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Long-Term Average Spectra From a Youth Choir Singing in Three Vocal Registers and Two Dynamic Levels

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Article Outline

Summary

Objectives/Hypothesis

Few studies have reported the acoustic characteristics of youth choirs. In addition, scant data are available on youth choruses making the adjustments needed to sing at different dynamic levels in different registers. Therefore, the purpose of this study was to acoustically analyze the singing of a youth chorus to observe the evidence of the adjustments that they made to sing at two dynamic levels in three singing registers.

Study Design

Single-group observational study.

Methods

The participants were 47 members of the Brooklyn Youth Chorus who sang the same song sample in head, mixed, and chest voice at piano and forte dynamic levels. The song samples were recorded and analyzed using long-term average spectra and related spectral measures.

Results

The spectra revealed different patterns among the registers. These differences imply that the singers were making glottal adjustments to sing the different register and dynamic level versions of the song. The duration of the closed phase, as estimated from the amplitudes of the first two harmonics, differed between the chest and head register singing at both dynamic levels. In addition, the spectral slopes differed among all three registers at both dynamic levels.

Conclusions

These choristers were able to change registers and dynamic levels quickly and with minimal prompting. Also, these acoustic measures may be a useful tool for evaluating some singing skills of young choristers.

Key Words: Youth singing, LTAS, Vocal registers, Dynamic levels

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Introduction

Most of the existing acoustic studies of choral singing have used adult singers as the participants. These studies have focused on differences between choral singing and classical solo singing[1, 2, 3, 4]; singing attributes of choral singers[5]; and on the effects of choral formation, choral size, acoustic quality of rooms, song selection, and blend.[6, 7, 8, 9, 10, 11, 12, 13, 14, 15] In contrast, few studies have evaluated the acoustics of youth choirs.

Howard et al[16] evaluated listeners' abilities to discriminate between boys and girls singing the same vocal part. They found that trained listeners could not distinguish between the singing of boys and girls younger than 11 years. A subsequent study reinforced this finding in which the authors reported almost identical spoken pitch and vocal ranges for boy and girl singers in this age range.[17] In contrast, White[18] reported that the long-term average spectra (LTAS) curves from boys had a spectrum peak around 5000 Hz, whereas the girls' LTAS had a relatively flat spectrum in the area of 5000 Hz. From this difference, she concluded that the peak at 5000 Hz indicates a "boy-like" sound. This indicates that the timbre difference in the higher harmonics has a greater effect on the perception of the "boy-like" sound than does the fundamental frequency.

Vocal training allows children to sing with greater pitch and dynamic ranges. Schneider et al[19] reported that children from singing or musically encouraging schools had an average fundamental frequency range of 32 semitones, and those from other schools had an average fundamental frequency range of 27 semitones. The former range was similar to previously reported ranges for children with vocal training,[20, 21] and the latter range was similar to previously reported ranges for untrained children.[22, 23, 24] In addition, youth with vocal training exhibit spectral differences that imply the use of different laryngeal and vocal tract gestures when singing in a classical style as opposed to a music theater one.[25]

Whether youths should sing in different vocal registers has been discussed as an aspect of healthy singing practices. For example, singing in head and mixed registers has been considered the healthier and better training method for them.[26, 27] The muscle adjustments in the larynx and vocal tract that allow us to change registers result in observable acoustic changes in the vocal and resonance components of sung vowels.[28, 29] As noted by Andrews,[30] when these adjustments are inappropriate, they can result in vocal problems among untrained or poorly trained young singers.

In addition to the choristers, acoustic studies of choruses must consider room acoustics. Ternström[13] recorded three choirs in each of three different rooms to determine the possible effects of the room acoustics on LTAS. He found that singers in an adult choir, but not those in either a child or a youth choir, adapted their vocal effort level ostensibly to accommodate differences in room absorption.

Ternström[13] also reported that changes in a choir's sound level resulted in nearly linearly proportional level changes in each frequency band of an LTAS analysis and introduced a frequency-dependent gain factor $g(f)$ to account for the spectral effect of sound pressure level (SPL) changes on the LTAS. This frequency-dependent gain factor can be computed for speech also. Nordenberg and Sundberg[31] found that the $g(f)$ changes for different amplitude levels of speech were nearly the same as those reported by Ternström[13] for different levels of choral singing. White[32] reported that $g(f)$-corrected LTAS revealed that the girls in her study sang at slightly higher mean intensity levels in the piano and mezzoforte conditions, whereas the boys had higher mean intensity levels in the forte condition. Thus, the $g(f)$-corrected LTAS can be used to provide information concerning the choral singing of children.

