics*

Introduction

In amateur choral singing in the Netherlands, there is a shortage of male choral tenors (1,2). At the same time, many ageing mezzo-sopranos who usually sing soprano parts are facing problems with their high notes, while their vocal range at lower pitches is extending. Taking into account the population statistics, this group of elderly women with mature voices, including altos, who want to keep on singing is growing rapidly in numbers. Could these low female voices be a potential new source of choral tenors? Female singers can be found in the tenor group of several of the 10,000 vocal groups that flourish in Holland (3). However, particularly in choirs performing classical repertoire they are not very abundant. This raises the question why it is not more common practice for female singers to join the tenors.

One can think of two reasons why female tenors are not represented in larger numbers yet. Convention may pose an obstacle in that perhaps conductors and musical directors simply do not like the very idea of mingling of the sexes in the tenor section, or some women hesitate to undertake the somewhat daring step to join a traditionally male voice group.

Besides these possible psychological factors, there are other factors in the voice itself, specifically questions about the degree of unison or blending of female and male tenors singing in the same range, which may lead to an unsatisfactory tenor sound (4). This raises the question whether females have comparable voice characteristics to males when they sing as tenors. In what areas are differences to be expected that might cause problems to the female singers?

Vocal range (size of the larynx)

The habitual speaking frequency for men is 110 hertz and for women 200 hertz on average (5). The laryngeal dimensions that determine the maximal mass and length of the vocal folds involved in vibration are mainly responsible for extension to the lower range, rather than length and size of the vocal tract itself (6). Many mezzo-soprano and alto singers are able to produce lower fundamental frequencies (C3: 131 Hz; D3: 147 Hz), suggesting that in these cases the size of the larynx is not a limiting factor. In addition, gains in vocal low range have been reported in women in their menopause as a consequence of structural changes in the vocal folds such as thickening and loss of elasticity (7,8). Mezzo-sopranos have the same vocal fold length as sopranos, which implies that the gain in the low range is due to an increased

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(Received 16 November 2009; accepted 29 January 2010)

ISSN 1401-5439 print/ISSN 1651-2022 online © 2010 Informa UK Ltd. (Informa Healthcare, Taylor & Francis AS)
DOI: 10.3109/14015431003667660

vocal fold mass resulting in more volume in their lowest range (6).

In conclusion, there are presumably many female singers with voices characterized by an extended low voice range which are potentially suited for choral tenor singing.

Closed quotients

Loud voice production in the low singing range is favored by a 'chest' register voice source with a high degree of vocal fold contact area. This voice characteristic can be monitored by the electroglottograph. Closed quotient (CQ) is defined as the percentage in time of the glottal cycle that vocal folds are closed, thereby acoustically separating the subglottal space from the vocal tract (9). Characteristic of most chest voice signals is the convex shape of the slope corresponding to glottal opening, reflecting the vertical phase difference in deep contact between the vocal folds (10). Generally speaking, male larynxes are larger in size than female ones and have thicker vocal folds, at least in the vertical direction (11). It is therefore easier for men to produce CQ levels of 60% and over in loud chest register.

Potential advantages of large closed quotients include the following: They allow higher subglottal pressure and consequently higher sound pressure levels. The closed glottis lowers the bandwidth (raises the quality) of the vocal tract as a resonator, as well as prevents the loss of sound into the lungs. A high CQ disproportionately boosts the high-frequency components of the sound. At a given subglottal pressure, air-flow is lower, increasing the time a sound can be sustained (6,9,12).

The purpose of this work is to determine whether the female tenor singer can reach the maximum of 60% closed quotient when singing loudly in chest register in the tenor range.

Registers and effort

It is important to realize how male and female solo singers in the classical repertoire approach the primary register transition from 'chest' to 'falsetto' voice source. In the male voice the change in the voice source is delayed, so that the extension to the highest pitches is accomplished with a 'chest' voice source. In classically trained female voices the transition event takes place much lower in the frequency range (C4 or D4) singing upward in their middle voice with a 'falsetto' voice source (13). Differences in registration might be responsible for changes in the vocal quality with subsequent lower volumes in the female voice. Women sing the tenor parts in their low to middle voice range, whereas male tenors usually sing in their middle to high range. A lower effort is needed by women to sing the same pitch as their male colleagues, resulting often in a lower intensity of singing.

