AERODYNAMICS OF VOCAL VIBRATO

Srihimaja Nandamudi

A Dissertation

Submitted to the Graduate College of Bowling Green
State University in partial fulfillment of
the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2017

Committee:

Ronald C. Scherer, Advisor

Mingsheng Li
Graduate Faculty Representative

Alexander Goberman

Jason Whitfield

ABSTRACT

Ronald C. Scherer, Advisor

Airflow vibrato is the fluctuation in average airflow while singing with vibrato. Understanding airflow vibrato relates to a deeper understanding of its importance to physiological, pedagogical, and clinical aspects. Two studies were performed to examine airflow vibrato. The subjects for Study 1 were four professional Western classical singers, and for Study 2 four highly trained amateur singers. Aerodynamic and acoustic measures were compared among vibrato, bleating (a primarily adductory gesture), and external epigastric pumping (EEP, a primarily subglottal pressure manipulation). Utterances included speaking (phonation and whisper) and singing (constant /a/ vowel, different pitches and loudness levels).

Study 1 demonstrated how airflow vibrato compares with fundamental frequency (F0) and intensity vibrato. The correlation between rates of airflow and F0 vibrato was moderately strong. Mean airflow vibrato extents were larger for the female singers than for the male singers, and increased with pitch increase for all four singers. For the males, average airflow extent was 30 and 75 cm^3/s for their lower and higher pitch, respectively, and for the females, 47 cm^3/s and 94 cm^3/s for their lower and higher pitch, respectively.

Study 2 was undertaken to better understand sources of airflow vibrato. Airflow modulations were produced during singing with vibrato and also while bleating and with external epigastric pumping. Bleating had the fastest alteration rate (9.5-12 Hz), whereas the other types had similar rates (vibrato: 4.8-6.0 Hz; EEP: 6.0–7.5 Hz). During phonation (combining all conditions), bleating had the largest airflow modulation extents (on average 144 cm^3/s, compared to 30 cm^3/s for vibrato and 46 cm^3/s for EEP).

Overall results suggest that airflow vibrato typically leads F0 vibrato, and often has a more complex waveshape than F0 vibrato. Hypotheses generated from the study include: (1) A

primarily subglottal pressure driven vibrato may provide relatively consistent but wide extents for both F0 and airflow vibrato. (2) A primarily glottal adduction driven vibrato may provide relatively low and inconsistent F0 vibrato extent, and high and inconsistent airflow extent. (3) A primarily CT driven vibrato may result in moderate to large F0 vibrato extent, and low airflow vibrato extent, with variable consistency.

This dissertation is dedicated to my parents Dr. N.V. Subbarao garu & Smt. Bhavani Nandamudi garu for making my dreams fly high.

ACKNOWLEDGMENTS

I will be forever grateful to Bowling Green State University for offering admission into the Ph.D. program and to work with Dr. Ronald C. Scherer. BGSU has touched my inner soul and brought out the best in me.

Ronald C. Scherer: Sir, I am sure I must have done some noble things in my past life to get a mentor like you. It’s a great honor to work with you, sir. Thank you for your guidance, time, patience, approachability, and compassion. You are truly inspirational. Your humble personality not only taught me academic lessons but also how to be a better human being. Even though I am going to graduate this year, I will never stop working with you and staying in touch. I am sure nobody tries to go away from you. You are a huge bundle of positive energy and joy. Thank you very much for your valuable lessons. You made me work hard and be focused, punctual, critical, and meticulous.

Dad and Amma: Thank you very much for believing in me and valuing my dreams. I know how many difficulties you both must have faced to send me so far away to achieve my dreams. You must be answering thousands of questions to thousands of people every day. Thank you for living in my dreams. You are my strength and you are my weakness. You have ignited the fire in my wings. I will be forever grateful for your sacrifices and for showing genuine happiness in my accomplishments.

Dissertation Committee: Sincere thanks to my dissertation committee- Dr. Alexander Goberman, Dr. Jason Whitfield, and Dr. Mingsheng Li for accepting my request and being on my committee. Thank you very much for your timely inputs on my project.

Stats myth: A huge thanks to Haitao Liu, a graduate student in the department of statistics, BGSU, for his tremendous help in the statistical analyses for my dissertation project. I am very grateful to you, Haitao, for spending your valuable time on my project in your busy schedule. The project would not have been completed on time without you. I am also thankful to Jingwei Xiong, alumni student from the department of statistics, BGSU, for helping with the statistical analysis of my preliminary project. Special thanks to Arthur (Bai-Yau Yeh), director of the Center for Business Analytics, for discussing the study design and applicable statistical methods with Dr. Scherer and me, and for allowing graduate assistants to help me on the statistical analysis.

CDIS: My sincere thanks to all the faculty and staff members in the department of communication sciences and disorders for your help. Thank you very much Nick (Nicholas May) for setting up the equipment for calibration, and sharing your calibration data. You made my job easy. Special thanks to Dr. John Folkins, Dr. Alexander Goberman, Dr. Lynn Hewitt, and Dr. Ronald Scherer for sharing their academic experiences through Pedagogy courses.

Other departments: Special thanks to Dr. Lisa Lockford for inviting me as a guest faculty to give a talk on “Basic Voice Science and Vocal Hygiene” to the student actors and performers. I thoroughly enjoyed your course on “Voice and Movement”. Thank you for appreciating the “actor” in me. Huge thanks to Dr. Todd Keylock for letting me take his course on “Exercise Physiology”, and for encouraging me to work on vocal exercise physiology. I am sure this will be our upcoming project. Special thanks to the voice faculty members in the College of Musical Arts at BGSU for volunteering in my preliminary project and painting “airflow vibrato” as a more interesting phenomenon.

BGSU Family:

Global Connections: I am very thankful to so many kind people around the earth, especially my “peops” in BG. I am ever grateful to the “Global Connections” organization of Bowling Green, OH, that has been a great help for international students like me. You taught me American culture, helped me to meet new people, exchanged knowledge on one’s culture, and

inculcated respect towards each other in spite of diversity. Thank you for organizing Christmas parties, thanksgiving dinners, shopping trips, summer trips, game nights, free furniture and food. You definitely played a big part by filling the gap between India and America. My sincere thanks to Julie, Kris, Marie, Wendy, Sarah, and many others.

Siva Priya Santhanam: Siva, thank you for being wonderful to me. You always will be my older sister. Thank you for your love, kindness, care, and great advices. May all your dreams come true!

I also thank the “India Student Association” of BGSU for giving me an opportunity to create a harmony in the BGSU campus by working on cross-cultural awareness programs. “Diwali Mela” has been a tremendous success. The association also has given me an opportunity to showcase my different dance styles and choreography. I sincerely thank other student associations on campus for organizing events for students’ welfare and togetherness.

Big thanks to Siva aunty and Dr. Shakthivel for considering me as their family member and including me in all their family events. Aunty, I am going to miss your idlis and Pongal, and of course you both! Many thanks to my host mom- Mary Kuhlman for accepting me as I am, and sharing her life time experiences. I am very thankful to Raj, Sayali, Arpan, Danielle, Sravanthi, and Devansh for not only sharing my good times but also my pains. Thank you for your constant support and encouragement. You all added more meaning in my life! Aparna Kiran Ayyagari, thank you very much for being a wonderful friend and host. I am very grateful to you.

Family back in India: I thank my older brother Kishan and sister-in-law Sri Lakshmi for their support. A big shout out to my huge crazy maternal family of four aunts and uncles, and six cousins. Thank you for your love and support.

My big thanks to all my friends back in India- Anu, Syamu, Kittu, Siddhu, Venkat, Jayanth, and Rachu. My undergraduate group from NIHH- “15teen maniacs” and masters group-

“Aurevoir rockers” for their constant support and encouragement. Thanks for believing in me and pushing me towards my dreams.

My sincere thanks to all the faculty and staff members at Ali Yavar Jung National Institute for the Hearing Handicapped, Secunderabad, INDIA. Special thanks to Mr. G. V. M. Hari Prasad garu, Dr. S. G. R. Prakash garu, Dr. S. B. Rathna Kumar garu, Mr. Rajendra Kumar garu, Mrs. Hari Priya garu, Dr. Vrushali Angadi ji, Mr. V. V. S. Sairam garu, Dr. Premalatha Subbarao garu, Dr. Nandhu Radhakrishnan garu, and Dr. Prakash Bhoominathan garu.

Last but not the least, I will be forever grateful to all my teachers in Sri Gowthami Public School, Rajahmundry, India, for their immense support and encouragement. You are the reason I always dream big. Special thanks to Mr. Chandra Shekhar garu, Mr. Rama Krishna garu, and Mr. Prem Kumar garu from Sri Chaitanya Junior Kalasala, Rajahmundry, India, for your inspirational speeches and constant reminders to do something for the society. My sincere thanks to Mrs. Durga Chimalakonda garu for tutoring me in all the courses from grade 1 to 12, and treating me as her family member.

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CHAPTER I. INTRODUCTION

Vocal Vibrato

Vibrato is commonly used in Western classical singing. Vibrato is typically considered as a relatively regular variation of fundamental frequency (subsequently given as F0), intensity, and timbre (Sundberg, 1995). Seashore (1947) described vibrato as “a pulsation of pitch usually accompanied with synchronous pulsations of loudness and timbre, of such extent and rate as to give a pleasing flexibility, tenderness, and richness to the tone” (Seashore, 1947, p.55-56). It is also considered to be a musical effect that adds expression to vocal (and instrumental) music.

The two most common measures of vibrato are the *frequency extent* within the vibrato cycle (i.e., typically the difference between the highest and lowest F0 value within the vibrato cycle given in Hz, semitones, or cents) and the number of F0 vibrato cycles in one second, called the *vibrato rate*, given in Hz (Sundberg, 1994). A third characteristic is the regularity of the F0 vibrato rate, which has been less studied. A perceptually ‘pleasant’ and ‘acceptable’ professional vibrato production is characterized by a fundamental frequency undulation rate of approximately 5 to 7 Hz and an extent of about ± 1 semitone (Hakes, Shipp, & Doherty, 1988).

Studies suggest that the production of vibrato involves primarily the cyclic contractions of the cricothyroid muscles to lengthen and shorten the vocal folds at the vibrato rate (thus changing the tension of the vocal fold tissue that alters the F0), the cyclic pulsations of the subglottal pressure to also alter the vocal fold tissue tension (Shipp, Doherty, & Hagland, 1990; Titze, 1989), and a peripheral reflexive negative feedback loop requiring a pair of agonist-antagonist muscles (like the cricothyroid vs. vocalis muscles) for vocal fold lengthening control and thus tension alteration (Titze, Story, Smith, & Long, 2002).

USA Standard Acoustical Terminology (1960) defined vibrato as “a family of tonal effects in music that depend on periodic variations of one or more characteristics of the sound wave. When the particular characteristics are known, the term ’vibrato’ should be modified accordingly; i.e. frequency vibrato, amplitude vibrato, phase vibrato, and so forth” (USA Standards Institute, 1960).

Acoustic and Aerodynamic Aspects of Vocal Vibrato

Interaction between F0 vibrato and intensity vibrato. The fluctuating fundamental frequencies of the F0 vibrato are accompanied by synchronous variations of intensity and loudness (Seashore, 1932) due to altering the relation between the source harmonics and the vocal tract resonances during the vibrato cycle. The relationship between F0 and intensity variations were explained by a resonances-harmonics interaction hypothesis (Horii, 1989). Horii considered two possibilities of amplitude modulations in intensity. The first possibility was resonances-harmonics interaction, and the second possibility an independent and separate active oscillation generator (Horii & Hata, 1988). According to the resonances-harmonics interaction hypothesis, for a given vocal tract configuration of a specific vowel and phonation with a specific fundamental frequency, there is a corresponding spectral resonance contour with resonance peaks and valleys that co-occur with a laryngeal source spectrum having harmonics. For a harmonic on the left of a resonance peak, boosting of the intensity of that harmonic will occur if the harmonic is increasing in frequency (as the F0 vibrato frequency increases), moving closer to the peak of the resonance, while if a harmonic lies to the right of the resonance peak, its intensity will reduce as it increases; the former is influenced by the left resonance skirt, the latter by the right resonance skirt. Thus, as the F0 and its harmonics encounter a resonance peak or valley in the singer’s current vocal tract configuration, they are either increased in intensity or decreased in intensity, accordingly. The resonances-harmonics interaction alters the amplitude of the F0 and its harmonics, and thus also the sound radiating from the lips, including the sound pressure level and spectral envelope.

If the frequency oscillation occurs on a positive slope of the resonance contour, the frequency and intensity modulation would be synchronous with each other, and be in-phase. If the frequency variations occur on a negative slope of the resonance contour, the frequency modulation (upward) and intensity modulation (downward) would be asynchronous and out of phase (also termed as “opposite phase”; Mason, 1965). Vennard (1967) reported two intensity vibrato cycles for each F0 vibrato cycle. This phenomenon will be seen if F0 (or a dominant source frequency) travels across the peak of the resonant contour. If it travels first up to the peak and then down the other side during the upward change of F0, it creates a rise and then a fall in intensity which is repeated as the second half of the vibrato cycle is produced, creating two modulations in amplitude of intensity during a single frequency modulation.

Interaction between F0 and subglottal pressure vibrato (laryngeal level). Both singers and nonsingers tend to increase the subglottal pressure (subsequently given as Ps) when raising the pitch, apparently due to the increase in the stiffness of the vocal folds as they are stretched during pitch rise (Elliot, Sundberg, & Gramming, 1995). Although the resonances-harmonics interaction alters the output sound pressure level (SPL), Ps is the main variable which controls the overall intensity (Ladefoged & McKinney, 1963; Rubin, LeCover, & Vennard, 1967; Titze, 1989; Titze & Sundberg, 1992). On average, singers double the Ps when they increase the F0 by one octave, and a doubling of the excess Ps over threshold causes SPL to increase by 8-9 dB for normal phonation, and less if mode of phonation is changed to pressed (Sundberg, Titze, & Scherer, 1993). Ps could potentially be a main contributor to amplitude modulations in intensity, because changes in Ps affects the dynamic glottal configuration, laryngeal flow resistance, and speed of the vocal folds closure (Large & Iwata, 1971).

Rothenberg, Miller, and Molitor (1988) measured the glottal airflow and subglottal pressure during vibrato when produced by a bass-baritone singer, and observed oscillations in the subglottal pressure synchronous with F0 fluctuations. They also observed oscillations in the acoustic amplitude (SPL) synchronous with F0 and Ps, even though inverse filtering was applied to cancel the effects of vocal tract resonance. These results were explained with two hypotheses. The first one was that oscillations in sound pressure level (and thus perceived loudness fluctuations) might have occurred secondary to undulations in Ps. The other hypothesis was that there may have been variations in vocal fold abduction co-occurring with airflow vibrato. Thus, they suggested a significant effect on the perceived loudness secondary to potential variations in waveform shape of the glottal airflow pulses due to subglottal pressure variations or adduction variations. They also suggested that the abdominally-induced vibrato is driven volitionally by Ps fluctuations, and this can be found in Western classical singers who are trained to produce laryngeal-mediated frequency modulations and Ps-mediated intensity modulations (Smith, 1970; Zemlin, 1968). Sundberg et al. (1993) did a study on singers to see the relationship between Ps and voice source characteristics, including the airflow (inverse filtered oral flow). They found that Ps is the main factor in the control of vocal loudness, which in turn affects the airflow. A rise in Ps leads to an increase in the peak glottal flow, which further increases the SPL. At low peak flow values (for higher glottal adduction-pressed voice), the singers were able to maintain the required intensity by increasing the closed phase duration. The resonances-harmonics interaction strategy was often noticed in female singers at high pitches due to F0-F1 matching (Raphael & Scherer, 1987; Sundberg, 1977). Thus, singers produce vibrato intensity changes using both resonances-harmonics interaction and alterations of Ps, probably simultaneously. The fluctuations in F0 and intensity during vibrato corresponds to observable oscillations in respiratory, laryngeal, and articulatory behaviors (Laukkanen, Vilkman, & Unto, 1992; Leydon, Bauer, & Larson, 2003), as well as the waveshape of the glottal airflow pulse that might have a significant effect on perceived quality and loudness.

Interaction between airflow, F0, intensity, and Ps vibrato. Large, Iwata, and Leden (1970) found that most of the vibrato samples obtained in their study were characterized by fluctuations in airflow, and were observed to be synchronous with intensity (amplitude) vibrato. Large and Iwata (1971) did a study on airflow rates for vibrato, using the term *"airflow vibrato"* apparently for the first time (Large & Iwata, 1971, p.55, line 9). The study showed that singing without vibrato used less mean airflow than singing with vibrato. The mean airflow (mL/s) during vibrato ranged from 50-280 mL/s in chest register (220 Hz), 35-245 mL/s in middle register (440 Hz), and 115-335 mL/s in head register (880 Hz) across six female amateur singers, and are larger than the mean airflows during straight tone singing, with a different range, from 5-60 mL/s across the registers and subjects. In chest register, the airflow fluctuations were correlated only with intensity vibrato, whereas in the middle and head registers, the airflow fluctuations were synchronous with both frequency and intensity undulations (the three being in-phase). This might indicate a stronger relationship of airflow, acoustic amplitude, and F0 with subglottal pressure at higher F0 levels. They also observed that airflow in vibrato consists of both AC (alternating fluctuations of airflow) and DC (constant airflow) factors. The relationship between airflow and intensity fluctuations were seen to be stronger as the pitch increased. The correlation was strongest in head register in comparison to middle and chest registers. They did not measure airflow vibrato extent and the phase difference between airflow, F0, and intensity vibrato. However, they reported the periods of airflow vibrato, which ranged from 0.17 to 0.24 s (4.167-5.882 Hz), 0.19 to 0.23 s (4.35-5.263 Hz), and 0.19 to 0.24 s (4.167-5.263 Hz) for the three registers, respectively. Therefore, the airflow vibrato rates stayed in a relatively constant range across different pitches and loudness levels. The subjects produced vibrato for at least a few seconds (assuming 2.5 – 3.0 seconds by considering the reported airflow vibrato rates and the number of airflow vibrato cycles visible in their figure 2, (Large & Iwata, 1971, p. 54), followed by straight tone production for a few seconds on the vowel /a/. Between the F0 and intensity undulations during vibrato, varying phase differences were observed, but never shown out of phase in their study. These results indicate that the airflow vibrato has a close relation with F0 and Ps. At lower pitches, the glottal flow resistance dominates in controlling vocal intensity (laryngeal control), whereas at high pitches, the vocal intensity is reported to be directly proportional to Ps, and therefore an increase in airflow will be seen (Hirano, Kurita, & Nakashima, 1983; Isshiki, 1965, 1964; Luchsinger, 1951; Rubin et al., 1969; Titze, 1989; van den Berg, 1956; Yanagihara & von Leden, 1966). Therefore, it could be hypothesized that the relationship between airflow, intensity, and F0 vibrato was strong in middle and head registers (the three parameters being in-phase), than chest register, due to Ps being the primary contributor.

There are few electromyography (subsequently given as EMG) studies that support the intrinsic and extrinsic laryngeal muscle activity, respiratory muscle activity, and their relationship with glottal flow resistance with increase and decrease in pitch (Koda & Ludlow, 1992; Sapir & Larson, 1993; Schlapp, 1973; Shipp et al., 1990), while producing vibrato.

Therefore, the acoustic properties of vibrato should be examined together with aerodynamic and physiological aspects of phonation as vibrato is involved with not only acoustic changes but also aerodynamic changes. It is apparent, then, that vibrato is a physiological, aerodynamic, acoustic, and perceptual phenomenon (Horii, 1989). The vibrato cycle is a cycle of changing laryngeal behavior, and thus there can be an expectation of changing transglottal pressure, glottal adduction, glottal area, glottal flow resistance, and corresponding glottal airflow (Sundberg et al, 1993). The mean airflow variations during vibrato production are called "*airflow vibrato"* in this study.

Work by Rubin, LeCover, and Vennard (1967)

There are few studies showing airflow vibrato and its relation to other production variables. One such study was reported by Rubin et al. (1967) who studied the relationship among vocal intensity, subglottal pressure, and airflow in singers while singing and producing vibrato. Figures 1-3 are from that study. For this discussion, it is assumed that there are negligible time delays among the three signals shown in the figures. For example, if there were a 10 ms delay among signals, with a vibrato rate of 6 Hz, the delay vs. period would only be 6% of the period.

The vertical lines in Figures 1-3 (parallel to the y-axis designations on the left) were added to the original figures to examine the phase relationship among the variables for the various singing conditions. In Figure 1, the relationship between airflow vibrato (A) and intensity vibrato (S) for the male's middle pitch was such that airflow peaks led intensity peaks by approximately 113 degrees (see below for the definition of phase calculations). For the highest pitch, airflow was nearly completely out of phase with both intensity and subglottal pressure. Figure 2 shows recordings for a female singing three loudness levels at the same fundamental frequency. For her middle loudness token, the airflow lagged intensity by approximately 72 degrees for the last three cycles shown, and for the loudest production, all three signals were essentially in phase with each other. Figure 3 show recordings for a female singing on a constant middle range pitch with a relatively strong vibrato in both the flow and intensity signals, for the three loudness levels. For the softest token, the flow lagged intensity by approximately 58 degrees, and for the middle loudness, flow lagged intensity by a similar value of 55 degrees. For the loudest token, however, flow and intensity were nearly out of phase despite the singer using the same pitch, with flow lagging intensity by approximately 152 degrees. For both the middle and highest loudness levels, the subglottal pressure was nearly out of phase with the airflow.

The results from the Rubin et al. (1967) study suggest that while singing, the vibrato-related oscillations of flow, subglottal pressure, and intensity may have varying phase relationships with each other. In addition, the airflow signals in Figure 3 illustrate that airflow vibrato may not be a regularly oscillating signal, but may have a complex shape. This apparently is the first study to measure aerodynamic aspects of vibrato, and to report the oscillations not only in F0 but also in Ps, intensity, and airflow.

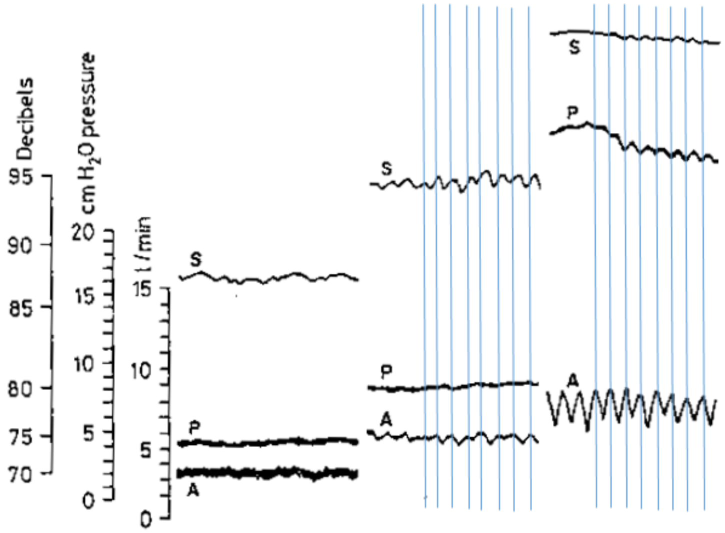

Figure 1. Figure 4 from Rubin et al. (1967), the caption of which was “Male- rise in airflow (A) and subglottic pressure (P) passing from low to middle to upper range at increasing levels of loudness (S).” The vertical lines are superimposed on the original figure at the location of the flow peaks to observe the phase relation between airflow, subglottal pressure, and intensity.

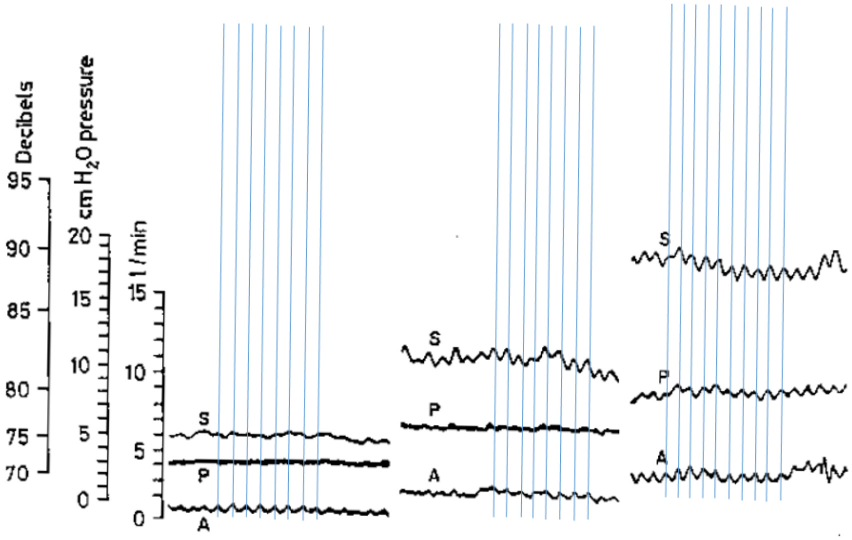

Figure 2. Figure 5 from Rubin et al. (1967), the caption of which was “Female – rise in airflow (A) and subglottic pressure (P) with increasing loudness (S) on the same fundamental frequency in her low range.” The vertical lines are superimposed on the original figure at the location of the flow peaks to observe the phase relation between airflow, subglottal pressure, and the intensity.

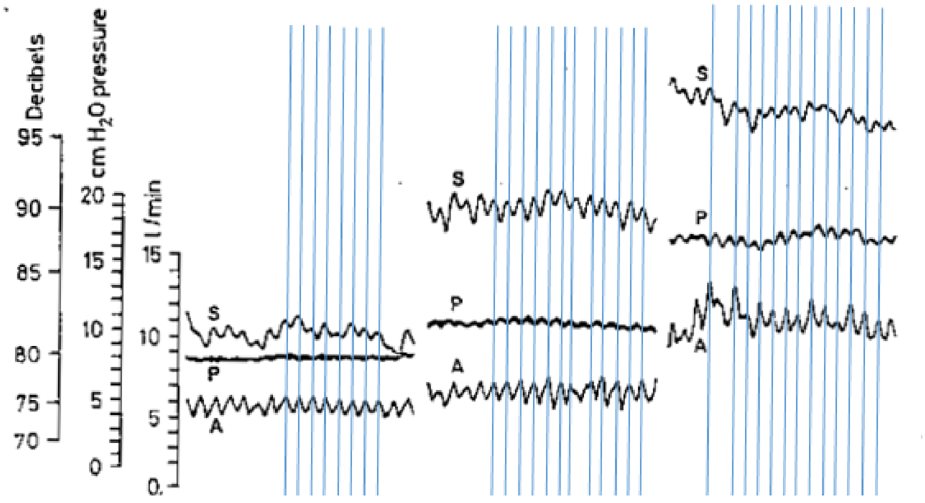

Figure 3. Figure 6 from Rubin et al. (1967), the caption of which was "Female – rise in airflow (A) and subglottic pressure (P) with increasing loudness (S) on the same fundamental frequency in her middle range. Irregular trace lines reflect a strong vibrato." The vertical lines are superimposed on the original figure at the location of the flow peaks to observe the phase relation between airflow, subglottal pressure, and the intensity.

Possible Contributors to Vibrato

Shipp, Leanderson, and Sundberg (1980) suggested two primary mechanisms that generate modulations in F0, intensity, and Ps. The first mechanism is laryngeally-mediated vibrato, where undulations are seen in F0 during vibrato due to periodic contractions of the cricothyroid (CT) muscle. They also mentioned that vibrato generated primarily from CT muscle action is more efficient in Western classical singing. These singers are assumed to have ability to inhibit the AC neural activation transmission along the recurrent laryngeal nerve to counterbalance the superior laryngeal nerve activity which leads to increase and decrease in vocal fold length due to rhythmic contraction in the CT muscle that results in systematic changes below and above the target pitch. Thus, the first mechanism assumes that CT action provides the vocal fold lengthening and tension variations to create F0 vibrato.

This mechanism is supported by a review of EMG studies by Hirano (1995) involving five subjects, where he found that the CT muscle appears to be the dominant muscle to control F0 vibrato. His studies were with four American singers and one Japanese singer. The CT muscle of all 5 subjects presented with oscillating activities during vibrato phonation" (Hirano, 1995, p. 12). The inhibition of the adductory system suggested in the Shipp et al. (1980) study, however, is not supported by the Hirano review. That is, the lateral cricothyroid muscle (LCA) also had similar oscillation activity for all 5 subjects, with one not always having LCA activity. The thyroarytenoid (TA) muscle "often presented with oscillation synchronous with vibrato in all 4 singers investigated, but not always" (Hirano, 1995, p.12).

The second mechanism suggested by Shipp et al., (1990) is abdominally-mediated vibrato, where undulations in F0 are due to the counteraction of intrinsic laryngeal muscles to abdominally induced Ps pulses. Subglottal pressure pulses would create increased flow resulting in corresponding fluctuations in F0 and intensity. Thus, the second mechanism primarily deals with subglottal pressure (Ps). Rothenberg et al., (1988) found that abdominally-mediated vibrato is primarily seen in non-Western styles, but may also be found to a lesser extent in Western classical singing.

The third possible source, which has been less extensively studied, is variation in the shape of the vocal tract, which includes the undulations of pharyngeal and oral cavity structures, tongue, jaw, and palate (Sundberg, 1995). Shipp et al., (1990) mentioned that less-skilled singers exhibit greater undulations in vocal tract structures. However, it is difficult and risky to measure the activity of pharyngeal and oral cavity structures during vibrato.

The current dissertation project investigates the potential sources of vibrato by considering three possible mechanisms that generate modulations in airflow (corresponding to changes in F0, Ps, and intensity). The laryngeally-mediated mechanism is bleating, the abdominally-induced mechanism is gently pushing the external wall of the epigastric region (right below the sternum), and the third mechanism is modifying the shape of the vocal tract by raising and lowering the tongue.

Modulation Sources Resembling Vibrato

Bleating. Titze (1994) described bleat as “machine-gun vibrato” with a range of its rate from 6-8 Hz. Bleat is often compared with trillo because of their similarities in adductory gestures. Trillo is described as “a rapid repetition of the same note, which includes repeated voice onset and offset. It is executed with the laryngeal adductor-abductor muscles, the lateral and posterior cricoarytenoid muscles, rather than with the cricothyroid or thyroarytenoid muscles” (Titze, 1994, p. 293). Titze, Finnagen, Laukkanen, Fuja, and Hoffman (2008) also studied phonatory giggle. They found reciprocal action of the posterior cricoarytenoid muscle (PCA) (for abduction) and LCA or TA (for adduction) synchronous with the giggle. The rate of giggle bursts in a bout was approximately 9.21 Hz. These faster rates with rapid voice onset and offset were also seen in trillo.

Trillo can be unusually faster, and has been reported to be in the range of 9-10 Hz (Hakes et al., 1987). A later study done by Hakes, Doherty, and Shipp (1990) reported trillo rates as fast as 12 Hz from performers of early music. They also mentioned that the source of trillo might be different from vibrato and trill due to its faster rate. Leanderson, Sundberg, and von Euler (1987) observed a consistent use of the diaphragm when performing trillo involving a repeated switching between glottal adduction and abduction. Leanderson and Sundberg (1988) explained trillo as a tone of constant pitch which is interleaved with short silent intervals. During such silent intervals, commonly seen in staccato singing, a singer abducts the vocal folds. They have observed the undulations in esophageal and gastric pressures during trillo, which reflects the adaptation of the pressure to the lung recoil. When the passive expiratory recoil forces are higher than the required pressure, the diaphragm is activated for reducing the subglottal pressure, most probably with the help of inspiratory intercostals. Later on, when the passive recoil forces are lower than the required phonatory pressure, the diaphragm reduces its activity and the abdominal wall (muscles of exhalation) is recruited for producing the pressure undulations. Thus, it's a subtle coordination of muscle activity and lung pressures.

Kirkpatrick (2008) mentioned that when oscillations of the vibrato become too fast, it begins to sound like a sheep bleating. This kind of rapid vibrato is unpleasant to hear in Western classical singing. He also mentioned that wobble, bleat, and straight tone are the three common problems seen in new singers learning vibrato. Wobble is typically associated with senescence and poor conditioned vocalists, while bleat is more likely seen in young singers or muscularly hyperactive (tensed) vocalists (Titze et al., 2002).

