Effects of *Bel Canto* Training on Acoustic and Aerodynamic Characteristics of the Singing Voice

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Summary: Objectives. This study was designed to assess the impact of 2 years of operatic training on acoustic and aerodynamic characteristics of the singing voice.

Study Design. This is a longitudinal study.

Methods. Participants were 21 graduate students and 16 undergraduate students. They completed a variety of tasks, including laryngeal videostroboscopy, audio recording of pitch range, and singing of syllable trains at full voice in chest, passaggio, and head registers. Inspiration, intraoral pressure, airflow, and sound pressure level (SPL) were captured during the syllable productions.

Results. Both graduate and undergraduate students significantly increased semitone range and SPL. The contributions to increased SPL were typically increased inspiration, increased airflow, and reduced laryngeal resistance, although there were individual differences. Two graduate students increased SPL without increased airflow and likely used supraglottal strategies to do so.

Conclusions. Students demonstrated improvements in both acoustic and aerodynamic components of singing. Increasing SPL primarily through respiratory drive is a healthy strategy and results from intensive training.

Key Words: Singing training–Professional voice–Classical singing–Aerodynamics–Respiration.

Bel canto, "beautiful singing," is the guiding principle of classical vocal training programs. Compared with other genres, it is a sophisticated, narrowly defined style that requires complex, time-intensive, and expensive training. Given the shrinking performance market,[1] it has become critical to demonstrate the efficacy of such training programs. It is expected that a systematic program of study will result in appreciable improvement of a student's timbre, phonatory efficiency, and stamina. Over the years, evidence has accumulated regarding specific aspects of the voice that demonstrate change after an academic program. Given the challenges of longitudinal studies, the measures obtained to date vary considerably and are not comprehensive. Although one might expect rather marked changes in an undergraduate program, graduate students typically enter programs with more training, and indices of change must be sensitive. Documented changes in the acoustic characteristics of the singing voice include fundamental frequency range, sound pressure level (SPL), vibrato, and nasalance. Early work noted increased fundamental frequency range with training. In a study of 14 undergraduate voice majors over a 2-year period (four consecutive semesters), the 10–90% fundamental frequency range increased, on average, from 20–26 semitones.[2] Furthermore, increases in semitone range have been demonstrated for training periods as short as 9 months.[3] Obtaining phonetograms of 21 first-year masters-level students, the investigators found a statistically significant increase in semitone range from 32.8 to 34.1. The highest note was based on the production of a "musically acceptable" tone.

Other authors assessed change in SPL at different pitches, analyzing phonetograms over time.[4] They found a 2.4-dB average increase in sound pressure across voice types. Researchers using a *messa di voce* task found several changes over a 3-year training period.[5] Their singers demonstrated a slight increase in SPL but more notably, a significant increase in vibrato extent (semitone range of oscillation around the target fundamental frequency). The change in vibrato extent corroborated previous work[6] in which extent increased significantly during the first year but not during the second. Change with training has also been found in vibrato rate.[7] After 3 years of training, vibrato rate was dependent on the singers' initial performances. Those with a faster vibrato reduced it, whereas those with a slower vibrato increased it. A consistent change over time was the reduction in standard deviation of vibrato rate, indicating a more regular vibrato.

Pitch production has also been investigated longitudinally to determine changes in the contribution of auditory and kinesthetic feedback to accuracy.[8] The investigators found that after a 3-year training program, singers relied more on kinesthetic than auditory feedback.

Finally, in a group comparison design, researchers investigated nasalance during vowels sung by trained and untrained singers.[9] An OroNasal System (Glottal Enterprises, Syracuse, NY) calculated the ratio of nasal airflow to oral airflow. No significant differences were found between groups, although the expected differences in nasalance between high and low vowels were observed. The lack of significant difference between groups suggests that with or without training, singers do not demonstrate inappropriate nasal resonance on vowels. This is not unexpected because velopharyngeal function has been found to be stable during speaking as well, with no changes with increasing age.[10]

An investigation of the impact of singing training on the speaking voice revealed no significant differences over time in perturbation values, fundamental frequency and SPL, or phoneme and sentence durations.[11] These findings confirm

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that although training impacts the singing voice, it has little effect on speaking.

