Measured characteristics of development in adolescent singers

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Abstract — **Electrolaryngographic recordings were made of spoken and sung voices of 256 trained and untrained singers aged 8-18. The authors examined measures of Larynx Closed Quotient (CQ) over a sung scale and spoken passage and related them to the parameters of sex, development and vocal training.**

A positive correlation between CQ and development was found for both the singing and spoken voices of boys. Girls, however, showed a negative correlation between sung CQ and development, but exhibited no correlation between spoken CQ and vocal development. Trained singers in both sexes exhibited slightly lowered mean sung CQ, with a reduced range of values and lower standard deviation, possibly demonstrating greater control over the vocal mechanism. It is proposed that this demonstration of qnuntifiable vocal differences could form the basis of a biofeedback tool for pedagogoy and vocal health monitoring.

Keywords: Larynx, Electrolaryngograph, Singer, Child, Adolescent, Voice Source, Closed Quotient, Sex, Age, Training.

I. Introduction

In recent years the introduction of computer based audio analysis tools have been introduced in number of singing studios with adult voices [1] to provide biofeedback on the voice during coaching and can provide both a pedagogic tool and a monitor of vocal health.

Laryngography is an established technique for making non-invasive recordings of the voice source. It passes a small electric current across two electrodes placed either side of the larynx. Variations in vocal fold closure change the resistive properties of the larynx, and the output waveform can therefore be analyzed in terms of vocal fold closure. It is both an accurate method of F0 estimation [2], and a direct method of analyzing the voice source. The Laryngograph output (Lx) and acoustic output from a microphone (Sp) is simultaneously recorded to allow comparison of vocal fold activity and acoustic properties of the voice.

Biofeedback tools based on Laryngographic analysis of F0 have been previously used with success in teaching children to pitch accurately [3]. Analysis of vocal fold Closed Quotient [4], spectrographic analysis and vocal tract modeling [5] have also been used to assess vocal production in adult singers and provide computer based feedback. As the young voice is still poorly understood, the use of such computer based voice analysis and feedback systems with young singers is problematic, as there is no complete model to use when analyzing the data.

Young people in the UK are still more likely to sing regularly than any other demographic group [6]. While it has been acknowledged for some time that the young voice is significantly different to that of the adult [7], there is still a limited amount of published research on the development of young voices, and in particular the voices of young singers.

During puberty, pubertal growth spurt causes a rapid increase in the rate of growth of skeletal and muscular tissue, including that of the larynx [8]. This usually starts in girls along with the start of breast development close to the onset of puberty. In males, the growth spurt occurs about half way through the pubertal physical changes on average when aged around 14 years (ibid). More recent studies of pubertal development [9], have indicated occurrence of pubertal onset in females as early as age 8, with average pubertal onset lower than accepted norms, although onset of menses has not changed significantly. Girls on average start puberty 0.5 to 1 year earlier than boys [8]. Brodnitz [10] suggests a direct link between the onset of menarche and the lowering of female spoken F0.

The primary growth in the larynx occurs in the membranous vocal fold length. This enlarges the larynx, particularly in males where the increase in testosterone level causes enlargement of the thyroid cartilage and thyroarytenoid muscle [11].

The majority of published research on young voices has largely concentrated on perceptual qualities such as vocal texture. (e.g. Laver [12]) or medical issues such as development (e.g. Kahane, [11], and Fitch and Giedd [13]).

There is a body of literature examining perceptual aspects of young voices (e.g. Gackle [14], Cooksey [15] and Wurgler [16] and some researchers have started to link medical data with data on the singing voice (e.g. Pedersen [17]; Harries *et al*, [18]). A number of studies have examined quantifiable aspects of young singers' voices from a variety of perspectives, using laryngography, (e.g Barlow and Howard [19, 20]), and voice range profile (VRP) (e.g. McAllister *et al* [21]). However, despite this, quantifiable voice analysis of young singers is still limited in scope and quantity, and there is still a need for expansion of the understanding of the operation of the voices of young singers, and the effects on them of singing, development and sex difference, before biofeedback tools based on these quantifiable voice analysis techniques can be effectively used in the singing studio.

