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Voice source characteristics of Child singers

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Abstract

The authors have undertaken a number of studies of the vocal characteristics of child and adolescent singers, including 'classically' trained and 'musical theatre' voices, and have recorded voice samples of spoken and sung voices of over 250 young trained and untrained singers using acoustic and electrolaryngographic measures. The data was analysed to examine the voice source of the subjects and to assess correlations between the parameters gender and training and the voice measurements.

This paper summarizes the results of three studies and relates them to other studies by the authors and other researchers on the voices of children and young people to give vocal practitioners and researchers an improved understanding of the young voice. These studies significantly add to the understanding of the voices of child and adolescent singers.

Study 1 involved recording the acoustic output and EGG (laryngographic) data from a large number of classically trained boys and girls from cathedral choirschools and specialist music schools in the UK. Subjects were recorded singing and speaking. Long term average spectra was used to assess characteristics of acoustic output, while the EGG waveform was used to estimate Closed Phase measurements of the voice source. Study 2 assessed voices of subjects training for musical theatre in stage school organisations in the UK and USA. Voices were recorded using acoustic and EGG means, and the EGG signal was used to derive the Closed Phase.

In the third study examined here, Glottal airflow was recorded under control of subglottal pressure. Inverse filtering was used to detect formant values. Closed phase and alternating airflow were measured in the inverse filtered signal.

Results from the three studies were strongly correlated. Study 1 found shorter Closed Phase for boys than girls for unchanged voices. It also found changes in Closed Phase measures for both boys and girls over the pubertal voice change, with a decrease in Closed Phase with development for girls, and an increase in Closed Phase with development for Boys. Non-significant differences in the relationship between Closed Phase and Fundamental Frequency (F0) were also observed as a function of training in both sexes.

Study 2 used a similar method and found similar patterns to study 1 in the patterns of closed phase vs F0 in male and female groups. Significant differences in closed phase measures were also observed between the two genres, with a significantly raised closed phase duration for the Musical Theatre singers.

Study 3 used a different methodology to derive closed phase and related the voice source characteristics to subglottal pressure. Again, a shorter closed phase for boys voices compared with girls was found. The study also found a significant higher alternating airflow amplitude for boys.

Introduction

Young people are more likely than any other demographic group to be involved in singing and voice training (Barlow, 2003). In particular, there is an increasing trend for young people who sing to train in

Contemporary Commercial Music (CCM) (LoVetri, 2003) such as musical theatre or 'pop' music styles. Specialist music schools which train young children in Western art music have existed for, in some cases, many centuries (for example choirschools) (Barlow and Howard, 2005), while stage schools and musical theatre academies have flourished through the 20th and into the 21st century (Barlow and Lovetri, 2009). There is also now an increasing focus on children and young people training in popular styles, with increases in popular music performance academies (Barlow, 2009).

While young voices have been of increasing interest to researchers in recent years, there is still a relatively small amount of published research which examines qualitatively or quantitatively the development of the singing voice of children and adolescents, and in particular those who train to a high level. While there is a certain amount of research on the effects of training, sex and pubertal voice change on the 'classically' trained voice (Welch and Howard, 2002; Barlow and Howard, 2005; Williams *et al*, 2005; McAllister, 1997; Fuchs et al, 1999; White, 1997; Sergeant and Welch 2009, Mecke and Sundberg, 2010 , etc.), there still a very small amount of research based material which examines both classical and CCM young voices and compares them directly. Given the numbers of young people involved, this is an important gap in the literature.

The authors have undertaken a number of studies of the vocal characteristics of child and adolescent singers, including 'classically' trained and 'musical theatre' voices, and have recorded voice samples of spoken and sung voices of over 250 young trained and untrained singers using acoustic and electrolaryngographic measures as well as airflow based data. The data was analysed to examine both the voice source and acoustic output of the subjects and to assess correlations between the multiple parameters of age, gender and training and the voice measurements.

This paper summarizes the results of three studies related to the voice source of children and relates them to other studies by the authors and other researchers on the voices of children to give vocal practitioners and researchers an improved understanding of the young voice. These studies significantly add to the understanding of the voices of child singers.

A special concern of the three studies presented were gender differences. Most studies that have investigated possible differences of girl's and boys' voices concentrated on the *sound* of the singers and analysed for example Long Time Average Spectra and formants. However, some authors detected gender differences in the voice source characteristics of children (e.g Pedersen,1997; White, 1997; Stathopoulos and Sapienza, 1997; Barlow and Howard, 2002).

In the studies reported here, the authors aimed to get a deeper insight into voice source characteristics to verify, specify or falsify the existence of such differences.

Voice source characteristics can be investigated using different methods. While *highspeed-videoglottography* allows the most direct insight to the vibrating vocal folds, this method is limited to a certain type of phonation (an /i/-like-vowel), difficult to perform on a large number of subjects and still not suitable for higher frequencies.