Although a number of studies have demonstrated these acoustic changes, there are no studies to date investigating the aerodynamic changes that occur with singing training. Because the ultimate goal of classical singing is the conversion of air into *bel canto*, it is essential to understand the mechanisms by which this is accomplished.

The following questions were addressed:

(1) How are semitone range and vocal SPL impacted by training?
(2) How are magnitude of inspiration, estimated subglottal pressure, airflow, and laryngeal resistance across registers affected by training?
(3) What are the patterns of estimated subglottal pressure, airflow, and resistance in relation to SPL?
(4) Are there differences in the effects of training between undergraduate and graduate students?

METHODS

Ethics

The study was approved by the Institutional Review Board at the University of Houston, and informed consent was obtained from all participants.

Training program

The participants were in a voice studies program that is essentially exclusive in its emphasis on the classical genre and on opera in particular. The performance expectations of vocal clarity, resonance, endurance, and resilience required in an unamplified theater with full orchestra are more robust than in other genres that routinely use amplification in performance.

As a vocal performance major, all students participated in a 1-hour lesson/wk and at least 1 or 2-hour studio class. In addition, graduate students had 1 hour of repertoire coaching and 1.5 hours of rehearsal with their studio accompanist. Unique to the program are the number of performance opportunities. Each of four main stage operas is double cast. There are four performances of each production as well as additional, separate outreach productions performed for school children bussed to campus. Opera rehearsals are 3 hr/day, 3 d/wk, with 9 weeks of rehearsals and three to four performances per production.

Given the intensive rehearsal and performance schedule, voice care is of paramount performance. For example, students are taught to pace themselves during blocking rehearsals, so the staging is "in their feet before putting it in the voice." The undergraduate students have performance opportunities in ensembles. There are five undergraduate large ensemble choirs that perform a total of thirty 1-hour concerts each year. There are also five student-led small ensembles that perform roughly thirty 1.5-hour concerts. The students performing in ensembles work closely with the voice faculty to maintain vocal health. Attention is paid to pacing, hydration, and rest periods to avoid vocal fatigue. As a final note regarding training, the vocal performance faculty members are all professional singers with at least 20 years each of full-time opera performance experience before university teaching positions.

Admission to the Voice Studies Area is by an audition, which is evaluated by seven to nine faculty members. Singers are judged according to the following dimensions: basic instrument, musicality, technique (posture, breath management, phonation, intonation, and resonance), musical accuracy and/or memory, diction (language or articulation), musical interpretation, dramatic interpretation (emotional involvement, communication, intensity, and variety), and physical presentation (body language, gestures, acting transitions, focus of the eyes, and stage deportment).

Following auditions, 8 to 10 students from roughly 200 applicants are admitted to the graduate program. For the undergraduate program, 15–18 students are admitted from more than 100 high school seniors who apply.

Participants

Participants in the present study were 21 graduate students (10 female and 11 male) and 16 undergraduate students (nine female and seven male). Of the undergraduate students, 11 were freshmen, with final data collected at the end of their sophomore year, and five were juniors, with final data collected at the end of their senior year. The age range of the freshmen was 18–19 years, with a mean of 18 years. The age range of the juniors was 19–21 years, with a mean age of 20 years. Of the undergraduate students, there were seven sopranos, two mezzo-sopranos, six tenors, and one baritone. The age of the graduate students ranged from 22–25 years, with a mean of 23.3 years. Of the graduate students, there were nine sopranos, one mezzo-soprano, five tenors, five baritones, and one bass-baritone. Graduate student data were obtained when they started the program and again 2 years later on program completion.

Tasks

As part of the comprehensive protocol, all students underwent a laryngeal videostroboscopic evaluation by an otolaryngologist (E.P.). If students demonstrated any pathology, or potential for problems, the results of their examinations were discussed with their voice teacher. In consultation with J.E., their training programs were modified with awareness of the vocal concern. In the cohorts presented, one undergraduate student and one graduate student were identified with potential laryngeal problems. Their data are not included in the present report.