Due to a lack of sufficient quantitative data, the completion of a developmental model of the voice of young singers is not yet available, and there are still several areas of research needed to build aspects of such a model. Without such a model the use of computer base voice analysis is limited when training children to sing, despite its successes with adult subjects. This paper examines the results of quantitative analysis on the voices of young singers, in particular the effect of pubertal development and singing training on the sung voice of young singers, which will expand the capability of quantitative assessment of young voices.

II. METHOD

Over 250 trained and untrained singers were recorded from a number of cathedral choirs and schools across the UK. Subjects were predominantly ethnically White British, with a small number of British Asian subjects. The subjects voices were recorded using a standard protocol a) reading aloud a passage of spoken text approximately 90s in duration to determine mean spoken F0 and b) singing a 2 octave ascending and descending scale to the vowel of /a/ covering the pitch range of G major. The spoken text was a section of the phonetically balanced short story 'Arthur the Rat', which has been used in a number of studies to determine mean spoken F0 [12, 17].

In the case of females or unchanged males the scale was sung from G3 (196 Hz) to G5 (784 Hz). In the case of changed male voices, the scale was sung from G2 (98 Hz) to G4 (392 Hz), or as near to G4 as the subject could reach. Subjects were asked to project the sound at a consistent mezzo-forte level, 'as if they were singing a solo'. If they were considered to be singing too loud or too quietly, or if there was considerable fluctuation in volume they were asked to repeat the scale. They were not required to sing the entire scale in one breath, but asked to breathe when necessary to maintain as regular a volume as possible. In the event of a subject running out of breath whilst singing or was considered to be singing too loudly or quietly, the subject was asked to repeat the scale.

TABLE I. AGE GROUPINGS OF SUBJECTS

Group	1	2	3	4	5
Age	8-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17+
Boys	32	36	18	14	11
Trained	20	22	10	8	6
Untr	12	14	8	6	5
Girls	21	40	22	15	17
Trained	11	27	12	9	9
Untr	10	13	10	6	8

The Lx output waveform from an electrolaryngograph [22] and the speech pressure waveform (Sp) from an AKG CK77 omnidirectional condensor microphone were recorded onto the two channels of a Fostex DA-5 DAT (Digital Audio Tape) recorder at 16 bit resuolution and 48kHz sampling rate. The microphone was mounted on a headset at ~10cm from the mouth to minimize fluctuations in amplitude caused by head movements, and also to maximize the ratio direct to reverberant sound. The recording locations were in the music department or rehearsal room of the school or choir involved. Due to the quantity of subjects and the diverse locations, anechoic recordings were not possible.

The microphone was powered by a Mackie 1402 VLZ-PRO low noise mixer. The Lx signal was viewed on an oscilloscope during the recording to maintain correct electrode positioning. This allowed the monitoring of SPL so that consistent volume levels were ensured as closely as possible, therefore reducing the possibility of CQ varying with volume. Recorded data was then transferred for analysis onto a PC system running undertaken using the Speech Studio™ and Quantitative Analysis™ software.

Electrolaryngography uses the measurement of electrical impedance to give a direct measurement of laryngeal activity. It is widely used for f0 estimation in laboratories and clinics [22].

Human tissue is a moderately good conductor of electricity, and the electrolaryngograph uses a constant voltage high frequency electric current passed between two electrodes placed externally either side of the neck at the level of the larynx.

The output waveform represents the current flowing between the electrodes. When the vocal folds are apart, the current must flow along a longer path between the electrodes, increasing impedance of the signal [23].

The current will thus be higher when the vocal folds are in contact than when they are apart. The current variation can therefore be analysed in terms of changes in vocal fold contact area, and quantifiable data can be extracted for analysis. A particular strength of the Lx signal when compared to other forms of voice analysis is its immunity to acoustic variation in the recording location.

The typical Lx waveform is shown in figure 1 giving the various phases of the vocal fold excitation.