In comparison, *Electroglottography* (EGG) is cheap, non-invasive, suitable for high frequencies and easy to use even for the investigation of large subject groups. It is also not subject to interference from the acoustic environment (Barlow and Howard, 2005). However, the interpretation of the EGG-waveform is not always clear, and in some cases not reliable. The EGG signal presents changes of voltage that reflect in most (but not all) cases the vocal fold contact area. (Titze, 1990). A generally low reliability of the CQ_{EGG} is reported for higher frequencies of male phonations (Childers et al., 1990). Particularly for breathy or falsetto-like phonation the common ways of calculating a CQ_{EGG} from the EGG-Signal are unreliable.(Alku *et al*, 1990, Herbst and Ternström, 2006).

Inverse filtering makes use of a filter which is the inverse of the modifier of the vocal tract to model the voice source. It is possible to perform on the audio signal as well as on the airflow signal. The inverse filtered airflow allows direct measurement of voice source characteristics such as closed phase, glottal leakage or alternating airflow. The inverse filtering audio signal can be integrated and analysed as the inverse filtered flow. However, some measurements like glottal leakage cannot be derived from the inverse filtered audio signal. The inverse filtering process, if done manually, is time consuming and cannot be performed reliably on frequencies above ~500 Hz. Moreover, the inverse filtering process itself is a source of error, and results can be affected by the acoustic of the recording environment, so to a anechoic environment is recommended for the recording process to ensure accurate results.

Two of the presented studies (studies (1) and (2)) make use of the EGG to estimate voice source characteristics and take advantage of the possibility to investigate a large number of subjects. Those two studies investigate subjects of different age and singing style. Study (3) is based only on a small number of subjects. In this study the voice source characteristics are measured using the inverse filtered airflow.

As voice source characteristics are strongly correlated to subglottal pressure, this study was done in control of subglottal pressure.

The comparison of the results of all three studies, involving singers from different age, gender and singing background obtained with different methods, allows conclusions to be drawn about general characteristics of children' voices in different singing styles.

Method

Different concepts of closed quotient

A parameter measured in all studies is the closed or contact quotient (CQ). The closed quotient is defined as the proportion of the vibration cycle where the glottis is closed. It is recommended to distinguish between the *closed quotient* measured via highspeed glottography or the inverse filtered airflow (CQ_{Flow}) and the *contact quotient* (CQ_{EGG}) measured via EGG. The CQ_{EGG} is defined as the part of the vibration cycle in that the vocal folds show maximum contact. It seems plausible that the phase of maximum contact is, if not identical, so somehow systematically connected to the closed phase. However, Herbst and Ternström (2006), even prefer the term "quasi contact quotient" for the quotient calculated from the EGG signal because the EGG does not show contact and decontact events, and the calculated quotient is not always connected to the contact quotient as defined above.

Study 1: Choral singers

Study 1 involved recording the acoustic output and EGG (laryngographic) data from a large number (>240) of classically trained boys and girls from cathedral choirschools and specialist music schools in the UK. All subjects were receiving regular vocal tutition, in addition to undertaking an effectively 'professional' role as a singer within the cathedral choir. Subjects were recorded singing and speaking in rehearsal rooms in each of the schools, rather than in anechoic spaces. Subjects sang both a verse of a song well know to them and also a 2 octave ascending and descending scale in G major. Long term average spectra was used to assess characteristics of acoustic output, while the EGG waveform was used to estimate Closed Phase and therefore CQ_{EGG} measurements of the voice source. The EGG signal was derived from a Laryngograph ® and the acoustic waveform was recorded using a headset mounted AKG CK-77 omnidirectional condenser microphone. Mean CQ_{EGG} were analysed in third octave bands using CQ_{EGG} data values derived by Laryngograph™ Speech Studio® software.

Study 2

Study 2 assessed singing and speaking voices of more than 40 boys and girls training for musical theatre in stage school organisations in the UK and USA. All singers were receiving vocal training, and were experienced at performing to a high level in professional ensembles. Voices were recorded in rehearsal spaces, using acoustic and EGG means under the same methodology as used in study 1, and the EGG signal was used to derive the CQ_{EGG}.

Study 3

In study 3, eleven pupils from a Stockholm music school, 6 girls and 5 boys, served as subjects. They were between 10 and 13 years old. All children were trained in the sense that their singing ability was tested before they were admitted to the school and that they sing every day in their class. However, no solo voice lessons are part of the education.

The study design was completely modelled on two similar studies with adult singers. (Sundberg et al 1999; Sundberg et al., 2005.)