Dealing with untrained amateur singers there are still other factors to be considered: Although a low register transition is common practice in classical female singing to avoid problems in the middle register, many women can easily keep up their chest voice source to pitches as high as B4-flat. On the other hand, male singers without professional training often experience considerable difficulty in sustaining in chest up to these high pitches. As a result, one commonly hears male choral tenors using a 'falsetto' voice source on the higher pitches.

In conclusion, when males and females sing in the tenor range, differences in registration and effort levels can be expected.

Resonance and vocal tract length

The larynx, pharynx, and the mouth, and sometimes the nasal cavity, together constitute the vocal tract. The shape of this resonating tube can change with the position of the articulators: the lips, the jaws, the tongue, and the larynx. Together these articulators determine the frequencies of the five most important resonances of the vocal tract, in sequence designated as F1 for lowest (0.5 kHz) to F5 for the highest frequency (4.5 kHz) (14). On average, the male vocal tract is about 15% larger than the female, with the consequence that formant frequencies are generally lower for males than for females. What are the implications of these differences in formant frequencies?

The lowest two resonances of the vocal tract (and partly the third) determine the vowel identity and are therefore called the vowel formants (6). Sundberg concluded in his review of differences between male and female speaking voices that the formant frequencies contribute only to a very small extent to the perceived maleness or femaleness of the voice. Fundamental frequency and amount of roughness in the voice were much more decisive in assessment of the voice gender (6). In another report (15) on two male tenors and two female altos both singing professionally, differences in the lowest three formants were found to be even less consistent in spite of the fact that altos usually sing with a falsetto voice source, whereas a tenor sings in his chest register. In that study, the main distinction between the two voice types was a higher 4th formant in the altos than in the tenors. The relative unimportance of the vowel formants for differentiation between the two sexes was also supported by Miller's demonstration (9) that male and female voices can adopt identical resonance strategies for the vowel formants within the same vocal range.

Frequencies of the higher formants, F4 and F5, depend on the non-articulatory factors such as vocal tract length much more than the lower formants (6). Clustering of the higher formants, which often involves F3, results in a strong formant that can even exceed the vowel formants in intensity, the so-called singer's formant (SF). Center frequencies for this SF are about 2.5 to 3.4 kHz for men, and considerably higher for women (9).

There is little information on how the higher formants contribute to the differences in perceived voice quality between male and female singers and, in this special case, their impact on choral tenor singing. On the other hand, the strong singer's formant and big volumes produced by professional opera singers are generally not required from choral voices (6). In fact, professionally trained singers have been shown to produce less energy in the singer's formant region when singing in a chorus compared with singing as a soloist (16).

Nonetheless, differences in frequency of the higher formants, as well as the presence or absence of clustering of formants into a singer's formant, have been considered as factors in comparing male and female amateur choral tenors.

Why test male amateur tenors?

Research on choral voices is still scarce. Sundberg reported on investigations of differences in singer's formant and several studies dealing with correct tuning in professional and amateur (choral) voices (6). Barlow and Howard (17) published an impressive amount of work on changes in voice source of adolescents, both girls and boys, who received vocal training and the impact of voice mutation. In the present paper, data are presented on range and on highest closed quotients, which were collected by means of an electroglottograph (EGG). Lower formant frequencies were obtained from power spectra, and long-time average spectra (LTAS) were used to assess frequency and relative power of the higher formants and, if present, a singer's formant.

Since there is not much understanding on how male choral tenors use their voice in terms of measurable voice characteristics, an equal number of male subjects was included in this study.

Hypothesis

Differences between male and female singers with respect to the extent of the lower frequency range, closed quotient, vowel formants, and frequency and intensity of the singer's formant may limit the suitability of female singers as choral tenors.