Therefore, $g(f)$-corrected LTAS may indicate physiological adjustments made by the members of a youth chorus when the chorus sings in different registers and at different dynamic levels. The purpose of the present study was to acoustically analyze the singing of a youth chorus to observe the evidence of the adjustments that they made to sing at two dynamic levels in three singing registers. The selected choir has been trained to sing in a variety of singing styles, including traditional youth choral, classical, belting, gospel, and musical theater styles.

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Method

Participants

The participants were the 41 girls and six boys who comprised the Concert Chorus of The Brooklyn Youth Choir Academy (BYC). The BYC was selected on the basis of national recognition and the training of the choristers in a variety of musical styles. In contrast to some youth choirs who are trained to use head voice only, the members of the BYC are trained to use head and chest registers and styles that include belting and gospel. The girls in the choir ranged in age from 11 to 18 years (mean age = 14.2 years). The boys in the choir ranged in age from 11 to 14 years (mean age = 12.2 years). All members of the BYC participated in vocal training for at least 9 months. The time of vocal training in the BYC for the children ranged from one to eight school years. The BYC rehearses twice weekly for 2 hours. All children self-reported that they were of good general health at the time of the recording, and none exhibited observable symptoms of upper respiratory infections or nasal congestion on the day of recording.

Procedures

The choristers sang two repetitions of *Happy Birthday*, providing at least 30 seconds of sound. The song was sung using the nasal /n/ for all consonants and the vowels /a/ and /i/ for all vowels in syllables strings of /nananini/ and /nininana/. These phonemes were used to reduce the complicating effects of sibilants on the long-term spectra from the singing sample. Although the /n/ phonemes are characterized by lowered energy in the spectrum, the effect of these phonemes on the overall spectrum was minimal because of their low amplitude and short duration. The vowels were selected to provide the widest range of first- and second-formant values. The two vowels occurred the same number of times in the song. The small number of vowels in the song made the replacement lyrics easy for the choristers to learn.

The choristers sang the musical selection three times at each of the two dynamic levels: piano and forte. They completed these tasks in three vocal registers: head, chest, and mixed, resulting in 18 productions of the song. All productions were sung in unison in the key of E major beginning on the note B_3 at a tempo of 96 beats per minute.

All singing tasks were recorded via an Audio Technica Model AT3032 (AudioTechnica US, Inc., Stow, OH) omnidirectional condenser microphone connected via a Marantz Model 670 (Marantz America, Inc., Mahwah, NJ) solid-state recorder. Each recording was digitized in the recorder at a rate of 44, 100 samples per second and saved as a separate .wav file. The microphone was positioned 3 m from the nearest choristers to be in the diffuse field, outside the reverberation radius of the room. The reverberation radius was calculated from measures obtained using a Gold Line Model GL60 (Gold Line, West Redding, CT) reverberation time meter. The reverberation time of a brief noise was repeatedly measured at a range of octave intervals from 125 to 4000 Hz. The volume of the room was divided by each of the reverberation times. The square root of this dividend was multiplied by 0.056 to provide the reverberation radius at each frequency. These were averaged, and the average was determined to be 2.6 m. The microphone was placed farther from the chorus to record the choral sound heard by the audience.

Choral singing
The choir stood in a semicircle around the microphone. For each production of the song, the choral director instructed the choristers as to the vocal register and dynamic level to use. The choral director then played an B_3 on a piano to cue the chorus to the note. The chorus then sang the piece *a cappella*. After each singing task, the choral director told the chorus on the next vocal register and dynamic level to use. Then she cued the choristers as to the pitch, and the choir began singing. The dynamic level and register combinations were sung in a random order. Thus, the choristers changed the register and/or the dynamic level for each production of the song. They made these adjustments without instruction.

Data analysis

The files were analyzed using a KayPentax Computerized Speech Lab Model 4500 (KayPENTAX, Lincoln Park, NJ) hardware-software analysis system. The song segments were analyzed using the LTAS function. Settings for the LTAS included a fast Fourier transform (FFT) window size of 256 points with no pre-emphasis or smoothing, a bandwidth of 172 Hz, and a Hamming window. The six LTAS for each register displayed on a single figure to compare the uniformity of the repetitions and any differences that may have occurred between the two dynamic levels (Figure 1, Figure 2, Figure 3).