Before data acquisition, singers performed their typical vocal warm-up until they reported being "performance ready." Registration and target notes were determined by J.E. Because a primary goal of vocal training is consistent timbre across the entire range, registration events become less evident as a student develops. In particular, more advanced students blend registers to negotiate passaggio, with the lower end of passaggio a mix of more chest and less head register and the higher end of passaggio a mix of more head than chest. In this study, the passaggio was typically achieved by a combination of establishing an appropriate tonal image; moderate vowel modification; a comfortably low laryngeal posture; and a consistent, stable breath management system. J.E. was familiar with the individual voices of each singer, initially through their auditions and reauditions and in the final evaluation, through lessons, performances, and juries. He established target notes clearly in each register and at a midpoint of passaggio.

Singers demonstrated their vocal range either by singing an ascending scale from their lowest to highest note or by producing arpeggios, beginning with their lowest note and ascending until the highest note was no longer "commercially viable." These tasks were used to calculate semitone range. The singers then produced "pah" syllable trains (seven consecutive "pah" at 1.5 syllables/s.) at full voice in chest register, passaggio, and head register. These tasks were used to determine intraoral pressure, airflow, laryngeal resistance, and SPL.

Recordings were made in a sound-attenuated booth using a head-mounted microphone (AKG C520) and digitized at 44.1 KHz in the Computerized Speech Lab (CSL, PENTAX, Montvale, NJ). To record SPL, intraoral pressure, and airflow, the Phonatory Aerodynamic System (PENTAX) was used, with a mask covering the nose and mouth. Calibration was completed before each recording session. No more than four singers were recorded per session, and no recording session lasted longer than 2 hours.

Analysis

Vocal range was determined in Praat.[12] The highest and the lowest commercially viable fundamental frequencies were identified and converted to semitones.[13] In cases of ambiguity of acceptability, a consensus was reached. All aerodynamic data were first inspected visually to ensure complete closure on the /p/ of the syllable trains, indicated by zero airflow. If complete closure was not achieved, the data were discarded. The initial and final syllables were discarded as well. The steady state portion of the airflow between pressure peaks was marked automatically in the program. Inspiration was measured immediately preceding each of the three trials. Subglottal pressure was estimated from intraoral pressure during the "pah" syllable trains. Laryngeal resistance was calculated from the pressure and airflow values. All aerodynamic measures were averaged across the three trials.

Reliability

To assess interjudge reliability, initial and final data from one graduate student and one undergraduate student were remeasured. For semitone range, there was no difference between original and repeated measures for the undergraduate student, and a difference of .6 semitones for the graduate. For the undergraduate and graduate students' SPL, the differences between original and repeated measures across data collection times and registers were .35 and .5 dB, respectively. For undergraduate pressure, flow, and resistance, the respective differences were 1.3 cm H_2O, 11.7 cm^3/s, and 9.4 cm H_2O/LPS. For graduate pressure, flow, and resistance, the respective differences were 1.1 cm H_2O, 6.7 cm^3/s, and 12.2 cm H_2O/LPS.

RESULTS

Semitone range

Range data are available for 12 undergraduate students and 19 graduate students. Semitone data were lost for three freshmen and one junior because of transitions between computers. Data were lost for one graduate student because of an elicitation error. As reported in Table 1, the mean change in semitones for the undergraduates was 25.8 (standard deviation, 3.8) to 28.6 (standard deviation, 4.8). A paired sample t test revealed that this difference was significant ($t = -2.5$, df = 11, $P = 0.014$). For the 19 graduate students, the mean change in semitones from the initial to final recording was 27.8–29.9. This difference was also significant ($t = -3.07$, df = 18, $P = 0.003$).