Materials and methods

Method of measurements

Voice recordings were processed by means of VoceVista 3.3, an advanced voice analysis computer program first introduced in 1996, now available together with Miller's book *Resonance in Singing* (9). An electroglottograph (EGG) was obtained from Eggs for Singers (www.eggsforsingers.eu). A Tascam US-122L interface was used to feed microphone and EGG signals into the computer. Principles of EGG are expounded by Barlow and Howard (17), Fourcin (18), and, very recently, Howard (19).

Subjects and protocol elements

A total of 12 singers were selected, 6 female and 6 male, all of them active as tenors in an amateur choir, singing a repertoire ranging from early Baroque and classical romantic to musical and pop. The protocol included a number of vocal tasks on the vowel [a]. These tasks were aimed at collecting the information required for testing the hypothesis formulated at the end of the Introduction section. Subjects were fitted with EGG electrodes, and all signals were recorded using VoceVista in combination with EGG, as described by Miller (9).

Protocol element 1. Lowest pitch. Differences in low range between the male and female singers were assessed by recording their lowest sung pitch.

Protocol element 2. Loud chest voice. In order to determine whether female tenor singers can reach the maximum of 60% closed quotient when singing loudly in chest register in the tenor range, a set of five vocal tasks was selected: 1) loud scale upwards, 2) messa di voce on top note of the scale, 3) chromatic fifth interval downwards, 4) shouting on top note, and 5) free imitation of the opera tenor. The range of sung scales varied between subjects from F (175–349 Hz) to A flat (208–415 Hz), and subsequently the pitches chosen for messa, shouting, and chromatic fifth phonation ranged from 349 to 415 Hz.

Protocol element 3. Vocal fry. To detect vowel formant frequencies, phonation in vocal fry was recorded (20). The procedure consisted of: phonation on vowel [a], an abrupt stop followed by an immediate continuation in vocal fry phonation, carefully maintaining a singing posture of the vocal tract.

Collecting data from voice analysis

Lowest sung pitch was assessed in VoceVista.

Loud chest voice phonations were screened for the highest closed quotient (CQ). The selected criterion level was 35%, the default setting in VoceVista, which generally allows for robust measurements, suitable for revealing relative differences between subjects or groups, should they exist. The results were analyzed by means of an ANOVA test for variance using the statistical package SPSS 17.0 for Windows XP/Vista.

The lower (vowel) formants F1, F2, and F3 were estimated from recorded phonations in vocal fry.

The higher formants (F3 and up) were studied with long-time average spectra (LTAS) of recorded sung chromatic fifth scales downwards (Protocol element 2, task 3) (9). To gain insight into the distribution of vocal energy in the higher frequencies, the frequency of every high-intensity peak was assessed, and its relative power in decibel was measured and compared with the decibel level of the highest vowel formant peak.

Results

Vocal range

The lowest sung pitch recorded from the male singers varied between 65 and 104 hertz. The lowest value suggests that one of the singers was more or less a bass. In the female group the lowest pitch ranged from 110 Hz to 131 Hz. There was no pitch overlap of lowest sung tone between the sexes.

Closed quotient (CQ)

Figure 1 represents the highest ratings on CQ measured in the male and female recordings of five different tasks in a loud chest quality. Closed quotients, expressed as a percentage, were assessed at a criterion level (CL) of 35%. The male tenors scored a slightly higher CQ in the performance of all five vocal tasks, but the difference was not significant at a confidence interval of 95%.

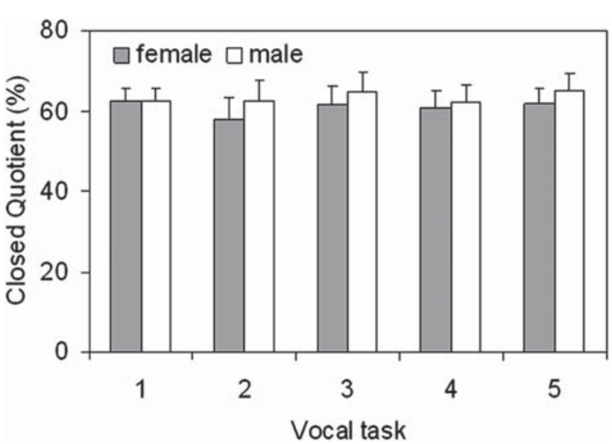

Figure 1. Mean highest closed quotients obtained from recordings of five loud voice qualities measured at a criterion level of 35%. Standard error was symmetrical. ANOVA test revealed no significant differences between female and male tenors within a confidence interval of 95%. Vocal tasks: 1 = loud scale up; 2 = messa di voce; 3 = chromatic fifth down; 4 = shouting; 5 = free imitation of an opera tenor.