The recordings were made in an anechoic chamber. The singers were instructed to sing a diminuendo from the loudest to the softest possible phonation on a constant pitch repeating the syllable "pa". The task was repeated several times; two different pitches, D4 and G4, were used. The airflow signal was recorded using a Rothenberg-Mask.The file was recorded and saved on a personal computer using the Soundswell Signal Workstation (Saven Hitech, Sweden) with a sampling frequency of 16000 Hz. Four different signals were recorded: The audio signal, the airflow, an electroglottography signal and the intra-oral pressure. The intral-oral pressure during the occlusion for the consonant /p/ was used to estimate the subglottal pressure. The airflow signal was calibrated using a calibration signal from a pressure tank with defined airflow, the intraoral manometer was calibrated using a water manometer.

For every subject, 10 to 15 equally spaced pressure values for each tone were selected and analysed. The airflow signal was inverse filtered using the Decap software programmed by Svante Granqvist The

EGG-signal was used as a help during the inverse filtering process, especially to determine phonations with zero-contact of the vocal folds.
The flow glottograms thus obtained allowed to measure CQ_{Flow}, the glottal leakage (DC Flow) and the alternating airflow amplitude (AC Amplitude). Additionally, the lowest observed pressure that produced phonation was noted as threshold pressure.

Results

Study 1

Figure 1 shows mean CQ_{EGG} values with standard error for unchanged voices of female choristers. Results show similar results between trained and untrained singers at lower pitches, but there are notably higher CQ_{EGG} values for untrained singers compared to trained singers in the 3 highest bands, with the difference increasing at higher pitches.
The standard error values for the untrained singers across the bands are significantly higher ($p=0.031$) than the standard error values for the trained singers, suggesting far lower variation in vocal production in trained compared to untrained singers. This is particularly the case in the upper octave.

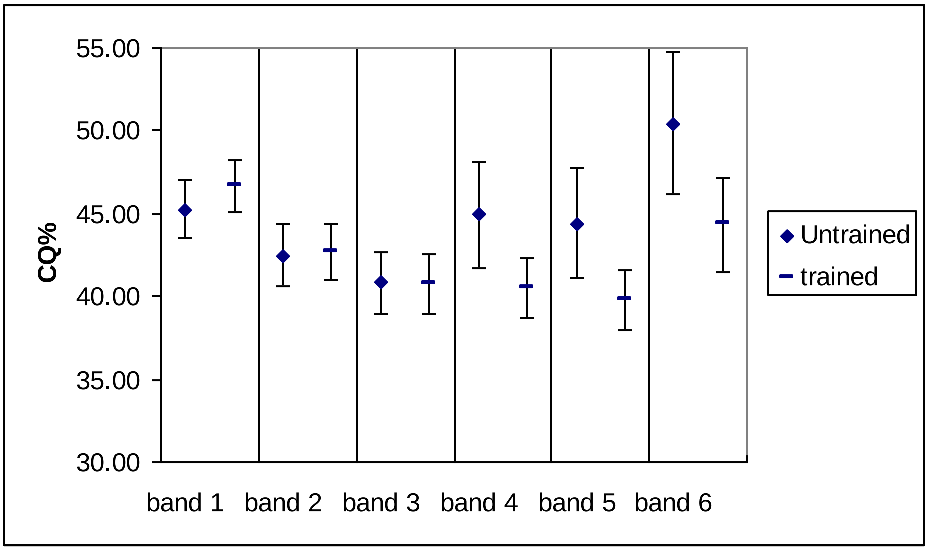

Figure 1 – Mean of CQ means with standard error for trained and untrained unchanged female voices in third octave bands

Male choristers (figure 2) exhibited mean CQ_{EGG} values at statistically significantly different values in a number of pitch ranges, with trained voices being significantly lower ($p<0.05$) than untrained in 2 bands and lower in a further 3, though not by a significant level. The CQ_{EGG} of the untrained boys dropped consistently with increased pitch, with a strong regressive linear correlation between musical pitch and CQ_{EGG}, This would indicate increased breathiness of voice to achieve higher notes.

While there are significant differences between untrained male and female voices in several pitch bands, this difference was not evident between male and female trained choristers. The female trained singers generally maintained a higher CQ_{EGG} across all pitches, though this difference was not statistically significant.