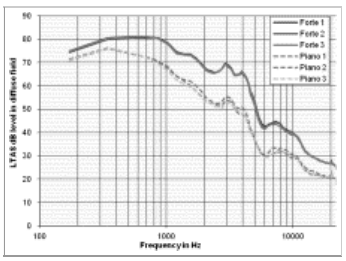

Figure 1
Comparison of LTAS for the repeated singing of the song at the forte and piano levels in the chest register.

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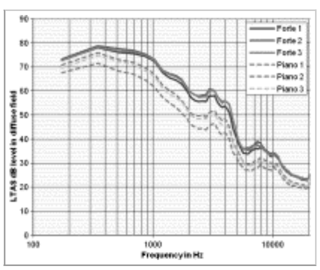

Figure 2
Comparison of LTAS for the repeated singing of the song at the forte and piano levels in the mixed register.

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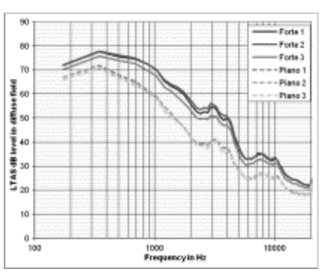

Figure 3
Comparison of LTAS for the repeated singing of the song at the forte and piano levels in the head register.

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L_{eq} differences and gain factor corrections

Because the spectrum slope changes with vocal loudness, the LTAS was adjusted to account for SPL difference.[13], [31], [32] The $g(f)$ indicates the extent of spectrum level changes at each frequency f for an overall SPL change of 1 dB. Computing the $g(f)$ required the following steps. For each production, the overall equivalent level (L_{eq}) was computed by converting the decibel values at each FFT point back to linear power, summing the power over all frequency bands and then returning the average value to decibels. This operation allowed the determination of the relative change in spectrum level at any frequency that is concomitant with a 1-dB change in L_{eq}. Thus, the value of $g(f)$ was then computed as the changes in level difference between forte and piano at each frequency (f) divided by the full-band L_{eq} difference between forte and piano. Assuming that the spectrum level changed linearly with the overall L_{eq}, the LTAS for a given L_{eq} could be predicted from the six recordings of the singing in each register. In this way, comparisons were made among the LTAS for the productions within each register, although they were not sung at the same L_{eq}. These calculations were done separately for all three vocal registers.

Each dynamic level and register combination was assessed twice to determine the stability of the choral singing. Because the choir may have used a slightly different L_{eq} even in what was nominally the same condition, the $g(f)$ was obtained for each condition. This calculation adjusted all of the frequency bands in the LTAS to account for the changes in L_{eq} between replications. Then, the residual differences between the observed and the predicted changes in spectrum level for each dynamic level and register combination were computed. The standard deviation across all frequencies of these residual differences was determined as a measure of the random scatter in the data.

Differences were determined among the LTAS in spectral tilt or the drop in amplitude from the region of the first formant to the region of the third formant. These differences were computed as the ratio of energy in the frequency band above 1000 Hz to energy below 1000 Hz. The room reverberation characteristics were subtracted from these ratios, and the resultant values were called the alpha ratios.[33]

In addition, two sets of comparisons were used to indicate the probable physiological adjustments of the singers to make dynamic and register changes in their singing. These were a comparison of the spectral tilt, as indicated by the alpha ratios to the L_{eq}, and a comparison of the H2-H1 difference with the L_{eq}. The H2-H1 difference was the amplitude difference between the second and first harmonic from an LTAS spectrum of three vowels from each production. The vowels used for this analysis were three of the /*a*/ vowels in the selection that were sung at 320 Hz. Because they had the same fundamental frequency, the harmonic structure was assumed to be equivalent. Any changes in the H2-H1 difference would reflect the dynamic and register adjustments made by the singers. The H2-H1 difference was used rather than the H1-H2 difference so that greater effort was depicted higher on the figure.

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Results

The three productions were compared at each vocal register and dynamic level combination. The standard deviations of the three productions for each register were also calculated. These comparisons revealed that the standard deviations were 1.9 dB or less for the piano conditions and 1.4 dB or less for the forte conditions. Therefore, any $g(f)$-corrected LTAS differences greater than 2 dB should represent a nonrandom effect. The choristers maintained similar LTAS patterns across frequencies for the productions at both dynamic levels in the chest register and at the piano level in the head register (Figure 1, Figure 3). More variability in the LTAS occurred across the productions at both dynamic levels in the mixed register and at the forte level in the head register (Figure 2, Figure 3). Because the productions were generally similar across productions, they were averaged at each register and dynamic level for further analysis.