Table I. Mean closed quotients and standard error for female and male tenors: variance between groups of different sex.

	Closed quotients		95% Confidence interval	
Gender	Mean	Standard error	Lower bound	Upper bound
Female	60.8	1.35	57.8	63.8
Male	63.4	1.35	60.4	66.4

The mean highest CQ calculated from the male samples was 63.4%, from female samples 60.8%, with a standard error of 1.35 (Table I).

Variance between males and females was analyzed and compared with variance between the subjects (Table II). Standard errors (SE) calculated from the means of subjects performing one vocal task and belonging to the same sex appeared to be 1.9 on an average base, which was similar in both groups. SE between groups of a different sex of 1.35 was lower, indicating that the variation between subjects was greater than the variation between groups of male and female singers.

Formants

The vowel formant frequencies F1, F2, and F3, estimated from a vocal fry phonation on vowel [a], are listed in Table III. Pitch of the sung tone varied with the subject, ranging from 330 to 429 Hz.

Data on the lowest two formants confirmed earlier observations that formant frequencies are lower in male voices. There was a similarity in frequencies of the third formant (vocal fry) found in both groups. The average value calculated from the male samples was 2753 Hz against 2908 Hz for the female phonations.

Higher formants were involved in the high-frequency peaks that showed up in the LTAS. For an impression of LTAS, see Figure 2A (female) and Figure 2B (male), clearly displaying peaks above 4 kHz. In VoceVista, voice volumes cannot be standardized. Instead, it is possible to compare the relative power of the frequency peaks. Relative power is expressed in decibel and the higher the value, the stronger the power of that particular frequency component. To ascertain the formants that contributed to the observed peaks in these spectra, two sources of information are relevant: 1) Where can we expect to find the higher formants? Higher formant frequencies of the human vocal tract are

Table II. Mean closed quotients and standard error for female and male tenors separated for the five vocal tasks: variance between subjects belonging to the same sex.

		Closed quotients		95% Confidence interval	
Gender	Vocal task	Mean	Standard error	Lower bound	Upper bound
Female	1	62.3	1.6	58.9	65.8
	2	58.0	2.4	52.7	63.3
	3	61.3	2.2	56.5	66.2
	4	60.7	2.0	56.3	65.0
	5	61.7	1.9	57.5	65.8
Male	1	62.3	1.6	58.9	65.8
	2	62.5	2.4	57.2	67.8
	3	64.8	2.2	60.0	69.7
	4	62.0	2.0	57.6	66.4
	5	65.2	1.9	61.0	69.3

about 2500 Hz (F3), 3500 Hz (F4), 4500 Hz (F5), and 5500 Hz (F6); and 2) The number of peaks that appeared in the LTAS. A higher formant cannot be involved in more than one peak, whereas up to three formants can approximate to give rise to one single peak. This information taken into account, the high-frequency peaks were arranged under three frequency domains, each domain possibly associated with two higher formants. In Table IV, decibel levels of the highest vowel formant peaks are listed in the last column. The **bold** table entries represent the high-frequency peaks with highest intensity in each of the samples. Clearly to be seen is that in LTAS of five out of six female tenors and three of the male tenors a peak turned up in the F4–F5 domain with center frequencies between 3.4 and 4.4 kHz. LTAS of another two male subjects exhibited the highest peaks in the F5–F6 domain, which were comparable in strength with the vowel formant peaks. LTAS of one male tenor displayed a high-frequency peak of considerable power for which three higher formants could be held responsible (subject 9).