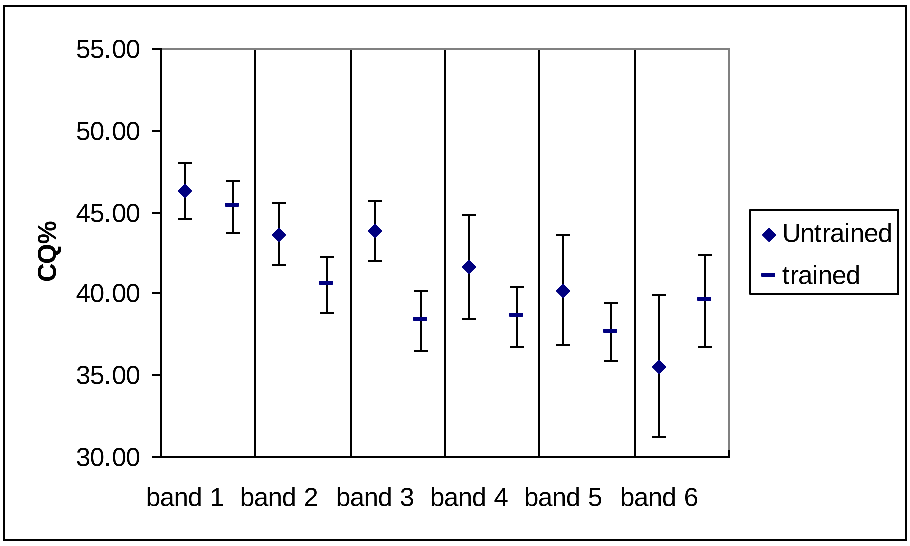

Figure 2 – Mean of CQ means with standard error for trained and untrained unchanged male singers in third octave bands.

Study 2

The participants in this study were being trained in both ‘classical’ (chorister) and ‘CCM’ voice, and all had experience performing at professional level using both voice types. Each participant was recorded singing in both styles, and these results were directly compared. Five individual sustained notes at 3rd octave intervals across the sung phrase were selected for individual analysis. A 500ms portion of the steady state part of each note was analysed for CQ_{EGG} and these results correlated against pitch.

Mean Closed Quotient for each note in each style was derived and results are shown in table 1. Mean CQ for 4 of the 5 notes analysed is higher for the ‘theatre’ voice than the classical, with the mean for C5 being nearly identical. Analysed as individual singers across all notes, 76% of mean CQs were higher in ‘theatre’ voice than in ‘classical’. A one tailed paired student’s T-test of the means demonstrated a significant difference between the two data sets (p=0.018).

There is a relationship between mean CQ and sung pitch for each style. For the ‘classical’ voice mean CQ starts at 26.2% and decreases slightly with increased pitch up to G4 (24.6%), and then rises with pitch to B4 and C5 (28.3%). Mean CQ of the ‘theatre’ voice is higher at C4 (31.1%), but otherwise shows a similar pattern, again decreasing slightly with increased pitches to G4 (29.2%), and rising to B4 (33.6%), though CQ drops slightly again at C5 to 31.1%.

Voice	Note/vowel	Freq (Hz)	CQ (%)	SD (%)
‘Classical’	C4 / æ	262	26.2	6.2
‘Theatre’	C4 / æ	262	31.1	2.9
‘Classical’	C5 / ɜ˞	523	28.2	5.9
‘Theatre’	C5 / ɜ˞	523	31.1	5.4
‘Classical’	Bb 4 / æ	466	28.3	4.8
‘Theatre’	B^b 4 / æ	466	33.6	3.6
‘Classical’	G4 / u	392	24.6	5.9
‘Theatre’	G4 / u	392	29.4	4.4
‘Classical’	E4 / u	329	25.6	6.2
‘Theatre’	E4 / u	330	31.1	5.4

Table 1 - Mean CQ% for selected notes in each style

Study 3

Figure 3 shows maximum and minimum pressure values in comparison to the corresponding values of adult singers and nonsingers. The threshold pressure, i. e. the lowest detected pressure that produced phonation, was higher for girls at the lower frequency, but the difference was not significant and not existent for the higher frequency. Therefore the results for boys and girls are combined in Figure 3. Threshold pressure was also very close to the results of untrained women. The children reached maximum pressures between 9 and 25 cm water column, 10 to 15 cm was common. The average maximum pressure was higher for girls, but again the difference was not significant. Not surprisingly, the maximum pressure of children was smaller than for adults, both trained and untrained. For the children, the maximum pressure was correlated with body height: Taller children reached usually higher pressure values, but the correlation was weak.