Brown and Scherer (1992) studied trillo in a singer by using a combination of electroglottography (EGG), videolaryngoscopy, and acoustic analysis. Their observations suggest that glottal adduction is the primary physiological control variable for the production of trillo. In their study, the EGG signals of trillo productions showed undulations that were in phase with the note reiterations. During the silent intervals in-between the note reiterations, the vocal folds were found to continue to vibrate. The coefficient of variation in frequency (CVF) of the dilated phase (least adducted phase of the EGG waveform) and constricted phase (most adducted phase of the EGG waveform) were found to be significantly different, in which the dilated phase showed higher CVF values than the constricted phase. The F0 fluctuations in trillo correspond to the rapidly alternating adductory-abductory motion of the vocal folds.

External epigastric pumping. Several studies have been reported on pulsatile increases of subglottal pressure by pushing suddenly at random intervals on the chest or abdomen of a phonating subject (Fromkin and Ohala, 1968; Isshiki, 1959; Ladefoged, 1963; van den Berg, 1957). There are also studies that have shown the activation of the glottal closure reflex due to sudden induced pressure changes (Baer, 1979; Horner, Innes, Murphy, & Guz, 1991; Nishino, 2000; Shaker, Bardan, Easterling, Dua, Xie, & Kern, 2003). Baer (1979) studied a single subject phonating three frequencies in chest and falsetto registers. In his study, the experimenter "pushed sharply, and at random intervals on [the subject's] chest" (Baer, 1979, p. 1272) in order to manipulate the subglottal pressure. A rapid and consistent rise in F0 with each push was observed at a latency of 30 ms in all conditions. EMG signals of the vocalis and interarytenoid muscles were obtained and they were seen to be more active during the increase in F0 with every push on the chest wall. It is noted that voluntary adjustments for initiating phonation need the activation of the central nervous system (CNS) and therefore the reaction times are seen to be at approximately 100-140 ms (Draper, Ladefoged, & Whitteridge, 1960; Izdebski & Shipp, 1976; Netsell & Daniels, 1974), whereas mechanical reflexes such as the eyeblink response to an acoustic startle stimulus, respiratory muscles to sudden changes in pressure, and the laryngeal protective-closure reflex, occur as fast as 30-80 ms (Atkinson, 1978; Landis & Hunt, 1939; Sawashima, 1974; Sears & Davis, 1968). Thus, in Baer's study, the latency of F0 rise of about 30 ms indicates a peripheral reflex rather than a voluntary response involving the CNS (Baer, 1979). The values of change in F0 were 4, 4, and 3 Hz/cm of H_2O, respectively, for the three conditions in chest voice, and 9 Hz/cm of H_2O during falsetto. It was also observed that there was no contribution of visual or auditory cues related to the experimenter's pushing and the subject's response. With these results, Baer suggested two alternative hypotheses for changes in F0 due to abdominally induced pressure changes. The first hypothesis represents the correction of a closed-loop control system to a perturbing signal, here manifested as the increase of pressure leading to abduction of the vocal folds. The second hypothesis represents the laryngeal protective-closure component of the startle reflex (a sudden increase in Ps). The uppermost ventral part of the abdominal wall is the epigastrium and is an extremely sensitive region which activates the diaphragm (Vennard, 1967). The protrusion of the epigastrium is observed during contraction of the abdominal wall musculature and the diaphragm, which makes the epigastrium a better region for inducing manual pressures for rhythmic changes in Ps (Davis, 2009).

Dromey, Reese, and Hopkin (2009) investigated laryngeal level amplitude modulations (dB SPL) by measuring EGG values in singers by manually applying pressure to the abdominal wall while phonating a vowel. These manual applications of pressures induced rhythmic Ps pulses and its corresponding laryngeal level rhythmic changes to the vocal folds' closing to opening peak ratios which were observed in the differentiated EGG signal. Corresponding amplitude modulations (dB SPL) were also seen, thus suggesting that Ps was the main contributor to vocal amplitude changes. They hypothesized that the F0 modulations secondary to rhythmic Ps pulses would likely be due to changes in the amplitude of passive vocal fold excursions, which during increased loudness raise the vocal fold tension, and thus the F0 (Titze, 1989). Rothenberg et al., (1988) suggested that instances of abdominally induced vibrato that are driven by volitional Ps fluctuations can be found in some Western classical singers who were trained to use laryngeally mediated vibrato, in which CT is primarily responsible for F0 modulations, with amplitude (intensity) modulations derived from it. Dromey et al.'s study also suggested laryngeally mediated amplitude modulations in most of their vibrato samples, thus indicating Ps as a potential contributor to amplitude modulations, because it indirectly influences glottal configuration, flow resistance, and closure type and speed, which could also affect EGG speed quotient values (Dromey et al., 2009).

Vocal tract changes. Vocal tract contributions to F0 and intensity modulations are less extensively studied. Shipp et al. (1984) observed rhythmic movements in jaw, tongue, and pharyngeal walls, and the corresponding amplitude (intensity) modulations during vibrato production. Western classical vocalists are instructed in a variety of drill, exercise, imagery, and physical sensation techniques which are designed to develop awareness and have precise control over vocal structures for optimal resonance, power, and vibrato (Sundberg, 2000). Griffin, Woo, Colton, Casper, and Brewer (1995) mentioned that female singers might manipulate their jaw and tongue to facilitate changes in intensity (SPL) without increasing their Ps. However, in their study, the airflow measurements, i.e., mean flow, peak flow, and Ps were seen to be higher and statistically significant in male singers at medium and high pitches which indicated that male singers depend on respiratory activity to increase their intensity in comparison to female singers.

Widening the jaw opening narrows the pharyngeal constriction and enlarges the tract at its open end (Sundberg & Skoog, 1997). Thus, jaw opening and lowering the tongue constitute an important and appropriate articulatory gesture for raising F1, especially in vowels. The changes in jaw and tongue movement cause corresponding changes in F0 and intensity. One of the drills proposed by Vennard (1967) is to pronounce “la, la, la,” while keeping the jaw in a low position. The only movement is to raise the front edge of the tongue to the hard palate and upper teeth and let it flap down. He assumed that this technique improves articulation and also makes the quality of the vowels better by “keeping the tongue out of the throat”. This indicates that it is not uncommon for singers to be trained to make acoustic changes secondary to supraglottic constriction changes, especially using jaw, tongue, lips, and other oropharyngeal structures. Most of the extrinsic laryngeal muscles (laryngeal elevators) connected to the larynx from the mandible, styloid process, floor of the mouth, tongue, and pharyngeal constrictors, influence laryngeal movements (Zemlin, 1968). Again, it is noted that oscillations in tongue and jaw are seen secondary to laryngeal modulations during vibrato or bleat production, especially in untrained or amateur singers (Kirkpatrick, 2008).

Whisper

Whisper is characterized by the presence of turbulent noise emanating from the larynx (Colton, Casper, & Leonard, 2006). Titze (1994) describes whisper as the sound created by turbulent glottal airflow in the absence of vocal fold vibration. Luchsinger and Arnold (1965) differentiated whisper from phonation in the following way: a) the shape of the glottis being an inverted Y, due to a closed anterior glottis and the presence of a posterior glottal gap. b) As the vocal folds are not in vibration, less vocal fold tension is seen in whisper than in phonation. As a result, the DC flow is set into non-periodic turbulence so that a noise is generated instead of a periodic tone. c) Whispering is more strenuous than speaking due to greater expiratory air volume in former. d) The Ps is lower in whisper than in phonation. Laver (1980) described the glottal configuration during whisper as “a triangular opening of the cartilaginous glottis, comprising about a third of the full length of the glottis.”

Konnai and Scherer (in press) found that airflow values were significantly higher for whisper than phonation in medium and loud conditions, whereas laryngeal flow resistance was found to be the same between phonation and whisper for males, but for females, greater for phonation. The airflow was also observed to increase with loudness at each level of adduction (breathy, normal, and pressed) in whisper.

Actors and singers use “stage whisper” for special effects (Poyatos, 2002). Bateman (2010) stated that whisper may be combined with modal voice or falsetto to form whispery voice or whispery falsetto. He also mentioned that whisper is rarely used in classical singing; however, there are numerous occurrences in twentieth century art music. Popeil (1998) indicated that pop singers may use an “air mix” as it is common for them to mix air into the sound to add an artistic color. Whisper in singing and speaking is important to measure as it has a wide range of Ps (1.3-17 cm H_2O), glottal airflow (0.9-1.71 L/s), glottal area (0.065-1.76 cm^2), and glottal perimeter (1.09-1.76 cm^2) values (Sundberg, Scherer, Hess, & Müller, 2010).

Electroglottography (EGG)

The electroglottographic (EGG) signal magnitude apparently reflects the changes in vocal fold contact area during phonation (direct measures of medial vocal fold contact: Hampala, Garcia, Švec, Scherer, & Herbst, 2015; Scherer, Druker & Titze, 1988; other important indications of dynamic vocal fold behavior: Childers & Larar, 1984; Fourcin, 1981; Lecluse, Brocaar, & Verschuure, 1975; Orlikoff, 1995). Measures of the EGG waveform are sensitive to vocal register, vowel, the degree of vocal fold adduction, and the intensity of phonation (Brown & Scherer, 1992; Chen, Robb, & Gilbert, 2002; Henrich, Roubeau, & Castellengo, 2003; Higgins, Netsell, & Schulte, 1998; Orlikoff, 1991; Scherer, Vail, & Rockwell, 1995).

For the Brown and Scherer (1992) study discussed above, both the EGG signal height (EGGH) and pulse width (EGGW, defined below; Scherer et al., 1995) of the signal varied with each trillo cycle, becoming taller and wider with greater adduction, and shorter and narrower with less adduction throughout the cycle, thus giving the impression that trillo was an adductory-controlled phenomenon from the orientation of EGG waveform interpretations. Hicks and Teas (1987) found no consistent, distinctive differences in the EGG waveforms with and without vibrato within different registers. However, they compared only waveform shapes, and no height and width measures were reported. Laukkanen, Vilkman, & Unto (2009) recorded EGG signals in a female amateur singer producing vibrato at three registers. The EGG amplitude modulations were seen only when there was a pitch shift from modal to falsetto, but not in each register, thus indicating no significant glottal adductory changes during vibrato. Guzman Rubin, Muñoz, & Jackson-Menaldi (2013) compared the contact quotient between sustained vowel phonation with and without vibrato, and found that there was no significant difference between them.

Dromey et al. (2009) measured the EGG speed quotient in order to investigate the laryngeal-level amplitude modulations. They had defined the EGG speed quotient in a previous study as “the ratio of the time taken for the vocal folds to open divided by the time taken for them to close” (Dromey et al., 1992, p. 44). As measured by the EGG speed quotient, they observed EGG amplitude modulations (laryngeal-level amplitude modulations) in their vibrato tokens. EGG amplitude modulation extent was found to be greatest in soft loudness level conditions for three pitches. These findings suggest that fluctuations in intensity and F0 occur during vibrato at the laryngeal level. They had two hypotheses to support laryngeal level modulations in F0 and intensity. The first possibility is that the laryngeal-level amplitude modulations may be driven by respiratory factors such as Ps. As EGG amplitude modulation extents were higher for soft conditions, the second possibility could be decreased vocal fold tension associated with lower laryngeal flow resistance that cause more susceptibility to fluctuations in amplitude at the laryngeal level. The rhythmic contractions in CT causes pitch fluctuations, and therefore the tension in the vocal folds increases and decreases accordingly. If the tension in the vocal folds is high, the amplitude of vibration would be smaller for a given amount of subglottal pressure, but when the tension in the vocal folds is less, the amplitude of vibration would be greater. Thus, the second possibility indicates the fluctuations driven by the neural inputs to the CT which generates F0 modulations, and corresponding acoustic amplitude modulations. They also observed that there was no association between the increase in mean airflow and increase in EGG amplitude modulation. But the mean airflow was seen to increase with loudness, whereas EGG amplitude modulations were lower for the loudest conditions. They also observed rhythmic variations in the EGG speed quotient, microphone signal, F0, intensity, and EGG closed-open quotients in response to manually applying pressure to the abdominal wall to cyclically vary Ps. The EGG speed quotient increased with cyclic increase in Ps.

Research Questions

The current project has two main research studies.

Study 1, "Airflow vibrato in four professional singers", asks the following research questions:

RQ1. What are the general characteristics of airflow vibrato in Western classical singing?

RQ2. Do airflow vibrato extent and F0 vibrato extent vary similarly within pitches and loudness levels in males and females?

RQ3. Is there a relationship between airflow vibrato rate and F0 vibrato rate?

Study 2, "Sources of airflow vibrato", asks the following research questions:

RQ4. Does airflow vibrato rate differ from airflow bleat rate?

-within and between pitches and loudness levels

-between light and heavy bleating with phonation and whisper

-between gender

RQ5. Does airflow vibrato extent differ from airflow bleat extent and airflow external epigastric (upper abdominal) pumping extent?

- within and between pitches and loudness levels
- between light and heavy bleating with phonation and whisper
- between shallow and deep pumping with phonation and whisper
- between gender

RQ6. Does F0 vibrato rate differ from F0 bleat rate and F0 external epigastric (upper abdominal) pumping rate?

- within and between pitches and loudness levels
- between light and heavy bleating with phonation
- between gender

RQ7. Does F0 vibrato extent differ from F0 bleat extent and F0 external epigastric (upper abdominal) pumping extent?

- within and between pitches and loudness levels
- between light and heavy bleating with phonation
- between shallow and deep pumping with phonation
- between gender

RQ8. Do subglottal pressure, average airflow, percent airflow, and intensity extent differ by

- gender,
- type of laryngeal source (phonation and whisper),
- type of task (speaking and singing),

- type of sub-tasks (speaking: normal, bleat, epigastric pumping, and vocal tract changes; singing: straight tone, vibrato, bleat, and epigastric pumping), and
- levels of sub-tasks (speaking: light and heavy bleat, shallow and deep epigastric pumping, and vocal tract changes for vowel and consonant; singing: straight tone- two pitches and three loudness levels, vibrato- two pitches and three loudness levels, and bleat- two pitches)?

CHAPTER II. METHODOLOGY

The current project consisted of two studies: Study 1, “Airflow vibrato in four professional singers,” and Study 2, “Sources of airflow vibrato”.

Subjects

For Study 1 (IRBNet ID#530803-4, see Appendix A), four professional singers volunteered. All subjects were currently active Western classical singers and teachers of singing with over 15 years of professional performance experience in regional, national, or international opera and recital venues. The subjects were two sopranos (S1 and S2; 37 and 57 years old), a tenor (T; 62 years old), and a baritone (B; 37 years old).

For Study 2 (IRBNet ID#911379-1, see Appendix B), four non-professional (highly trained amateur) singers participated in the study. The subjects were two sopranos (F1 and F2; 23 and 19 years old, respectively), and two baritones (M1 and M2; 29 and 28 years old, respectively). F1, M1, and M2 had undergraduate degrees in music, and M1 had a graduate degree in music as well. F2 was currently a music minor. All subjects had a minimum of 10 years of singing training and experience in choirs, musicals, and intermediate level opera. The study was advertised in the Department of Communication Sciences and Disorders and the College of Musical Arts using recruitment flyers (see Appendix C).

All singers signed a consent form that explained the purpose, procedures, risks, and benefits of the study (see Appendices D and E). They also were given a health and voice history form to fill out (see Appendices F and G). All subjects were healthy at the time of recording, and had no history of voice problems or other related health issues within the last month.

Instrumentation

Figure 4 shows a schematic of the instrumentation set up. The microphone [Model 33-3013, RadioShack Corporation, Fort Worth, TX], aerodynamic system with a circumferentially vented flow mask (Glottal Enterprises, Syracuse, NY; model MSIF-2 S/N 2049S), and electroglottograph (Kay Elemetrics, Lincoln Park, NJ, USA) were set up inside an IAC sound-treated booth (Industrial Acoustic Company, Bronx, NY, USA; model 402A, S/N 3806). The rest of the equipment was situated outside the booth and included the signal acquisition system with digital oscilloscope (DATAQ Instruments, Inc., Akron, OH, model DI-720, with WINDAQ software), and Dell computer (OptiPlex 780, Round Rock, TX). The pneumotachograph flow mask and oral pressure transducer were calibrated based on standard procedures of constant flow (with the use of rotameter flowmeters) and constant pressure (with the use of a U-tube manometer), respectively, with uncertainty within approximately ±3%. Static calibrations for pressure and airflow were completed (see appendix VIII for details).

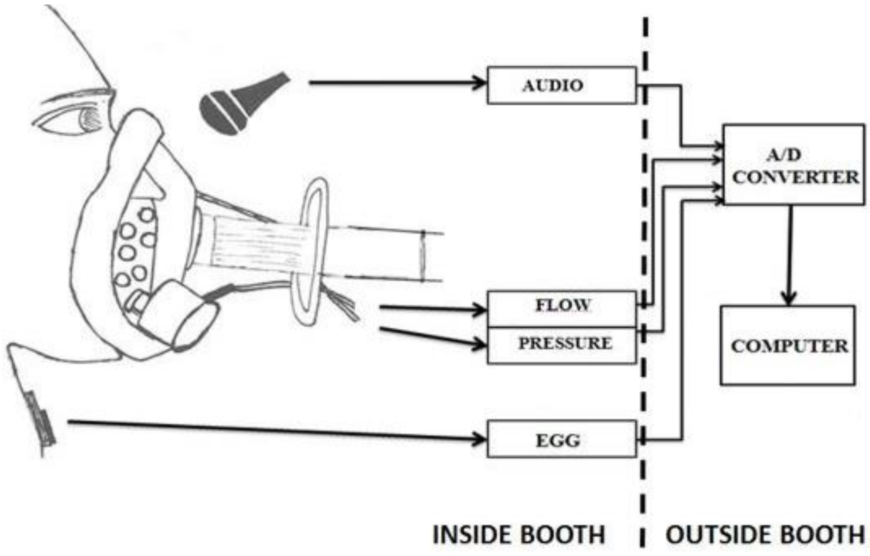

Figure 4. Experimental set up.

Recording Procedures

The experiment took place at the Voice Physiology Laboratory, Bowling Green State University. The microphone and sound level meter (SLM) were placed at a constant distance from the subject's mouth (approximately 6 inches). The subject held the vented pneumotachograph mask against her or his own face such that it could be removed easily by the subject at any time. Included in the vented mask was a small sterilized tube attached to a pressure transducer. The lip occlusion method of estimating subglottal pressure from oral pressure was used for a set of utterances.

The electroglottograph (EGG) was used to obtain waveforms of the assumed changes in vocal fold contact area. The device includes two small plates that were placed on the skin over the right and left thyroid laminae. The signal obtained is a demodulated variation of the impedance (high frequency, low amperage) through the neck as the vocal folds vibrate. The airflow, oral air pressure, EGG signal, and sound intensity signals were recorded into separate channels of the DATAQ A/D converter using a sampling rate of 20,000 Hz per channel and DATAQ's WinDAQ software. The flow signal was backward and forward smoothed within custom software using Matlab® to maintain sample time alignment with other recorded signals. The smoothing technique does not affect the vertical shifting and preserves the time. For display purposes and further analyses, the data for the airflow and intensity signals were downsampled so that the values were reported every 10 milliseconds (20,000 samples per second divided by 200 is 100 samples per second, i.e., 0.01 seconds or 10 ms between data points). In Praat (Version 5.3.77, www.praat.org), the setting for F0 values was also set to 0.01 seconds for display purposes. The .wav file extracted from Sigplot also preserves the time.

Tasks

Study 1: airflow vibrato in four professional singers. The subjects performed sustained singing of the vowel /a/ with at least 4 or 5 vibrato cycles per syllable between /p/ productions using three pitches. For male singers (Tenor and Baritone), lower modal (P1), higher modal (P2), and head (not falsetto) (P3) registers were used, and for female singers (2 sopranos) modal (P1), middle (P2), and head (not falsetto or whistle) (P3) registers were used. Before the actual recordings, each subject was asked to sing first at a comfortable level of loudness, and then to sing softer than the comfortable level, and louder than the comfortable level, but within the range of their performance region. The instructions were given on the three loudness levels to be corresponded to musical dynamic ranges of piano (L1), mezzo forte (L2), and forte (L3) at a given register. The three pitches used by the singers depended on his or her vocal classification and range (see Table 1). Thus, there were nine conditions, namely, P1L1, P1L2, P1L3, P2L1, P2L2, P2L3, P3L1, P3L2, and P3L3.

Table 1

Frequencies of the three pitches sung by the four singers of Study 1

Voice Classification	P1	P2	P3
Tenor	D3 (147 Hz)	D4 (294 Hz)	G4 (392 Hz)
Baritone	A2 (110 Hz)	A3 (220 Hz)	F4 (349 Hz)
Soprano-1	C4 (261 Hz)	A4 (440 Hz)	G5 (784 Hz)
Soprano-2	C4 (261 Hz)	A4 (440 Hz)	G5 (784 Hz)

Study 2: sources of airflow vibrato. The four subjects performed speaking and singing tasks. Under speaking tasks, there were two sub-tasks, phonation and whisper. Speaking fundamental frequency was used for most of the speaking tasks as it correlates with perceived pitch of the subject's voice (Baken & Orlikoff, 2000). Auditory cues were given in between using a keyboard up on subject's request to maintain the pitch at similar range. Under singing tasks, there was only phonation. Table 2 gives the outline of all tasks performed by the subjects. The frequencies of pitches P1 and P2 sung by the baritones were A2 (110 Hz) and A3 (220 Hz), and for the sopranos were A3 (220 Hz) and A4 (440 Hz), respectively.

Table 2

Speaking and singing tasks of Study 2

Tasks	Sub-tasks	Levels
Speaking (Phonation) and Speaking (Whisper)	1. Sustained vowel /a/ production between /b/ and /p/, i.e. /ba:p:ba:p:../ at speaking fundamental frequency (SFF) a. With phonation b. With whisper	[No further levels under normal phonation and whisper]
	2. Bleating during the vowel production of /ba:p:ba:p:../ a. With phonation b. With whisper	Bleating under two levels: light (somewhat breathy) and heavy (somewhat pressed)
	3. External epigastric pumping while the subject was producing the vowel /a/ at SFF a. With phonation b. With whisper	External epigastric pumping under two levels: shallow (less pressure) and deep (more pressure)
	4. Production of /a:l::a:l::a:l::…/ a. With phonation b. With whisper	No further levels under /a:l::a:l::a:l::…/ productions
Singing (Phonation)	1. Straight tones using /ba:p:ba:p:../	Singing straight tones on two pitches (P1 and P2), where P2 is one octave higher than P1, and three loudness levels - piano (L1), mezzoforte (L2), and forte (L3) [P1L1, P1L2, P1L3, P2L1, P2L2, & P2L3]
	2. Vibrato tones using /ba:p:ba:p:../, where singer produces at least 4-5 cycles of vibrato during vowel production	Singing vibrato on two pitches (P1 and P2), where P2 is one octave higher than P1, and three loudness levels - piano (L1), mezzoforte (L2), and forte (L3) [P1L1, P1L2, P1L3, P2L1, P2L2, & P2L3]
	3. Bleating while singing the vowel /a/ using /ba:p:ba:p:../, where singer bleats during the vowel production	Subject bleats on two pitches (P1 and P2), where P2 is one octave higher than P1, and two levels under each pitch, i.e. light (breathy) and heavy (pressed) P1- light and heavy; P2- light and heavy
	4. External epigastric pumping while the subject sings a straight tone at comfortable pitch and loudness, using vowel /a/	External epigastric pumping under two levels: shallow (less pressure) and deep (more pressure)

Measures and Procedures

Study 1: airflow vibrato in four professional singers. Figure 5 is an example of airflow vibrato for Soprano-1 singing her lowest pitch (P1) and softest loudness (L1). The airflow values were measured every 10 milliseconds using Praat software. Figure 5 shows airflow vibrato with a rate of about 5.5 Hz. The interval between consecutive black vertical lines indicates one vibrato cycle. The dashed horizontal lines designate the peak and valley of an airflow vibrato cycle, respectively. The difference between flow values for the peak and the valley gives the airflow extent for that vibrato cycle.

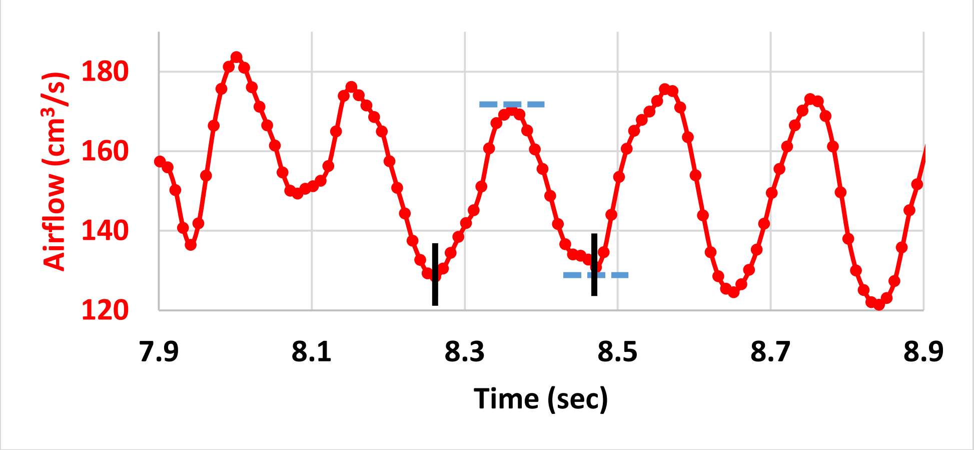

Figure 5. Airflow vibrato for Soprano-1 singing her lowest pitch (P1) and soft level of loudness (L1). The short vertical bars indicate local minima to demarcate periods, and the two blue dashed bars indicate the peak-to-peak measure of flow extent.

Figure 6 is an example illustrating the phase relationship between airflow vibrato and F0 vibrato. The phase between the airflow vibrato and F0 vibrato was measured to be approximately 75°, where flow (the red dashed-line signal) is leading. This was determined by using the formula: $\Theta = (t2-t1)/(t3-t2) * 360^o$, where $t1$ is the time of the peak of the airflow vibrato cycle, $t2$ is the time of the peak of the nearby F0 vibrato cycle, and $t3$ is the time of the peak of the next

F0 vibrato cycle. Positive values indicate that the airflow vibrato cycle leads the F0 vibrato cycle, and negative values indicate that the airflow vibrato cycle lags the F0 vibrato cycle. The typical finding in this study is that airflow vibrato leads F0 vibrato, but not by constant values.

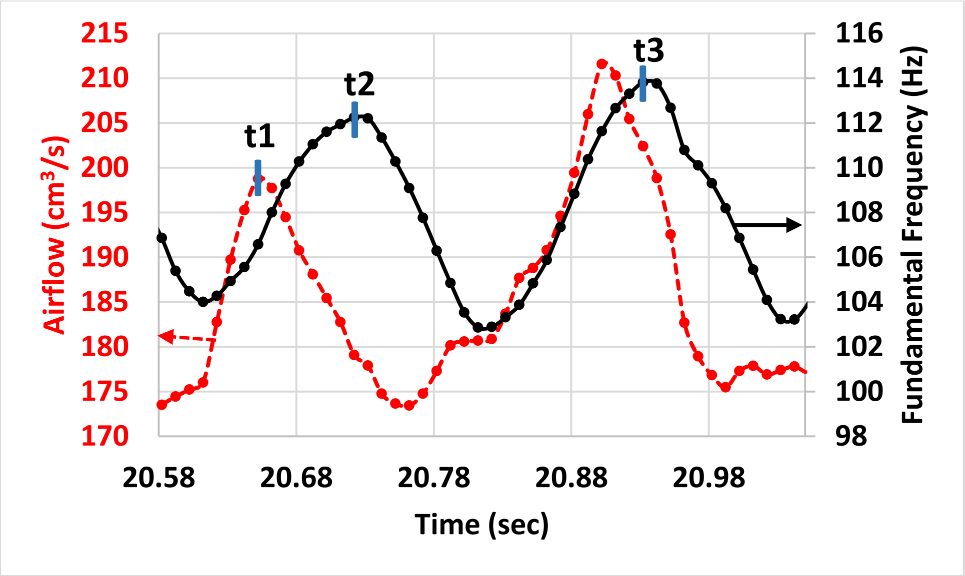

Figure 6. Maximum peaks on the airflow (dashed red line) and F0 vibrato (solid black line) waveforms used to measure the phase between airflow and F0 vibrato. Here the airflow vibrato leads the F0 vibrato by approximately 75 degrees. The short horizontal arrows indicate the correct axis for the signal.

The airflow vibrato rate (the number of primary airflow undulations per second during vibrato production) and the airflow vibrato extent (the difference between the peak (maximum) and valley (minimum) airflow values during each airflow vibrato production) were measured and compared to simultaneous F0 vibrato productions. Thus, the dependent variables were rate and extent of airflow vibrato and F0 vibrato, and the phase difference between airflow vibrato and F0 vibrato. The independent variables were pitch (P1, P2, and P3) and loudness levels (L1, L2, and L3).

A three-way ANOVA was performed for a 3 x 2 x 2 three-factor design (3 loudness levels, 2 pitches, and 2 genders) in order to compare the mean differences of F0 vibrato extent and airflow vibrato extent. Correlation coefficients were measured to see the strength of relationship between airflow and F0 vibrato rates. Phase values are reported without statistical analysis. The regularity and consistency of the airflow waveforms are interpreted subjectively depending on the presence or absence of multiple peaks, the shape of the waveform (quasi-sinusoidal), and its relation to F0 vibrato. The average oral pressures for all nine conditions are reported by taking the average of pressures during the lip occlusion of stop consonant /p: / production. The average intensity values were measured using Praat for all nine conditions.

The electroglottographic signal was usable for only two of the subjects (the Tenor and Soprano-2). EGGW50 (pulse width) and Normalized Rate Quotient (NRQ) were measured for the subjects. EGGW50 is the relative pulse width of the EGG waveform at the 50% height location, and is associated with laryngeal adduction (Scherer, Vail, & Rockwell, 1995).

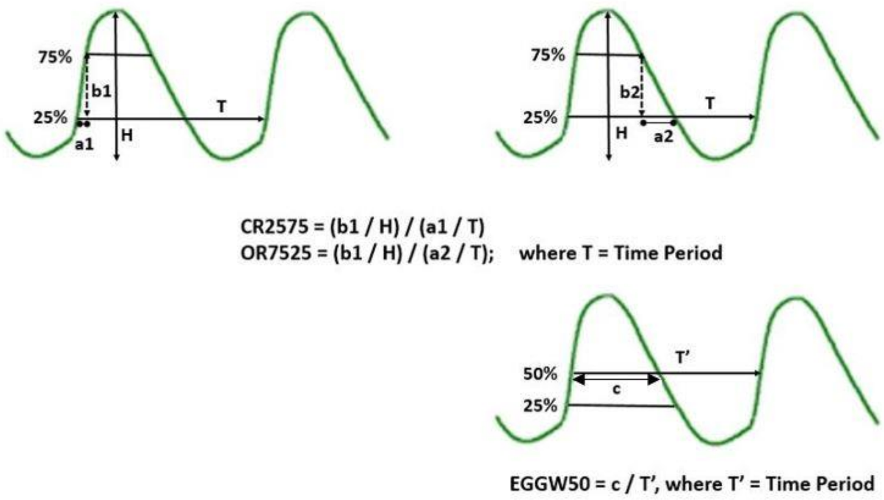

Figure 7. Three EGG waveforms, with distances and labels to accompany the definitions for the left-hand-side closing quotient, the right-hand-side opening quotient, and the EGGW50 normalized width measure. Note that *b1* has the same value as *b2*.