The $g(f)$ analysis revealed the differences in spectral gain across frequencies between the piano and forte productions for each register. Differences in $g(f)$ mainly occurred between the chest and the other two registers (Figure 4). When singing in head and mixed registers, the adjustments the choristers made to differentiate piano and forte productions resulted in lower gain factors for the frequencies greater than 3 kHz than those when singing in chest register. However, the LTAS spectra for all the three registers exhibited similar spectral tilts in this frequency range. In contrast, at frequencies between 200 and 900 Hz, the chest production differences resulted in a steeper slope and lower levels than those exhibited by the other two registers. Thus, the gain in high-frequency energy from piano to forte was larger when the choristers sang in the chest register.

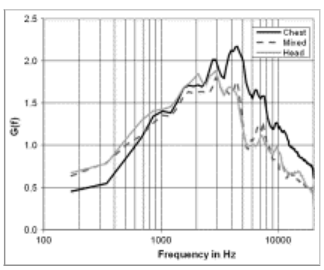

Figure 4
The $g(f)$ based on the average power in the three productions at each dynamic level in each vocal register. The $g(f)$ indicates how much the spectrum level would change at any frequency *f* when there is an SPL change of 1 dB for the signal (assuming a linear relationship).

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Two $g(f)$-corrected LTAS slopes were generated, one for the piano condition similar to those sung by the choristers in the head register (Figure 5) and one for the forte condition similar to those sung in the chest register (Figure 6). For the singing in the piano condition, the three registers were similar up to 1 kHz; then the head register singing was marked by a steeper slope in the region of 1–4 kHz (Figure 5). In the region of 4–6 kHz, the piano condition chest register singing exhibited a steeper slope and remained at lower amplitudes in the higher frequencies. The mixed and head register singing in the piano condition exhibited similar LTAS patterns for the low frequencies less than 1 kHz and the high frequencies greater than 3.5 kHz.

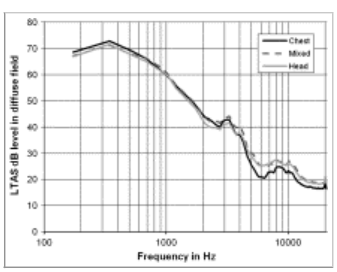

Figure 5
The $g(f)$-corrected average LTAS from the three piano repetitions in each register.

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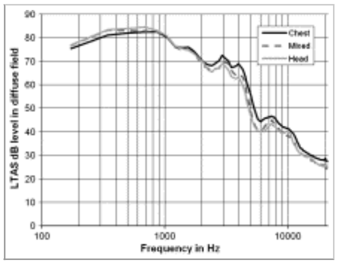

Figure 6

The $g(f)$-corrected average LTAS from the three forte repetitions in each register.

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As shown in Figure 6, the $g(f)$-corrected LTAS patterns across the singing in the three registers were different for the forte condition. For the frequencies less than 700 Hz, the singing in the mixed and head registers had higher amplitudes than that in the chest register. This pattern was reversed for the frequencies greater than 2 kHz, with the mixed and head register singing exhibiting lower amplitudes than the chest register singing. The slope difference between the chest register singing and the singing in the two other registers was greatest in the range of 2–5 kHz, with the mixed and head register singing producing steeper slopes. Except for the 400- to 800-Hz range, the $g(f)$-corrected LTAS patterns for the mixed and head registers were similar throughout the frequency range.

Similarly, the L_{eq} differed among the three vocal registers and two dynamic levels (Figure 7). As displayed in Figure 7, the plot of the interaction between the alpha ratio and the L_{eq} revealed a positive correlation across the registers and dynamic levels. The dynamic levels were separated at an L_{eq} level of approximately 81 dB, although the singing of one head forte production had an L_{eq} below that level. The head register productions for both dynamic levels were marked by the greatest slope, as shown by the smaller alpha ratio, and the smallest amplitude, as shown by the lowest L_{eq}. In contrast, the chest register productions were characterized by the gentlest slope, as shown by the greatest alpha ratio (the least negative, when the alpha ratio is expressed in decibels), and the greatest amplitude, as shown by the highest L_{eq}. As was found for the LTAS results, the replications were very similar for the piano productions in head and chest registers and the forte productions in the mixed and chest registers, whereas some variability was observed for the piano productions in the mixed register and the forte productions in the head register. Thus, the choristers were able to adjust their voice mechanisms to sing the registers and dynamic levels consistently across the trials.