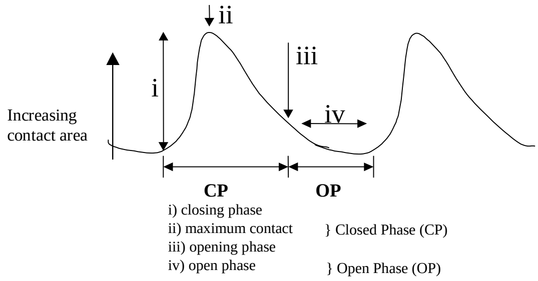

Fig. 1 Idealised electrolaryngograph output waveform (from [4:206]

TABLE II. SUNG CQ DATA FOR TRAINED MALE SINGERS

Age	8.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17+
	CQ%	CQ%	CQ%	CQ%	CQ%
Mean CQ	40.70	39.24	40.15	41.94	47.04
Stdev	7.84	8.27	6.14	6.04	5.46
Mode	39.70	37.68	41.02	42.23	44.27
Median	40.13	38.42	40.34	41.63	47.23
Lower qtile	35.46	33.52	35.56	38.30	43.04
Upper qtile	45.30	44.15	44.25	43.90	50.80

For analysis purposes the data was divided into male and female subjects, and then ordered by age of the subjects. The data was grouped into 2 year age brackets as shown in table 1.

TABLE III.: SUNG CQ DATA FOR UNTRAINED MALE SINGERS

Age	8.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17+
	CQ%	CQ%	CQ%	CQ%	CQ%
Mean CQ	39.74	42.24	45.26	46.76	49.80
Stdev	6.48	7.30	6.22	4.88	7.82
Mode	37.90	41.07	46.51	47.54	56.81
Median	38.55	41.45	45.32	47.12	51.20
Lower qtile	34.99	37.12	41.38	44.29	43.82
Upper qtile	44.13	47.47	49.15	49.60	55.41

Further division into ‘trained’ and untrained was made by classifying subjects with less than 6 months of vocal training as ‘untrained’ and those with 2 years or more as ‘trained’. Subjects falling between the two categories were disregarded, leaving 226 subjects for analysis.

III. RESULTS

Results previously reported by the authors examined closed quotient values of ascending and descending sung scales and phrases using cycle-by-cycle scatterplots [6], [19] and divided into third octave bands, [19], [24].

Paired t tests of means demonstrated a significant increase ($p>0.05$) in mean CQ in all pitch bands for changed boys compared to unchanged, with a further increase in CQ for trained compared to untrained boys. Girls demonstrated a significant decrease in sung CQ in all pitch bands across the voice change ($p<0.05$%)

TABLE IV. SUNG CQ DATA FOR TRAINED FEMALE SINGERS

Age	8.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17+
	CQ%	CQ%	CQ%	CQ%	CQ%
Mean CQ	42.83	40.87	39.14	40.88	33.60
Stdev	6.99	8.58	8.76	8.54	7.10
Mode	40.51	39.00	37.20	40.08	36.25
Median	42.74	40.14	38.20	40.29	32.42
Lower qtile	38.31	34.97	33.28	34.76	28.10
Upper qtile	47.55	45.95	44.58	46.52	38.93

TABLE V. SUNG CQ DATA FOR UNTRAINED FEMALE SINGERS

Age	8.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17+
	CQ%	CQ%	CQ%	CQ%	CQ%
Mean CQ	45.98	40.86	41.54	41.21	36.46
Stdev	7.80	6.66	7.97	7.40	7.02
Mode	43.06	38.61	39.46	41.83	38.54
Median	44.96	40.72	41.12	41.17	35.96
Lower Qtile	40.46	35.50	35.84	35.97	31.85
Upper Qtile	51.06	45.88	47.21	46.93	41.27

For this study Xlstat was used to generate standard descriptive statistics from the closed quotient values across the entire sung scale, including mean CQ, standard deviation, paired two-tailed student's t tests of means for each comparison, maxima and minima CQ values, median and quartile CQ values.