The Normalized Rate Quotient (NRQ), a measure similar to the EGG Speed Quotient of Dromey et al. (2009), was obtained as a ratio of *CR2575* divided by *OR7525* (see Figure 7), *viz.*, NRQ = *CR2575 / OR7525*. The closing slope ratio, CR2575, is defined as the normalized rise *(b1/H)* divided by the normalized run *a1/T*, where *b1* is the EGG waveform height corresponding the segment between 25% and 75% of the peak-to-peak amplitude *H*, *a1* is the time segment corresponding to *b1*, and *T* is the cycle period. The opening slope ratio, *OR7525*, is defined by the normalized rise *b2/H* divided by the normalized run *a2/T*, where *b2* is the EGG waveform height corresponding to the segment between 75% and 25% of *H*, and *a2* represents the time for the signal to drop from the 75% to the 25% level (Fisher et al., 1996). When the NRQ expression is simplified, NRQ = *a2/a1*, the ratio of the duration to lower the EGG signal from 75% to 25% of the height on the right hand side to the duration to raise the EGG signal from 25% to 75% of the height on the left hand side of the EGG cycle. NRQ is a negative quantity because it is the ratio of a positive slope (left hand side) and a negative slope (right hand side). The closing and opening slope measures depend upon the speed and manner of vocal fold movement during contact. A larger negative NRQ value means that the medial vocal fold surfaces come together faster or separate slower. The two measures (EGGW and NRQ) were obtained for a sequence of about 3-4 cycles at both the peaks and the valleys of the airflow vibrato cycles. The values were averaged at the peaks and averaged at the valleys to give representative EGGW and NRQ values for each utterance. Pairwise t-tests were performed to observe if there was any statistically significant difference in glottal adduction between peaks and valleys of airflow vibrato.

Study 2: sources of airflow vibrato. The airflow and F0 modulation extents and rates, and all the other measures - average airflow, average intensity, intensity extents, and oral pressures were measured using the same method mentioned in Study 1 for vibrato. Another measure is percent airflow, which is average airflow extent for vibrato, bleat, or external epigastric pumping conditions, divided by the corresponding average airflow value for the condition. Table 3 gives an outline of obtained measures from individual tasks. Each subject was screened before the actual recordings to make sure that they were able to perform all the tasks in the study, primarily vibrato, bleat, and their sensitivity to external epigastric pumping. Each task had three recordings, each recording had three repetitions, and each token was used from each recording. For a few measures, more than one token was taken from each recording in case of flow mask leak or inaccurately obtained oral pressures. For example, for one of the subjects, the oral pressure tube was clogged with excessive saliva during certain tasks, and those recordings were not used.

Table 3

Outline of measures for study 2

Tasks	Sub-tasks	Variables
Speaking (phonation and whisper)	SFF with phonation and whisper	**Dependent variables**: average airflow (cm^3/s), average intensity (dB IL), and average oral pressure (cm of H2O) **Independent variables:** gender (2) and laryngeal source (2- phonation and whisper)
	Bleating with phonation and whisper	**Dependent variables:** airflow bleat rate (Hz), airflow bleat extent (cm^3/s), F0 bleat rate (Hz), F0 bleat extent (ST), average airflow (cm^3/s), average intensity (dB IL), intensity extent (dB), average oral pressure (cm of H2O), and % airflow **Independent variables**: gender (2), laryngeal source (2), and type of bleat (2- light and heavy) *Note: Whisper does not have F0 measures
	External epigastric pumping (EEP) with phonation and whisper	**Dependent variables**: airflow EEP rate (Hz), airflow EEP extent (cm^3/s), F0 EEP rate (Hz), F0 EEP extent (ST), average airflow (cc/s), average intensity (dB IL), intensity extent (dB), and % airflow **Independent variables:** gender (2), laryngeal source (2), and type of epigastric pumping (2- shallow and deep)
	Production of /a:l::a:l::/ with phonation and whisper	**Dependent variables**: average airflow (cm^3/s), average F0 (Hz), average intensity (dB IL), and average oral pressure (cm of H2O) **Independent variables**: gender (2), laryngeal source (2), and tongue position (2- raised or consonant and lowered or vowel)
Singing (phonation)	1. Straight tones	**Dependent variables:** average airflow (cm^3/s), average intensity (dB IL), and average oral pressure (cm of H2O) **Independent variables:** gender (2), pitches (2), and loudness levels (3)
	2. Vibrato	**Dependent variables**: airflow vibrato rate (Hz), airflow vibrato extent (cm^3/s), F0 vibrato rate (Hz), F0 vibrato extent (ST), intensity extent (dB), average airflow (cm^3/s), % airflow, average intensity (dB IL), and average oral pressure (cm of H2O) **Independent variables:** gender (2), pitches (2), and loudness levels (3)
	3. Bleating	**Dependent variables**: airflow bleat rate (Hz), airflow bleat extent (cm^3/s), F0 bleat rate (Hz), F0 bleat extent (ST), average airflow (cm^3/s), average intensity (dB IL), intensity extent (dB), average oral pressure (cm of H2O), and % airflow **Independent variables**: gender (2), pitch (2), type of bleat (2)
	4. External epigastric pumping	**Dependent variables**: airflow EEP rate (Hz), airflow EEP extent (cm^3/s), F0 EEP rate (Hz), F0 EEP extent (ST), average airflow (cm^3/s), average intensity (dB IL), intensity extent (dB), and % airflow **Independent variables:** gender (2), and type of epigastric pumping (2)

For statistical analysis, a repeated measures 2-crossed and 3-staged ANOVA model was used to compare the mean differences among different levels of tasks. The 2-crossed indicates crossed effect of subjects and gender on measures, and 3-staged is speaking (phonation), speaking (whisper), and singing. The main effects of gender (2 levels: Male, Female), task (2 levels: Speaking- Sp, Singing- Sn), sub-tasks (3 levels: Bleating, Vibrato, External Epigastric Pumping-EEP), and levels of sub-tasks (24 levels: normal phonation (Sp), normal whisper (Sp), lighter bleat (Sp), heavier bleat (Sp), shallow pumping (Sp), deep pumping (Sp), low pitch piano straight tone (Sn), low pitch mezzoforte straight tone (Sn), low pitch forte straight tone (Sn), high pitch piano straight tone (Sn), high pitch mezzoforte straight tone (Sn), high pitch forte straight tone (Sn), low pitch piano vibrato (Sn), low pitch mezzoforte vibrato (Sn), low pitch forte vibrato (Sn), high pitch piano vibrato (Sn), high pitch mezzoforte vibrato (Sn), high pitch forte vibrato (Sn), low pitch lighter bleat (Sn), low pitch heavy bleat (Sn), high pitch lighter bleat (Sn), high pitch heavier bleat (Sn), shallow pumping EEP (Sn), and deep pumping EEP (Sn) were given. The interaction between gender and tasks, gender and sub-tasks, and gender and levels of sub-tasks was also given. The multiple level variate main effects and interaction effects were interpreted using a significance value of $p < 0.05$. Tukey's HSD (honest significant difference) test was used for post-hoc analyses wherever necessary to further see the differences among the sub-groups. For few of the conditions, individual paired and intersample t-tests were done in order to remove the effects of whisper among the speaking tasks, as the whisper results were different from speaking phonation and singing tasks.

The measures of modulations in airflow, F0, and intensity were measured by using the vowel segment of /ba:p:ba:p:../ (same as in Study 1). The subjects were asked to produce vibrato and bleat during the vowel portion. Bleating is similar to trillo. Although bleat was not part of their singing training, all the subjects were able to bleat at a satisfactory level. Bleating is also called machine-gun vibrato, and is perceptually like a sheep bleat or a giggle. During the task of external epigastric pumping, the student researcher stood next to the subject, and placed two fingers (index and middle fingers) on the external epigastrium region of the subject. The epigastrium is the upper abdominal portion right below the sternum, and the lung pressure is highly sensitive to external pressure applications at that location (Vennard, 1967). The subject was asked to produce a sustained vowel /a/ using phonation and whisper. During the production, the student researcher gently moved her fingers to and fro (perpendicular to the body) on the epigastric region externally. There was no pressure transducer used to monitor the rates or actual pressure of the pumping during the experiment. There was shallow or lighter pressure and deep or more pressure used during the epigastric pumping. None of the subjects felt discomfort, pain, and/or rejected the tasks. The remaining tasks are given in Table 2. EGGW measures were obtained in the same way as mentioned in Study 1 for vibrato, at the peaks and valleys of the airflow modulations. Pairwise t-tests were performed to compare the differences in EGGW and NRQ between peaks and valleys of airflow modulations during vibrato.

Because of the relatively low number of sample points within each vibrato cycle, the measures of rate, extent, and phase for the various modulated signals of this project were easily obtained because they involved the maximum and minimum values of the modulation cycles. That is, the peaks and valleys were clearly represented by single sample points (e.g., see Figure 5 that shows between 15 and 21 points per cycle), and thus for those measures reliability measures were not necessary. For complex signal modulation cycles, a consensus approach was used to decide on the relevant peaks and valleys for the measures (two researchers made joint decisions).

CHAPTER III. RESULTS

Study 1: Airflow Vibrato in Four Professional Singers

Airflow vibrato and the phase. Figures 8-11 illustrate the range of complexity of airflow vibrato waveshapes, from regular and consistent airflow vibrato cycles to inconsistent cycles with multiple peaks. This range suggests that there is a more complex and different genesis for airflow vibrato than for F0 vibrato. Figure 10, for example, shows airflow vibrato having a complex form since there are approximately 2 to 3 airflow cycles for each F0 cycle. Because the cycles of the airflow vibrato waveform apparently do not need to be in-phase with the cycles of the F0 vibrato waveform, the question of degree of interdependence between the two phenomena is raised. The complex (ranging from regular and consistent to irregular and inconsistent) waveshape of the airflow vibrato in Figure 10 suggests that it is possible to have one, two, or three variations of airflow within one cycle of F0 vibrato. Figure 11 suggests that there can be portions of the airflow vibrato cycle that are relatively flat, meaning essentially no change in flow.

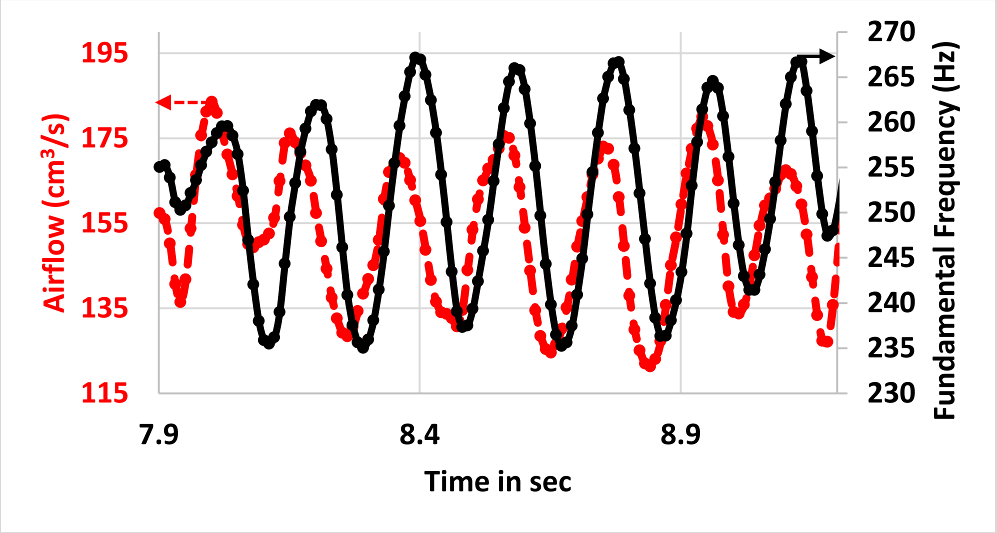

Figure 8. Example of a relatively consistent airflow vibrato leading F0 vibrato by 54.5°. The condition is Soprano-1 singing the pitch P1 with loudness L1.

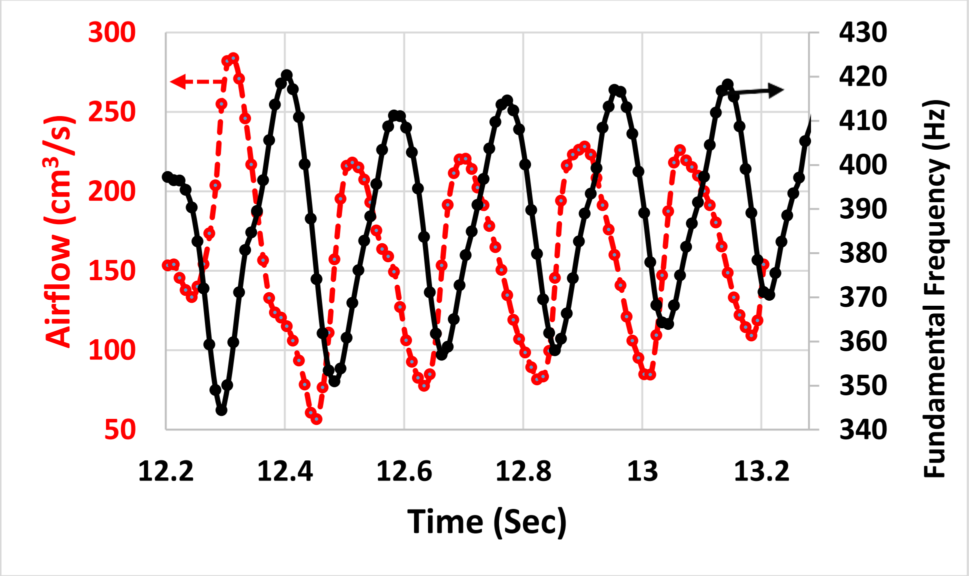

Figure 9. Example of a relatively consistent airflow vibrato, somewhat less sinusoidal appearing than in Figure 8, leading F0 vibrato by 130°. The condition is Soprano-2 singing the pitch P3 with loudness L2.

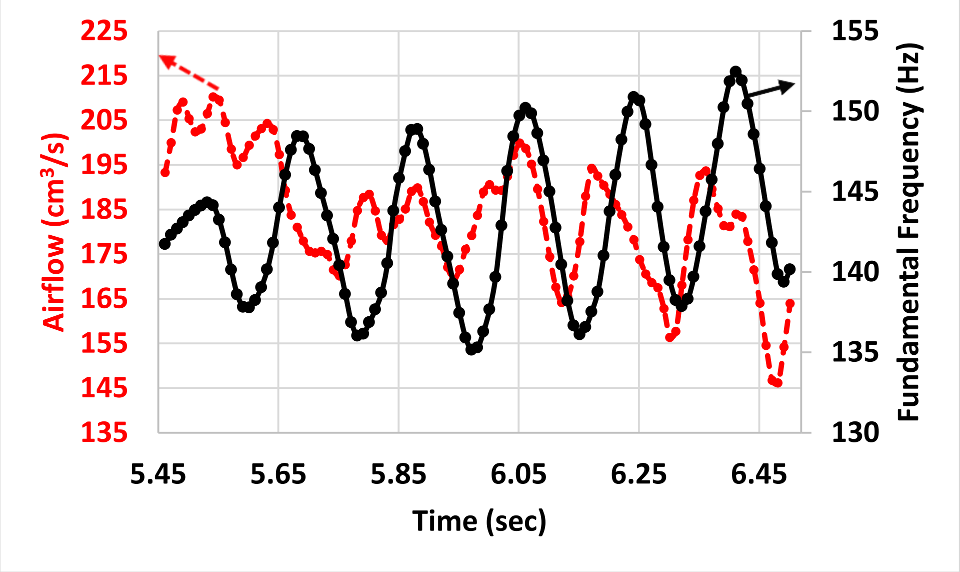

Figure 10. Example of inconsistent undulations in airflow vibrato leading F0 vibrato (considering the first peak of each cycle), by an average of 105°. The condition is the Tenor singing the pitch P1 with loudness L1.

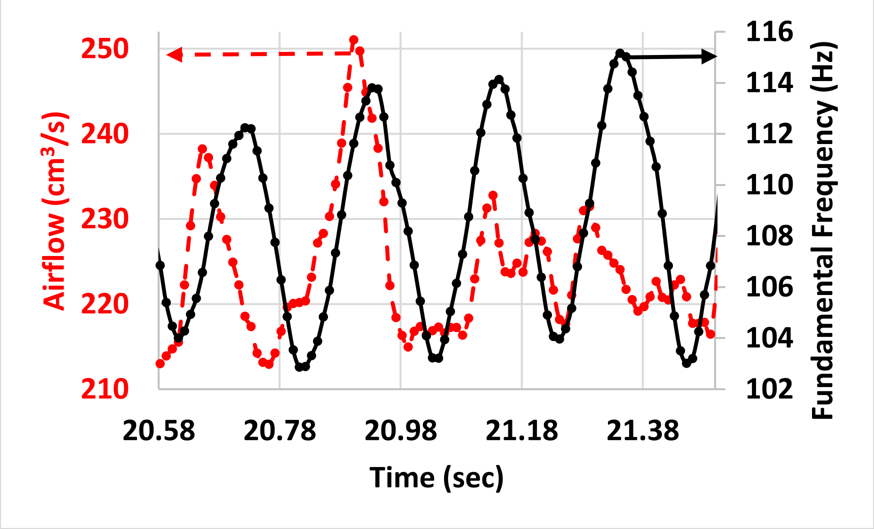

Figure 11. Example of irregular but consistent airflow vibrato cycles that indicate high level of complexity. The airflow vibrato appears to lead F0 vibrato by about 75°. The condition is the Baritone singing the pitch P1 with loudness L3.

Rate of airflow vibrato and its relationship to rate of F0 vibrato. The rate of airflow vibrato was measured and compared with the rate of F0 vibrato. Figure 12 shows the rates for both for all conditions (4 singers X 3 pitches X 3 loudness levels). The relationship between the rate of airflow vibrato and rate of F0 vibrato was seen to be strong (R^2=0.7456). This suggests that similar mechanisms govern the rate of both types of vibrato. Because only 4-5 cycles were used to obtain vibrato rates, a relatively small number of cycles, and the airflow vibrato waveform can be complex (non-sinusoidal), the calculation for airflow vibrato rate is less valid or at least more difficult to obtain, and thus the relationship might actually be stronger than indicated in this project's sample. Figure 13 shows a condition (data point circled and labeled #1 in Fig. 12) where the flow and F0 vibrato rates were most dissimilar – the rate of F0 vibrato (5.26 Hz) is seen to be faster than the approximate rate of airflow vibrato (4.84 Hz), assuming the secondary oscillations are within single cycles. Figure 14 shows the condition where both flow and F0 vibrato rates were similar (5.34 Hz and 5.51 Hz respectively), with slight differences in signal waveshapes (data point circled and labeled #2 in Fig. 12).

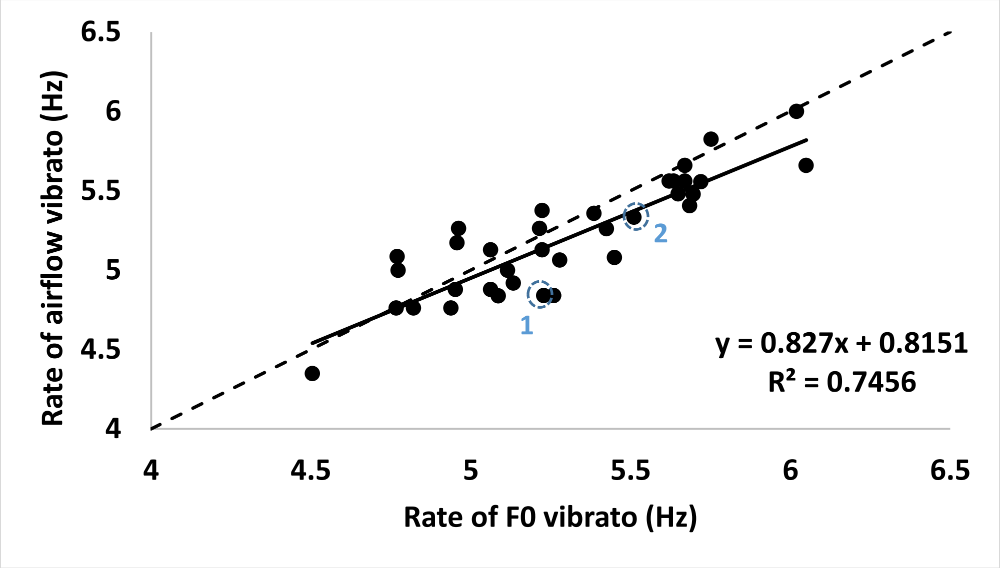

Figure 12. Rate of airflow vibrato vs rate of F0 vibrato for all conditions and subjects. The regression suggests that F0 vibrato tends to be slightly faster than airflow vibrato. The dashed line is the 1-1 line.

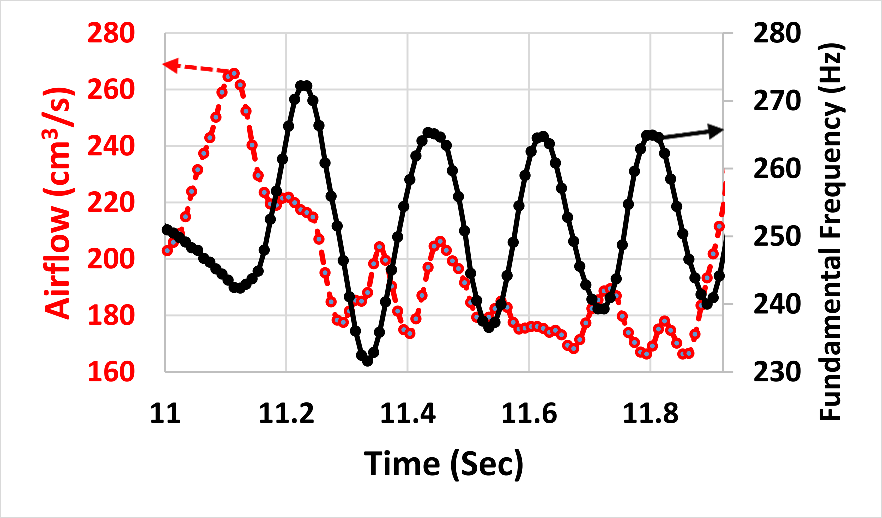

Figure 13. Flow and F0 vibrato waveforms corresponding to circle #1 in Figure 12, a case where the airflow vibrato rate is different from the F0 vibrato rate, and also with different waveshape. The condition is the soprano-2 singing the pitch P1 with loudness L2.

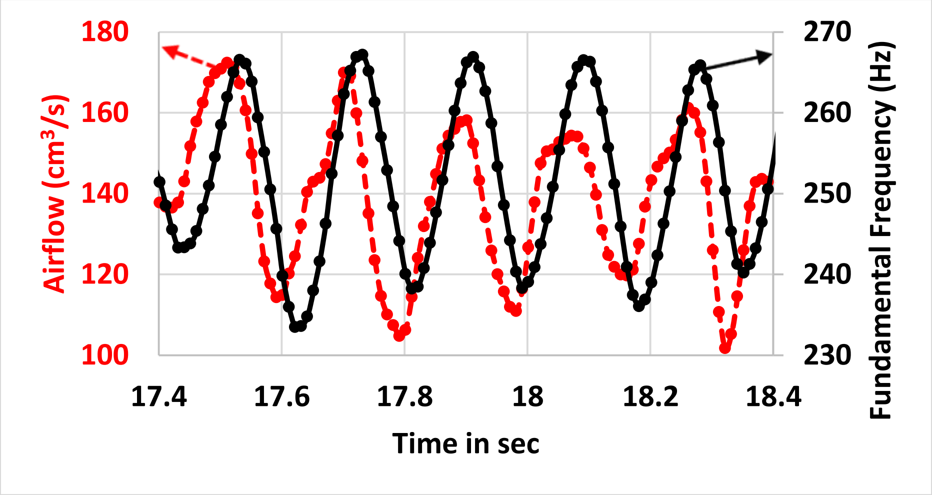

Figure 14. Flow and F0 vibrato waveforms corresponding to circle #2 in Figure 12, a case where the vibrato rates are similar, with slightly different waveform shapes. The condition is the soprano-1 singing the pitch P1 with loudness L2.

Extent of airflow vibrato. Table 4 provides airflow vibrato information for each subject across the pitch and loudness conditions. The baritone's range of airflow vibrato extent was 4.5 to 188.8 cm^3/s, with an average airflow vibrato extent of 53 cm^3/s, and an average rate of airflow vibrato of 4.93 Hz. The Tenor produced a range of airflow vibrato extent of 4.8 to 113.12 cm^3/s, an average airflow vibrato extent of 62.8 cm^3/s, and an average rate of airflow vibrato of 5.64 Hz. Soprano-1 had a range of airflow vibrato extent of 31.4 to 171.4 cm^3/s, an average airflow vibrato extent of 68.3 cm^3/s, and an average rate of airflow vibrato 5.3 Hz. Finally, Soprano-2 had a range of airflow vibrato extent of 21.6 to 146.7 cm^3/s, an average airflow vibrato extent of 66.3 cm^3/s, and an average rate of airflow vibrato of 5.6 Hz. Thus, across the four subjects and across the pitch-loudness conditions, the extent of the airflow vibrato could be quite narrow (near 5 cm^3/s) to quite wide (near 190 cm^3/s). The average airflow vibrato extent across the subjects, however, was confined to a relatively narrow range, between 53 and 68 cm^3/s, and the airflow vibrato rates, 4.9 to 5.6 Hz, were within acceptable rates reported for F0 vibrato rates.

A three-way ANOVA (gender, pitch, and loudness) was performed to compare the mean differences between the two genders, two pitches, and three loudness levels for the airflow vibrato extent. A summary of results is presented in Table 5. Main effect results revealed that airflow vibrato extent was significantly different between two pitches, $F(1, 97) = 98.86$, $p < 0.001$. Airflow vibrato extents were also significantly different when compared between the pitches, $F(1, 97) = 14.37$, $p < 0.001$. But it was not significantly different when compared among the three loudness levels, $F(2, 97) = 0.533$, $p = 0.59$. Figure 15 shows the mean airflow vibrato extent values for each of the singers for each of the three loudness levels (where the two lower pitches P1 and P2 have been collapsed). Figure 16 shows the mean airflow vibrato extents compared within each subject relative to pitch. This shows that for each of the singers, higher pitch had greater mean airflow vibrato extent values than for lower pitch. Figure 17 shows the comparison of mean airflow vibrato extent values between the male and female singers between the two pitches. A statistically significant difference in airflow vibrato extent was noticed within the subjects and between the subjects, when the pitch was increased. In addition, the female singers tended to have greater airflow vibrato extents than the male singers, especially during P2 conditions.

Table 4

Airflow vibrato information for the Baritone (B), Tenor (T), Soprano-1 (S1), and Soprano-2 (S2) subjects for three pitches (P1, P2, P3) and three loudness levels (L1, L2, L3).

Pitch and Loudness Level	Range of vibrato flow extent (cm^3/s)	Average vibrato flow extent (cm^3/s)	Average flow (cm^3/s)	(Range of flow extent)/(Average flow)	Average rate of airflow vibrato (Hz)
B-P1L1	14.3-23.0	17.1	245.4	0.05-0.09	4.35
B-P2L1	4.5-21.2	15.8	231.5	0.02-0.09	5
B-P3L1	9.2-34.8	18.1	185.2	0.05-0.19	4.8
B-P1L2	39.6-91.6	64	319.6	0.12-0.29	5.3
B-P2L2	30.5-75.8	57.6	237.9	0.13-0.32	4.8
B-P3L2	27.3-85.6	53	160.2	0.2-0.53	5.1
B-P1L3	66.5-188.8	112	330.2	0.2-0.6	4.9
B-P2L3	61.2-103.5	83	304.4	0.2-0.34	4.9
B-P3L3	35.2-78.5	53.2	92.4	0.38-0.85	5.2
T-P1L1	4.8-41.3	24.1	140.2	0.03-0.3	5.6
T-P2L1	13.4-66.3	45.2	168.7	0.08-0.4	6
T-P3L1	25.5-89.8	58	185.6	0.14-0.5	5.7
T-P1L2	60.9-113.1	91.2	109.8	0.85-1.03	5.83
T-P2L2	86.7-104.5	96.1	90.7	0.96-1.09	5.6
T-P2L3	Mask leak				5.1
T-P1L3	26.0-83.2	57.6	180	0.15-0.46	5.7
S1-P1L1	44.1-51.1	46	111.7	0.40-0.46	5.1
S1-P2L1	31.4-64.4	52	98	0.32-0.7	5.33
S1-P3L1	47.3-62.8	59.3	88.6	0.53-0.8	5.5
S1-P1L2	50.4-74.7	59.1	120.3	0.42-0.62	5
S1-P2L2	71.2-171.4	102	150.3	0.50-1.14	5.3
S1-P3L2	69.5-111.0	92	208.9	0.3-0.53	5.4
S1-P1L3	47.3-71	59.3	88	0.54-0.81	5.48
S1-P2L3	69.5-111	92	208.3	0.33-0.53	5.36
S2-P1L1	28.7-88.0	57	197	0.15-0.45	4.8
S2-P2L1	24.9-42.6	34	150.3	0.2-0.3	4.6
S2-P3L1	21.6-34.4	27.1	103.8	0.2-0.33	4.84
S2-P1L2	75.6-146.7	101.1	125.7	0.6-0.9	4.84
S2-P2L2	73.2-99.4	77.2	167.4	0.4-0.6	4.92
S2-P3L2	88.5-116.1	102	228.1	0.40-0.51	4.84
S2-P1L3	24-47.2	34.5	104	0.23-0.45	4.84
S2-P2L3	88.5-116.3	102	229	0.39-0.51	4.84

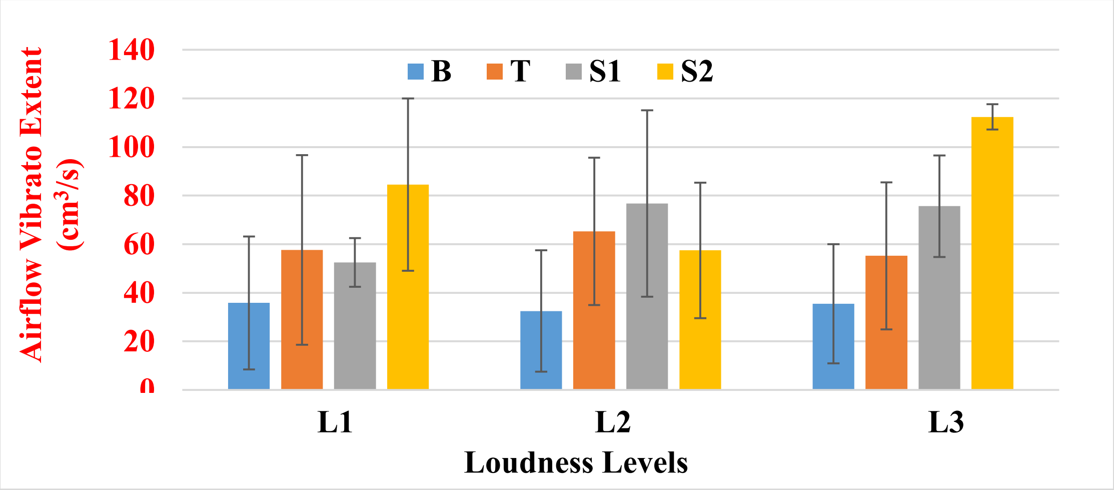

Figure 15. Mean and standard deviation values of airflow vibrato extent for each of the singers (B,T,S1,S2) for the three loudness levels (L1, L2, L3) collapsed across the two lower pitches (P1+ P2).