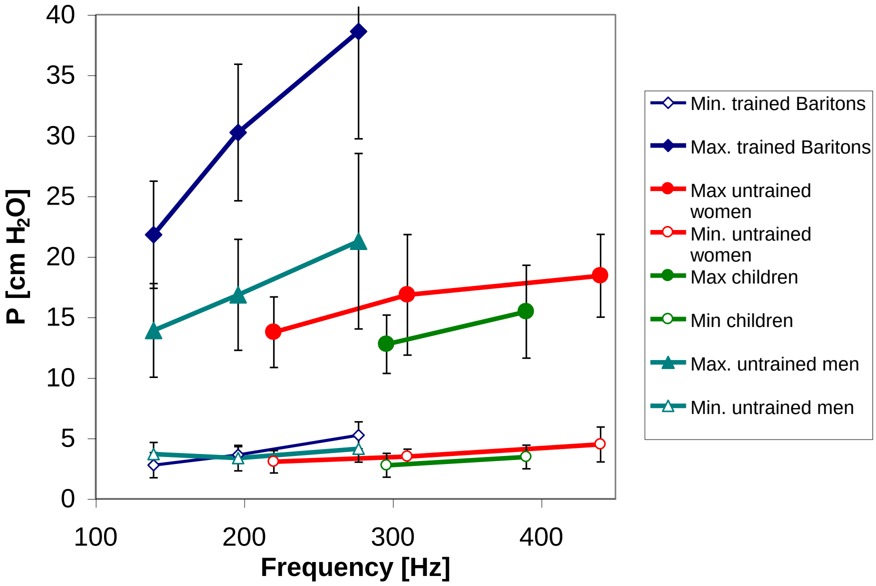

Figure 3 – Maximum pressure and Threshold pressure of the investigated children, trained Baritons (data from Sundberg et al, 1999), and untrained men and women (data from Sundberg et al 2005).

The AC amplitude correlated linearly with the subglottal pressure for all singers with a determination coefficient of at least 0.85 for all singers. If the measurements for all girls and boys are combined, a significant difference is visible: The regression lines for girls and boys are nearly parallel, but 75% of the girls' values lie below the regression line for boys, and 75% of the boys' values lie above the regression line for girls (see Figure 4). The difference in the AC amplitude in relation to subglottal pressure can be estimated via the regression lines for every single singer. The mean slope for girls is smaller than for boys. .

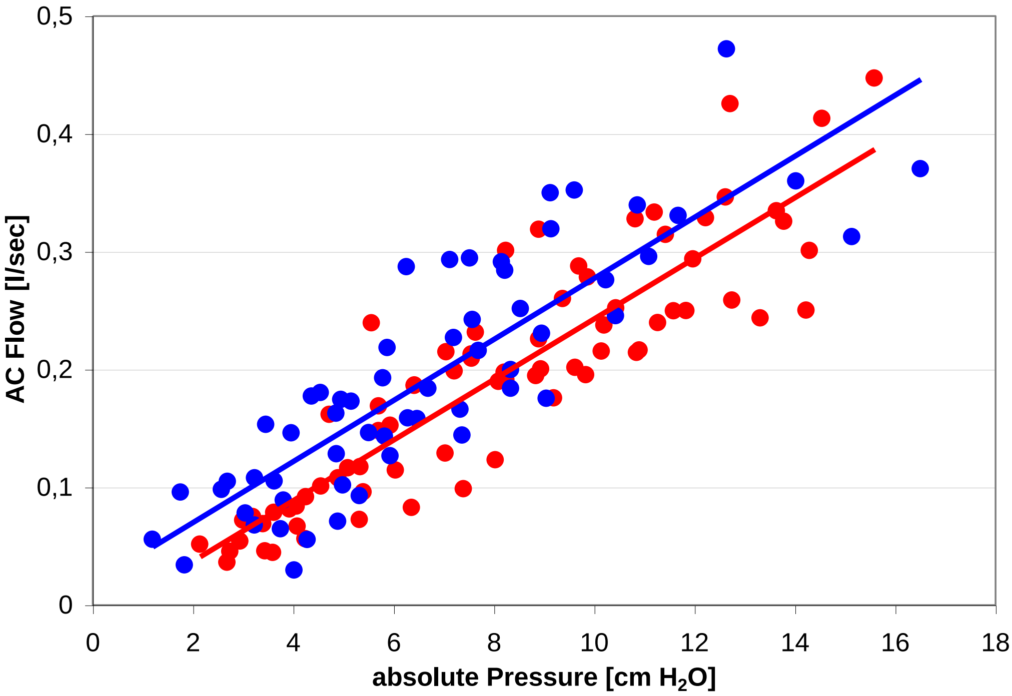

Figure 4 – Measured AC Amplitude and pressure values of all girls (red circles) and all boys (blue circles) with linear regression lines.

Glottal leakage was pressure dependent, too. Generally, higher pressure leads to higher DC flow, but the correlation was weaker than with the AC amplitude. Figure 5 shows data of one boy, AC amplitude data is marked with blue circles, DC flow with violet squares. In this case the DC flow grows nearly parallel to the AC flow, but for other singers the DC flow line was more flat. Note that the glottal leakage was sometimes higher than the AC amplitude. That was the case in 35% of the boy-phonations and 29% of the girl-phonations. The mean regression line of the DC flow was steeper for boys than for girls, like for the AC amplitude, but because of the high variance of the data, the difference can not be considered significant.