In order to assess which domain of the higher formants carried the most power, decibel levels of the two strongest high-frequency peaks were plotted (Figure 3). Sets of co-ordinates obtained from the 12 subjects were arranged into five categories (see caption Figure 3) corresponding with the **bold** table entries of Table IV. A trend line revealed that the ratio in relative power between lower- and higher-frequency peaks was rather stable for 9 out of 12 subjects and did not change with gender or frequency domain (Figure 3). Data of two male singers (subjects 9 and 12) and one female (subject 6) showed a deviation from the trend line, strongly suggesting the presence of a cluster (singer's or speaker's formant).

Discussion

In all vocal tasks the male tenors performed slightly better on highest closed quotient than the female tenors. However, the observed differences were not significant at a confidence level of 95%. The mean highest closed quotient measured at the 35% criterion level was for the female tenors still 60%. This indicates that the female tenors in this study were potentially capable of producing the loud chest voice required for the dynamic range in choral tenor singing, at least in the higher part of their tenor range.

As expected, lower center frequencies of the lowest two vowel formants were found in male subjects (Table III). However, as pointed out in the introduction, the influence of the lower formants on the perception of gender appears to be limited (6,9,15). Too little information is available to assert whether these differences might affect the mixing of male and female voices within the tenor group.

The high center frequencies between 4 and 5 kHz which were found for the higher formants in the LTAS of singers in this study came as a surprise. These high-frequency peaks, which are generally referred to as the speaker's formant, have been observed in the speaking voice as well as in the extreme yelling sounds in which F4 strengthens F5 rather than F3 (9). Recently, Lee et al. (21) reported that opera singers have more energy concentration in the singer's formant/speaker's ring region, in both singing and speaking voices. Furthermore, another region of energy concentration was identified at even higher frequencies of 8–9 kHz.

With respect to the amateur tenors in this trial, the yelling type of resonance strategy might not be part of their vocal repertoire when singing a tenor part in a choir. It was noticed that many of the males developed higher intensities in the 3 kHz part of the spectrum in the free aria task compared with

Table III. Vowel formant frequencies in hertz (Hz) estimated from a vocal fry phonation on vowel [a] of six female (F) and six male tenors (M).

		Frequencies in vocal fry (Hz)			
Subject	Gender	Fundamental	F1	F2	F3
1	F	404	820	1200	2900
2	F	393	820	1400	2650
3	F	393	930	1300	3000
4	F	417	880	1350	2900
5	F	429	1050	1650	2900
6	F	405	920	1400	3100
7	M	345	600	1050	2800
8	M	345	700	1150	2560
9	M	345	600	1300	3100
10	M	333	750	1170	2500
11	M	357	720	1250	2860
12	M	405	790	1120	2700

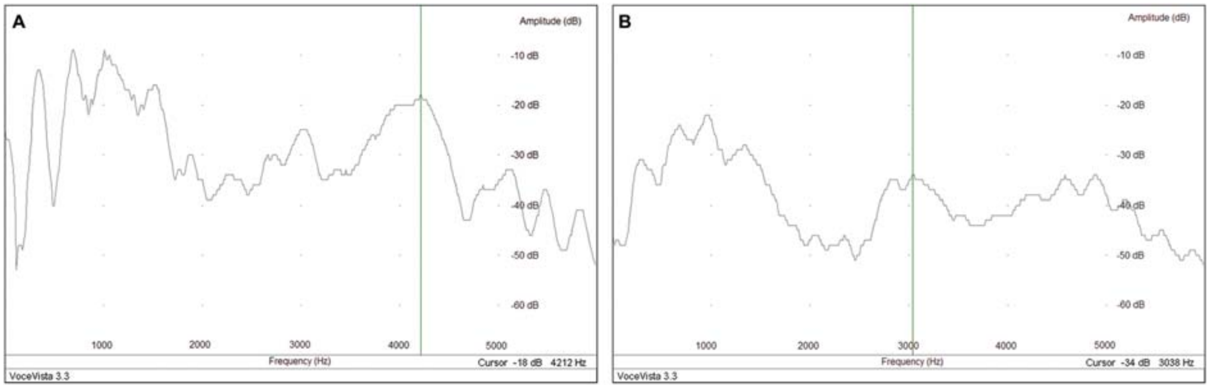

Figure 2. A: LTAS from a chromatic fifth interval down, sung by a female tenor (subject 3). B: LTAS from chromatic fifth interval down, sung by a male tenor (subject 7).

singing a chromatic fifth down. High peaks in the singer's formant region are much more common in male singing (9). Larynx lowering, or at least a wide pharynx, is important to male voices because it is needed for the generation and maintenance of the singer's formant (6). It is conceivable that the occurrence of peaks of 4 kHz and higher in the LTAS of most of the women and some of the men is just one strategy that can be altered with proper training. It is suggested that this aspect deserves further investigation.