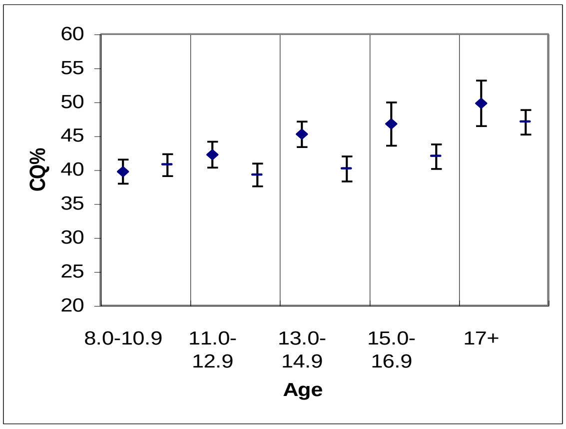

Fig. 2: Mean Sung CQ and standard deviation of boys

♦ untrained singers - trained singers

Figure 2 shows the mean closed quotient with standard deviation for male trained (table 2) and untrained singers (table 3). Figure 3 shows mean closed quotient with standard deviation for female trained (table 4) and untrained singers (table 5)

The range of closed quotients used across a sung scale may also be informative about the degree of voice control of a singer. As maxima and minima are prone to anomalistic values, the upper and lower quartiles were of CQ values were calculated, in addition to the median. The results are plotted in figures 4 and 5.

Further analysis examined the closed quotient of the spoken voice. Age in years and months was plotted against mean spoken CQ for the recording of ‘Arthur the Rat’ for both male and female subjects. Results are shown in figures 6 (male) and 7 (female).

IV. DISCUSSION

For male singers the mean CQ remains fairly constant over the first 3 groups, varying only slightly around 40% (+/- 1%). However, apart from a slight drop between the first and second groups, Mean CQ rises steadily across the last 4 groups, to a highest value of 47%.

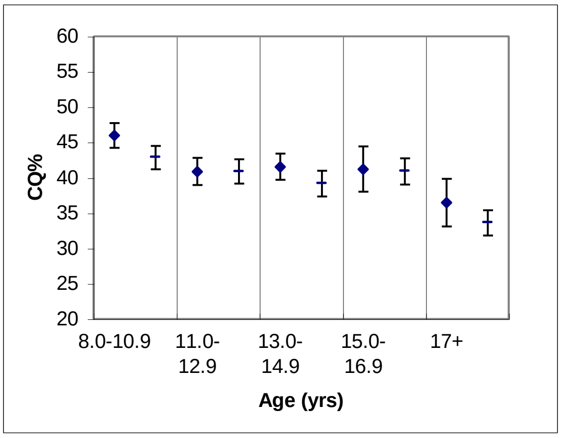

Fig. 3: Mean Sung CQ and standard deviation of girls

♦ untrained singers - trained singers

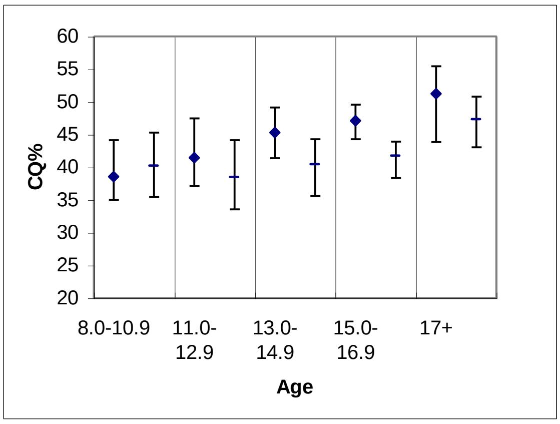

Fig. 4: CQ Median and interquartile ranges of boys

♦untrained singers - trained singers

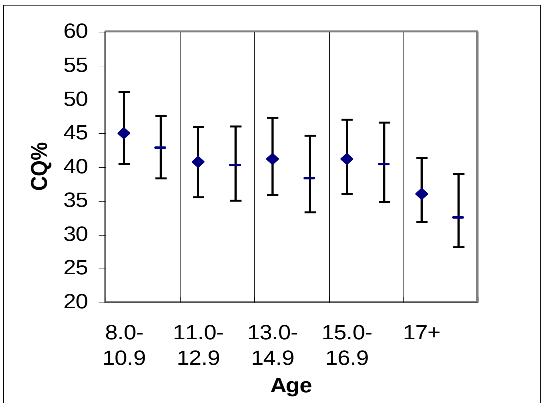

Fig. 5: CQ Median and interquartile ranges of girls

♦untrained singers - trained singers

Untrained boys demonstrate an even clearer, highly linear increase in CQ across all age groups from 40% in the Under 11 age group, to 50% in the over 17 age group.