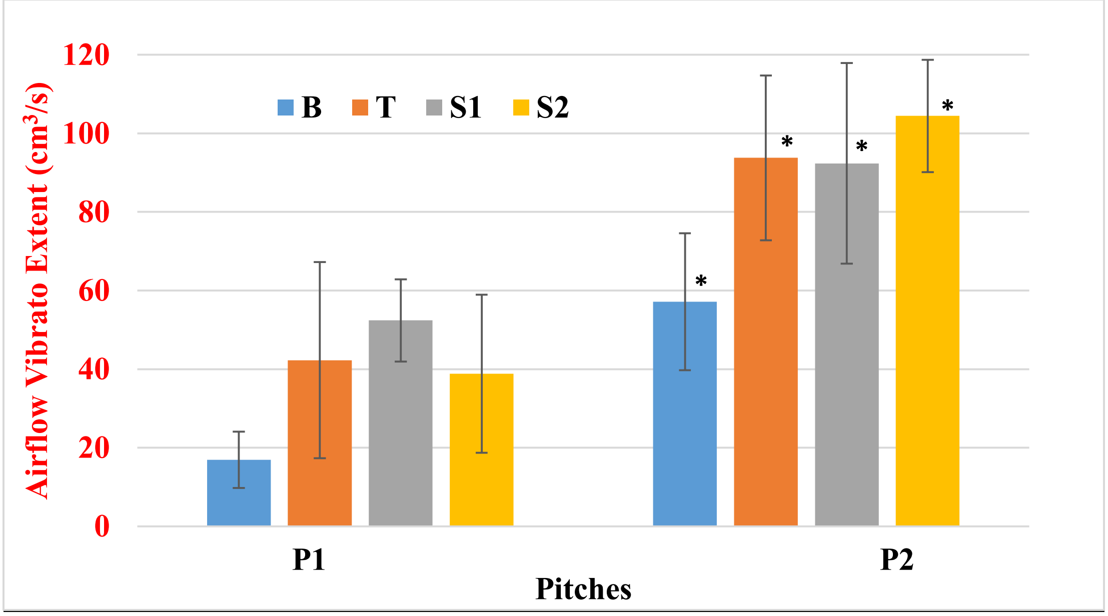

Figure 16. Mean values and standard deviations of airflow vibrato extent between the two lower pitches for each of the singers (B,T,S1,S2) collapsed across the three loudness levels (L1+L2+L3). All comparisons were statistically significantly different.

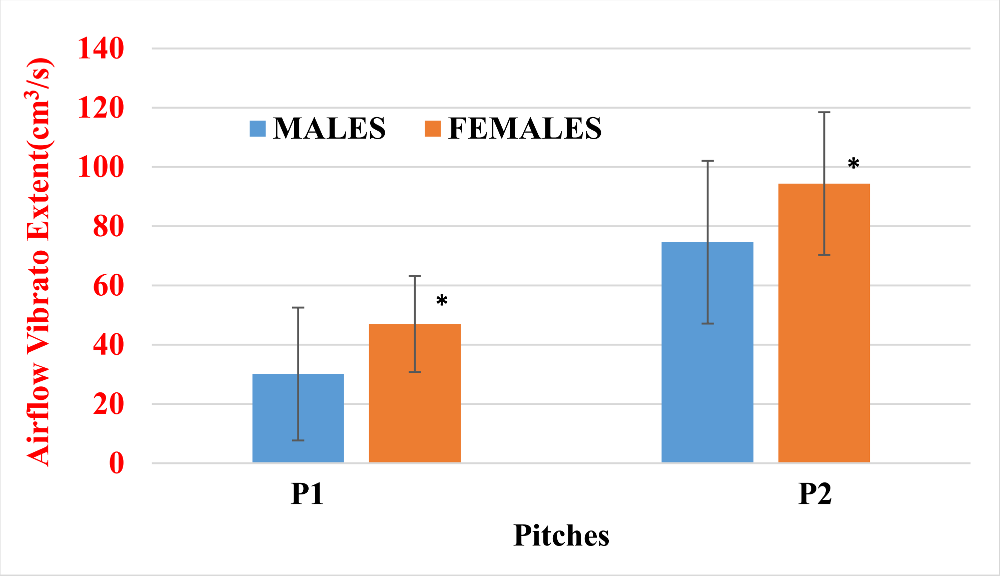

Figure 17. Comparison of mean values of <u>airflow vibrato extent</u> between the male (B+T) and the female (S1+S2) singers for the two lower pitches (P1, P2) collapsed across the three loudness levels (L1+L2+L3).

Table 5

Three-way ANOVA Summary Table for airflow vibrato extent

Source	Sum of Squares (*SS*)	*df*	Mean Squares (*MS*)	*F*	*p*
Pitch	53389	1	53389	98.861	**0.000**[*]
Loudness	576	2	288	0.533	0.5885
Gender	7758	1	7758	14.366	**0.0002**[*]
Pitch x Loudness	633	2	317	0.586	0.5582
Loudness x Gender	431	2	216	0.399	0.6718
Pitch x Gender	6	1	6	0.010	0.9193
Residuals	52384	97	540	-	-

Extents of F0 vibrato. Table 6 gives information on F0 vibrato for all subjects in all conditions. The table shows that the Baritone had an average F0 vibrato extent of 1.56 ST, and his average rate was 4.9 Hz. The Tenor had an average F0 vibrato extent of 1.4 ST and an average F0 vibrato rate of 5.7 Hz. Soprano-1 produced an average F0 vibrato extent of 2.2 ST, and her average rate was 5.7 Hz. Soprano-2 had an average F0 vibrato extent of 2.3 ST, and an average rate of 5.33 Hz. These general results indicate that the men had less F0 vibrato extent than the women, and the Baritone had the slowest rate.

A three-way ANOVA was performed to compare the mean differences among gender, the two pitches, and the three loudness levels. A summary of results is presented in Table 7. Main effect results revealed that F0 vibrato extent was significantly different between the two pitches, $F(1, 106) = 76.83$, $p < 0.001$. F0 vibrato extent was also significantly different between gender, $F(1, 106) = 112.89$, $p < 0.001$. But the measure was not significantly different when compared among the loudness levels, $F(2, 106) = 0.846$, $p = 0.432$. These results for each individual again suggest an essential lack of influence of subglottal pressure (alone) to govern vibrato flow extent across the three loudness levels for each singer. Figure 18 shows the mean F0 vibrato extent in semitones (STs) for each of the three loudness levels**.** Figure 19 shows the mean F0 vibrato extent in STs of two pitches for each singer.

Table 6

F0 vibrato information for the Baritone (B), Tenor (T), Soprano-1 (S1), and Soprano-2 (S2) subjects for three pitches (P1, P2, P3) and loudness (L1, L2, L3).

Pitch and Loudness Level	Range of extent (Hz)	Range of extent (ST)	Average extent (ST)	Rate (Hz)	Average rate (Hz)
B-P1L1	6.17-9.55	0.99-1.53	1.22	4.0-5.0	4.51
B-P2L1	6.03-9.44	0.97-1.52	1.32	4.55-5.0	4.80
B-P3L1	8.2-11.1	1.31-1.75	1.62	4.55-5.0	4.80
B-P1L2	10.1-25.3	0.84-2.1	1.50	4.55-5.26	5.0
B-P2L2	19.0-24.6	1.6-2.01	1.73	4.76-5.0	4.80
B-P3L2	17.1-26.5	1.43-2.21	1.80	4.35-5.0	4.80
B-P1L3	8.2-31.9	0.4-1.6	1.22	4.8-5.26	5.10
B-P2L3	27.6-34.0	1.4-1.73	1.61	4.54-5.26	5.0
B-P3L3	35.5-47.0	1.77-2.35	2.03	4.76-5.26	5.0
T-P1L1	9.9-14.6	1.2-1.77	1.60	5.26-5.88	5.63
T-P2L1	5.5-16.9	0.66-2.02	1.64	5.26-7.14	6.02
T-P3L1	8.91-17.9	1.05-2.15	1.70	5.55-6.66	6.10
T-P1L2	15.4-30.3	0.92-1.81	1.51	5.56-5.88	5.80
T-P2L2	23.9-36.7	1.43-2.22	1.90	5.56-5.88	5.72
T-P3L2	18.5-35.6	1.11-2.14	1.72	5.56-5.88	5.70
T-P1L3	9.3-20.1	0.42-0.92	0.60	5.0-6.25	5.70
T-P2L3	12.6-13.9	0.57-0.67	0.63	5.0-5.88	5.43
T-P3L3	11.5-17.5	0.52-0.74	0.70	5.0-5.56	5.22
S1-P1L1	25.23-31.9	1.84-2.20	2.0	5.0-7.14	5.70
S1-P2L1	22.7-33.6	1.54-2.33	1.94	5.26-5.88	5.51
S1-P3L1	20.1-31.2	1.35-2.15	1.80	5.26-6.7	5.70
S1-P1L2	35.3-52.9	1.4-2.12	1.90	4.76-5.6	5.12
S1-P2L2	50.1-57.6	2.0-2.28	2.20	5.0-5.6	5.22
S1-P3L2	41.2-65.9	1.61-2.63	2.30	5.0-5.6	5.40
S1-P1L3	74.3-127.6	1.64-2.83	2.40	5.0-5.6	5.22
S1-P2L3	90.2-122.6	1.97-2.73	2.51	4.8-5.6	5.10
S1P3L3	91.6-114.9	2.07-2.54	2.40	5.0-5.88	5.30
S2-P1L1	21.12-29.9	1.43-2.02	1.80	4.35-5.6	4.94
S2-P2L1	24.9-42.6	1.74-2.31	2.0	4.76-5.88	5.23
S2-P3L1	21.7-34.4	1.55-2.2	1.90	5.0-5.88	5.50
S2-P1L2	75.6-146.7	1.83-2.92	2.41	5.0-5.6	5.23
S2-P2L2	73.2-99.6	1.9-2.92	2.40	4.76-5.88	5.13
S2-P3L2	88.5-116.1	1.72-2.72	2.30	4.76-5.88	5.1
S2-P1L3	115.0-166.3	2.79-3.8	3.30	5.26-5.88	5.70
S2-P2L3	130.7-155.2	2.5-2.74	2.72	5.26-5.88	5.50
S2P3L3	37.4-52.1	1.64-2.3	2.0	5.6-5.88	5.62

Table 7

Three-way ANOVA Summary Table for F0 vibrato extent

Source	**Sum of Squares (*SS*)**	***df***	**Mean Squares (*MS*)**	***F***	***p***
Pitch	5218	1	5218	76.826	**0.0000***
Loudness	115	2	57	0.846	0.432
Gender	7667	1	7667	112.885	**0.0000***
Pitch x Loudness	84	2	42	0.619	0.54
Loudness x Gender	0	2	0	0.003	0.997
Pitch x Gender	1	1	1	0.012	0.912
Residuals	7199	106	68	-	-

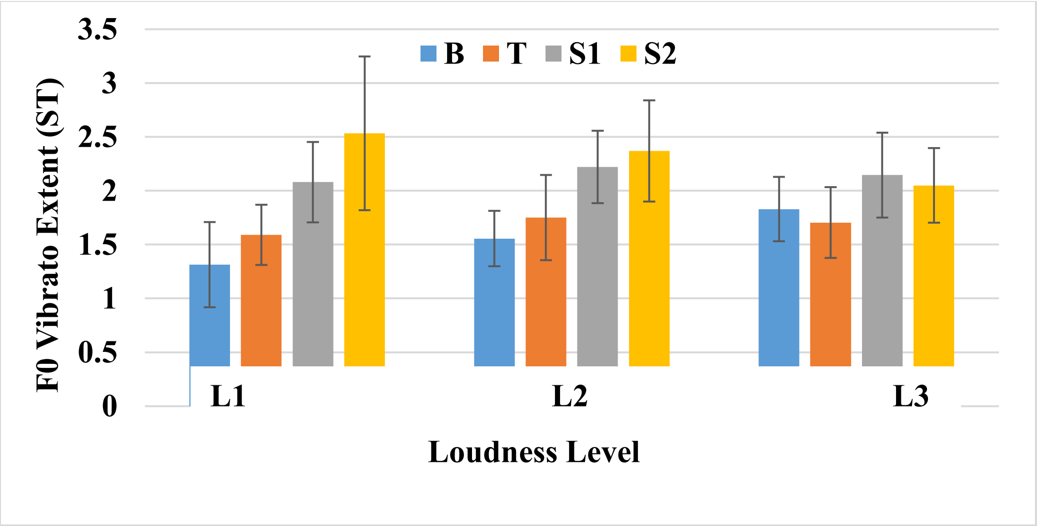

Figure 18. Mean values of F0 vibrato extent for each singer (B,T,S1,S2) for the three loudness levels (L1, L2, L3) collapsed across the three pitches (P1+P2+P3).

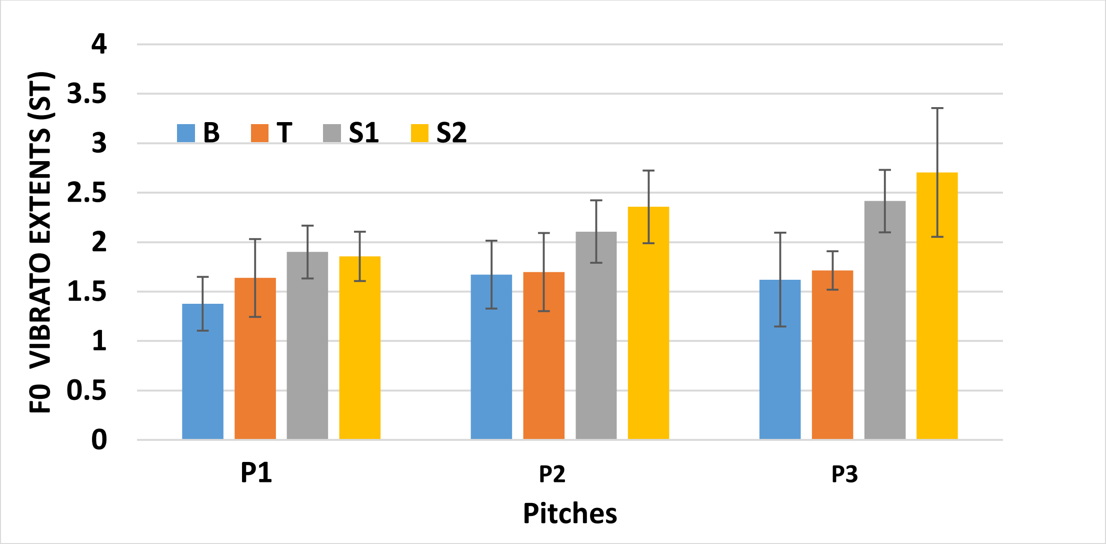

Figure 19. Mean values of F0 vibrato extent for each singer (B,T,S1,S2) for the three pitches (P1, P2, P3) collapsed across the three loudness levels (L1+L2+L3).

Relation between intensity and airflow in vibrato. To determine how airflow vibrato compared to intensity variation of the audio signal (captured while the mask was on the face), the intensity was also obtained every 10 ms using Praat software. It is noted that the dB values to be reported here are relative only within an utterance and do not correspond to SPL *per se*.

Figure 20 provides an example of airflow vibrato compared to both intensity of the audio signal (Fig. 20a) and F0 (Fig. 20b) for Soprano-1 singing pitch P2 with loudness L2. The figure indicates that the intensity vibrato waveform is more complex than the airflow vibrato waveform and F0 vibrato waveform in this case, and leads the flow, whereas the F0 lags the flow (by about 115 degrees). The flow and intensity were approximately completely out of phase for the last few cycles seen in Figure 20. The intensity range was approximately 3.5 dB for this utterance.

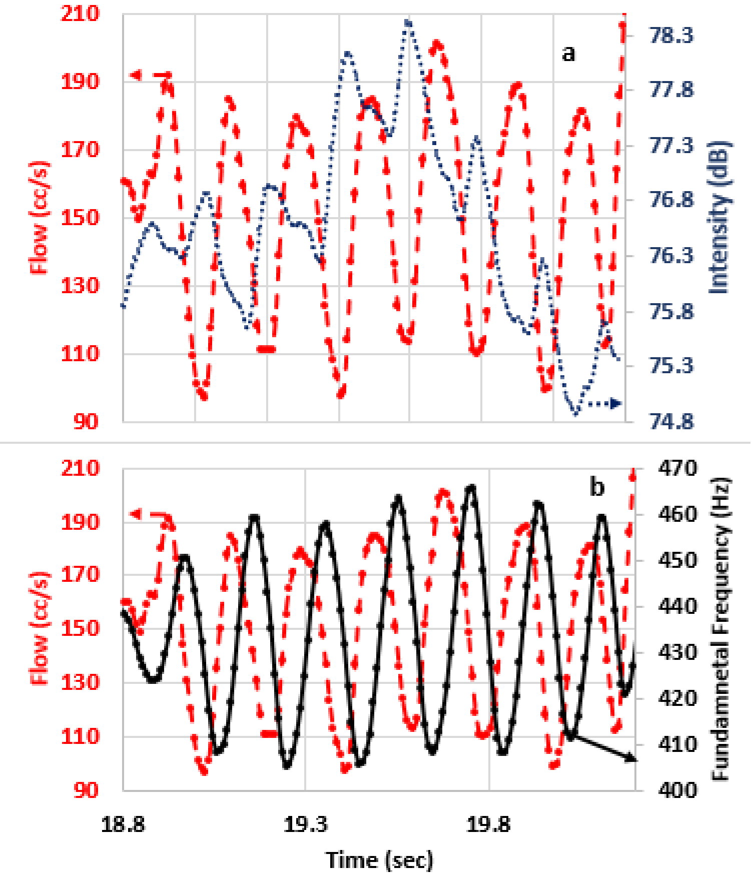

Figure 20. Airflow vibrato compared with intensity variation (a) and F0 (b) for Soprano-1 singing at her middle pitch (P2) and loudness (L2).

Figure 21 is another example of a comparison of airflow vibrato with intensity variation (Fig. 21a) and F0 vibrato (Fig. 21b), this time for the Tenor singing pitch P1 with loudness L3. F0 vibrato appears with a quasi-sinusoidal waveshape, whereas both the airflow vibrato and intensity vibrato variation are more complex, with airflow leading F0 by about 75 degrees. Intensity appears to lag the flow and be nearly in phase with F0 for the first part of the utterance shown, but then out of phase for the last vibrato cycle. Intensity varied by approximately 2.5 dB.

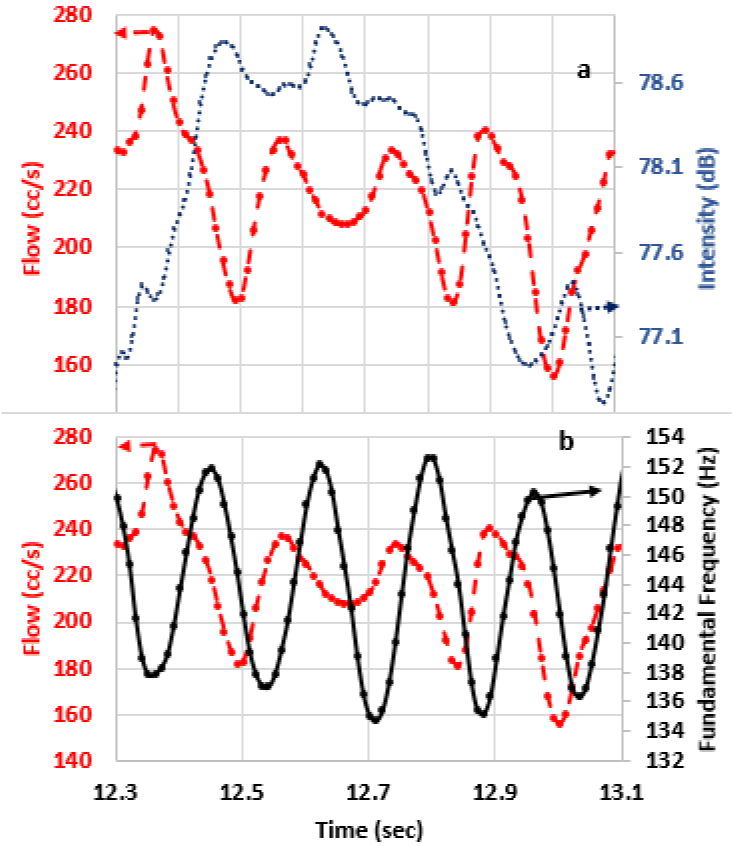

Figure 21. Airflow vibrato compared with intensity variation (a) and F0 (b) for the Tenor singing at his lowest pitch (P1) and loudest level (L3).

For a third example, shown in Figure 22, the Baritone sang his first pitch P1 with loudness L3. Airflow vibrato was irregular, and intensity demonstrated double peaks to flow and F0 vibrato single peaks (suggesting that a lower harmonic of the F0 vibrato was passing above and then below the first formant during one vibrato cycle, although the dB range of change was only about 1.2 dB).

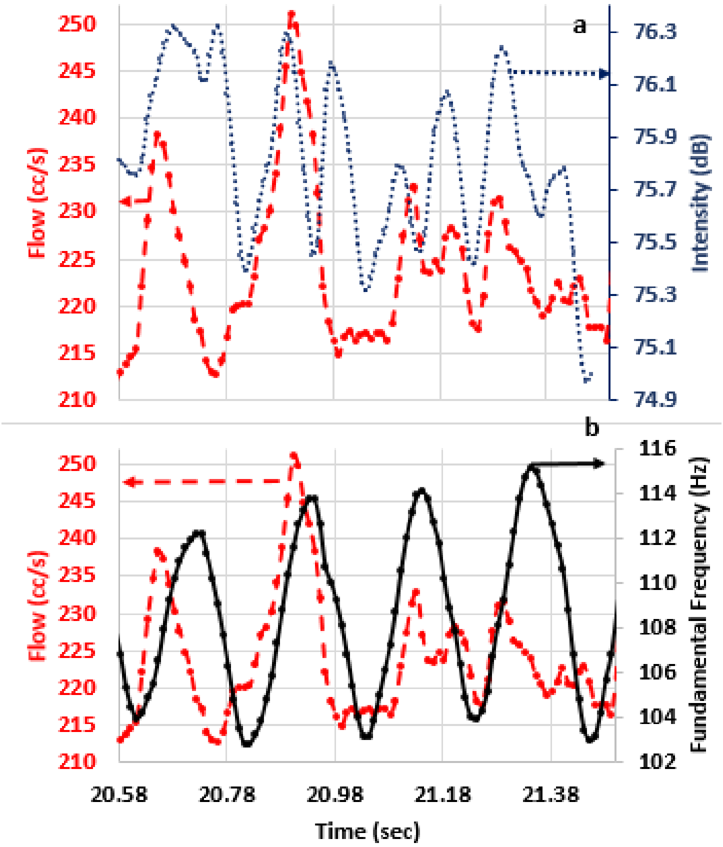

Figure 22. Airflow vibrato compared with intensity variation (a) and F0 (b) for the Baritone singing at his lowest pitch (P1) and loudest level (L3).

The final example of the relationship among airflow vibrato, intensity variation, and F0 vibrato is shown in Figure 23. Here the Baritone sang his first pitch P1 with loudness L1. F0 vibrato is somewhat irregular, and both airflow vibrato and intensity variation are quite irregular, with a relatively large range of intensity (*c.* 5 dB from the beginning of the utterance and *c.* 2 dB during most of it, Fig. 23a). The variation of flow does not appear to have a discernable relation with intensity variation. The airflow vibrato appears to have a varying relation with F0 vibrato – gross variation related to each F0 vibrato cycle, and minor triplet variations within each F0 cycle. Average oral pressure and intensity values were reported in Table 8 and Table 9, respectively, for all nine conditions. The intensity vibrato extents were measured in a similar method used for F0 and airflow vibrato extents, and are reported in Table 10.

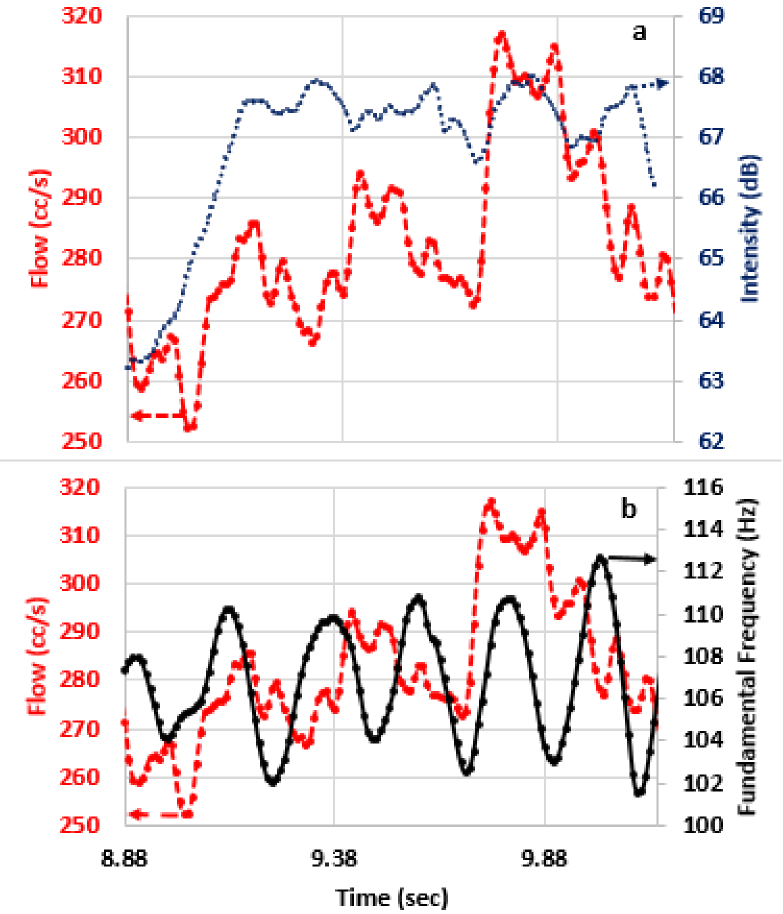

Figure 23. Airflow vibrato compared with intensity variation (a) and F0 (b) for the Baritone singing at his lowest pitch (P1) and lowest loudness level (L1).

Table 8

Average oral pressure values (cm of H_2O) of all four subjects for the Baritone (B), Tenor (T), Soprano-1 (S1), and Soprano-2 (S2) subjects for three pitches (P1, P2, P3) and three loudness levels (L1, L2, L3).

Subjects	P1L1	P1L2	P1L3	P2L1	P2L2	P2L3	P3L1	P3L2	P3L3
Soprano-1	4.9932	7.2575	9.3218	7.6697	10.7866	12.7303	13.7446	18.6249	25.5823
Soprano-2	6.8223	10.5878	11.4532	12.308	15.5498	19.0706	22.0157	29.7445	36.4544
Baritone	5.0143	6.7694	10.772	13.452	15.479	20.554	19.0927	26.3691	29.4469
Tenor	4.9619	6.4619	11.6036	11.341	18.0317	23.9001	20.241	21.0411	28.8692

Table 9

Average intensity values (dB) of all four subjects for the Baritone (B), Tenor (T), Soprano-1 (S1), and Soprano-2 (S2) subjects for three pitches (P1, P2, P3) and three loudness levels (L1, L2, L3).

Subjects	P1L1	P1L2	P1L3	P2L1	P2L2	P2L3	P3L1	P3L2	P3L3
Soprano-1	66.86	74.58	78.21	71.61	76.89	80.9	71.35	78.9	83.29
Soprano-2	68	73.47	78.26	73.74	77.28	80.43	72.21	75.32	78.86
Baritone	67.52	72.44	77.22	73.85	76.55	79.21	76.27	79.8	80.48
Tenor	64.18	72.25	76.27	67.31	75.96	79.37	70.52	76.51	79.76

Table 10

Intensity vibrato extents (dB) of all four subjects for the Baritone (B), Tenor (T), Soprano-1 (S1), and Soprano-2 (S2) subjects for three pitches (P1, P2, P3) and three loudness levels (L1, L2, L3).

Conditions	Soprano-1 M (SD)	Soprano-2 M (SD)	Baritone M (SD)	Tenor M (SD)
P1L1	2.38 (0.27)	3.25 (0.85)	1.55 (0.4)	1.47 (0.21)
P1L2	1.7 (0.52)	3.25 (0.07)	1.1 (0.3)	0.9 (0.1)
P1L3	2.37 (0.32)	2.34 (0.81)	1.37 (0.12)	0.7 (0.35)
P2L1	1.59 (0.47)	3.78 (1.47)	0.9 (0.14)	1.53 (0.28)
P2L2	1.5 (0.61)	1.48 (0.04)	1.1 (0.3)	1.69 (0.64)
P2L3	0.93 (0.15)	1.91 (0.44)	1.18 (0.24)	1.67 (0.27)

EGG width measurement and airflow vibrato. Airflow vibrato may reasonably be caused by changes in adduction, less adducted for higher flows within the vibrato cycle, and greater adduction for lower flows within the cycle. To attempt to test this hypothesis, EGGW was measured at the peaks and valleys of the airflow vibrato. It is noted that the EGG waveform is related to membranous vocal fold contact rather than posterior glottal activity (Hampala et al., 2015; Henrich et al., 2003; Scherer et al., 1988).

Two to three consecutive glottal cycles of the EGG waveform were analyzed at all primary peaks and valleys of the airflow vibrato waveforms under all conditions for the Soprano-1 and the Tenor. EGG signals from Soprano-2 and Baritone were not possible to obtain. In Soprano-2, poor EGG signals were seen due to relatively thick tissue in the neck region, and the Baritone was not comfortable wearing the EGG device. T-tests for EGGW values between peaks and valleys indicated` no significant differences. Figure 24 provides two examples, one for Soprano-1 (Fig. 24a) and one for the Tenor (Fig. 24b). In Fig. 24a, the EGGW values corresponding to the peak of the airflow vibrato are shown to be 0.30 and 0.32, and the valley values of EGGW are 0.31 and 0.33, indicating that there is no difference in EGGW between the two extremes. Similar non-differences are shown in Fig. 24b. Therefore, airflow vibrato appears to be independent of EGGW measures, and suggests that EGGW is insensitive to these flow variations, or airflow vibrato is not due to anterior glottis adductory changes.

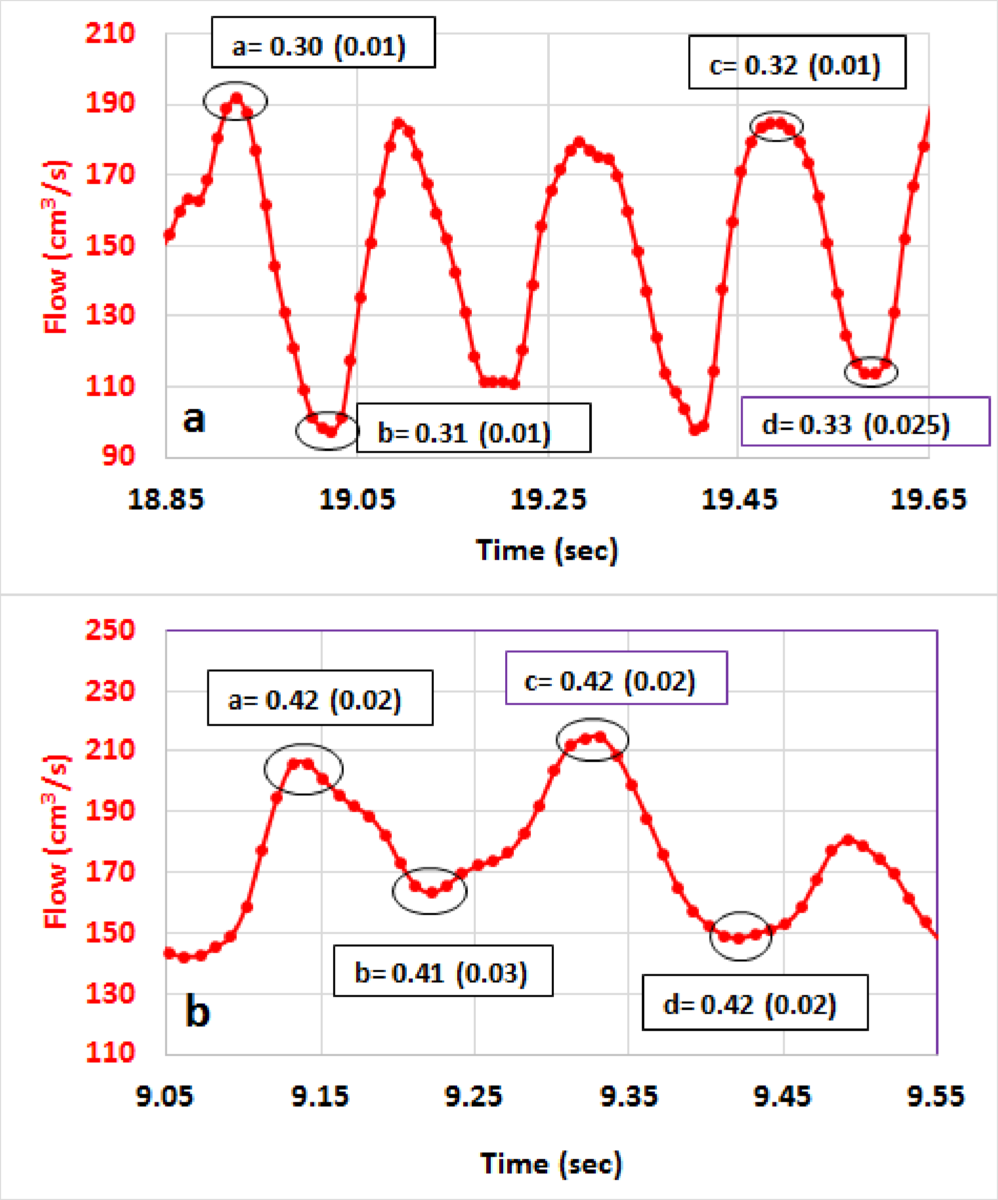

Figure 24. EGGW means and standard deviations at peaks and valleys of airflow vibrato for (a) the Soprano-1 singing her middle pitch (P2) and middle loudness (L2), and (b) the Tenor singing his lowest pitch (P1) and middle loudness (L2). Within the figures, ‘a’ and ‘c’ indicates the EGGW values at the airflow vibrato peaks, and ‘b’ and ‘d’ indicates the EGGW values at the airflow vibrato valleys.