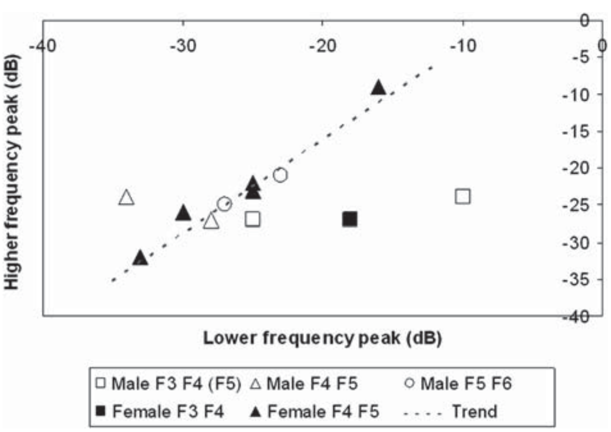

Figure 3. In VoceVista the relative power of a frequency peak is expressed in decibel; the higher the value (closer to zero), the stronger the power of that particular sound component. To determine the power distribution in the higher-frequency domains, decibel levels of the two highest peaks found in domains of F3 up to F6 were plotted. Sets of co-ordinates obtained from 6 female (filled symbols) and 6 male subjects (open symbols) were arranged according to their sex and frequency domain with highest peak value into five categories (see caption for meaning of the symbols). A trend line, computed from data of 9 out of 12 subjects, reveals a rather fixed power ratio. Two male singers (subjects 9 and 12) and one female (subject 6; see also Table IV) showed a deviation from this trend, indicating the presence of a singer's formant (squares to the right of the trend line) or a speaker's formant (open triangle to the left).

One of the female tenors revealed a different resonance strategy compared to the other females. Her LTAS showed a high intensity peak at a frequency of approximately 3 kHz. The presence of a singer's formant in her voice can be explained by a background as a professionally trained soprano.

Two observations made in this study have not been mentioned yet. When singing a scale upwards in soft phonation, all subjects, male and female alike, exhibited a tendency to change from chest voice source to falsetto in the passaggio region roughly between 350 and 420 Hz. Falsetto voice source distinguishes itself by a shift in dominant resonance from the second to the first harmonic and by a drop in closed quotient from 60% to 30% or 40% (9). In loud voice qualities no register transition could be detected. The second observation concerns the vowel formants. When subjects sang in loud chest voice on vowel [a], two dominant strategies became apparent from the power spectra. The first one was the first formant boosting the second or third harmonic (F1H2/H3) which is typical for the yelling type of sound. The second strategy consisted of the second formant enhancing the third harmonic (F2H3). This type of formant tuning, which is quite common in the professional male tenor voice (9), was observed in data of all subjects tested.

The group of male tenors exhibited more variation in vocal range and resonance strategies at higher frequencies than the female tenors. This leads to the conclusion that the female tenors belong to a more select group. Why are strong higher formants important to a singer in general? An advantage above an orchestra spectral peak around 500 Hz (14) seems not particularly important to choral singing, which is often without accompaniment. But a second point might be of more relevance: low frequencies radiate in all directions, while high partials are only radiated forward with much more acoustic intensity which enables the singer to produce more sound with less

Table IV. Frequency in Hertz (Hz) and relative intensity in decibel (dB) of frequency peaks that were observed in the higher formant domains of the LTAS of 12 subjects (F = female and M = male). Relative intensity is expressed in dB and, the higher the value (closer to zero), the stronger the power of that particular frequency component. Bold table entries refer to formant domains containing peak frequencies with the most power. Decibel levels of the highest vowel formant peaks that were measured in the vowel formant domain of F1 and F2 are listed in the column on the right. See figure 2A and 2B for a female and male example of LTAS.