In direct contrast to the male subjects, the mean sung CQ for female subjects appears to start high and fall over the increasing age groups.

The general trend is downwards, although there appears to be a plateau across the <13 to the <17 age groups in which variation is slight. A similar trend is evident in both singers (figure 9, table 5) and non-singers (figure 7, table 6). For both singers and non-singers the <13 and <17 age groups have near identical values of ~41%, with a slight variation in the <15 age group.

The pattern of median values for boys are very similar to the pattern of mean values for the same group. For both singers and nonsingers there is a generally positive trend for CQ median with increased age across adolescence. The upper and lower quartiles track the median very closely maintaining a steady range from the median of about 5% above and below (+/- 1%). This indicates a normal distribution to the data with minimal skew as the median is centred between the two quartiles.

For male singers the CQ median drops slightly from 40.1% to 38.4% over the first 2 groups, and then rises steadily thereafter to the oldest group at a value of 47.2%. The lower quartile follows the median very closely at about 5% below the median (+/- 1%). The upper quartile however has a slightly negative slope for the first 4 groups (from 45.3% in the under 11 age group to 43.8% in the under 17 age group) before rising to 50.8% in the oldest group. The interquartile range widens very slightly from group 1 to group 2, but then narrows considerably from 10.6% in group2 to 5.6% in group 4. While the range widens slightly again in group 5 it is still narrower than all the other groups excepting group 4.

For untrained boys the interquartile range behaves in an almost exactly similar manner as for the male singers. There is a slight widening over the first 2 groups from 9.8% to 10.6%, and then the range narrows considerably over the next 3 groups to a value of 5.3%. This then widens again in the over 17 age group.

The principal difference between the male singers and non-singers is that the CQ values for the median and the quartiles are higher at all levels for non-singers than for singers.

Median CQ values for female subjects also follow the patterns of the mean CQ values. Values generally drop across the increasing age groups, with the exception of a slight increase in the under 17 age group which breaks up the otherwise linear descent in median CQ.

The upper and lower quartiles follow the median closely, with the upper quartile ~6% above the median value (+/- 1%) and the lower quartile ~5% below the median at all points (+/- 1%).

There is no significant difference between the median CQ values shown at different age groups between the female trained and untrained singers, with both groups behaving in a nearly identical manner. Untrained singers have a very slightly higher median at most age groups. This is not at a statistically significant level (p>0.05).

Stathopolous [25] postulated that children have generally incomplete closure of the glottis due to a larger glottal ‘chink’ compared to adults. This should in theory lead to lower closed quotient values, which would increase over the period of pubertal development.

This data would appear to support that hypothesis for males, as there is a positive correlation between age and closed quotient for the sung data, and also between spoken FO and spoken CQ for the spoken data, with a linear coefficient of 0.53 between mean spoken CQ and age. These two different methodologies present similar findings, which further supports results presented by the authors on third octave analysis of the voice.

The conclusion to be drawn is that male pubertal development increases the level of contact of the vocal folds for both sung and spoken voice, possibly due to the closure of the glottal chink.

The effect of training male children and adolecscents is less clearly defined. However, in all bar the youngest age group, both the mean CQ and the position of the interquartile range are lower for trained singers than for untrained, though not at a statistically significant level (p>0.05). Standard deviations are also lower for trained singers, though again not significantly so.

This evidence of lower CQ for trained singers may however be indicative of a higher degree of control over vocal production, and in particular may suggest that untrained singers have a higher tendency to use pressed voice than trained singers.