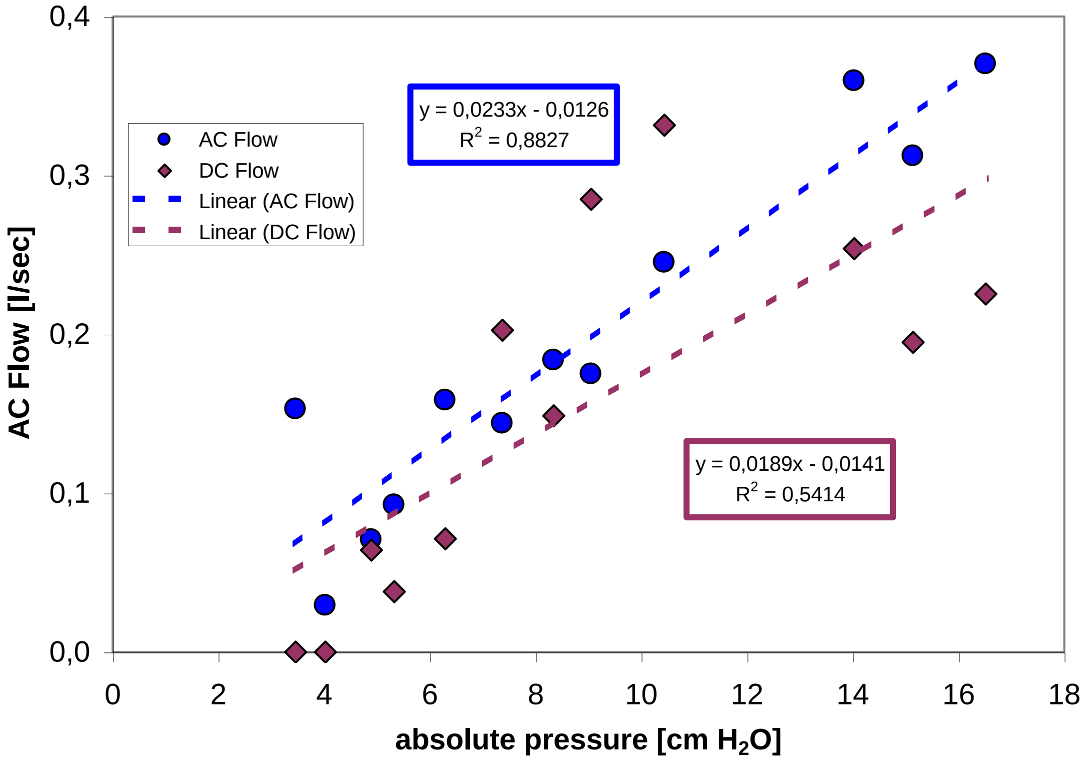

Figure 5 - AC flow and DC flow of singer O. T. (12 year old boy) at 294 Hz.

It is known that the CQ_{Flow}t of adults is low for low pressures and approaches a maximum when the pressure rises. (Sundberg et al., 1999, Sundberg et al., 2005) This can be described a function of the form

$$CQ_{Flow}=A\text{-}e\text{-}L^{*}\ P_{norm}+\ln(A),$$

were P_{norm} correspondents to the *normalized excess pressure*, which is defined as $(P\text{-}P_{Threshold})/P_{Threshold}$. At Threshold Pressure, P_{norm} equals 0, at double threshold pressure, P_{norm} is 1.

For 9 of the 11 children such a regression could be found. Figure 6 shows the data of one girl and the approximation. In this case the regression function fits well with the data points. For other singers the approximation was less exact, and for two singers it was impossible to find a single similar function.

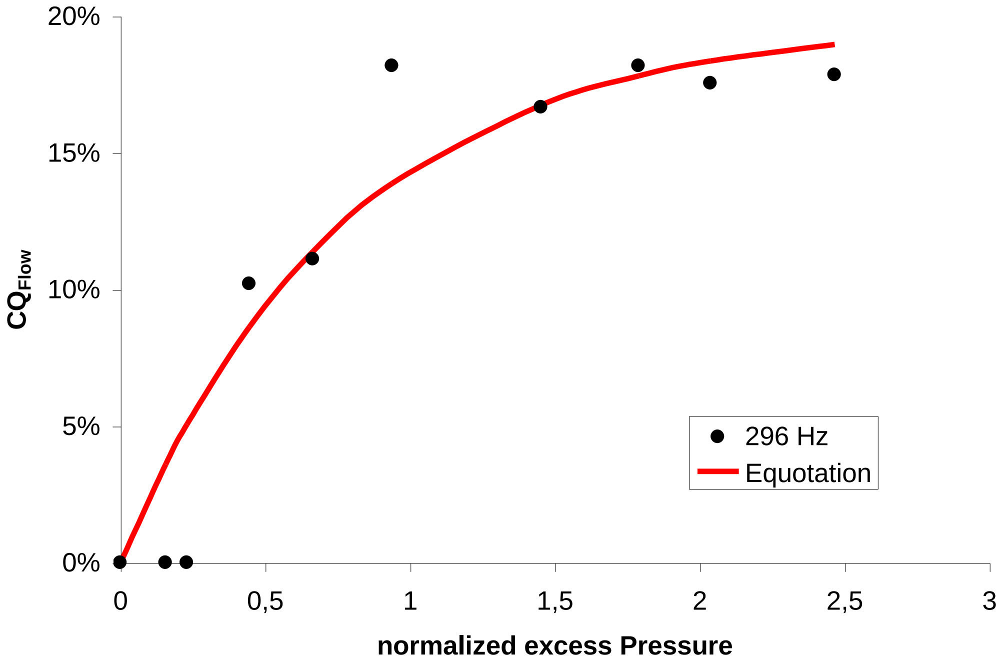

Figure 6 - Closed Quotient 296 Hz of singer E. C. (10 year old girl)