Sound pressure level

Table 1 illustrates the initial to final SPL for each register. It can be seen that for chest register, the graduates demonstrated virtually no change, whereas the undergraduates increased SPL dramatically, with the difference approaching statistical significance ($t = 2.1$, df = 10, $P = 0.06$). For the passaggio, both undergraduates and graduates increased somewhat. Both undergraduates and graduates increased SPL over time to a comparable degree in the head register. The difference between initial and final SPL in head register for graduates reached statistical significance ($t = 2.8$, df = 13, $P = 0.015$). When averaging across all registers, the undergraduate change from initial to final recording was statistically significant ($t = 2.7$, df = 31, $P = 0.010$).

Aerodynamic measures

The target measure will be increased SPL. The patterns used to accomplish this will be highlighted for each register, for both

TABLE 1.
Undergraduate and Graduate Initial and Final Semitone Range and SPL

	Graduate		Undergraduate	
Measure	Initial Mean (SD)	Final Mean (SD)	Initial Mean (SD)	Final Mean (SD)
Semitone range	27.8 (4.9)	29.9 (4.5)	25.8 (3.8)	28.6 (4.8)
Chest register dB SPL	87.3 (5.2)	87.4 (2.8)	80.1 (6.3)	85.2 (5.1)
Passaggio dB SPL	98.4 (4.0)	99.7 (4.9)	93.5 (5.0)	95.2 (5.7)
Head register dB SPL	100.7 (5.7)*	103.1 (6.6)*	96.4 (6.2)	99.1 (7.7)
Overall dB SPL	95.5 (7.7)	96.7 (8.8)	89.9 (9.2)*	93.1 (8.6)*

Abbreviation: SD, standard deviation.
* Indicates a significant difference.

TABLE 2.
Initial and Final Aerodynamic Values for Undergraduate Chest Register

Singer	In. Insp.	Fin. Insp.	In. P_o	Fin. P_o	In. Flow	Fin. Flow	In. Res.	Fin. Res.	In. SPL	Fin. SPL
UGS1	0.46	0.81	13.38	19.26	310	400	60.91	45.8	87.4	96.9
UGS2	0.68	0.58	7.4	7.82	130	150	54.77	49.8	73.9	81.1
UGS3	0.32	0.51	6.58	7.04	150	110	40.7	63.3	86.7	81.4
UGS4	0.49	0.81	9.2	8.7	150	170	56.7	50.7	76	81.9
UGM1	0.95	0.46	9.2	7.2	260	90	35.3	72.8	86.8	81.8
UGT1	0.42	0.36	16.7	10.4	160	180	103	57.5	89.5	84.4
UGT2	0.65	0.72	5	10.1	260	240	18	39.5	74.8	90.2
UGT3	0.35	0.85	6.3	18.35	60	210	117.3	81.7	71.9	90.4
Mean	0.54	0.64	9.2	11.1	185.0	193.8	60.8	57.6	80.9	86.0
Standard deviation	0.21	0.18	4.0	4.9	83.3	96.6	33.6	14.2	7.3	5.8

Notes: Insp., P_o, Res., and SPL are inspiration in liters, pressure in centimeter H_2O, flow in cubic centimeters per second, resistance in centimeter H_2O per LPS, and SPL in decibels, respectively. In. and Fin. are initial and final, respectively.

undergraduate and graduate students. Looking at the mean values in Table 2, overall for undergraduate chest register, when SPL increased, inspiration, estimated subglottal pressure, and airflow increased as well. By contrast, laryngeal resistance, calculated as estimated subglottal pressure divided by airflow, decreased because of increased airflow. Five of eight undergraduates demonstrated this pattern in the chest register. For two of three undergraduates who did not increase SPL after 2 years (UGS3 and UGM1), two demonstrated increased laryngeal resistance, with decreased airflow.

For undergraduate passaggio (Table 3), overall, pressure and flow increased proportionally, with no change in resistance. Five of six students increased SPL, although patterns within individuals are more idiosyncratic in passaggio. The student (UGS1) who increased SPL most dramatically, from 100 to 107 dB, nearly doubled pressure and more than doubled prephonatory inspiration and airflow, while decreasing laryngeal resistance. UGS2 followed the same pattern, increasing SPL from 84 to 92 dB, again with nearly doubled inspiration and a healthy increase in airflow. In cases in which resistance increased (UGM1 and UGT2), SPL increased only slightly or decreased. The very high airflow values are worthy of comment. First, the high airflows are supported by increased prephonatory inspirations. Second, we carefully monitored all productions during data acquisition and again after recording. In no instance were high airflows associated with breathiness. Third, the calibration of our instrumentation was precise and timely, and we are confident in the data.