		Long Time Average Spectra (LTAS)						Highest Vowel Formant peak
		F3 F4 domain		F4 F5 domain		F5 F6 domain		
Subject	Gender	Hz	dB	Hz	dB	Hz	dB	dB
1	F	3038	-25	**3980**	**-23**			-22
2	F	2770	-25	**4284**	**-22**			-18
3	F	3080	-16	**4218**	**-9**			-13
4	F	2730	-30	**4295**	**-26**			-20
5	F	2919	-33	**4182**	**-32**			-28
6	F	**3116**	**-18**			4784	-27	-18
7	M	3092	-23			**4903**	**-21**	-20
8	M	2621	-28	**3402**	**-27**	4647	-30	-18
9	M	**3384**	**-10**	**3384**	**-10**	4701	-24	-11
10	M	2430	-27	3378	-31	**4683**	**-25**	-22
11	M	**2943**	**-25**	3902	-31	4975	-27	-25
12	M	2970	-34	**3896**	**-24**			-22

effort (6). This suggests that choral tenors in classical repertoire can benefit from increased power in the higher frequency components of the voice as long as the sound stays within aesthetically tolerable limits.

The closed quotients revealed a high individual variation as well. The large variance between subjects of the same gender suggests that many more tenors should be tested. In time, after collecting more data, it will be possible to sort out some of the most important factors determining the individual variation. The effects on intensity of vowel formants indicate the need for a vocal training that can smooth out these differences. One way to achieve this and simultaneously improve the dynamic range of choral tenors is designing a training program aimed at control of the closed quotient.

High closed quotients are often accompanied with increased levels of subglottal pressure (22), potentially to values high enough to hurt the voice. Evans and Howard (23) provide CQ values for two very loud voice qualities, belt and opera, showing that belt has very much higher values. Sundberg investigated different types of belting and found similar results (personal communication). However, some belting qualities could be produced at a high sound pressure level (SPL) and with a high CQ at a much lower subglottal pressure, suggesting that other strategies were involved in raising the CQ. Two voice qualities might contribute to this rise in CQ without increasing subglottal pressure too much: Titze (24) describes the impact of strong higher formants as a source—vocal tract interaction, changing the impedance of the vocal tract and improving it as a resonator (24,25); Yanagisawa et al. (26) describes it as a twang quality boosting the higher frequencies between 2 and 4 kHz. As a second key quality with a comparable effect on CQ, the shouting voice contains valuable prospects. Shouting, referred to as 'overdrive' by Sadolin (27), is a prominent voice quality used in all music styles when singing very loud. According to the author's own experience subglottal pressure stays low in shouting quality (unpublished results).

Since voice source characteristics and resonance strategies are such crucial factors in determining voice quality, real-time display of CQ (as measured by means of EGG) and power spectra may be very useful elements (28) in a training program for amateur tenors.

Conclusions

The results confirm that the mature female voice may indeed be a source of potential tenors for amateur choirs. The male/female difference in closed quotient appears not to be an issue, since the female singers could achieve comparable closed quotients, and, secondly, all of the choral tenors tend toward the use of falsetto at high pitches in their tenor range. The expected male/female difference with respect to the center frequency of the singer's formant is also contradicted by the available data since the majority of male and female tenors showed high-frequency peaks of 4 kHz or higher.

The observed differences in the extension of the low range and in center frequency of the vowel formants between male and female subjects may possibly result in poor mixing of male and female voices within the tenor group. On the other hand, high variations in the voice characteristics as found among the male tenors in this study might lead to identical mixing problems. More research is needed to elucidate if the above indeed poses a problem and whether it would be responsive to training.

Acknowledgements

Thanks to Don Miller for his generous supply of good advice and help. Thanks to Fokke Buwalda for his assistance with the statistical analysis and critical comments. Thanks to Wim Ritzerfeld and Christien Brouwer for their critical reading of the manuscript. Thanks also to the singers for their willing co-operation.

***Declaration of interest*:** The author reports no conflicts of interest. The author alone is responsible for the content and writing of the paper.

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