Normalized rate quotient (NRQ) and airflow vibrato. The meaning of the NRQ measure is that, because it is the normalized EGG left-side rise slope divided by the normalized right-side fall slope (between the 25% and 75% height locations of each EGG waveform), the larger the negative value of the NRQ measure, the faster the contact between the two vocal folds compared to the separation of the two vocal folds. Does this differ between the max and min of the airflow vibrato cycles? If so, it would indicate a mechanical and physiological differentiation between the two regions.

NRQ values for two peaks and values from all nine conditions of pitch and loudness for Soprano-1 and the Tenor were obtained and averaged. Figure 25 shows the results. With a few exceptions, the airflow vibrato maxima (peaks) and minima (valleys) had similar NRQ values for each of the two singers. In general, there were higher NRQ (less negative) values for Soprano-1 than for the Tenor, and the pattern of change across conditions was similar for both singers. The lower pitch P1 had the greatest negative NRQ values, suggesting that the increase in vocal fold contact area during closure was relatively faster than the decrease in vocal fold contact area later during vocal fold separation during contact, compared to the other two pitches used. The largest negative value was approximately -9, indicating 9 times faster increase than decrease in contact area. In comparison, for the highest pitch P3, Soprano-1 had NRQ values close to -1, indicating approximately the same rate of increase and decrease on either side of the EGG waveform (suggesting a relatively sinusoidal waveform).

Except for one condition (number 2 on the x-axis), the Tenor had values of NRQ that were more negative than Soprano-1, which might be reasonable given the expected larger size of the larynx in the Tenor. For the middle pitch, the NRQ values for the airflow vibrato peaks were greater for both the Soprano-1 and the Tenor (conditions 4 and 5 in Fig. 25). Curiously, the minimum values of NRQ for P1L2 for the Tenor had higher NRQ values than for the peak values. The NRQ values were lowest (most negative) for P1 and highest (least negative) for P3, with values for P2 near P3. In general, NRQ depended on pitch but not on loudness. Wilcoxin-sign tests were performed to compare the values at the peaks and valleys for Soprano-1 and the Tenor, and results were not statistically significantly different. Thus, the NRQ values did not differentiate between the peaks and valleys of the airflow vibrato waveform, nor did the EGGW (adduction) measure, suggesting that the EGG waveform may not be sensitive to the peaks and valleys of the airflow vibrato, but somewhat sensitive in general to pitch (greater slope ratio for lower pitches).

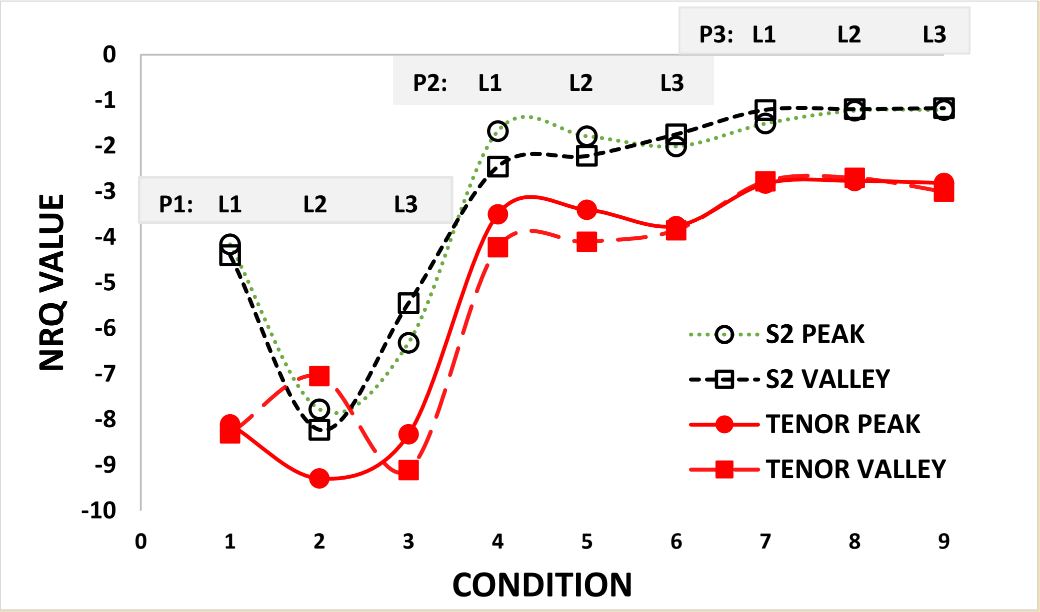

Figure 25. NRQ values for Soprano-2 and the Tenor for all 9 conditions of pitch and loudness.

Study 2: Sources of Airflow Vibrato

Raw data of airflow, F0, and intensity modulations. The airflow, F0, and intensity vibrato and modulations in Study 2 were analyzed using the same methods as in Study 1. A few examples of F0 and airflow modulations during bleat and external epigastric pumping are given next. Figures 26-29 represent the modulations due to bleat (adductory change maneuver). The phase differences among airflow, F0, and intensity vary over a wide range. Airflow leading both F0 and intensity was predominantly seen in almost all of the conditions and can be seen in Figures 26-29. Figures 27a and 27c show an example of F0 with airflow and intensity respectively in anti-phase while subject M1 was using a light bleat at high pitch in a singing task. Figure 27b shows less or negligible phase difference between airflow and intensity. But when the same subject was producing bleat while whispering the vowel /a/, as seen in Figure 28, there was a phase difference between airflow and intensity ranging from 70-13 degrees, where airflow leads intensity. There was also a variety of waveform shapes observed for F0 and airflow. Figure 29 shows a highly irregular F0 modulation with regular and consistent airflow changes during bleat while subject F1 was producing lighter bleat at high pitch in the singing task.

Figures 30 (a,b,c)–31 represent airflow, F0, and intensity modulations due to external epigastric pumping (EEP). In Figure 30, subject F1 was phonating the vowel /a/ during EEP. The phase differences among F0, airflow, and intensity were 0 degrees to low values (up to 60-70 degrees, predominantly airflow leading). The synchronization here is due to subglottal pressure variations because of the nature of the stimuli (pushing on the epigastric region). Similarly, during whisper tasks of EEP, there were large synchronous variations in airflow and intensity, as seen in Figure 31. These results suggest that when the three waveforms (airflow, F0, and intensity) are nearly in phase with each other (approximately 0 to 50 degrees, airflow leading), Ps may be a primary causative factor (Scherer et al., 1988a).

In general, then, as shown earlier, bleat and vibrato have similar results in terms of phase differences, with airflow leading and having a wide range of phase differences across the two pitches and three loudness levels, whereas for the external epigastric pumping, the three signals are nearly in phase with each other.

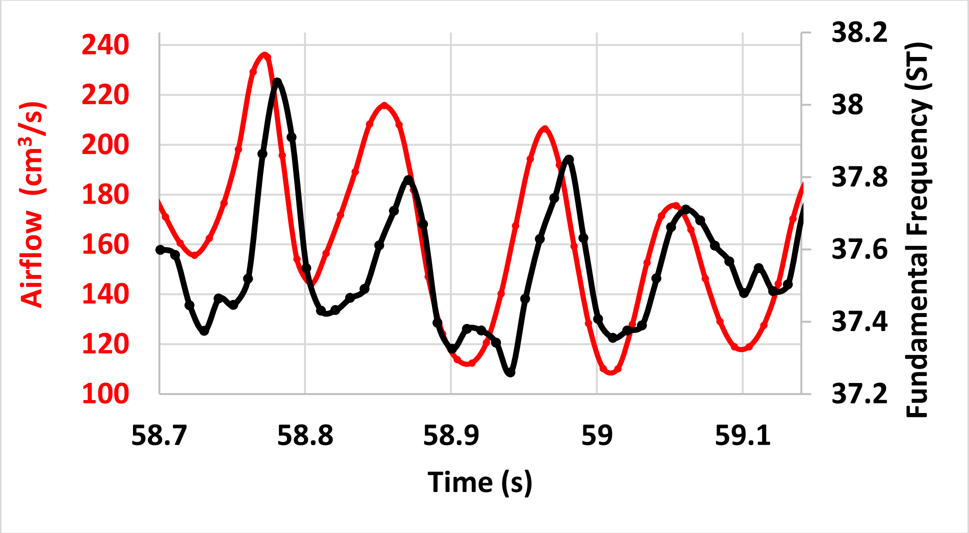

Figure 26. Airflow and F0 modulations while subject F2 was producing heavy bleat during the speaking phonation task. Here, airflow leads F0 in all four cycles, and the phase difference ranged from 27–55 degrees.

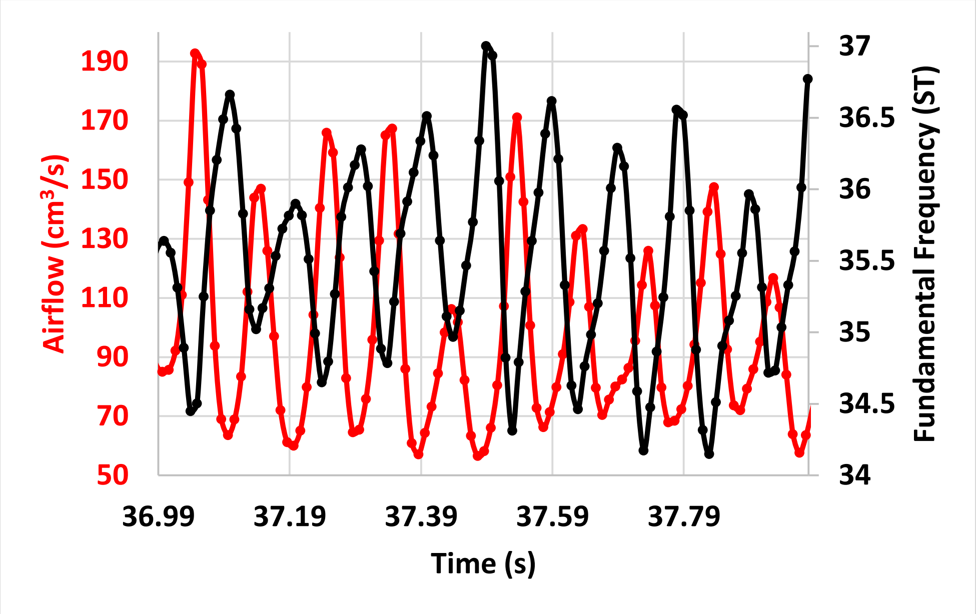

Figure 27a. Airflow and F0 modulations while subject M1 was producing lighter bleat at high pitch during the singing task. Here, the airflow leads F0 in all the cycles, and they are almost anti-phasic. The phase difference ranged from 118 – 190 degrees.

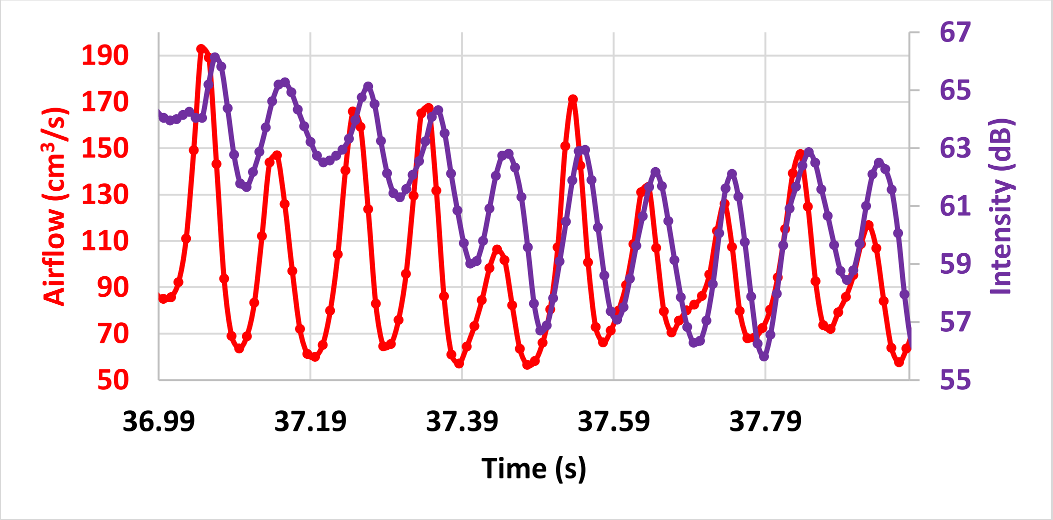

Figure 27b. Airflow and intensity modulations during bleat for the same condition given above Fig. 27a. Here, the airflow leads intensity in all cycles, and the phase difference between them ranged from 22–87.3 degrees.

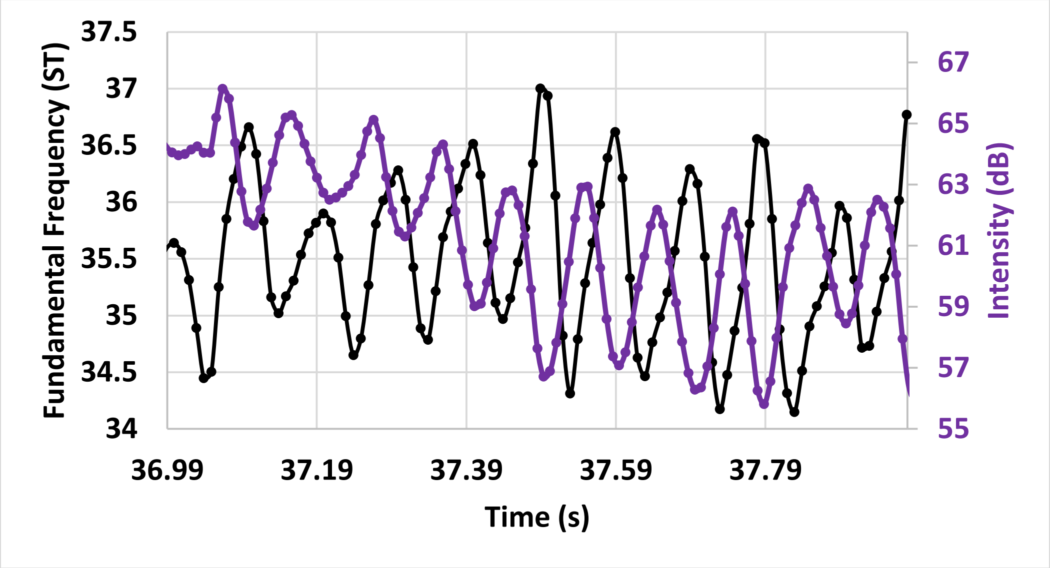

Figure 27c. F0 and intensity modulations during bleat for the same condition given in the figures 27a and 27b. Here, the intensity leads F0 in all cycles, and the phase difference between them ranged from 100–153 degrees.

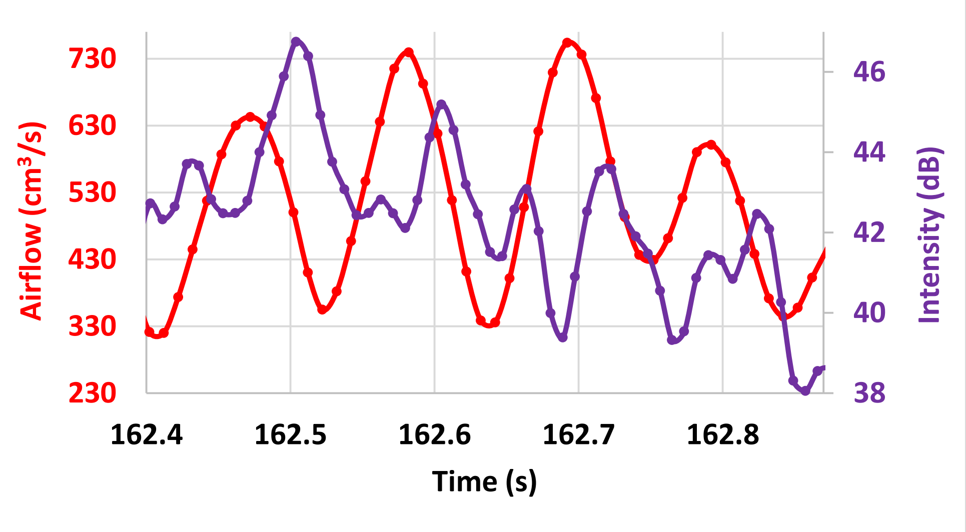

Figure 28. Airflow and intensity modulations while subject M2 producing lighter bleat during the speaking whisper task. Here, the airflow leads intensity (the secondary peaks are included in the intensity modulation cycles for the measurements). The phase difference ranged from 70–113 degrees.

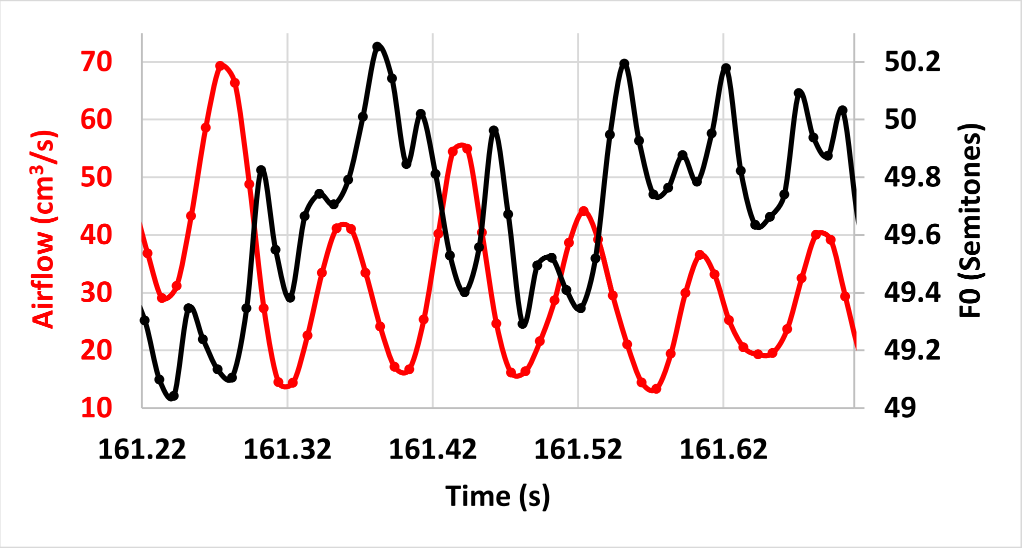

Figure 29. Example of the most irregular F0 modulations during bleat, and regular semi-sinusoidal undulations in the airflow, while subject F1 was producing lighter bleat at high pitch. Airflow leads F0 in all the cycles (considering prominent F0 peaks). The phase difference ranged from 72.4–145 degrees.

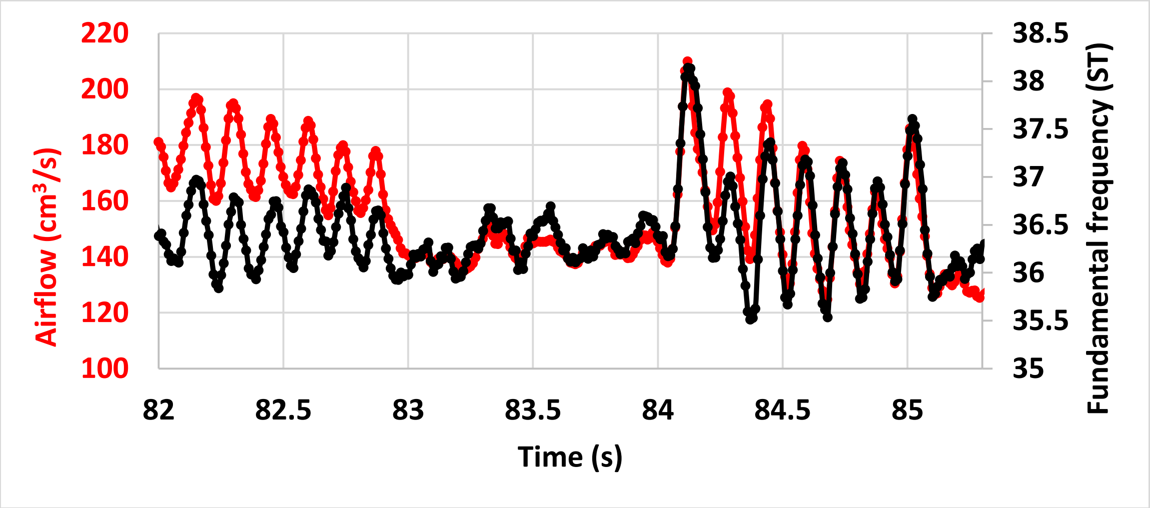

Figure 30a. Airflow and F0 modulations during external epigastric pumping while subject F1 was phonating the vowel. Airflow leads F0 for most of the cycles. The section from 82–83 seconds was during shallow pumping, with the phase difference ranging from 0–30 degrees, and section 84–85.14 seconds was during deep pumping, with the phase difference ranging from 2 to 54 degrees.

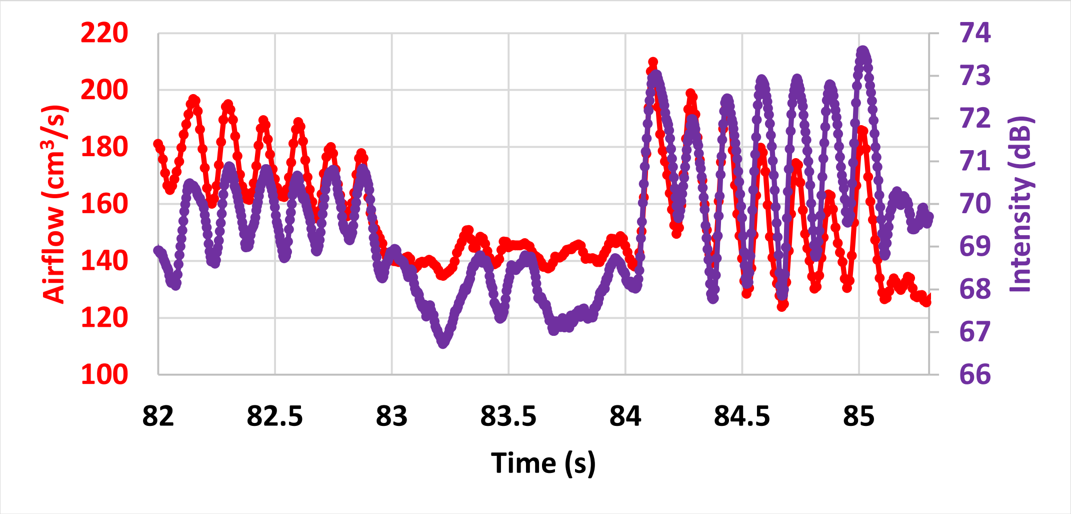

Figure 30b. Airflow and intensity modulations during external epigastric pumping for the same condition given in Figure 30a. For shallow pumping, the phase difference ranged from 0–28 degrees. For deep pumping, the phase difference was 0 degree, i.e., in-phase.

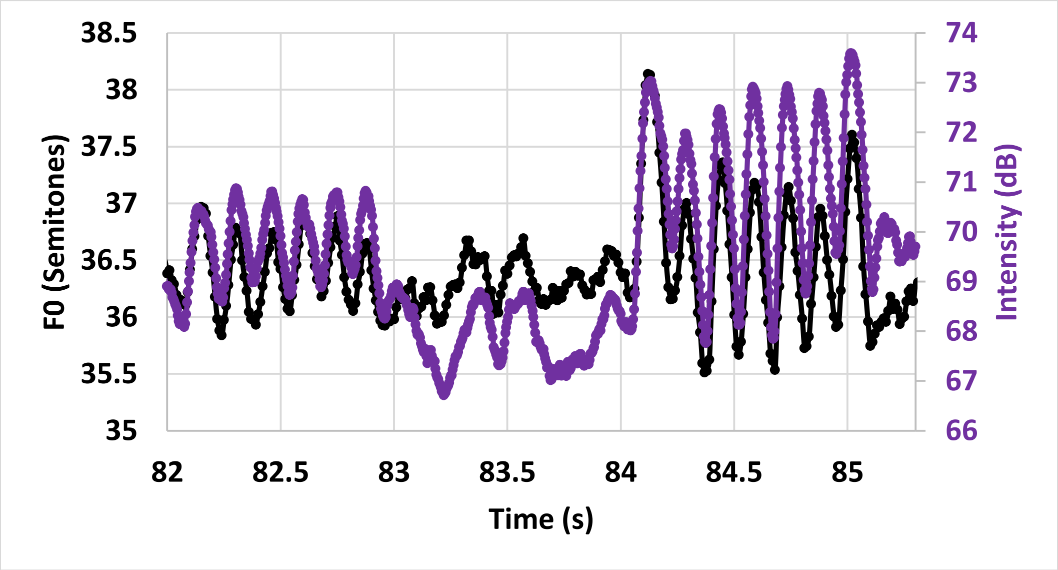

Figure 30c. F0 and intensity modulations during external epigastric pumping for the same condition given in above. For shallow pumping, the phase difference ranged from 0–28 degrees, where intensity was leading if not in-phase. For deep pumping, the phase difference was 0 degree, i.e., in-phase.

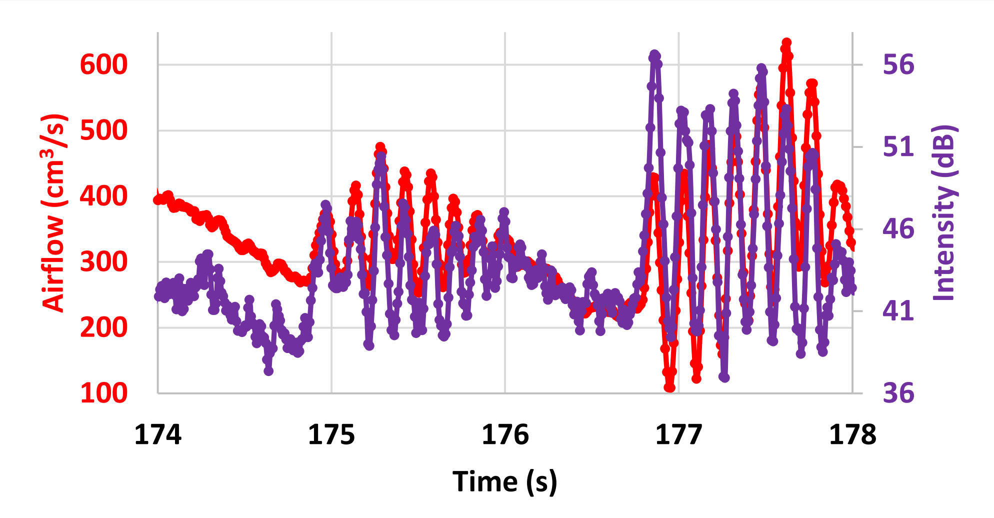

Figure 31. Airflow and intensity modulations during external epigastric pumping while subject M2 was sustaining whisper on the vowel /a/. The phase difference between them was 0 degree, i.e., in-phase. The section from 175–176 seconds was during shallow pumping, and the section from 176.7–177.8 seconds was during deep pumping.

Airflow and F0 modulation rates. The airflow bleat rates and airflow external epigastric pumping rates during speaking and singing, and airflow vibrato rates during singing, were compared, and the values are reported in Tables 11, 12, and 13 for the four singers. It is noted that the epigastric pumping rate was determined by the experimenter applying the pumping, and was not determined by the subject who received the epigastric pumping. Figure 32 shows the mean airflow modulation rates of bleat (B), external epigastric pumping (E), and vibrato (V) during singing (sing), speaking phonation (Sp-P), and speaking whisper (Sp-W). The statistical model used for these results was repeated measures 2-crossed and 3-staged nested ANOVA (fixed variables). ANOVA results for airflow modulation rates of bleat (adductory change maneuver: speaking and singing), external epigastric pumping (Ps change maneuver: speaking and singing), and vibrato (singing) are given in Table 14. The full model explains 85% of the variation in airflow modulation rate (R^2=0.85). Table 14 shows a statistically significant main effect on tasks (speaking phonation, speaking whisper, and singing), $F(2, 121)=14.2$, $p < 0.001$, partial $\eta^2=0.23$; sub-tasks (bleat-phonation and whisper, epigastric pumping-phonation and whisper, and vibrato), $F(4, 121)=251.56$, $p < 0.001$, partial $\eta^2=0.91$; and levels of sub-tasks, $F(13, 121)=2.92$, $p < 0.001$, partial $\eta^2=0.09$. Interaction between the factors was not significant, $F(13, 121)=1.13$, $p=0.34$, partial $\eta^2=0.09$. Further, Tukey's honest significance test was used for ANOVA post-hoc analysis for pairwise comparisons. Table 15 has the results of paired post-hoc comparisons of airflow modulation rates for different sub-tasks. Table 16 shows the results (*p*-values) of paired post-hoc comparisons for airflow modulation rates. Table 16 indicates that airflow bleat rates for the female subjects were statistically significantly higher [Least Squared Mean (LSM)=10.69, $p < 0.001$] than airflow external epigastric pumping rates and airflow vibrato rates for both male and female subjects. There was no statistically significant difference in airflow bleat rates between males and females. Although airflow external epigastric pumping (singing) rates of males were statistically significantly higher than airflow vibrato rates of males and females [LSM=7.01, $p < 0.001$], the airflow external epigastric pumping rates were not as fast as airflow bleat rates. Further, the levels of sub-tasks (independent variables- pitches, loudness levels, type of bleat, and type of external epigastric pumping) did not affect the airflow modulation rates significantly. In general, the airflow external epigastric pumping (singing and speaking) rates were seen to be similar or closer to airflow vibrato rates.

Table 11

Airflow bleat rate mean values (Hz) and standard deviations for speaking (phonation), speaking (whisper), and singing tasks for four singers (F1, F2, M1, and M2)

Bleat (Singing) CONDITIONS	**Singing**		**Bleat (Speaking)**	**Speaking**	
	MEAN (Hz)	**SD**		**MEAN (Hz)**	**SD**
BLL- F1	10.39	1.01	**BPL-F1**	9.81	1.4
BLL-F2	9.43	1.55	**BPL-F2**	11.94	0.25
BLL-M1	10.4	0.33	**BPL-M1**	9.57	0.75
BLL-M2	11.07	0.51	**BPL-M2**	9.56	2.2
BLH- F1	11.37	0.37	**BPH-F1**	10.54	2.61
BLH-F2	10.31	0.71	**BPH-F2**	10.68	0.05
BLH-M1	10.03	0.55	**BPH-M1**	10.61	0.56
BLH-M2	10.26	0	**BPH-M2**	9.62	0.54
BHL- F1	12.05	0.21	**BWL-F1**	10.17	3.42
BHL-F2	10.32	0.45	**BWL-F2**	10.82	0.41
BHL-M1	10.1	0.14	**BWL-M1**	9.27	0.57
BHL-M2	11	0.71	**BWL-M2**	9.97	1.62
BHH- F1	10.59	1.18	**BWH-F1**	6.68	1.07
BHH-F2	11.09	0.39	**BWH-F2**	8.79	0.14
BHH-M1	9.75	0.15	**BWH-M1**	8.19	0.72
BHH-M2	10	1.57	**BWH-M2**	8.58	0.35

Note: BLL- bleat low pitch light; BLH- bleat low pitch heavy; BHL- bleat high pitch light; BHH- bleat high pitch heavy; BPL- bleat phonation light; BPH- bleat phonation heavy; BWL- bleat whisper light; BWH- bleat whisper light

Table 12

Airflow external epigastric pumping (E) rate mean values in Hz and standard deviations for speaking (phonation), speaking (whisper), and singing tasks in all four subjects (F1, F2, M1, M2).