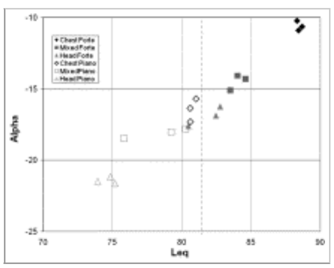

Figure 7

Comparison of alpha ratio with L_{eq} for both productions at each vocal register and dynamic level combination.

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Results of the H2-H1 difference and L_{eq} comparison from the selected vowels were similar to those of the alpha ratio and L_{eq} comparisons from the complete song productions. The forte vowels in each register were sung at greater L_{eq} levels and H2-H1 differences than those when the chorus sang them at a piano level. Figure 8 reveals that the forte vowel productions in the chest register differed from those produced in the mixed and head registers; the latter registers did not differ from each other. Among the piano vowel productions, the head register productions were made at lower L_{eq} levels and more negative H2-H1 differences than the other two registers. Thus, the mixed register vowels were sung similar to the head register for forte vowels and similar to the chest register for the piano vowels.

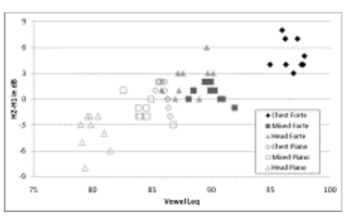

Figure 8

Comparison of H2-H1 difference with L_{eq} for the productions in each of the three registers at both dynamic levels.

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A repeated-measure analysis of variance with the L_{eq} and H2-H1 difference as dependent variables and the dynamic level and register as independent variables indicated the same patterns, with the H2-H1 difference clearly being separated between the forte and piano singing and among the registers. The main effect of register was significant for both the H2-H1 difference ($F(2,4) = 17.016$, $P = 0.011$, $\eta_p^2 = 0.895$, $\beta = 0.928$) and the dynamic level ($F(1,2) = 74.691$, $P = 0.012$, $\eta_p^2 = 0.976$, $\beta = 0.981$). A significant interaction between the register and the dynamic level also occurred ($F(2,4) = 25.802$, $P = 0.005$, $\eta_p^2 = 0.928$, $\beta =$ 0.986). An LSD pairwise post hoc test revealed that significant differences occurred between the chest and head registers but neither differed significantly from the mixed register. For the L_{eq} data, the vowels sung by the choristers also exhibited significant differences for both the main effects and the interaction: register ($F(2,4) = 102.781$, $P < 0.0001$, $\eta_p^2 = 0.981$, $\beta =$ 1.00), dynamic level ($F(1,2) = 8931.609$, $P < 0.0001$, $\eta_p^2 = 1.00$, $\beta = 1.00$), and register by dynamic level ($F(2,4) = 28.637$, $P =$ 0.004, $\eta_p^2 = 0.935$, $\beta = 0.992$). An LSD pairwise post hoc test revealed that significant L_{eq} differences occurred among all of the registers.

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Discussion

As hypothesized, these choristers exhibited different LTAS patterns across the dynamic levels and across the three vocal registers. The *g*(*f*)-adjusted LTAS spectra revealed expected different patterns at the two dynamic levels, with higher L_{eq} levels for the singing at the forte level.[13, 32] Their ability to sing the different vocal registers and dynamic levels that resulted in different *g*(*f*)-adjusted LTAS spectra is consistent with Barlow and LoVetri's[25] report of different spectra from singing in different musical styles. In addition, the choristers were able to consistently achieve the adjustments for the different registers and dynamic levels regardless of the settings for the previous repetition. Thus, they exhibited ease in singing all of the register and dynamic level combinations.

The *g*(*f*)-adjusted LTAS spectra indicated that these youth choristers made adjustments across the registers when singing the piano condition that differed from those made when singing forte. Their chest register singing in the piano condition was characterized by a stronger fundamental partial and steeper spectral slope in the frequency range of 4–5 kHz. The frequency range of 1–3 kHz was marked by a steeper spectral slope for the head register singing. Except for the 2- to 4-kHz frequency range, the piano singing in the mixed register was characterized by *g*(*f*)-adjusted LTAS spectra that were similar to those for the head register singing. These spectral differences indicate that the choristers used different glottal and vocal tract adjustments to sing in the chest and head registers in the piano condition.