The children usually phonated with a closed quotient of zero for low pressures. A closed quotient of zero was detected when the derivative of the EGG-signal showed no closing peak at all. About half of the children used this phonation mode for more than one pressure value. One boy used zero-contact singing until he reached four times his threshold pressure. It was impossible to calculate an approximation of the mentioned form for this singer.

Figure 7 shows the average approximations for adults and children. For the mean values of children only 4 singers with the lowest sum of squares between their approximation function and the measured data were used.

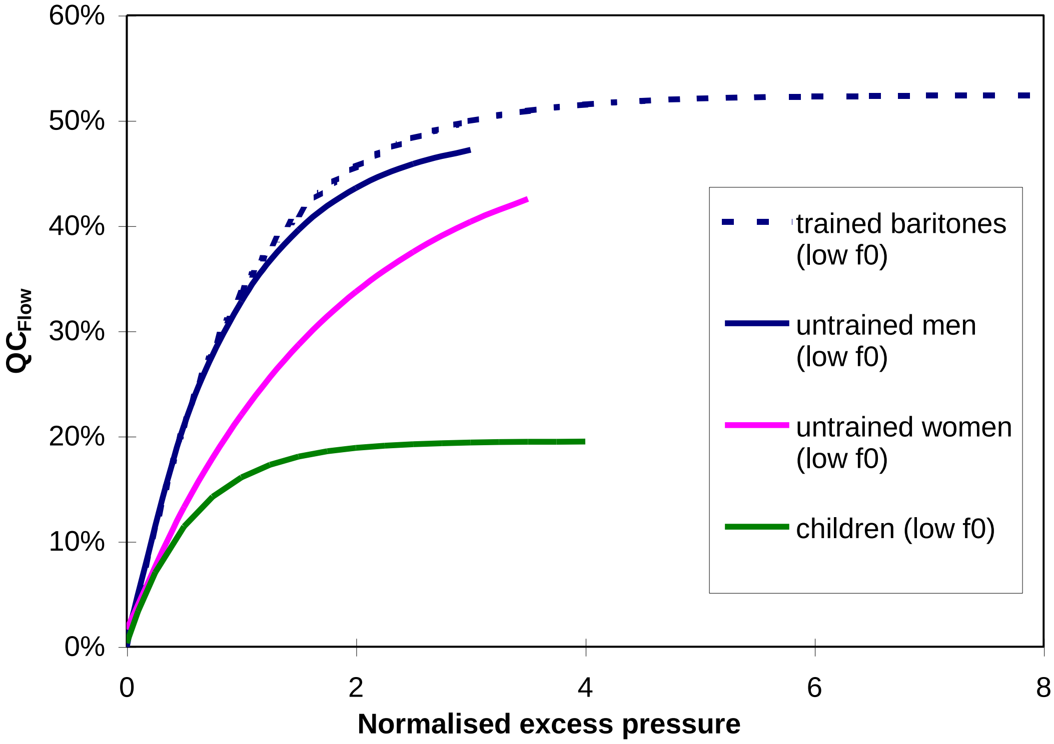

Figure 7 – Approximated CQ_{Flow} in relation to subglottal pressure for children and adults (data for adults according to Sundberg et al. 1999 and Sundberg et al. 2005).

The maximum closed quotient is much lower for children than for adults, it usually stabilized around 20%, for one girl at 30%. This result fits with the data of Peta White who used the same method and 11 year old children and found closed quotients between 15 and 25%. (White, 1997)

The measured closed quotients were higher for girls than for boys. Consequently, the regression function for girls approached a higher value, and girls used less zero-contact-phonation

Discussion

General comparison of the results

Results from the studies were strongly correlated. Study 1 found shorter CQ_{EGG} for boys than girls for unchanged voices. Non-significant differences in the relationship between Closed Phase and F0 were also observed as a function of training in both sexes.

Study 2 found similar patterns in the CQ_{EGG} vs F0 patterns in male and female groups. Significant differences in CQ_{EGG} measures were also observed between the two genres, with a significantly raised CQ_{EGG} duration for the Musical Theatre singers. Significant differences were also observed in the acoustic spectra between the voice types.