EEP	**SINGING**		**EEP**	**SPEAKING (Phonation & Whisper)**	
CONDITIONS	**MEAN (Hz)**	**SD**	**CONDITIONS**	**MEAN (Hz)**	**SD**
ES-F1	6.25	0	**EPS-F1**	6.6	0.49
ES-F2	7.08	0.59	**EPS-F2**	7.37	0.19
ES-M1	6.99	0.07	**EPS-M1**	6.52	0
ES-M2	7.58	0.16	**EPS-M2**	7.02	0.17
ED-F1	6.11	0.79	**EPD-F1**	6.4	0.38
ED-F2	6.04	0.89	**EPD-F2**	5.71	0
ED-M1	6.68	0.12	**EPD-M1**	6.39	0.19
ED-M2	6.81	0.2	**EPD-M2**	6.64	0.86
			EWS-F1	6.74	0.1
			EWS-F2	6.32	0.09
			EWS-M1	6.82	0.22
			EWS-M2	7.2	0.43
			EWD-F1	6.98	0.23
			EWD-F2	5.49	0.69
			EWD-M1	6.71	0.06
			EWD-M2	6.19	0.09

Note: S- SHALLOW, D- DEEP, Speaking tasks: P- PHONATION, W- WHISPER

Table 13

Airflow and F0 vibrato rate mean values in Hz and standard deviations for two pitches (P1 and P2) and three loudness levels (L1, L2, and L3) for all four subjects (F1, F2, M1, M2)

Vibrato	**Airflow vibrato rate**		**F0 vibrato rate**	
CONDITIONS	**MEAN (Hz)**	**SD**	**MEAN (Hz)**	**SD**
VP1L1-F1	5.09	0.59	5.29	0.49
VP1L1-F2	5.81	0.22	5.8	0.37
VP1L1-M1	5.82	0.37	5.57	0.31
VP1L1-M2	4.81	0.32	5.15	0.36
VP1L2-F1	5.43	0.68	5.42	0.12
VP1L2-F2	5.68	0.51	5.78	0.34
VP1L2-M1	5.85	0.42	5.52	0.06
VP1L2-M2	5.41	0.92	5.05	0.15
VP1L3-F1	5.27	0.17	5.37	0.1
VP1L3-F2	5.83	0.97	5.42	0.38
VP1L3-M1	6.11	0.7	5.72	0.16
VP1L3-M2	5.06	0.33	5.13	0.13
VP2L1-F1	5.51	0.09	5.49	0.21
VP2L1-F2	5.93	0.28	6.13	0.21
VP2L1-M1	5.74	0.13	5.59	0.06
VP2L1-M2	5.07	0.56	5.25	0.12
VP2L2-F1	5.37	0.31	5.35	0.28
VP2L2-F2	6.01	0.79	6.08	0.37
VP2L2-M1	5.97	0.25	5.75	0.17
VP2L2-M2	5.48	0.26	5.49	0.21
VP2L3-F1	5.14	0.68	5.41	0.45
VP2L3-F2	6.16	0.41	5.74	0.31
VP2L3-M1	6.17	0.14	6.07	0.15
VP2L3-M2	5.42	0.29	5.41	0.15

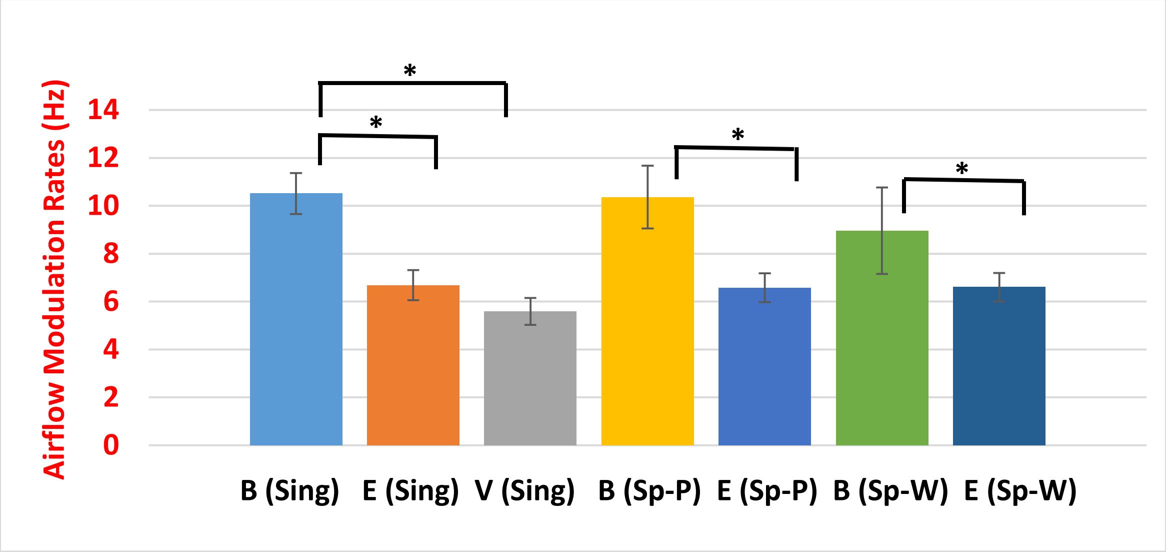

Figure 32. Means and standard deviations of airflow bleat rates, airflow external epigastric pumping rates, and airflow vibrato rates during singing, speaking (phonation), and speaking (whisper) tasks. The sub-tasks were bleat singing B(Sing), external epigastric pumping singing E(Sing), vibrato V(Sing), bleat during speaking phonation B(Sp-P), external epigastric pumping during speaking phonation E(Sp-P), bleat during speaking whisper B(Sp-W), and external epigastric pumping during speaking whisper tasks. The asterisk indicates statistical significance between the groups with *p-value < 0.05.*

Table 14

2-crossed and 3-staged nested ANOVA table for airflow modulation rates

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
Gender (main)	1	0.1894279	0.1894279	0.27	0.6071
Task (main)	2	20.2616184	10.1308092	14.20	**<.0001**
Gender*Task (interaction)	2	2.0384804	1.0192402	1.43	0.2427
Sub-tasks (main)	4	717.6721249	179.4180312	251.56	**<.0001**
Gender*Sub-tasks (interaction)	4	5.9105976	1.4776494	2.07	0.0872
Level(task*sub-tasks) (main)	13	27.0380144	2.0798473	2.92	**0.0008**
Gender*level(task*sub) (interaction)	13	10.4430129	0.8033087	1.13	0.3412

Table 15

Post-hoc pairwise comparisons of airflow modulation rates

Gender	Sub-tasks	Task	Least Squared Means (LSM)	LSM Number
Females	Bleating	Singing	**10.6936938**	1
Females	EEP	Singing	6.3701000	2
Females	Vibrato	Singing	5.6013139	3
Males	Bleating	Singing	**10.3313025**	4
Males	EEP	Singing	7.0128363	5
Males	Vibrato	Singing	5.5745472	6
Females	Bleating	Speaking	**10.9222645**	7
Females	EEP	Speaking	6.5175936	8
Males	Bleating	Speaking	**9.8870150**	9
Males	EEP	Speaking	6.6406146	10

Note: EEP- external epigastric pumping

Table 16

Results (p-values) for the paired post-hoc comparisons of airflow modulation rates

LSM numbers (Table 13)	1	3	4	5	6	7	8	9	10
1		**<.0001**	0.9291	**<.0001**	**<.0001**	0.9992	**<.0001**	0.1823	**<.0001**
2	**<.0001**	0.2015	**<.0001**	0.7708	0.1645	**<.0001**	1.0000	**<.0001**	0.9992
3			**<.0001**	**0.0001**	1.0000	**<.0001**	0.0576	**<.0001**	**0.0162**
4				**<.0001**	**<.0001**	0.6614	**<.0001**	0.8932	**<.0001**
5					**<.0001**	**<.0001**	0.9421	**<.0001**	0.9913
6						**<.0001**	0.0444	**<.0001**	**0.0120**
7							**<.0001**	0.0823	**<.0001**
8								**<.0001**	1.0000
9									**<.0001**

The means (in Hz) and standard deviations of F0 modulation rates for bleat (speaking and singing) and external epigastric pumping (speaking and singing) are given in Table 17 and Table 18, respectively. The means and standard deviations of F0 vibrato rates are already given in Table 13. The ANOVA model explains 93.8% variation of F0 modulation rates (R^2=0.938). The summary table of these results is given as Table 19, and the results show a significant main effect for tasks (speaking phonation and singing), $F(1, 123)=51.6$, $p < 0.001$, partial $\eta^2=0.3$; and sub-tasks (bleating-speaking and singing, epigastric pumping- speaking and singing, and vibrato), $F(3, 123)=541.84$, $p < 0.001$, partial $\eta^2=0.93$. Interaction effects were seen between gender and sub-tasks, $F(3, 123)=5.59$, $p < 0.002$, partial $\eta^2=0.12$; and between gender and levels of sub-tasks, $F(11, 123)=2.1$, $p < 0.02$, partial $\eta^2=0.16$. Figure 33 shows the mean F0 modulation rates of bleat (B), external epigastric pumping (E), and vibrato (V) during singing (sing), and speaking phonation (Sp). Tukey's HSD test was used for post-hoc pairwise comparisons, and the results are given in Table 20 and Table 21. The *p-values* in Table 21 show that females singing bleat has statistically significantly higher F0 rates than singing and speaking tasks of external epigastric pumping, and vibrato in both male and female subjects [LSM=10.786, $p < 0.001$]. The levels of sub-tasks (independent variables- pitches, loudness levels, type of bleat, and type of external epigastric pumping) did not affect the F0 modulation rates significantly. In general, the F0 external epigastric pumping (singing and speaking) rates were seen to be similar or closer to F0 vibrato rates.

Figure 34 compares the airflow and F0 modulation rates of bleat (speaking and singing), external epigastric pumping (speaking and singing), and vibrato (singing). The figure indicates bleat as a separate phenomenon with fastest rates of airflow and F0 modulations approximately in the range of 9.0- 12.2 Hz. The correlation between F0 and airflow bleat rates was found to be very strong ($R^2=0.86$). The correlation between F0 and airflow vibrato rates was seen to be moderately strong ($R^2=0.67$), and for external epigastric pumping, the correlation was very strong ($R^2=0.87$). The airflow and F0 vibrato rates are approximately in the range of 4.75-6.25

Hz, and for epigastric pumping rates were 5.5-7.5 Hz. Therefore higher correlation exists between F0 and airflow vibrato cycles if the source is primarily Ps or glottal adduction.

Table 17

Means (in Hz) and standard deviations of F0 bleat rates (B) for all four subjects (F1, F2, M1, M2)

Sing (L- Light, H-Heavy)	**MEAN (Hz)**	**SD**	**Speak (L- Light, H-Heavy)**	**MEAN (Hz)**	**SD**
BP1L-F1	10.13	1.84	BPL-F1	12.21	3.3
BP1L-F2	9.32	1.71	BPL-F2	11.71	0.4
BP1L-M1	10.64	0.1	BPL-M1	9.81	1.4
BP1L-M2	10.84	0.83	BPL-M2	9	1.41
BP1H-F1	11.22	0.58	BPH-F1	10.75	2.27
BP1H-F2	10.31	0.71	BPH-F2	10.57	0.21
BP1H-M1	9.82	0.26	BPH-M1	10.63	0.83
BP1H-M2	9.69	0.44	BPH-M2	10	0.1
BP2L-F1	12.35	0.22			
BP2L-F2	10.53	0.39			
BP2L-M1	10.1	0.14			
BP2L-M2	10.82	0.41			
BP2H-F1	10.82	0.41			
BP2H-F2	11.62	0.71			
BP2H-M1	10.03	0.39			
BP2H-M2	9.71	1.16			

NOTE: No F0 during whisper; Singing: two pitches- P1 and P2; Speaking: phonation (P) and whisper (W); Light (L) and Heavy (H)

Table 18

Means (in Hz) and standard deviations of F0 external epigastric pumping (E) rates of speaking and singing tasks

Sing (S- Shallow, D- Deep)	**Mean (Hz)**	**SD**	**Speak (S- Shallow, D-Deep)**	**Mean (Hz)**	**SD**
ES-F1	6.65	0.28	EPS-F1	6.5	0.62
ES-F2	6.78	0.76	EPS-F2	7.11	0.23
ES-M1	6.86	0.4	EPS-M1	6.69	0.23
ES-M2	7.51	0.27	EPS-M2	7.12	0.48
ED-F1	5.84	0.4	EPD-F1	6.46	0.29
ED-F2	5.84	1.01	EPD-F2	5.6	0.17
ED-M1	6.64	0.17	EPD-M1	6.32	0.28
ED-M2	6.65	0.56	EPD-M2	6.61	0.62

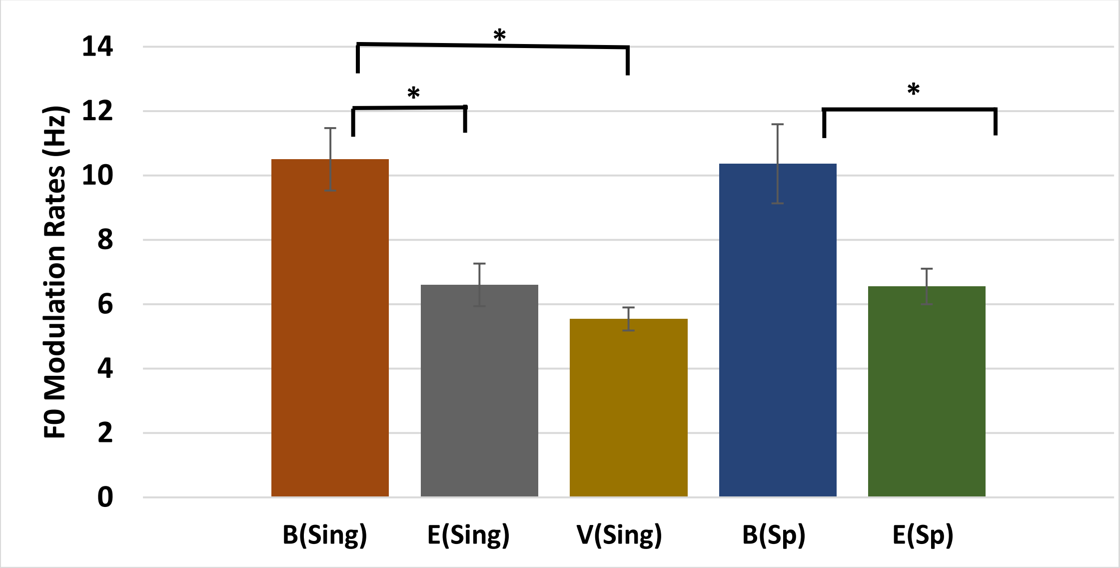

Figure 33. Means and standard deviations of F0 bleat rates, F0 external epigastric pumping (EEP) rates, and F0 vibrato rates during singing and speaking (phonation) tasks. The sub-tasks were bleat singing- B(Sing), external epigastric pumping singing- E(Sing), vibrato- V(Sing), bleating during speaking task- B(Sp), and EEP during speaking task- E(Sp). The asterisk “*” indicates statistical significance between the groups with *p-value < 0.05*.

Table 19

Summary table of ANOVA results for F0 modulation rates

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Gender	1	0.9126071	0.9126071	2.20	0.1406
Task	1	21.4135778	21.4135778	51.60	**<.0001**
Gender*Task	1	0.4126610	0.4126610	0.99	0.3206
Sub-task	3	674.5612810	224.8537603	541.84	**<.0001**
Gender*Sub-task	3	6.9549222	2.3183074	5.59	**0.0013**
Level(task*sub)	11	7.3563952	0.6687632	1.61	0.1034
Gender*level(task*sub)	11	9.6458577	0.8768962	2.11	**0.0240**

Table 20

Post-hoc pairwise comparisons of F0 modulation rates

Gender	Sub-tasks	Tasks	LS MEAN	LS Number
Females	Bleating	Singing	**10.7857444**	1
Females	EEP	Singing	6.2789000	2
Females	Vibrato	Singing	5.6079686	3
Males	Bleating	Singing	**10.2060500**	4
Males	EEP	Singing	6.9127134	5
Males	Vibrato	Singing	5.4738861	6
Females	Bleating	Speaking	**10.8479125**	7
Females	EEP	Speaking	6.4165425	8
Males	Bleating	Speaking	**9.9344020**	9
Males	EEP	Speaking	6.6840553	10

Note: EEP- external epigastric pumping

Table 21

Results (p-values) for the paired post-hoc comparisons of F0 modulation rates

LSM no.s (Table 19)	**1**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1		**<.0001**	0.2556	**<.0001**	**<.0001**	1.0000	**<.0001**	0.0427	**<.0001**
2	**<.0001**	0.2001	**<.0001**	0.6229	0.0537	**<.0001**	1.0000	**<.0001**	0.9609
3			**<.0001**	**<.0001**	0.9967	**<.0001**	0.0516	**<.0001**	**0.0015**
4				**<.0001**	**<.0001**	0.3459	**<.0001**	0.9887	**<.0001**
5					**<.0001**	**<.0001**	0.8730	**<.0001**	0.9994
6						**<.0001**	**0.0100**	**<.0001**	**0.0002**
7							**<.0001**	0.0746	**<.0001**
8								**<.0001**	0.9980
9									**<.0001**

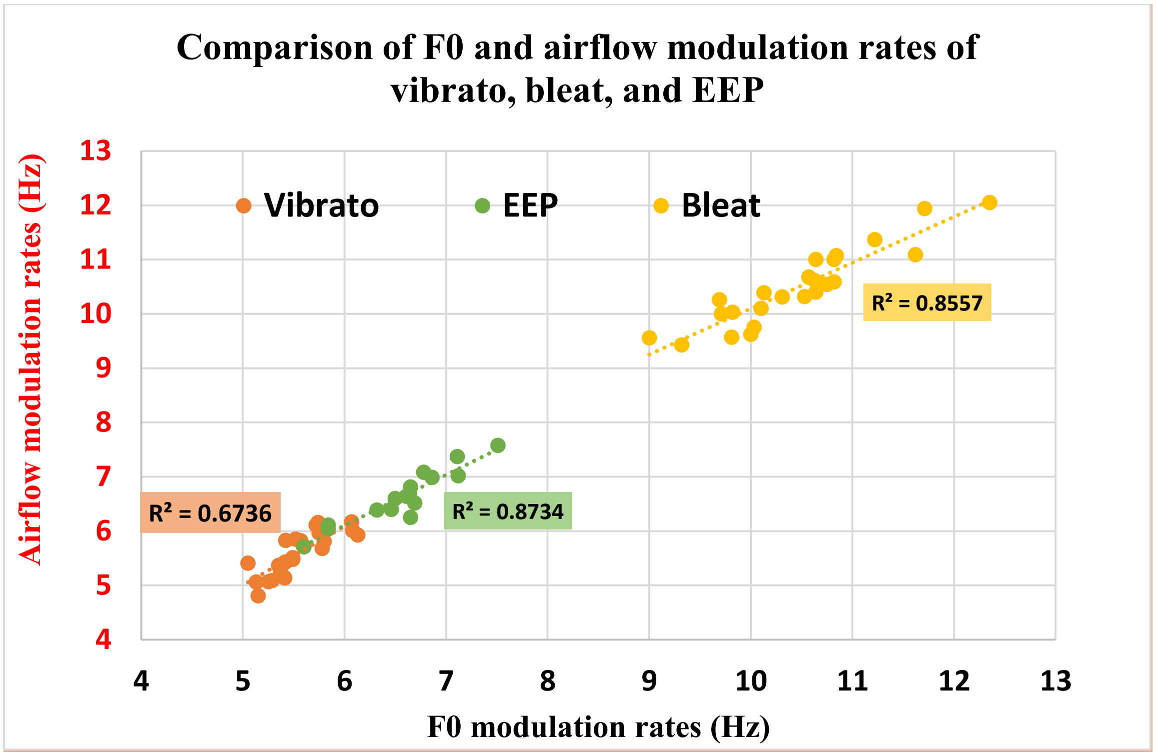

Figure 34. Comparison of airflow and F0 modulation rates of vibrato, external epigastric pumping (EEP), and bleat. Individual R^2 values in the figure indicates the correlation between F0 and airflow modulation rates of each sub-task.

Airflow, F0, and intensity modulation extents. Table 22 gives means (in cm^3/s) and standard deviations of airflow modulation extents for bleat (adductory change maneuver- speaking: phonation-P, whisper-W, L-light, and H-heavy and singing), external epigastric pumping (Ps change maneuver- speaking phonation, speaking whisper, and singing; S-shallow, D-deep), and vibrato. The model explains 75% of the variation in airflow modulation extent (R^2=0.7497). The summary ANOVA table is reported in Table 23, and the results show a significant main effect for gender, $F(1, 518)=77.09$, $p < 0.001$, partial $\eta^2=0.2$; tasks, $F(2, 518)=386.32$, $p < 0.01$, partial $\eta^2=0.72$; sub-tasks, $F(4, 518)=169.76$, $p < 0.01$, partial $\eta^2=0.69$; and levels of sub-tasks, $F(13, 518)=21.58$, $p < 0.01$, partial $\eta^2=0.48$. An interaction effect was found to be significant between gender and task, $F(2, 518)=9.21$, $p < 0.01$, partial $\eta^2=0.06$; and also between gender and sub-tasks, $F(4, 518)=4.36$, $p < 0.01$, partial $\eta^2=0.06$. Figure 35 shows the mean airflow modulation extents for bleat (B), external epigastric pumping (E), and vibrato (V) during singing (g), speaking (s-phonation and whisper). Tukey's HSD test was used for post-hoc pairwise comparisons, and the results are given in Table 24 and Table 25. Overall, male singers had larger airflow modulation extents than females [LSM(males)=117 cm^3/s, LSM(females)=86 cm^3/s, $p < 0.01$]. This could be due to larger vocal folds and the larger larynx size for males than females. Combining the sub-tasks and all the levels, the airflow modulation extents for speaking whisper tasks were found to be statistically significantly larger than for speaking phonation and singing tasks [M=234.3 cm^3/s, SD=33.27 cm^3/s, $p < 0.01$]. As whisper is generated by posterior glottal abductory changes, these results most likely indicate a direct contribution of an enlarged posterior glottis due to a more relaxed contraction of the interarytenoid muscles and more contraction of the posterior cricoarytenoids muscles (Tsunoda et al., 1994) for large airflow changes.

Table 25 shows that the airflow bleat extents for males (LSM number 13) during speaking whisper tasks were statistically significantly different from all the remaining sub-tasks. Excluding the speaking whisper tasks, in general for singing and speaking phonation tasks, the airflow bleat extents were statistically significantly larger than airflow vibrato extents and airflow external epigastric pumping extents for both males and females (LSM numbers 1, 4, and 9). However, airflow bleat extents during speaking phonation tasks in females (LSM number 7) were seen to be lower in comparison with other airflow bleat extents [M=59.26 cm^3/s, SD=4.8 cm^3/s]. To check the reliability of this particular measure, i.e. airflow bleat extents in females during speaking tasks, multiple repetitions were made and confirmed. This could be due to less training to bleat but qualitatively it is perceived as bleat (produced only with adductory gestures).

Figure 35 shows the airflow modulation extents of bleat (speaking, followed by singing), vibrato (two pitches-P1 and P2, and three loudness levels- L1, L2, and L3), and external epigastric pumping (speaking, followed by singing) for each subject. The airflow bleat extents for speaking phonation (P) and whisper (W), and singing have two sub-levels, which are light (L) and heavy (H). Additionally, singing tasks for bleat have two pitches (P1 and P2). For airflow epigastric pumping extents for speaking phonation (P), speaking whisper (W), and singing, there are two sub-levels, which are shallow (S) and deep (D) pumping. Figure 35 shows that the largest airflow modulation extents are for bleat for all subjects, especially during whisper and the heavier condition (BWH) [M=469.5 cm^3/s, SD=92 cm^3/s, $p < 0.01$]. This strong relation between whisper and bleat (especially heavier than lighter) might indicate similar physiological involvement in both cases (i.e., adductory in nature).

After bleat, airflow epigastric pumping extents during whisper were seen to be larger, especially during deeper (more pressure) pumping (EWD) [M=167 cm^3/s, SD=41 cm^3/s, $p < 0.01$]. This indicates increase of airflow modulation extents secondary to increase in subglottal pressure changes. But the most effective contributor for large airflow modulation extents would be adductory-abductory changes as seen in bleat, which would significantly change the glottal area. The airflow vibrato extents were slightly smaller or similar to airflow epigastric pumping extents during speaking phonation (EPS and EPD) and singing (ES and ED). The post-hoc pairwise comparisons among two pitches and three loudness levels of vibrato did not show statistically significant differences in airflow vibrato extents. This might indicate that the primary source of airflow modulations during vibrato could be respiratory-related, but these airflow modulations are easily affected by changes in glottal adduction, glottal area, and laryngeal flow resistance (as the airflow vibrato extents were not affected by increase in pitch and loudness in the current study).

For external epigastric pumping, airflow modulation extents increased from shallow to deep pumping in both males and females, and was statistically significant for males [Males: M=74.6 cm^3/s, SD=15.33 cm^3/s, $p=0.02$; Females: M=36.7 cm^3/s, SD=19.8 cm^3/s, $p=0.3$]. This indicates larger respiratory pumping and large-sized larynges undergo greater airflow modulations than shallow pumping and small-sized larynges (there was no intent on the experimenter's part to use more pumping force on the epigastric area of the males).

Table 22

Means (in cm^3/s) and standard deviations of airflow modulation extents of bleat (B), external epigastric pumping (E), and vibrato (V) for all four subjects (F1, F2, M1, M2)

CONDITIONS	**F1**	**SD**	**F2**	**SD**	**M1**	**SD**	**M2**	**SD**
BPL	46.96	25.03	59.33	15.35	127.71	44.85	208.15	110.41
BPH	46.76	17.58	83.97	14.42	95.98	27.58	230.86	75.99
BWL	94.06	57.79	238.66	95.49	316.74	76.86	175.84	98.06
BWH	297.04	74.43	577.89	94.83	456.95	115.02	546.02	84.56
EPS	27.19	6.79	18	6	52.32	6.09	24.66	9.01
EPD	42.93	19.25	35.16	8.86	134.95	27.35	88.62	36.92
EWS	163.85	24.09	45.57	17.97	189.97	27.33	48.87	10.16
EWD	169.07	35.5	94.38	43.24	291.74	40.05	112.01	44.87
VP1L1	17.49	8.51	38.34	14.46	36.5	6.01	25.45	14.38
VP1L2	22.15	17.1	31.24	13.63	19.75	12	19.48	9.73
VP1L3	24.99	16.45	34.21	9.98	36.8	22.61	22.65	11.17
VP2L1	19.62	8.8	37.04	14.67	24.65	9.43	34.12	0.56
VP2L2	23.6	7.67	38.86	15.92	32.9	7.86	27.06	8.41
VP2L3	22.32	11.24	33.18	15.02	46.68	9.72	34.97	17.04
BP1L (Sing)	48.55	26	184.8	20.94	82.5	20.64	230.15	25.01
BP1H (Sing)	41.27	19.14	190.75	41.51	130.95	19.11	245.94	34.59
BP2L (Sing)	44.55	18.85	201.65	44.37	119.49	20.72	174.3	16.53
BP2H (Sing)	42.74	15.98	247.89	69.1	169.75	35.62	237.74	87.07
ES (Sing)	32.01	12.5	17.42	4.97	31.21	5.87	22.52	6.07
ED (Sing)	46.67	25.56	26.67	14.07	82.96	14.5	66.13	16.16

Note: Bleat (B), epigastric pumping (E), vibrato (V), phonation (P), whisper (W), light (L), heavy (H), shallow (S), deep (D), two pitches (P1 and P2), and three loudness levels (L1, L2, and L3)

Table 23

Summary table of ANOVA results for airflow modulation extents

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Gender	1	283159.548	283159.548	77.09	**<.0001**
Task	2	2837841.216	1418920.608	386.32	**<.0001**
Gender*Task	2	67636.493	33818.247	9.21	**0.0001**
Sub-task	4	2494041.317	623510.329	169.76	**<.0001**
Gender*Sub-task	4	64045.686	16011.422	4.36	**0.0017**
level(task*sub)	13	1030212.282	79247.099	21.58	**<.0001**
Gender*level(task*sub)	13	62969.364	4843.797	1.32	0.1965

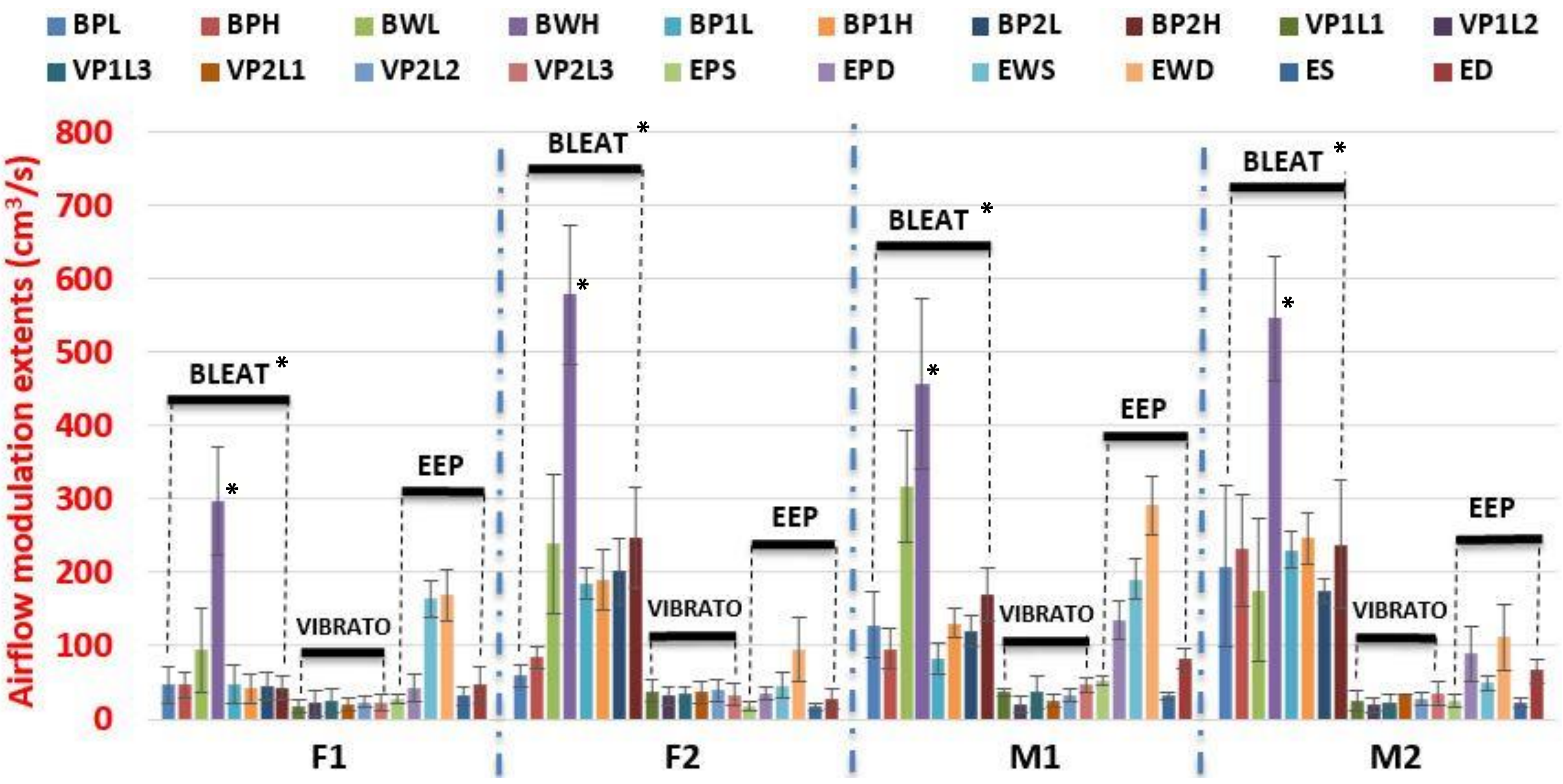

Figure 35. Means (cm^3/s) of airflow bleat extents (B), airflow external epigastric pumping (EEP) extents (E), and airflow vibrato extents (V) during different tasks. The vertical dashed blue line separates each subject. The asterisk(*) on bleat indicates statistically significant difference ($p < 0.05$) from vibrato and EEP, and asterisk on BWH indicates statistical significant difference ($p < 0.05$) from all the remaining levels of sub-task. The sub-tasks are bleat phonation light (BPL), bleat phonation heavy (BPH), bleat whisper light (BWL), bleat whisper heavy (BWH), bleat sing low pitch light (BP1L), bleat sing low pitch heavy (BP1H), bleat sing high pitch light (BP2L), bleat sing high pitch heavy (BP2H), vibrato (P1L1, P1L2, P1L3, P2L1, P2L2, and P2L3), EEP phonation shallow (EPS), EEP phonation deep (EPD), EEP whisper shallow (EWS), EEP whisper deep (EWD), EEP sing shallow (ES), and EEP sing deep (ED).