For undergraduate head voice (Table 4), the overall pattern is again one of increased inspiration, increased pressure, increased flow, and reduced resistance leading to an increase in SPL. UGS3 exemplifies this pattern, increasing SPL by nearly 20 dB. Individual differences are again apparent however. UGT3, for example, increased flow but decreased pressure, with a resulting drop of roughly 10 dB.

For graduate student chest voice (Table 5), 12 of 14 students increased SPL, although not to the same degree as the undergraduates. The aerodynamic pattern producing the greatest increases differed markedly from those seen in the undergraduates. GT2 and GB-B increased SPL by 5 and 8 dB, respectively. For both singers, pressure and flow decreased, suggesting a nonaerodynamic contributor to increased intensity.

For graduate student passaggio (Table 6), five of seven increased SPL. The most dramatic increase, nearly 10 dB by GT1, was accomplished with a roughly 10 cm H_2O increase in pressure, with a doubling of flow and an increase in

TABLE 3.
Initial and Final Aerodynamic Values for Undergraduate Passaggio

	In. Insp.	Fin. Insp.	In. P_o	Fin. P_o	In. Flow	Fin. Flow	In. Res.	Fin. Res.	In. SPL	Fin. SPL
UGS1	0.72	1.74	29.24	49.9	300.0	730.0	91.8	63.8	100.1	107.3
UGS2	0.64	1.10	15.58	21.0	110.0	180.0	133.5	111.6	84.3	92.2
UGM1	1.03	0.46	16.99	15.2	320.0	120.0	50.7	117.4	93.8	94.5
UGT1	1.40	0.80	45.71	30.6	270.0	200.0	163.3	140.1	99.2	102.8
UGT2	0.92	1.07	12.9	15.0	290.0	330.0	42.1	43.4	96.5	95.1
UGT3	1.16	1.30	31.53	34.5	280.0	280.0	111.3	117.2	92.7	94.8
Mean	0.98	1.08	25.3	27.7	261.7	306.7	98.8	98.9	94.4	97.8
Standard deviation	0.28	0.44	12.6	13.5	76.3	220.3	47.1	37.0	5.7	5.9

Notes: Insp., P_o, Res., and SPL are inspiration in liters, pressure in centimeter H_2O, flow in cubic centimeters per second, resistance in centimeter H_2O per LPS, and SPL in decibels, respectively. In. and Fin. are initial and final, respectively.

TABLE 4.
Initial and Final Aerodynamic Values for Undergraduate Head Register

Singer	In. Insp.	Fin. Insp.	In. P_o	Fin. P_o	In. Flow	Fin. Flow	In. Res.	Fin Res.	In. SPL	Fin. SPL
UGS1	0.61	1.47	38.6	48.0	130.0	750.0	277.5	60.2	105.8	109.9
UGS2	0.53	0.61	18.1	13.7	130.0	80.0	126.2	152.5	93.9	97.0
UGT2	0.13	1.11	15.6	19.6	270.0	360.0	53.9	52.7	91.8	94.5
UGM1	0.96	0.56	19.1	17.3	270.0	80.0	66.7	188.2	101.7	102.8
UGS3	0.53	1.19	11.2	30.4	80.0	310.0	127.6	96.2	90.5	109.3
UGT3	1.50	1.54	38.5	30.0	240.0	370.0	53.9	52.7	104.4	92.9
Mean	0.84	1.08	23.5	26.5	186.7	325.0	117.6	100.4	98.0	101.1
Standard deviation	0.38	0.42	12.0	12.5	83.1	246.6	85.4	57.9	6.7	7.4

Notes: Insp., P_o, Res., and SPL are inspiration in liters, pressure in centimeter H_2O, flow in cubic centimeters per second, resistance in centimeter H_2O per LPS, and SPL in decibels, respectively. In. and Fin. are initial and final, respectively.

inspiration from 1.5 to 3.2 L. The 4-dB increase by GS1 was effected by a doubling of flow, a slight increase in inspiration, and no increase in pressure. In contrast, the 3-dB decrease by GB-B was due to decreases in inspiration, pressure, and flow. GT4's reduced resistance, caused by increased flow with no change in pressure, also yielded reduced SPL.