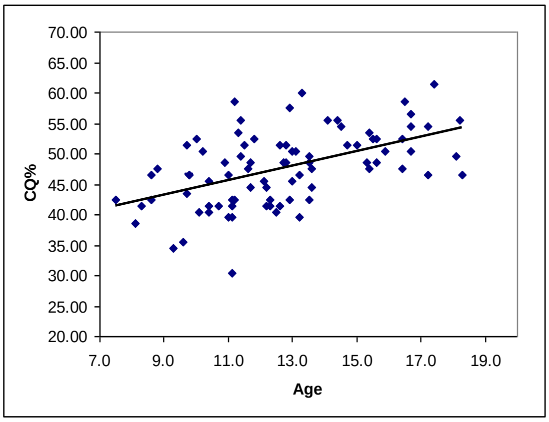

Fig. 6: Mean spoken CQ against age for boys

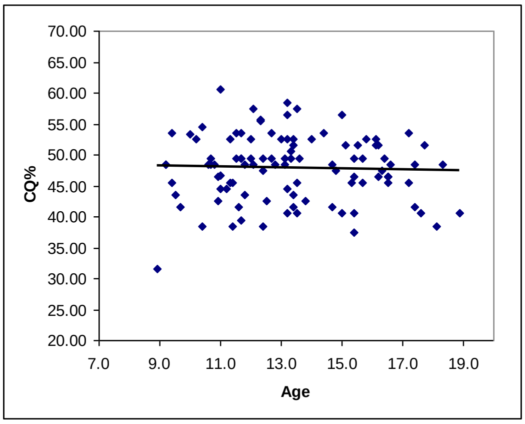

Fig. 7: Mean spoken CQ against age for girls

For girls, however, the results are contrary to the hypothesis, in that a significant decrease in mean sung CQ is evident between the youngest and oldest groups, with a gradual decrease in CQ across the age groups. This again supports previous work by the authors [19, 24].

Perceptual studies of the female singing voice [9] have described a 'breathy' tone appearing in the voice of female adolescents over the period of pubertal voice development. Researchers have discussed the development of a 'mutational triangle' caused by the widening of the lateral angle in the female larynx during the growth spurt.

Results presented here support the concept that a female singing voice gets more rather than less breathy over puberty, possibly caused by the development of a mutational triangle. It is interesting to note that again, female 'trained' singers appear to have lowered CQ when compared to 'untrained'. This is not necessarily to be expected, as trained adult opera singers have been shown to have higher CQ than untrained adult singers [26]. However, it is suggested that the higher values of the untrained children may be due to the use of a higher degree of pressed or 'forced' phonation to achieve the sung tones than used by trained singers.

Another point of note is that while there is a distinct correlation between development and sung CQ, this relationship does not exist in the spoken voices of girls, with a correlation coeffiecient of zero (0.06) between age and spoken CQ. This may suggest differing vocal production strategies between sung and spoken voice for child and adolescent females. This is an important consideration for both voice analysis and synthesis research.

V. Conclusions

With all of the statistical measures used above there are only very small differences between the results of the singers and non-singers in each sex. This does not however demonstrate that there are no changes in voice source which are a direct result of vocal training.

These small differences, while generally not statistically significant, may well have important effects on the vocal tone which needs to be considered in analyzing, modeling or synthesizing the voices of children and adolescents.

There are, however, significant differences in the results of each measure for each individual age group within a sex. Results appear to support the hypothesis that closed quotient values will increase for boys spoken and sung voices over the pubertal voice change, which will result in a less breathy vocal production, and is likely to be an important difference between the adult and child voiced sound.

For girls, the results support previous findings that closed quotient values decrease over the pubertal voice change for the sung voice, corroborating perceptual analyses which have documented the development of a increased breathiness in the singing voices of female adolescents. These results do not support the hypothesis that a similar effect occurs in the spoken voice of female adolescents.

These particular measures show that age related pubertal development is a major factor in the voice source characteristic of adolescent subjects.

It is proposed that the demonstration of statistically significant measures of vocal fold activity which relate to specific parameters of training, gender and development demonstrate that vocal fold closed quotient could be used as the basis for a laryngographic based biofeedback system for child singers.

While a significant amount of work still needs to be done in the construction of a model of vocal development - particularly in linking the Lx and acoustic data, these results would allow a baseline model of understanding of 'normal' behaviour which could be used as the basis for understanding the results of visual feedback.

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