Table 24

Post-hoc pairwise comparisons of airflow modulation extents

Gender	Sub-task	Task	LSM	LSM Number
Females	Bleating	Singing	**118.501670**	1
Females	EEP	Singing	30.078068	2
Females	Vibrato	Singing	29.327586	3
Males	Bleating	Singing	**162.140623**	4
Males	EEP	Singing	50.817450	5
Males	Vibrato	Singing	29.994918	6
Females	Bleating	Speak(phon)	57.221927	7
Females	EEP	Speak(phon)	29.831261	8
Males	Bleating	Speak(phon)	**152.403319**	9
Males	EEP	Speak(phon)	74.149750	10
Females	Bleating	Speak(whis)	**317.918813**	11
Females	EEP	Speak(whis)	117.185931	12
Males	Bleating	Speak(whis)	**387.396164**	13
Males	EEP	Speak(whis)	160.577914	14

Note: EEP- external epigastric pumping

Table 25

Results (p-values) for the paired post-hoc comparisons of airflow modulation extents

LSM (Table 23)	**1**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1		**<.0001**	**0.0029**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.4010	0.0515	**<.0001**	1.0000	**<.0001**	0.0894
2	**<.0001**	1.0000	**<.0001**	0.9840	1.0000	0.8656	1.0000	**<.0001**	0.2474	**<.0001**	**<.0001**	**<.0001**	**<.0001**
3			**<.0001**	0.8288	1.0000	0.4091	1.0000	**<.0001**	**0.0257**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
4				**<.0001**	**<.0001**	**<.0001**	**<.0001**	1.0000	**<.0001**	**<.0001**	0.0696	**<.0001**	1.0000
5					0.8588	1.0000	0.9744	**<.0001**	0.9501	**<.0001**	**0.0010**	**<.0001**	**<.0001**
6						0.4515	1.0000	**<.0001**	**0.0306**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
7							0.8133	**<.0001**	0.9969	**<.0001**	**0.0049**	**<.0001**	**<.0001**
8								**<.0001**	0.1852	**<.0001**	**<.0001**	**<.0001**	**<.0001**
9									**<.0001**	**<.0001**	0.6486	**<.0001**	1.0000
10										**<.0001**	0.2836	**<.0001**	**<.0001**
11											**<.0001**	**0.0008**	**<.0001**
12												**<.0001**	0.2759
13													**<.0001**

Table 26 shows the means (in semitones) and standard deviations of F0 modulation extents during bleat (two pitches-P1 and P2, P-phonation, L-light, and H-heavy), external epigastric pumping (P-phonation, S-shallow, and D-deep), and vibrato (two pitches- P1 and P2, and three loudness levels- L1, L2, and L3) for speaking (phonation) and singing tasks. The model explains 63.4% of the variation in F0 modulation extent (R^2=0.634). The summary of the ANOVA table is reported in Table 27, and the results show a significant main effect on gender, $F(1, 514)=325.46$, $p < 0.01$, partial $\eta^2=0.39$; task, $F(1, 514)=5.02$, $p < 0.05$, partial $\eta^2=0.01$; sub-tasks, $F(3, 514)=6.38$, $p < 0.01$, partial $\eta^2=0.15$; and levels of sub-tasks, $F(11, 514)=19.13$, $p < 0.01$, partial $\eta^2=0.29$. An interaction effect was seen to be significant between gender and levels of sub-tasks, $F(11, 514)=12.56$, $p < 0.01$, partial $\eta^2=0.21$. The post-hoc pairwise comparisons were done and there was no statistically significant difference seen in tasks, sub-tasks, and levels of sub-tasks. Overall, males tend to have higher F0 modulation extents than females [LSM(males)=1.81 ST, LSM(females)=0.98 ST, $p < 0.01$].

Figure 36 shows the pairwise comparisons between male and female singers across different levels of sub-tasks. The figure shows that in general males have a statistically significantly higher F0 modulation extents than females ($p < 0.05$). During bleat tasks (speaking and singing), the F0 bleat extents tend to increase from lighter bleat to heavier, and were seen more significantly in male subjects [Speaking: M=1.63 ST, SD=0.47 ST; Singing: M=2.015 ST, SD=0.41 ST]. This trend was opposite during high pitch heavy bleat condition [Males: M=1.58 ST, SD=0.35 ST; Females: M=0.68 ST, SD=0.24 ST], and this may be due to stiffer vocal folds for increasing the pitch.

During external epigastric pumping, the F0 modulation extents were higher in deep (more pressure) conditions than shallow (less pressure) in both male and females but was statistically significant in males alone [Speaking: M=2.8 ST, SD=0.72 ST, *p*=0.0024; Singing: M=1.91 ST, SD=0.44 ST, *p*=0.0022]. This indicates that F0 modulation extents are greatly affected by changes in subglottal pressure, and are directly related. During vibrato, in general there was no statistically significant difference seen in F0 vibrato extents among the three loudness levels in the four subjects. When comparison was made between low pitch (P1) and high pitch (P2), the F0 vibrato extents were statistically significantly higher in P1 than in P2 for males [P1: M=2.38 ST, SD=0.48 ST, *p*=0.027], whereas in females, F0 vibrato extents in P2 were slightly higher than P1, but not statistically significant [P2: M=1.32 ST, SD=0.29 ST, *p*=0.12]. This indicates that the increase of vocal fold tension with increase of pitch may or may not contribute to determining the extent of the F0 vibrato extent, since the relationship differed between the males and females, unless there is a gender difference in the production of different pitches. The highest F0 vibrato extent in females was seen in the P2L3 condition in comparison with other conditions. This might suggest a slightly higher contribution of subglottal pressure on F0 vibrato extents at higher pitches in females.

Table 26

Means (in semitones) and standard deviations of F0 modulation extents of bleat (B), external epigastric pumping (E), and vibrato (V) for speaking and singing tasks

CONDITIONS	F1	SD	F2	SD	M1	SD	M2	SD
BPL	0.66	0.44	0.26	0.1	1.27	0.65	1.53	0.2
BPH	1.19	0.41	0.4	0.17	1.61	0.47	1.65	0.46
EPS	0.77	0.18	0.89	0.23	0.83	0.14	0.95	0.34
EPD	1.32	0.45	1.1	0.19	2.04	0.34	3.56	1.1
VP1L1	1.24	0.14	0.94	0.29	2.34	0.53	3.07	0.42
VP1L2	1.15	0.21	0.88	0.19	2.13	0.53	2.5	0.49
VP1L3	1.38	0.28	0.8	0.26	2.08	0.37	2.13	0.52
VP2L1	1.4	0.16	1.19	0.38	1.41	0.29	1.87	0.35
VP2L2	1.23	0.25	1.28	0.22	1.6	0.44	2.05	0.47
VP2L3	1.61	0.49	1.22	0.21	1.67	0.24	1.94	0.18
BP1L (Sing)	0.49	0.38	1.27	0.77	1.64	0.22	1.47	0.73
BP1H (Sing)	1.57	0.41	1.26	0.32	2.01	0.23	2.02	0.59
BP2L (Sing)	0.59	0.13	0.99	0.27	2.18	0.41	2.57	0.83
BP2H (Sing)	0.55	0.22	0.81	0.26	1.73	0.25	1.42	0.45
ES (Sing)	0.6	0.34	0.41	0.1	0.56	0.14	0.78	0.25
ED (Sing)	1.07	0.23	0.62	0.14	0.92	0.25	2.89	0.63

Note: BPL & BPH- bleat phonation light and heavy; EPS & EPD- epigastric pumping phonation shallow and deep; VP1L1-VP2L3: vibrato two pitches and three loudness levels; BP1L-BP2H: bleat two pitches light and heavy; ES & ED- epigastric pumping shallow and deep

Table 27

Summary table of ANOVA results for F0 modulation extents

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Gender	1	71.22269809	71.22269809	325.46	**<.0001**
Task	1	1.09904736	1.09904736	5.02	**0.0255**
Gender*Task	1	0.06384452	0.06384452	0.29	0.5893
Sub-task	3	19.15128922	6.38376307	29.17	**<.0001**
Gender*Sub-task	3	0.35965865	0.11988622	0.55	0.6498
Level(task*sub)	11	46.05434814	4.18675892	19.13	**<.0001**
Gender*Level(task*sub)	11	30.24217450	2.74928859	12.56	**<.0001**

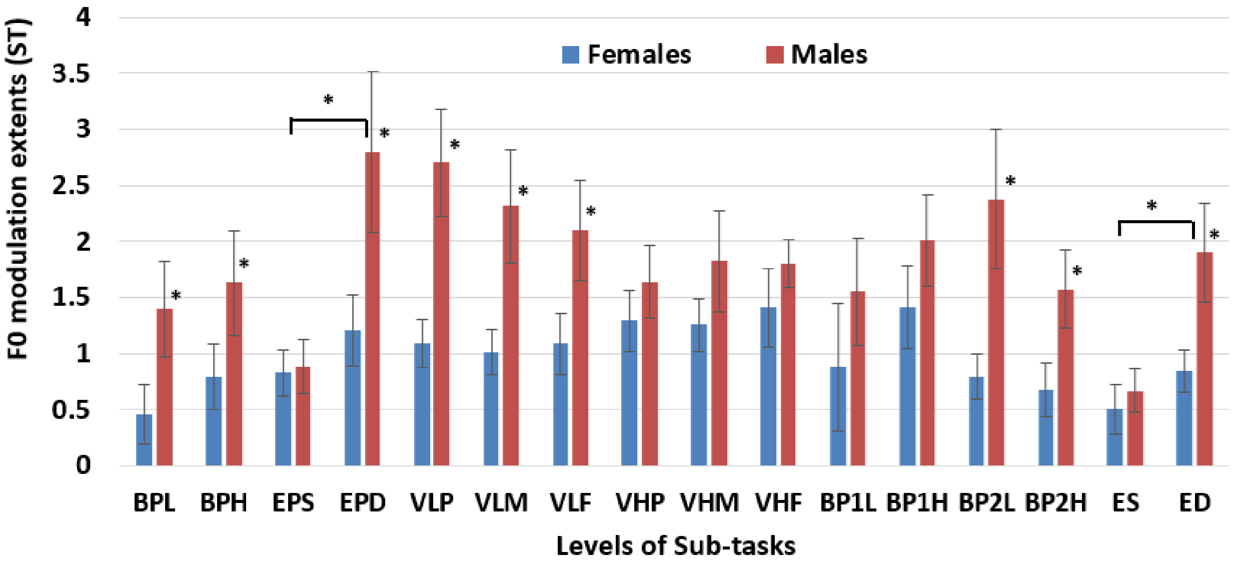

Figure 36. Means and standard deviations of F0 bleat extents (B), F0 EEP extents (E), and F0 vibrato extents (V) during singing and speaking (phonation) tasks. For bleat, PL- phonation light, PH- phonation heavy, P1 and P2- low and high pitches, L and H- light and heavy. For EEP, PS- phonation shallow, PD- phonation deep, ES- singing during shallow pumping, and ED- singing during deep pumping. For vibrato, VLP, VLM, and VLF- low pitch piano, mezzoforte, and forte; VHP, VHM, and VHF- high pitch piano, mezzoforte, and forte.The asterisk indicates statistical significance between the groups with *p-value < 0.05.*

Table 28 gives the means (dB) and standard deviations of intensity modulation extents during vibrato, bleat (adductory change maneuver- speaking phonation, speaking whisper, and singing), and external epigastric pumping (Ps change maneuver- speaking phonation, speaking whisper, and singing). The ANOVA model explains 70% of the variation in intensity modulation extents ($R^2=0.7$). The summary of the ANOVA results is given in Table 29, and shows a significant main effect in gender, $F(1, 591)=9.92$, $p < 0.01$ partial $\eta^2=0.02$; tasks, $F(2, 591)=406$, $p < 0.01$, partial $\eta^2=0.58$; sub-tasks, $F(4, 591)=28.2$, $p < 0.01$, partial $\eta^2=0.16$; and levels of sub-tasks, $F(13, 591)=18.8$, $p < 0.01$, partial $\eta^2=0.29$. The interaction effect was significant between gender and sub-tasks, $F(4, 591)=6.3$, $p < 0.01$, partial $\eta^2=0.04$; and also between gender and levels of sub-task, $F(13, 591)=4.6$, $p < 0.01$, partial $\eta^2=0.09$. Tukey's test for post-hoc analysis results are presented in Table 30 and Table 31. The intensity modulation extents during speaking whisper tasks were found to be statistically significantly higher in comparison with speaking phonation and singing tasks [M=7.44 dB, SD=2.1 dB, $p < 0.01$]. This could be due to higher DC flow and greater glottal area changes secondary to activity in the posterior glottis during whisper in comparison with phonation. The intensity modulation extents for males were found to be statistically significantly higher than for females [M=3.65 dB, SD=1.1 dB, $p < 0.02$]. This might indicate greater subglottal pressures, larger airflow modulation extents, larger laryngeal size, and greater horizontal excursion of vocal folds contributing to the higher intensity modulation rates in males.

Table 31 shows that intensity extents for the external epigastric pumping (EEP) during speaking whisper tasks for males were statistically significantly higher than all the remaining tasks excluding speaking whisper tasks of epigastric pumping and bleating in females [M=8.42 dB, SD=1.67 dB, $p < 0.01$]. In comparing speaking phonation and singing tasks, intensity EEP extents are highest [Females: M=4.27 dB, SD=0.94 dB; Males: M=4.17 dB, SD=1.16 dB], followed by intensity bleat extents for males [M=3.05 dB, SD=1.01 dB]. As the intensity depends on the subglottal pressure, direct changes in Ps during external epigastric pumping also leads to changes in intensity. During the rise of Ps, intensity increases, and vice-versa. Therefore, intensity EEP extents are highest, especially during whisper, due to greater laryngeal airflow and glottal area changes. These intensity modulations are secondary to changes in Ps. Also, as stated in the section of airflow bleat extents about the hypothesis on the close relation between bleat and whisper (that generated larger airflow bleat extents), similarly intensity bleat extents were also higher during whisper. This could potentially indicate laryngeally mediated intensity modulations secondary to adductory-abductory changes in bleat as supported by a study done by Dromey et al. (2009) on amplitude (intensity) modulations during vibrato.

The intensity vibrato extents of males and females had a similar range of intensity bleat extents as in females [Bleat: Singing- M=1.65 dB, SD=0.6 dB; Speaking- M=1.35 dB, SD=0.06 dB]. The intensity vibrato extents were the lowest in compared with intensity external epigastric pumping extents and intensity bleat extents. This could lead to a hypothesis of a combination of subglottal pressure, glottal adduction, and laryngeal flow resistance, and its being neither primarily respiratory related nor purely laryngeal adductory.

Figure 37 shows the intensity modulation extents during different levels of bleat and external epigastric pumping. During speaking phonation and singing tasks (P1 and P2), the intensity bleat extents decrease from lighter to heavier bleat, and this could be due to an increase of glottal adduction and laryngeal flow resistance. In speaking whisper tasks, the intensity bleat extents increased significantly from lighter to heavier bleat, which is opposite to phonation, and this could be due to increased DC flow due to greater enlargement of the posterior glottis [Males, BWH: M=9.9 dB, SD=3.67 dB, $p < 0.01$; Females, BWH: M=8.6 dB, SD=3.91 dB, $p < 0.01$]. During external epigastric pumping (Speaking phonation- EPS and EPD, Speaking whisper- EWP and EWD, Singing-ES and ED), the intensity external epigastric pumping extents increased from shallow to deep pumping conditions, and was statistically significant in males [EPD: M=6.38 dB, SD=1.53 dB, $p < 0.01$; EWD: M=11.06 dB, SD=2.02 dB, $p < 0.01$; ED: M=4.65 dB, SD=0.72 dB, $p < 0.01$]. This leads to an hypothesis that intensity modulations during singing (especially vibrato) may be more related to respiratory events in male singers and more to a combination of respiratory and resonances-harmonics interaction in women (Horii, 1989).

Table 28

Intensity modulation extents (dB) of bleat, external epigastric pumping, and vibrato means and standard deviations of speaking (phonation and whisper) and singing

CONDITIONS	F1-MEAN	SD	F2-MEAN	SD	M1-MEAN	SD	M2-MEAN	SD
BPL	1.61	0.6	1.8	0.7	2.85	0.75	3.56	1.48
BPH	1	0.72	0.97	0.42	2.25	0.84	3.52	0.98
BWL	4.42	0.6	6	2.98	3.56	0.92	4.72	1.74
BWH	6.74	2.07	10.39	5.74	6.82	3.87	12.95	3.47
EPS	2.07	0.5	4.82	1.35	2.11	0.84	1.81	0.74
EPD	3.9	0.81	6.27	1.1	5.78	0.85	6.98	2.21
EWS	5.92	1.34	8.67	1.29	8.05	1.91	3.49	0.71
EWD	6.3	1.7	8.87	1.03	14.24	1.63	7.88	2.41
VP1L1	2.48	1.06	0.86	0.43	1.44	0.76	1.91	0.99
VP1L2	2.27	0.89	1.09	0.45	1.53	0.53	2.67	0.88
VP1L3	2.65	0.78	0.92	0.16	1.65	0.65	2.84	0.78
VP2L1	3.05	0.84	0.73	0.26	0.96	0.36	1.38	0.45
VP2L2	1.36	0.44	0.66	0.33	1.41	0.43	0.83	0.42
VP2L3	1.41	0.46	0.71	0.38	1.48	0.26	0.93	0.19
BP1L (Sing)	2.35	0.86	2.68	1.31	2.84	0.9	2.63	0.61
BP1H (Sing)	0.94	0.55	1.34	0.34	2.72	0.41	2.43	0.98
BP2L (Sing)	2.67	1.01	0.76	0.24	4.68	1.3	3.28	1.8
BP2H (Sing)	0.98	0.1	1.48	0.39	3.78	1.21	1.79	0.93
ES (Sing)	2.61	1.34	1.55	0.22	1.42	0.26	1.38	0.32
ED (Sing)	3.75	1.75	2.57	0.66	3.47	0.85	5.82	0.59

Note: BPL & BPH- bleat phonation light and heavy; BWL & BWH- bleat whisper light and heavy; EPS & EPD- epigastric pumping phonation shallow and deep; EWS & EWD- epigastric pumping whisper shallow and deep; VP1L1-VP2L3: vibrato two pitches and three loudness levels; BP1L-BP2H: bleat two pitches light and heavy; ES & ED- epigastric pumping shallow and deep

Table 29

Summary of ANOVA results for intensity modulation extents

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Gender	1	27.989740	27.989740	9.92	**0.0017**
Task	2	2291.262807	1145.631404	405.99	**<.0001**
gender*task	2	4.379911	2.189956	0.78	0.4607
Sub-task	4	318.053973	79.513493	28.18	**<.0001**
gender*sub-task	4	71.080794	17.770199	6.30	**<.0001**
level(task*sub)	13	689.684119	53.052625	18.80	**<.0001**
gender*level(task*sub)	13	167.011114	12.847009	4.55	**<.0001**

Table 30

Post-hoc pairwise comparisons of intensity modulation extents (pho-phonation; whi-whisper)

Gender	Sub-tasks	Tasks	LSM	LSM Number
Females	Bleating	Sing	1.68297419	1
Females	EEP	Sing	2.81399714	2
Females	Vibrato	Sing	1.53333605	3
Males	Bleating	Sing	3.11738182	4
Males	EEP	Sing	3.07900811	5
Males	Vibrato	Sing	1.58375761	6
Females	Bleating	Speak pho	1.33441429	7
Females	EEP	Speak pho	4.47331143	8
Males	Bleating	Speak pho	2.86362813	9
Males	EEP	Speak pho	4.17780833	10
Females	Bleating	Speak whi	6.96642258	11
Females	EEP	Speak whi	7.76006190	12
Males	Bleating	Speak whi	6.33315152	13
Males	EEP	Speak whi	8.59101333	14

Note: EEP- external epigastric pumping

Table 31

Results (p-values) for the paired post-hoc comparisons of intensity modulation extents

LSM (Table 29)	**1**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1		1.0000	**0.0060**	0.0625	1.0000	0.9999	**<.0001**	0.3058	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
2	0.3284	0.0997	1.0000	1.0000	0.1284	0.1292	0.0448	1.0000	0.2191	**<.0001**	**<.0001**	**<.0001**	**<.0001**
3			**0.0002**	**0.0095**	1.0000	1.0000	**<.0001**	0.0948	<.0001	**<.0001**	**<.0001**	**<.0001**	**<.0001**
4				1.0000	**0.0003**	**0.0027**	0.0873	1.0000	0.4036	**<.0001**	**<.0001**	**<.0001**	**<.0001**
5					**0.0132**	**0.0214**	0.1811	1.0000	0.5551	**<.0001**	**<.0001**	**<.0001**	**<.0001**
6						1.0000	**<.0001**	0.1217	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
7							**<.0001**	0.1192	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
8								0.0763	1.0000	**<.0001**	**<.0001**	0.0135	**<.0001**
9									0.3102	**<.0001**	**<.0001**	**<.0001**	**<.0001**
10										**<.0001**	**<.0001**	0.0011	**<.0001**
11											0.9843	0.9939	0.1057
12												0.4058	0.9779
13													**0.0011**

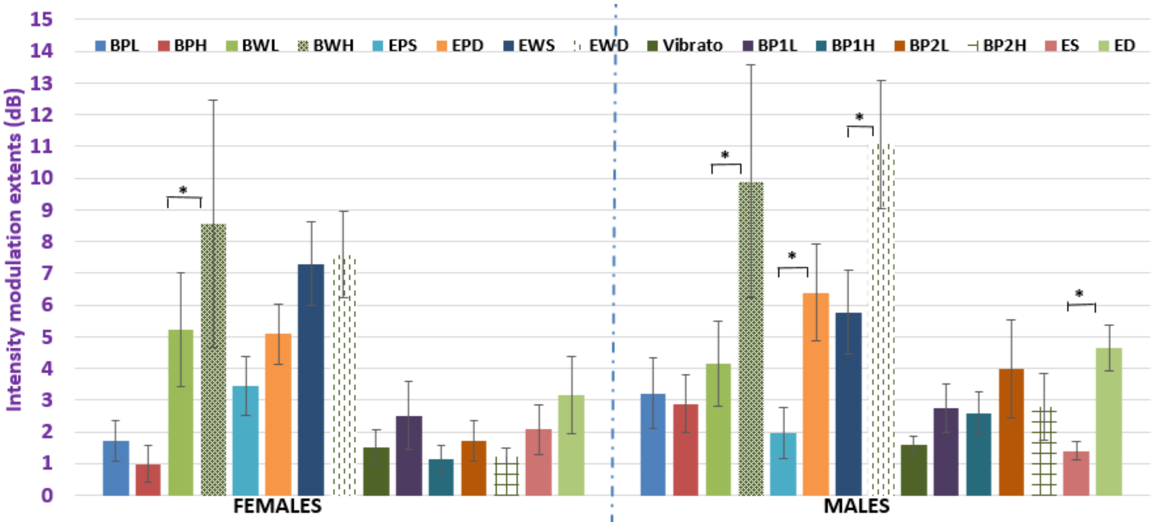

Figure 37. Mean intensity modulation extents (in dB) and standard deviations during bleat, external epigastric pumping (EEP), and vibrato for speaking phonation, speaking whisper, and singing tasks. The levels are bleat phonation light (BPL), bleat phonation heavy (BPH), bleat whisper light (BWL), bleat whisper heavy (BWH), EEP phonation shallow (EPS), EEP phonation deep (EPD), EEP whisper shallow (EWS), EEP whisper deep (EWD), vibrato, bleat low pitch light (BP1L), bleat low pitch heavy (BP1H), bleat high pitch light (BP2L), bleat high pitch heavy (BP2H), EEP shallow (ES), and EEP deep (ED).The asterisk (*) indicates p<0.05 between the pairs indicated

Other measures

Oral pressures (cm of H_2O) and intensities (dB). The means and standard deviations of intensities (dB) and oral air pressures (cm of H_2O) for different conditions were reported in Table 32 and Table 33, respectively. Within each sub-task, the intensities (dB) were seen to increase from piano to forte in singing tasks. Within the subjects, in general, intensities (dB) were increased from lighter to heavier bleat. But there was no significant rise in intensities from shallow to deep conditions during external epigastric pumping. The ANOVA model explains 75.2% of the variation in oral pressures. The summary of ANOVA results are given in Table 34, and it shows a statistically significant main effect in gender, $F(1, 201)=20.44$, $p < 0.01$, partial $\eta^2=0.09$; tasks, $F(2, 201)=24.7$, $p < 0.01$, partial $\eta^2=0.2$; and levels of sub-tasks, F(15, 201)=33.48, $p < 0.01$, partial $\eta^2=0.71$. An interaction effect was significant between gender and tasks, $F(2, 201)=6.14$, $p < 0.01$, partial $\eta^2=0.06$. The pairwise post-hoc analysis shows statistically significantly higher pressures (cm of H2O) in singing tasks in comparison with speaking phonation and whisper [M=9.7 dB, SD=0.61, $p < 0.01$]. Females have greater oral pressures than males and is statistically significant [Females: M=9.7 dB, SD=0.62 dB, $p < 0.01$]. In straight tones and vibrato, the oral pressures increased from piano to forte. During bleat (speaking phonation, whisper, and singing: P1 and P2), the heavier conditions had higher oral pressures than lighter, and the highest pressures were seen in high pitch heavy bleat (BP2H) [M=15.53 dB, SD=0.81 dB, $p < 0.01$].

In both P1 and P2 conditions, higher lung pressures were required to produce heavier bleats than light. This might also indicate why intensities (dB) increase from lighter to heavier bleats. The F0 bleat extents were also higher in heavier conditions, and this could be due to greater lung pressures. The intensity bleat extents were, however, seen to be lower in heavier bleat conditions, and this may be due to increased glottal adduction. Therefore, due to greater lung pressures, average intensity (dB) increased from lighter to heavier bleat, whereas intensity modulations during bleat did not primarily depend on subglottal pressure but on laryngeal adductory functioning. For example, Figure 32 shows that increase in glottal adduction (from BPL - BPH, BP1L - BP1H, and BP2L - BP2H) decreases the intensity bleat extent, and posterior glottal activity (during whisper) and increase in glottal area increases the intensity bleat extent. Similarly, increase in average intensities (dB) secondary to increase in subglottal pressures were seen in vibrato, but intensity vibrato extents were seen to be lower due to its dependence on laryngeal adductory functioning.

Average airflow (cm^3/s) and percent airflow (%). Table 35 gives the means and standard deviations of average airflow (cm^3/s) for all the speaking and singing tasks. The ANOVA model explains 72% of the variation in laryngeal airflow. Table 36 gives the summary results of ANOVA, and it shows a statistically significant main effect in tasks, $F(2, 3078)=412.3$, $p < 0.01$, partial $\eta^2=0.21$; sub-tasks, $F(7, 3078)=13.36$, $p < 0.01$, partial $\eta^2=0.03$; and levels of sub-tasks, $F(20, 3078)=16.53$, $p < 0.01$, partial $\eta^2=0.1$. An interaction effect was significant between gender and tasks, $F(2, 3078)=3.4$, $p < 0.05$, partial $\eta^2=0.002$; gender and sub-tasks, $F(7, 3078)=11.43$, $p < 0.01$, partial $\eta^2=0.025$, and gender and level of sub-tasks, $F(20, 3078)=6.67$, $p < 0.01$, partial $\eta^2=0.042$. The post-hoc pairwise comparisons did not show statistically significant differences in sub-tasks and levels of sub-tasks. Overall, the average airflow (cm^3/s) was seen statistically significantly higher in females than in males [M=201.57 cm^3/s, SD=26.84 cm^3/s, $p < 0.01$]. Statistically significantly higher airflows were seen in speaking whisper tasks in comparison with speaking phonation and singing [M=379.5 cm^3/s, SD=54.06 cm^3/s, $p < 0.01$]. There was no significant difference in airflows within different levels of sub-tasks, except higher airflows in normal whisper than in normal phonation (speaking task) [Females: M=560.74 cm^3/s, SD=56.6 cm^3/s, $p < 0.01$; Males: M=455.14 cm^3/s, SD=55 cm^3/s, $p < 0.01$], in high pitch heavy bleat than high pitch light [Females: M=231.51 cm^3/s, SD=16.8 cm^3/s, $p < 0.01$; Males: M=177.31, SD=9.47 cm^3/s, $p < 0.01$], and heavy bleat during whisper [Females: M=505.04 cm^3/s, SD=77.1 cm^3/s, $p < 0.01$; Males: M=335.23 cm^3/s, SD=50 cm^3/s, $p < 0.05$].

Table 37 gives the means and standard deviations for the ratio of the airflow modulation extent and the corresponding average airflow, in percent [[(airflow modulation extents)/ (average airflow)]*100] during bleat, external epigastric pumping, and vibrato. The ANOVA model explains 78% of the variation in percent airflow. Table 38 shows the summary of ANOVA results, and it shows a significant main effect in gender, $F(1, 32)=13.71$, $p < 0.01$, partial $\eta^2=0.3$; task, $F(2, 32)=17.43$, $p < 0.01$, partial $\eta^2=0.52$; and sub-tasks, $F(3, 32)=11.03$, $p < 0.01$, partial $\eta^2=0.51$. Interaction between factors was not significant, $F(10, 32)=0.5$, $p=0.9$, partial $\eta^2=0.14$. Males had statistically significantly larger percent airflows than females [M=67.5%, SD=52%, $p=0.02$]. Overall, bleating tasks were seen to have statistically significant percent airflows compared to vibrato and external epigastric pumping [M=91.5%, SD=47%, $p < 0.01$]. The percent airflows were statistically significantly higher in external epigastric pumping tasks than vibrato [M=37.05%, SD=21.7%, $p < 0.05$; vibrato: M=22.7%, SD=8.3%]. In vibrato, the percent airflows were in the range of approximately 20.5 – 25%, and there was no significant difference when compared among two pitches and three loudness levels. In external epigastric pumping tasks, the percent airflows were approximately in the range of 20.7 – 32.5% during shallow pumping and 45 – 52.5% during deep pumping conditions. Overall, the percent airflows were statistically significantly higher in deep pumping than shallow [M=49%, SD=23%, $p=0.0052$]. There was no significant difference observed between whisper and phonation in percent airflows. For bleat, the percent airflows were approximately in the range of 50.5 – 113% in lighter bleat, and 82 – 126% in heavier bleats. Speaking whisper Sp-W) tasks were found to have highest percent airflows followed by singing (Sg) tasks [Sp-W: M=104%, SD=55%; Sg: M=98%, SD=45.2%; Speaking phonation: M=67%, SD=38.2%, $p > 0.05$]. The highest percent airflows were seen in heavy bleat during whisper followed by lighter bleating at high pitch (P1) in singing tasks [Sp-W: M=127%, SD=62%; Sg: M=113%, SD=52.4%]. None of the differences were statistically significantly different due to larger standard deviations.