The patterns across register for the forte condition were somewhat different. The mixed and head registers were sung with more energy in the region of the fundamental frequency through the first-formant frequency, up to approximately 700 Hz. For the frequencies greater than 2 kHz, the chest register was sung with more energy, with the mixed register singing exhibiting a slope between those of the singing from the other two registers in the region of 2–5 kHz. Again, these differences indicate that the choristers sang differently across the three registers. It should be remembered that these spectral differences occurred across a song that was sung at the same pitch level; hence, any LTAS differences indicate different adjustments to create specific singing outcomes.

As noted earlier, the *g*(*f*)-adjusted LTAS spectra revealed differences between the two dynamic levels. The greater amplitudes of the forte productions would be associated with greater subglottal pressure.[34] Similarly, these greater amplitudes agree with other reports of longer contact quotient durations during forte singing.[35] The piano condition productions had LTAS slopes that were more similar across the three registers but differed in the 2- to 5-kHz region.

The different LTAS patterns indicated that the children in the choir were able to adjust their dynamic level in all three registers. The relatively flat spectral slopes for the forte production LTAS could be a result of two glottal adjustments. First, the relatively flat spectral slopes could indicate that the choristers used a longer closure phase in the glottal cycle. This glottal adjustment is typical of adults when they sing more loudly.[36] As would be expected, the relatively flat spectral slopes that indicate a longer closure phase were most marked for the chest register.[35] Second, the relatively flat spectral slopes could be a result of medial face of the vocal folds completing adduction rapidly.[36] The youths in this study may have adducted their vocal folds more quickly and, thus, excited more energy at higher frequencies. These youth choristers may have made this glottal adjustment to achieve the vocal sound that they associate with forte singing.

The H2-H1 measurements provided more specific data on the adjustments made by this group of choristers. The amplitude difference between the first two harmonics has been associated with the closed quotient in speakers.[37, 38, 39] The H2-H1 difference data clearly separated the singing at the two dynamic levels and singing in the different registers at the dynamic levels. The head register piano singing had smaller H2-H1 differences than those of the mixed and chest register singing. In addition, the chest register forte singing had greater H2-H1 differences than those of the mixed and head register singing. The greater H2-H1 differences for the forte productions are consistent with reports of greater closed quotient in this register[35] in which the vocal folds are thicker. In addition, the greater H2-H1 differences also indicate that the choristers tended to exhibit smaller closed quotients when singing in the head register at both dynamic levels. Although the adjustments of the individual choristers cannot be determined from the group data, the data from the present study support this speculated difference in voice control.

Comparisons of the alpha ratio with the L_{eq} indicated that the register adjustments at both dynamic levels affected the tilt of the LTAS spectrum. A steeper spectral slope has been associated with lower amplitude speech and singing and with vocal folds that close more slowly.[13, 31, 32, 36] As shown in Figure 7, the alpha ratios indicated steeper spectral slopes for the head register singing than those for the mixed register singing, which were steeper than those for the chest register singing. The same pattern occurred for the LTAS at both dynamic levels. Thus, these choristers made glottal adjustments when they changed their singing register. Such adjustments are a normal aspect of singing at these different levels. These young choristers reproduced these adjustments when singing all repetitions of each register and dynamic level combination. The alpha ratios for the head forte and chest piano were similar, indicating that different laryngeal adjustments are made to sing at these different register and dynamic level combinations. However, data from individual singers are needed to determine the specific laryngeal adjustments used to create the different vocal register and dynamic level combinations.

Only one production in the head voice differed from the others. In contrast, at the forte level, the three registers exhibited different acoustic output for the alpha ratio comparison. In particular, the chest register productions had greater L_{eq} values and smaller alpha ratios. These numbers suggest that, for these young choristers, the control needed to create piano voice restricts the range of acoustic variation available through different glottal adjustments. The freer use of the mechanism at the forte level was indicated by the greater differences among the registers, particularly the chest register.

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Conclusion

These data indicate the consistent ability of these youth choristers to adjust their singing to different styles and sing in a manner that created different acoustic spectra among the vocal registers and the dynamic levels. They did this most effectively for the forte productions. Future investigations will require evaluating individual trained youth choral singers to determine the acoustic spectrum patterns they might exhibit for these register and dynamic level combinations. Visual perceptual measurements from flexible laryngeal endoscopy would verify if the physiological adjustments made to sing these register and dynamic level combinations are healthy ones. A similar design could also be used to determine the effects of a year of choral rehearsal and training on the choristers' abilities to quickly create distinctly different glottal adjustments. It would also be interesting to determine if other youth choirs can make the register and dynamic level adjustments as quickly and as consistently.

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