Study 3 used a different methodology to derive the closed quotient and related the voice source characteristics to subglottal pressure. Again, a shorter CQ_{Flow} for boys voices compared with girls was found. CQ_{Flow} was correlated with subglottal pressure such that CQ_{Flow} grows with subglottal pressure until a maximum is reached. The study also found a significant higher alternating airflow amplitude for boys.

Higher Alternating Airflow for boys

The higher alternating Airflow of boys found in study 3 can be explained in two different ways:

First, boys could have longer vocal folds. As the subjects were 10 to 13 years old and more or less close to voice change, this seems possible. But despite the fact that one boy showed signs of voice change, no differences in the speaking voice or the lowest possible phonation frequency of girls and boys were found. Furthermore, no connection between speaking voice or lowest fundamental frequency and AC amplitude could be found.

Second, a higher alternating airflow could be the result of a more “relaxed” phonation. This explanation fits some of the other findings. However, it is unclear why boys should phonate in a more relaxed manner than girls.

Comparability of CQ_{EGG} and CQ_{Flow}

As explained in the method section, CQ_{EGG} and CQ_{Flow} are different measures that should be distinguished. It seems plausible that both measures are connected in the sense that a phonation with a higher CQ_{EGG} should also exhibit a higher CQ_{Flow}, but considering that a low correlation of both measures is reported especially for breathy and falsetto-like voices (Herbst and Ternström, 2006; Childers et al., 1990; Alku et al, 1990). and that breathiness is a common phenomenon in children’s voices (McAllister et al., 1994), a systematic connection could be doubted.

However, regardless of methodological differences, in both studies (1) and (3) the measured CQ-values suggest that girls sing with a longer closed phase than boys: Significantly higher CQ_{EGG} values were found for untrained girls and for untrained boys in study (1), and higher CQ_{Flow} values were found for girls than for boys in study (3). While study (1) found this in an investigation of a large number of subjects, study (3) worked with only 11 subjects, but found that result to be independent of subglottal pressure.

CQ-Differences of the subject groups

While it should be taken into account that this could be an accidental agreement, the finding that girls sing with a longer closed phase that boys is supported by White (1997) and by Stathopoulos and Sapienza (1997). Study 3 also found a higher amount of zero contact singing exhibited by the boys. Due to the relatively small number of subjects involved in this study, the gender differences regarding CQ_{Flow} were not significant. However, another study with the same singers (Mecke and Sundberg 2010) found significant differences in the CQ_{Flow} of girls and boys when the subglottal pressure was not taken into account. Together with a lower fourth formant frequency, this difference was one of only two significant differences found between boys and girls receiving the same singing education.

The fact that the trained British male and female choristers in study (1) had no such differences in their CQ_{EGG} implicates that vocal education can reduce those differences to an insignificant level. However, not all forms of singing training reduce the differences, as the Swedish subjects in study (3) showed. The CCM sample did not have sufficient boys to be able to make a comparable analysis between boys and girls singing in CCM styles, and this is an area for further investigation.A shorter closed phase is usually sign of a more breathy phonation,, while a longer closed phase is sign of a more "pressed" phonation, though none of the measured CQ_{EGG} suggest a high degree of 'pressed' voice. As the closed phase is dependent on the subglottal pressure for low pressures, the shorter closed phase of boys measured in study (1) could also be the sign of a soft phonation.

Although not statistically significant due to large standard error values, this could possibly demonstrate the use of higher subglottal pressure by untrained girl singers in the upper end of the range to achieve notes, suggesting that they are having to work harder to get to those pitches. However, study 3 shows that the differences between girls and boys are independent of the subglottal pressure.

Study (2) illustrates that CCM singing of children is characterised by a higher CQ_{EGG} and higher sound levels, "choral" singing by a lower CQ_{EGG}. This findings suggest that the untrained girls in study (1) and the girls in study (3) tend to phonate in a more CCM-like manner, especially for the higher notes, while boys tend to sing in a more "choral"-like manner. However, there is also the possibility that different vocal fold characteristics of girls and boys lead to different CQ values, such as those that Titze (1989) calculated for adult male and female voices.

The British choral training girls and boys receive lead to a more "choral" singing of the girls, while the Swedish music school did not have such an effect on the voice source, since differences between girls and boys were still measurable.

Conclusion

Voice Source characteristics of children are pressure-dependent in the same manner as those of adults, though the maximal subglottal pressure and the closed quotient are smaller for children. However, exact closed quotient-values of children are difficult to determine because of a high glottal leakage.

Comparing the voices of girls and boys, two studies found lower CQ-values for boys than for girls before puberty. Boys showed also more zero-contact singing and a higher glottal leakage. A significantly higher alternating airflow amplitude was also found for boys. Singers using CCM styles had a small but statistically significant increase in contact quotient than choristers, possibly indicating higher subglottal pressure and a higher degree of pressing in voice production.

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