In the head register (Table 7), four of six graduate students increased SPL. GT1 and GT2, both with a 7-dB increase, followed the expected pattern of nearly doubled inspiration and increased pressure and flow with resultant decreased resistance. In contrast, the student with the greatest decrease of 12 dB SPL, GB4, reduced inspiration and airflow by roughly half, with a slight decrease in pressure.

To address the potentially greater changes in early undergraduate years compared with later, Table 8 displays differences from the freshman to junior years and junior year to graduation. It must be noted that this breakdown yields relatively small numbers for comparison. For the chest register and passaggio, the younger undergraduates demonstrated greater change in an optimal direction for all measures. For head register, although the younger undergraduates demonstrated minimal change in SPL, they produced greater inspiration, pressure, airflow, and reduced resistance compared with the older undergraduates. In general, the trend was for younger undergraduates to demonstrate greater positive changes.

DISCUSSION

This study was designed to determine the effects of an academic training program on acoustic and aerodynamic features of the singing voice. The acoustic results are consistent with previous studies, with both undergraduate and graduate students significantly increasing their commercially viable semitone range. Furthermore, undergraduates significantly increased SPL

TABLE 5.
Initial and Final Aerodynamic Values for Graduate Chest Register

Singer	In. Insp.	Fin. Insp.	In. P_o	Fin. P_o	In. Flow	Fin. Flow	In. Res.	Fin. Res.	In. SPL	Fin. SPL
GS1	1.10	1.10	12.0	16.0	110.0	250.0	100.1	60.7	108.0	109.0
GS2	0.90	0.35	11.6	9.1	250.0	60.0	44.2	162.3	109.2	110.6
GS3	0.66	0.54	9.8	11.0	210.0	180.0	44.7	59.2	106.7	107.6
GS4	0.71	0.45	9.6	7.9	140.0	120.0	68.0	66.0	108.9	110.6
GM1	0.94	0.84	12.2	11.6	150.0	110.0	74.8	106.3	102.9	107.5
GT1	0.40	1.10	22.7	14.9	290.0	300.0	74.4	49.1	100.0	107.2
GT2	0.51	0.54	14.5	13.5	290.0	210.0	47.1	60.9	97.8	103.5
GT3	0.79	0.81	9.3	8.9	170.0	130.0	52.0	67.2	99.1	101.8
GT4	1.45	1.30	14.5	15.4	320.0	240.0	43.0	59.6	97.9	100.8
GB1	0.99	0.66	13.2	13.1	200.0	300.0	63.0	41.7	98.1	99.0
GB2	1.40	1.00	11.1	9.1	130.0	200.0	78.8	43.6	101.0	102.2
GB3	0.30	0.49	10.6	10.4	80.0	100.0	123.5	97.4	94.8	94.6
GB4	0.89	1.27	14.9	13.1	150.0	140.0	100.7	96.7	91.2	86.8
GB-B	0.46	0.48	19.3	13.7	280.0	200.0	65.7	67.0	94.3	102.2
Mean	0.82	0.78	13.2	12.0	197.9	181.4	70.1	74.1	100.7	103.1
Standard deviation	0.35	0.32	3.8	2.6	76.7	74.6	24.5	32.1	5.7	6.6

Notes: Insp., P_o, Res., and SPL are inspiration in liters, pressure in centimeter H_2O, flow in cubic centimeters per second, resistance in centimeter H_2O per LPS, and SPL in decibels, respectively. In. and Fin. are initial and final, respectively.

TABLE 6.
Initial and Final Aerodynamic Values for Graduate Passaggio

Singer	In. Insp.	Fin. Insp.	In. P_o	Fin. P_o	In. Flow	Fin. Flow	In. Res.	Fin. Res.	In. SPL	Fin. SPL
GS1	1.50	1.81	28.3	28.7	210.0	440.0	128.6	62.0	101.0	105.5
GB1	1.03	1.42	21.4	22.3	270.0	380.0	75.9	56.4	96.0	96.7
GT1	1.49	3.16	26.5	37.2	250.0	570.0	104.4	62.9	98.3	107.7
GT2	0.93	1.48	25.2	32.0	400.0	470.0	60.6	63.9	101.6	104.6
GB-B	0.96	0.56	41.6	29.8	270.0	180.0	41.6	156.9	102.1	98.6
GT4	1.50	2.14	20.1	20.4	280.0	460.0	65.9	43.3	101.5	98.4
GB4	0.49	0.75	22.5	34.3	100.0	110.0	209.7	302.4	97.3	98.8
Mean	1.13	1.62	26.5	29.2	254.3	372.9	98.1	106.8	99.7	101.5
Standard deviation	0.39	0.88	7.3	6.1	89.6	166.7	57.1	94.1	2.4	4.3

Notes: Insp., P_o, Res., and SPL are inspiration in liters, pressure in centimeter H_2O, flow in cubic centimeters per second, resistance in centimeter H_2O per LPS, and SPL in decibels, respectively. In. and Fin. are initial and final, respectively.

across all registers, although only the SPL increase in head register was significant for graduate students.

The increase in semitone range with training was expected. A key feature of vocal training programs is extension of range produced within the acceptable parameters of *bel canto*. Effortless production of high notes is given considerable attention and practice in both individual lessons and studio classes.

The increase in SPL across registers was also expected for the undergraduate students. Formal training focuses on production of an effortless, efficient voice that will maintain an easily audible vocal presence with clearly defined individual voice characteristics, regardless of environment, whether full orchestra, chamber group, or piano.

It is also reasonable that graduate students would only show change in SPL in the head register. Particularly in higher voices, vocal production is shaped to maximize vocal fold closure, creating a clear distinction between the production of head register and falsetto. Head register is characterized by complete vocal fold closure and a resulting higher SPL. In the present singers, head register was produced with a lower laryngeal position; a stable breath management system; and a clear, powerful tone, easily distinguishing it from falsetto.

To our knowledge, this is the first study to assess aerodynamic changes with singing training. We highlighted the patterns of change in estimated subglottal pressure and airflow contributing to SPL. As noted, most students increased SPL with training. Because increased SPL has the potential for vocal fold damage due to high collision forces, yet is a required component of performance, the mechanism by which students achieved the increase is of interest. In increasing SPL, most students reduced laryngeal resistance by increasing airflow, typically with a proportional increase in estimated subglottal pressure. This strategy appears inconsistent with some earlier work on respiratory and laryngeal contributions to intensity change. For example, Stahopoulos and Sapienza[14] found increased estimated subglottal pressure and laryngeal resistance, with slightly reduced airflow in their study of 20 adults who increased vocal intensity. The task, however, was speaking, and the mean greatest intensity was only 77–81 dB SPL. Another study using a speaking task[15] made a clear distinction between laryngeal and respiratory contributions to increased intensity. The loudest intensities produced in Finnegan et al were 97–99 dB SPL, much more comparable to the present work. Obtaining direct measures of tracheal pressure, airflow, and electromyography of the thyroarytenoid muscle, they were able to isolate a measure of respiratory drive that was unaffected by laryngeal activity. Alveolar pressure, created by respiratory muscle activity and elastic recoil of the lungs,

TABLE 7.
Initial and Final Aerodynamic Values for Graduate Head Register

Singer	In. Insp.	Fin. Insp.	In. P_o	Fin. P_o	In. Flow	Fin. Flow	In. Res.	Fin. Res.	In. SPL	Fin. SPL
GT1	1.50	3.30	35.5	43.0	350.0	410.0	97.2	100.0	100.0	107.2
GT2	0.65	1.31	33.7	43.9	440.0	490.0	73.7	85.5	97.8	103.5
GT4	1.83	1.64	30.5	32.0	220.0	200.0	131.8	153.3	97.9	100.8
GB3	0.81	0.88	32.8	31.6	70.0	100.0	404.4	295.3	94.8	94.6
GB4	1.27	0.65	43.2	41.4	120.0	70.0	345.0	454.4	103.2	86.8
GB-B1	0.83	0.40	22.0	37.3	450.0	210.0	46.6	169.4	94.3	102.2
Mean	1.15	1.37	33.0	38.2	275.0	246.7	183.1	209.7	98.0	99.2
Standard deviation	0.46	1.04	6.3	5.0	148.6	153.9	138.9	128.8	3.00	6.70

Notes: Insp., P_o, Res., and SPL are inspiration in liters, pressure in centimeter H_2O, flow in cubic centimeters per second, resistance in centimeter H_2O per LPS, and SPL in decibels, respectively. In. and Fin. are initial and final, respectively.

TABLE 8.
Difference Values for Freshman to Junior Versus Junior to Graduating Students

Register and Year	Inspiration	Pressure	Resistance	Airflow	SPL
Chest register					
Freshman to junior (n = 5)	0.23	4.61	−8.04	52.0	11.29
Junior to graduation (n = 3)	−0.12	−2.68	4.87	−63.3	−5.11
Passaggio					
Freshman to junior (n = 3)	0.44	7.78	−10.65	205.00	3.99
Junior to graduation (n = 2)	−0.59	−8.46	21.75	−135.00	2.16
Head register					
Freshman to junior (n = 4)	0.29	12.00	−48.08	197.5	−0.29
Junior to graduation (n = 2)		8.67	45.08	20.00	9.93

was the primary contributor to intensity. Although there was a tendency for both laryngeal resistance and thyroarytenoid activity to increase with intensity, there was not a correlation between thyroarytenoid activity and laryngeal resistance. The authors postulated that thyroarytenoid contraction may change the cover-body relationship, permitting greater amplitude of displacement of the cover. This would allow for increased intensity without increased laryngeal resistance. The potential reduction of laryngeal resistance is validated in another study[16] distinguishing normal voice from breathy or pressed qualities. As expected, pressed voice was produced with the highest laryngeal resistance and breathy voice with the lowest. It is of interest that a normal voice was produced with laryngeal resistance closer to that of breathy rather than pressed. These findings relate to the present study because of the target vocal quality required during high-intensity productions. The participants were required to sing in "full voice," as though they were on stage in a large theater without amplification. In *bel canto*, a pressed vocal production is never acceptable; the reduced laryngeal resistance with concomitantly increased inspiration, despite high intensity, reflects this training goal.

In the chest register, two graduate students demonstrated increased SPL without concomitant augmentation of pressure and flow. In these cases, it is suggested that the students increased vocal power by making supraglottal modifications to tune the vocal tract. It is likely that this occurs more frequently than demonstrated in the present data. The production task was highly constrained by syllable type, and jaw movement was restricted by wearing a mask. In actual performances, singers would take advantage of the freedom to modify vowels and alter the upper vocal tract to align formants with harmonics. This would allow singers to increase SPL even beyond that which can be achieved by aerodynamics. It is noteworthy that the two students who clearly demonstrated this strategy were graduates. The undergraduate students may be focusing more on developing a stable, consistent system of breath management and support, rather than supraglottal modification to project on stage.

Although this study focused on advanced singers in a classical voice training program, the vocal demands of the program make the findings relevant to other genres as well, especially when considering multiple performances over extended periods with little recovery time. It appears that with well-qualified advanced training, the focus on effortless, well-supported vocal production results in the ability to increase SPL in a healthy, sustainable manner. Vocal projection effected by increased respiratory drive (including components of both inspiratory magnitude and subglottal pressure), reduced laryngeal resistance, and a clear vocal quality should assist in preventing laryngeal muscle and laryngeal tissue fatigue,[17] thus providing the basis for a long performance career.

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