Higher percent airflows in males support larger airflow modulation extents in them during bleat, external epigastric pumping, and vibrato. Even though average airflows were seen to be higher in females, they tend to have lower percent airflows in comparison with male subjects. The average airflows were seen to be highest in whisper, but the percent airflows during whisper were only higher in bleat, with no significant difference in external epigastric pumping. This supports a stronger positive correlation between whisper and bleat, and this combination showed larger airflow and intensity modulation extents, larger average airflows, and greater percent airflows. Although in external epigastric pumping the percent airflows increased from shallow to deep pumping, it was not statistically significant. This indicates that airflow pulses generated due to increase in subglottal pressure are not enough to produce larger modulation extents. Neither average airflows nor percent airflows were seen to be higher during vibrato, suggesting that it is not as purely adductory as bleat is, nor requires greater lung pressures to generate vibrato.

Table 32

Means and standard deviations of intensities (dB) speaking and singing tasks

CONDITIONS	F1 (dB)	SD	F2 (dB)	SD	M1 (dB)	SD	M2 (dB)	SD
NP	67.2	1.15	77.92	0.63	54.03	4.23	70.65	0.88
NW	43.64	1.46	70.36	3.65	34.32	1.48	47.83	1.14
BPL	64.23	1.2	65.56	1.26	54.7	1.31	63.49	2.29
BPH	71.51	0.66	76.81	0.3	61.19	1.78	73.93	0.19
BWL	40.63	0.6	49.91	1.66	42.45	3.81	46.73	1.74
BWH	45.53	1.13	62.87	0.79	48.92	0.69	55.64	0.21
EPS	69.83	0.83	66	1.22	73.9	0.48	73.03	1
EPD	70.69	1.47	67.59	0.52	73.59	0.5	73.37	0.2
EWS	44.83	1.71	67.5	0.17	44.96	2.22	51.29	0.33
EWD	46.44	1.98	68.28	4.47	46.25	0.62	52.51	1.33
NP1L1	59.98	2.27	65.36	1.83	58.75	1.82	59.87	2.5
NP1L2	68.01	1.32	71.7	0.86	62.88	1.87	66.71	1.23
NP1L3	71.67	0.21	72.71	0.34	68.01	0.3	67.87	0.91
NP2L1	68.39	0.55	72.75	0.35	65.59	2.31	68.41	1.68
NP2L2	77.39	0.54	77.84	0.9	72.86	1.47	74.79	1.48
NP2L3	81.01	0.48	80.52	0.46	78.36	0.78	78.08	0.86
VP1L1	57.38	1.49	61.86	1.56	57.66	0.87	61.73	1.91
VP1L2	67.46	2.13	68.9	1.13	62.53	0.78	65.67	1.37
VP1L3	70.26	1.01	71.9	0.77	67.73	0.5	66.08	0.94
VP2L1	66.54	1.36	71.76	1.13	65.45	4.36	66.94	4.44
VP2L2	77.34	0.63	77.77	0.8	72.93	0.95	75.54	2.2
VP2L3	79.87	0.78	79.29	0.82	78.81	1.13	78.45	0.49
BP1L (Sing)	58.38	1.88	62.81	5.73	62.06	0.64	61.14	0.11
BP1H (Sing)	74.95	0.87	61.95	1.09	67.64	1.08	66.55	1.18
BP2L (Sing)	67.22	2.97	70.05	1.96	60.44	0.67	63.1	3.39
BP2H (Sing)	78.75	0.96	76.94	1.03	74.43	3	77.09	0.37
ES (Sing)	79.82	0.33	76.49	1.2	76.84	1.39	68.61	0.11
ED (Sing)	78.95	1.07	76.63	0.84	77.66	1.12	68.69	0.79

Note: NP & NW- normal phonation and whisper; BPL & BPH- bleat phonation light and heavy; BWL & BWH- bleat whisper light and heavy; EPS & EPD- epigastric pumping phonation shallow and deep; EWS & EWD- epigastric pumping whisper shallow and deep; NP1L1-NP2L3: straight tones two pitches and three loudness levels; VP1L1-VP2L3: vibrato two pitches three loudness levels; BP1L-BP2H: bleat two pitches light and heavy; ES & ED- epigastric pumping shallow and deep

Table 33

Average oral pressure means (cm of H_2O) and standard deviations of speaking and singing tasks at different levels of sub-tasks (excludes external epigastric pumping tasks)

CONDITIONS	F1	SD	F2	SD	M1	SD	M2	SD
NP	7.41	0.4	9.6	0.38	4.63	0.2	9.43	0.56
NW	7.55	0.74	8.3436	0.78	4.32	0.43	8.04	0.42
BPL	7.79	0.93	6.62	0.53	4.7	0.39	7.82	0.65
BPH	10.91	0.6	11.79	0.9	5.14	0.63	10.19	0.31
BWL	6.39	0.4	4.98	0.95	4.39	0.82	8.21	0.87
BWH	9.7	0.85	9.05	0.38	7	1.42	10.57	0.53
NP1L1	5.07	0.75	7.24	0.1	4.45	0.8	7.51	0.79
NP1L2	6.16	0.36	10.97	0.54	5.18	0.34	9.05	0.51
NP1L3	8.52	0.56	12.54	0.63	6.49	0.22	10.61	0.74
NP2L1	5.67	0.84	11.02	0.38	6.32	0.48	9.07	0.34
NP2L2	10.08	0.1	14.14	0.73	7.85	0.31	12.61	0.87
NP2L3	13.46	0.97	15.72	0.51	10.51	0.06	16.38	0.15
VP1L1	4.29	0.34	7.75	0.46	4.75	0.53	6.05	1.42
VP1L2	6.4	0.51	10.13	1.36	5.55	0.19	7.63	0.25
VP1L3	7.28	0.39	12.56	0.51	7.13	0.16	9.24	0.45
VP2L1	6.2	0.68	10.56	0.72	6.38	1.24	8.19	0.43
VP2L2	10.15	1.48	13.89	1.24	9.44	1.15	13.66	0.72
VP2L3	14.21	0.19	16.49	0.07	14.11	0.94	17.55	0.35
BP1L (Sing)	6.57	0.25	8.35	1.78	5.39	0.15	8.85	1.62
BP1H (Sing)	11.62	0.63	10.34	0.08	8.16	0.4	11.8	0.34
BP2L (Sing)	8.58	0.51	6.03	0.55	5.23	0.18	8.65	0.8
BP2H (Sing)	17.88	1.13	16.56	0.25	11.27	2.08	16.39	0.51

Note: NP & NW- normal phonation and whisper; BPL & BPH- bleat phonation light and heavy; BWL & BWH- bleat whisper light and heavy; NP1L1-NP2L3: straight tones two pitches and three loudness levels; VP1L1-VP2L3: vibrato two pitches three loudness levels; BP1L-BP2H: bleat two pitches light and heavy

Table 34

ANOVA summary table for oral pressures

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Gender	1	77.636558	77.636558	20.44	**<.0001**
Task	2	187.559661	93.779830	24.70	**<.0001**
gender*task	2	46.608301	23.304151	6.14	**0.0026**
Sub-task	2	14.404458	7.202229	1.90	0.1528
gender*sub(task)	2	1.311556	0.655778	0.17	0.8415
level(task*sub)	15	1906.927449	127.128497	33.48	**<.0001**
gender*level(task*sub)	15	81.197557	5.413170	1.43	0.1379

Table 35

Means (cm^3/s) and standard deviations of average airflow for all the tasks

CONDITIONS	F1 (cm^3/s)	SD	F2 (cm^3/s)	SD	M1 (cm^3/s)	SD	M2 (cm^3/s)	SD
NP	185.43	12.74	114.35	15.55	136.67	11.69	111.64	17.18
NW	731.57	47.51	389.91	65.62	293.98	6.86	616.3	103.61
BPL	127.84	37.65	187.81	26.35	153.27	36.67	405.58	16.21
BPH	104.498	30.15	160.39	9.35	114.44	3.32	156.21	25.96
BWL	356.27	38.31	197	18.49	450.13	68.86	167.34	24.34
BWH	610.9	78.44	399.17	75.69	394.08	61.12	276.38	38.65
EPS	155.45	24.01	118.18	7.95	136.87	9.59	122.01	3.78
EPD	145.78	17.82	121.75	12.05	149.17	29.06	144.93	9.45
EWS	356.27	38.31	236.61	99.11	399.05	81.17	288.07	14.32
EWD	576.83	65.37	210.72	84.58	382.6	35.76	256.8	35.1
NP1L1	148.23	23.09	146.88	14.14	195.8	8.3	147.58	28.94
NP1L2	172.29	8.56	132.94	9.75	179.91	13.95	117.77	6.21
NP1L3	171.49	4.46	124.04	13.44	172.66	18.3	114.02	9.26
NP2L1	100.54	4.56	290.67	11.66	139.93	17	121.05	47.95
NP2L2	128.4	11.21	255.92	14.5	155.87	11.08	142.29	20.71
NP2L3	160.21	11.29	281.83	19.59	189.63	19.95	152.83	42.55
VP1L1	126.21	31.22	121.24	20.36	147.89	15.61	122.33	18.47
VP1L2	124.8	8.86	93.83	2.57	153.51	16.27	94.31	15.28
VP1L3	137.72	14.7	92.24	16.14	148.25	6.81	90.96	6.41
VP2L1	40.71	12.13	245.4	21.35	132.74	53.7	127.26	12.46
VP2L2	91.43	23.92	224.87	16.06	152.65	10.77	174.63	13.47
VP2L3	120.7	20.21	241.43	18.79	213.1	16.14	171.04	12.3
BP1L (Sing)	102.04	43.51	204	42.13	145.85	28.52	151.74	4.21
BP1H (Sing)	77.17	13.51	181.85	3.96	158.98	18.41	141.4	38.91
BP2L (Sing)	57.83	10.74	289.83	65.24	98.31	2.65	94.97	15.63
BP2H (Sing)	105.91	2.36	357.11	31.16	118.17	18.94	236.44	0.002
ES (Sing)	138.31	23.87	205.5	45.27	102.85	12.63	107.31	11.2
ED (Sing)	128.9	21.55	178.47	42.17	112.88	12.8	116.7	3.48

Note: NP & NW- normal phonation and whisper; BPL & BPH- bleat phonation light and heavy; BWL & BWH- bleat whisper light and heavy; EPS & EPD- epigastric pumping phonation shallow and deep; EWS & EWD- epigastric pumping whisper shallow and deep; NP1L1-NP2L3: straight tones two pitches and three loudness levels; VP1L1-VP2L3: vibrato two pitches three loudness levels; BP1L-BP2H: bleat two pitches light and heavy; ES & ED- epigastric pumping shallow and deep

Table 36

Summary of ANOVA results for average airflow

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Gender	1	256.086	256.086	0.06	0.8125
Task	2	3751524.641	1875762.320	412.30	**<.0001**
gender*task	2	30964.377	15482.189	3.40	**0.0334**
Sub-tasks	7	425436.134	60776.591	13.36	**<.0001**
gender*sub(task)	7	364014.203	52002.029	11.43	**<.0001**
Level(task*sub)	20	1503818.306	75190.915	16.53	**<.0001**
gender*level(task*sub)	20	607044.321	30352.216	6.67	**<.0001**

Table 37

Percent airflow values for bleat, external epigastric pumping, and vibrato

CONDITIONS	**F1**	**F2**	**M1**	**M2**
BPL	36.73	31.59	83.32	51.32
BPH	44.74	52.35	83.86	147.79
BWL	26.4	121.15	70.37	105.08
BWH	48.62	144.77	115.96	197.56
EPS	17.49	15.21	38.23	20.21
EPD	29.45	28.88	90.47	61.15
EWS	45.99	19.26	47.61	16.97
EWD	29.31	44.79	76.25	43.62
VP1L1	13.85	31.62	24.68	20.81
VP1L2	17.75	33.29	12.87	20.65
VP1L3	18.15	37.09	24.82	24.9
VP2L1	48.2	15.09	18.57	26.81
VP2L2	25.81	17.28	21.55	15.5
VP2L3	18.49	13.74	21.9	20.44
BP1L (Sing)	47.58	90.59	56.56	151.67
BP1H (Sing)	53.49	104.9	82.37	173.94
BP2L (Sing)	77.04	69.57	121.55	183.52
BP2H (Sing)	40.35	69.42	143.65	100.55
ES (Sing)	23.14	8.48	30.34	20.98
ED (Sing)	36.21	14.94	73.5	56.67

Note: BPL & BPH- bleat phonation light and heavy; BWL & BWH- bleat whisper light and heavy; EPS & EPD- epigastric pumping phonation shallow and deep; EWS & EWD- epigastric pumping whisper shallow and deep; VP1L1-VP2L3: vibrato two pitches and three loudness levels; BP1L-BP2H: bleat two pitches light and heavy; ES & ED- epigastric pumping shallow and deep

Table 38

Summary of ANOVA results for percent airflows

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Gender	1	8218.12804	8218.12804	13.71	**0.0008**
Task	2	20908.69916	10454.34958	17.43	**<.0001**
gender*task	2	2440.88039	1220.44020	2.04	0.1472
Sub-task	3	19850.04023	6616.68008	11.03	**<.0001**
gender*sub(task)	3	2262.72863	754.24288	1.26	0.3053
Level(task*sub)	10	10020.27537	1002.02754	1.67	0.1313
gend*level(task*sub)	10	3021.03192	302.10319	0.50	0.8746

Vocal tract constriction changes. Average airflow (cm^3/s), F0 (ST), and intensity (dB) measures were compared for the /ala:la:…/ utterances, i.e., between a narrow oral cavity [consonant (C) production - /l: /] and a wide oral cavity [vowel (V) production - /a/], during phonation and whisper, and the values are reported in Table 39. The measures tend to decrease when the tongue rises and touches the alveolar ridge to produce the consonant /l/, and increases when the tongue lowers to produce the vowel /a/. During phonation, the average airflow was 132.5 cm^3/s, and the average airflow modulation extent between vowel and consonant was 12.5 cm^3/s. Therefore, the percent airflow was 9.4%. The average intensity modulations between vowel and consonant was 3.2 dB. The average F0 modulations in females was 0.14 ST and in males was 0.17 ST. During whisper, the average airflow was 391.33 cm^3/s, and the average airflow modulation extent between vowel and consonant was 57.5 cm^3/s. Therefore, the percent airflow was 14.7%. The average intensity modulations between vowel and consonant was 8 dB. The results show that airflow and intensity could be significantly modulated by changing vocal tract constriction. Newly trained singers (amateurs) might produce vibrato with an additional support of changing vocal tract constriction as it is easy to manipulate the shape of the oral and pharyngeal structures. The less or no modulations in F0 during vocal tract changes shows that they are primarily laryngeal mediated.

Table 39

Airflow (AF), intensity, and F0 values at vowel (V) and consonant (C) production during phonation (P) and whisper (W)

Subject	**AF_V (cm^3/s)**	**SD**	**AF_C (cm^3/s)**	**SD**	**Intensity_V (dB)**	**SD**	**Intensity_C (dB)**	**SD**	**F0_V (ST)**	**SD**	**F0_C (ST)**	**SD**
F1-P	168.59	13.86	139.91	19.6	66.66	0.25	61.99	0.3	36.45	0.1	36.35	0.15
F2-P	127.24	5.72	112.43	8.17	77.32	0.53	73.34	0.51	36.47	0.13	36.3	0.13
M1-P	124.01	11.96	121.88	9.21	66.86	0.69	64.77	0.92	23.6	0.05	23.58	0.06
M2-P	134.93	13.56	130.68	8.73	75.55	0.21	73.52	0.77	24.03	0.3	23.71	0.35
F1-W	573.63	36.91	488.22	70.39	42.25	1.08	32.17	1.19				
F2-W	237.64	31.28	196.23	30.3	49.28	1.93	41.38	1.77				
M1-W	287.67	31.19	252.87	26.27	43.08	0.36	39.75	0.16				
M2-W	581.4	47.77	512.98	38.12	51.75	2.91	41.99	1.41				

Note: No F0 during whisper; V- Vowel (Wide oral cavity); C- Consonant (Narrow oral cavity)

CHAPTER IV. DISCUSSION

Study 1: Airflow Vibrato in Four Professional Singers

The purpose of this study was to expand the information available on airflow vibrato, motivated by the assumption that a more complete understanding of the production mechanism for vibrato would lead to a better understanding of laryngeal mechanics and pedagogical applications. This study is descriptive relative to understanding the phenomenon of airflow vibrato, and does not attempt to determine the specific causes of airflow vibrato (which is related more to Study 2).

Study 1 provides characteristics of airflow vibrato produced by four professional singers singing three pitches and three loudness levels. Results indicate that airflow vibrato is a real phenomenon, with strong correspondence to fundamental frequency (F0) vibrato. Airflow vibrato waveforms are more complex than F0 vibrato waveforms, however, and the greater complexity raises important questions about the causation of airflow vibrato.

RQ1. What are the general characteristics of airflow vibrato in Western classical singing? The general characteristics of F0 vibrato are rate, extent, regularity, and waveform shape (Sundberg, 1995). Similarly, airflow vibrato can also be characterized by rate, extent, regularity, and waveform shape (Figures 8 -11). Study 1 measured the first two characteristics of airflow vibrato and has included observations concerning the latter two. The rates of airflow vibrato ranged from 4.0 – 6.5 Hz (basically identical to the F0 vibrato rates), and a similar range was reported in the studies by Large and Iwata (1971) and Rubin et al. (1967). The airflow vibrato peak-to-peak extents ranged from 16 cm^3/s to 112 cm^3/s. This appears to be the first study to measure the airflow modulation extents during vibrato, and therefore there do not appear to be other studies with which to compare the quantitative results obtained here.

The similarities in airflow and F0 vibrato rates indicate their dependence on a similar subset of physiological variables. Although regularity and waveform shape were not specifically measured in this study, the airflow vibrato waveforms were seen to have a range from regular, essentially sinusoidal-looking waveforms to having an inconsistent irregularity to the waveforms, compared to relatively regular F0 vibrato waveforms. It is quite reasonable to assume that the complexity in the airflow vibrato waveform should be due to its sensitivity to subtle changes in laryngeal flow resistance (and thus related to glottal adduction, glottal area, and subglottal pressure).

The phase difference between airflow and F0 vibrato varied over a wide range in which airflow leads F0 vibrato predominantly. The phase difference between them ranged from 34^o to 197^o. Positive phase difference values indicate airflow leading F0 vibrato. Typically prominent peaks consistently near F0 vibrato peaks were chosen for phase measurements, neglecting the minor components of the more complex waveforms.

RQ2. Do airflow vibrato extent and F0 vibrato extent vary similarly within pitches and loudness levels in males and females? Airflow and F0 vibrato extents increased with a rise in pitch for all four subjects (Figure 16). The airflow vibrato extents more than doubled for three of the four subjects when the pitch rose from P1 to P2. Interestingly, despite an assumed smaller larynx, the airflow vibrato extent was larger for the two females than for the baritone (the tenor had similar values to the two sopranos). For the males, on average airflow vibrato extents increased from 30 cm^3/s to 75 cm^3/s from the lower to the higher modal pitch, and for females, increased from 47 cm^3/s to 94 cm^3/s (Figure 17). Increase in pitch was associated with a statistically significant difference within subjects and between males and females. Out of four subjects, three of them showed a tendency for slightly lower airflow vibrato extents (3 – 27

cm^3/s) with increase in loudness levels. This indicates that a rise in Ps may not be enough to increase the airflow vibrato extents. But raise in Ps and F0 are required to increase the airflow vibrato extents. Although airflow vibrato extents were larger for females, average airflow during vibrato production was seen to be higher in males (220 cm^3/s at P1 and 197.5 cm^3/s at P2) compared to females (154.5 cm^3/s at P1 and 132.5 cm^3/s at P2).

Contrary to an increase in pitch, when loudness levels were increased from piano to forte, there was no significant effect observed on the airflow vibrato extents for all the subjects (Figure 15). However, females had higher airflow vibrato extents for the three loudness levels when compared with the males (at L3: 94 cm^3/s for females, and 46 cm^3/s) and was statistically significant at forte. For males; again it is noted that the baritone had lower extent values than the two sopranos, but the tenor had similar values). The average airflows (cm^3/s) during vibrato did not change with increase in loudness levels. Usually, the glottal airflow increases with rise in Ps. But no change in average airflows with increase in Ps might suggest increase in glottal flow resistance.

The airflow vibrato extent value was less than the average airflow produced during the vibrato cycle. The percentage was defined as (airflow vibrato extent / average airflow)*100 and was 18% and 47% for males and females, respectively, at P1, and 38% and 56% at P2. When the two pitches were combined, at the piano loudness level, the percentage of laryngeal airflow during each vibrato cycle was 32.4% and 47% for males and females, respectively. Increase in loudness level from piano to mezzoforte did not change the percentage values significantly in females, 49.4% at L1, 48% at L2, and 59% at L3. In males, baritone did not show significant change in percentage airflows with increase in loudness, 15% at L1, 12% at L2, and 11.2% at L3. Whereas, in tenor, the percentage airflow was doubled from piano to mezzoforte, and came dropped down at forte (L1- 37.3%, L2- 65.13%, and L3- 31%). The average airflows were higher in males, and this could be due to larger laryngeal sizes. But larger percent airflows in females might be due to more frequent cycles (higher pitches).

The F0 vibrato extents were statistically significantly higher in P2 than in P1 for all thr subjects (Figure 19). For males, the F0 vibrato extent did not change significantly with increase in pitch, and was in the similar range from 1.52 – 1.67 ST. For females, the F0 vibrato extents significantly increased from 1.9 to 2.6 ST from low pitch to high pitch. Similar ranges (0.5 – 2.00 ST) were reported by Horii (1989), Prame (1997), Shipp et al. (1980), and Sundberg (1995). But lower extents of 0.25 – 0.5 ST were reported by Seashore (1932 and 1947). The higher F0 vibrato extents in females along with larger airflow vibrato extents and percent airflows, not only suggest greater relative CT activity change but also might suggest higher subglottal pressure, less laryngeal flow resistance, or more posterior glottal area variation. The increase in loudness levels did not significantly affect the F0 vibrato extents in both males and females (Figure 18). Interestingly, there was no specific trend due to increase or decrease in loudness level, and the effect was differently seen in each subject; e.g., the baritone showed an increase in F0 vibrato extent from loudness level L1 to L3, soprano-2 showed decreased F0 vibrato extent due to an increase in loudness, and the tenor and soprano-1 showed a slight increase in L2 and a slight decrease in L3 (Figure 18). Thus, increase in loudness levels showed different effects on F0 vibrato extents on subjects. This might indicate F0 vibrato extents do not primarily depend on subglottal pressure (in females, 11.26 cm of H_2O at L1, 15.43 cm of H_2O at L2, and 19 cm of H_2O at L3; in males, 12.35 cm of H_2O at L1, 15.69 cm of H_2O at L2, and 21 cm of H_2O at L3) but more on a combination with laryngeal level activity.

In the Dromey et al. (1992) study, the difference between the EGG Speed Quotient values was greatest for their softest productions but was not affected by change in pitch, whereas in the current study the difference for the comparable measure, NRQ, did not appear to be significant across either loudness levels, but had relatively greater negative values for the lowest pitch compared to the two higher pitches (Figure 25) (across subjects). The values did not differentiate the peaks and valleys of the vibrato cycles (Figure 25). Thus, this aspect of vocal fold dynamics, along with the non-differentiating EGGW values at the peaks and valleys (Figure 24), do not appear to be discerning features, suggesting that there may be little difference in membranous glottal adduction and changing vocal fold contact behavior throughout the vibrato cycles for these singers. Essentially "through elimination", the changing airflows during airflow vibrato may thus suggest posterior glottal area variation during vibrato. Sundberg (1995a) shows a singer whose airflow during singing varies by about 100 cm^3/s, attributed to "ad/abduction undulation in the glottis" (p. 49). This example also suggests that the adduction mechanism may include posterior glottis area variation. Thus, the posterior glottal area variation to create the relatively large airflow vibrato is a hypothesis that needs to be tested.

RQ3. Is there a relationship between airflow vibrato rate and F0 vibrato rate? The airflow and F0 vibrato rates were seen to have a similar range of 4.5 – 6.0 Hz. The rates were not affected by change in pitch and loudness levels. They tended to maintain similar vibrato rates across all nine conditions. A similar range (4.9 – 6.5 Hz) of F0 vibrato rates were reported by DeJonckere (1995), Rubin et al. (1967), Seashore (1932 and 1947), Shipp et al. (1980), Sundberg (1995), , and Titze et al. (2002). These studies also support the current study's F0 vibrato rates which were not affected by change in pitch and loudness levels.

The airflow vibrato rates essentially coincided with F0 vibrato rates. The relation between F0 vibrato rates and airflow vibrato rates was seen to be moderate to strong (R^2=0.75). It is expected that the relationship found here is weaker than it actually was, due to the necessity of measuring only 3 to 4 vibrato cycles for each token. This small number often did not allow high accuracy of the "actual" rate that 8 to 10 vibrato cycles would have given. The question arises, Could there be a mechanism that would produce an airflow vibrato rate different from an F0 vibrato rate? It seems quite unlikely that there is such a mechanism.

Other observations for Study 1. Causative factors are most likely quite different between airflow vibrato and F0 vibrato. F0 vibrato should be dependent on vocal fold effective stiffness, length, and mass changes throughout the vibrato cycle, whereas airflow vibrato should be most sensitive to variations in the laryngeal airflow resistance (more flow with less resistance due to greater glottal area) and subglottal pressure (more flow with greater subglottal pressure). Both F0 vibrato and airflow vibrato may be dependent on vocal fold length change, however, suggesting that a subtle length change should raise the F0 value as well as increase glottal area, raising the airflow value, and thus, F0 vibrato and airflow vibrato should be in phase with each other. The results of this study and the numerous figures of this report strongly indicate that indeed airflow vibrato is synchronized with F0 vibrato, with airflow vibrato typically leading F0 vibrato. However, this study does not appear to suggest the specific causation of the timing difference between the airflow vibrato and F0 vibrato.

In addition, when one examines the extent of airflow change within an airflow vibrato cycle, it would appear that simple and subtle vocal fold lengthening should not result in airflow vibrato extents that range from 60 cm^3/s to over 100 cm^3/s. This size of airflow extent suggests change in glottal adduction and/or change in subglottal pressure to account for much of the airflow vibrato extent. The EGGW measure was used as a possible indicator of glottal adduction, but its values were not statistically different between the peaks and valleys of the airflow vibrato waveform. That would tend to discount gross glottal adduction, and leave subglottal pressure variation as a primary cause. However, airflow vibrato extent did not vary systematically with increases in loudness, which should be governed by relatively large increases in subglottal pressure, and thus airflow vibrato may not be highly dependent on subglottal pressure. That is, if airflow vibrato extent increased with loudness, subglottal pressure would be suspected to play a role in altering the extent, but since extent was not increased overall, subglottal pressure may not be a primary underlying factor even within the vibratory cycle.

Thus, there is therefore a return to the possibility of variation in the posterior glottal area as a direct source of airflow vibrato. The posterior glottal area was not viewed nor measured in this study. There is a logical reason to suspect the posterior glottis relative to the quality of the voice produced by the professional Western classical singer. That is, if a singer wishes to preserve the sound quality produced by the larynx, it is rather doubtful that the singer would choose to alter the anterior glottal adduction a great deal, unless the person is intentionally producing an ornament such as trillo in which glottal adduction appears to be the dominant factor (Hakes et al., 1988; 1987) (typically a singing student attempts to get rid of this “bleat” vibrato behavior as he or she is developing a “smooth” vibrato). Thus, it is hypothesized that the posterior glottal area varies in such a manner that it creates airflow vibrato. Because airflow vibrato and F0 vibrato are often synchronized with each other, it is further hypothesized that as the cricothyroid (CT) and vocalis (VOC) muscle contraction levels alter to govern vocal fold tissue tension to change the fundamental frequency, the interarytenoid muscles are also changing in a synchronized manner with the CT and VOC. The phase delays between airflow vibrato and

F0 vibrato constitute another area of needed explanation, but may relate to the phasing between the vocal fold lengthening mechanism (CT and VOC) and the posterior adductory system (the interarytenoid muscles, or the more complicated antagonistic actions of the adductory system in general).

Some other interesting findings also need valid explanations. (1) What explains the complexities of the airflow vibrato cycle? That is, how can an airflow vibrato cycle (a) have double or triple peaks, (b) greatly changing flow patterns across just a few contiguous cycles, or (c)even have flat portions when the F0 vibrato continues with its regular nearly-sinusoidal changes? (2) The airflow vibrato extent tended to be greater for the female singers than the male singers, by about 25 cm^3/s. Is this due to more cycles per second and a relatively larger posterior glottal opening for the females? (3) Airflow vibrato extent was greater for the middle pitch (P2) than for the lowest pitch (P1) across the singers and loudness levels. Do longer vocal folds (greater glottal area on average) and higher subglottal pressures for the higher pitch generate the difference in the airflow vibrato extent?

The second study of this dissertation addresses the question of “What are possible causes of airflow vibrato?” This is a logical outgrowth of Study 1 that explored the descriptions of airflow vibrato but did not explain its causation. Study 2 will not complete the task of finding causative factors, but should shed some light on the subject.

Study 2: Sources of Airflow Vibrato

The purpose of Study 2 was to investigate different possible sources that may cause modulations in airflow resembling vibrato. The literature review suggested two main sources that lead to airflow modulations (and also modulations in F0 and intensity) resembling vibrato. The first source was bleat, which is primarily produced by rapid repeated adductory-abductory action of the glottis, leading to laryngeally-mediated F0, airflow, and intensity modulations. The second source was subglottal pressure variation, typically achieved in reported research through pushing on the chest wall. Study 2 used both bleating and chest wall pumping to support an adductory-source and a pulmonary source (Ps change), respectively, to induce airflow variations. Relative to chest wall pumping, this study used external epigastric pumping to move the diaphragm and change the lung pressure accordingly (Vennard, 1967). This lead to changes in F0, intensity, and airflow, due to subglottal pressure variation.

Another source that was hypothesized to cause changes in airflow was vocal tract constriction changes (typically relegated to timbre vibrato due to vocal tract shaping variation as seen with tongue, jaw, and other structures oscillating at the vibrato frequency). The airflow would change significantly above the glottis only if the constriction were narrow or closed. In Study 2, /al:al:a.../ productions were used, where the tongue touches the alveolar ridge and hard palate during the consonant /l/ production, and therefore the amount of air going through the oral cavity would be less in comparison to airflow during vowel /a/. The findings suggested that there was no effect on the airflow vibrato due to the relatively small additional airflow resistance when the tongue was placed high for the /l/.

In Study 2 the speaking tasks of bleat (adductory change maneuver), external epigastric pumping (Ps change maneuver), and vocal tract constriction changes included not only phonation but also whisper. Whisper was studied as it is characterized by no vocal fold vibration but with an open posterior glottis, and thus the airflow modulations due to imposed bleat and external epigastric pumping would be purely flow through the posterior glottis (and perhaps a portion of the non-moving anterior glottis; Sundberg et al., 2010). Thus, the use of whisper may help help to test the hypothesis made at the end of Study 1 that the posterior glottis variation, or merely the presence of the posterior glottis may account for much of the airflow vibrato variations. That is, if airflow varied due to either bleating or epigastric pumping, then this may be a reasonable cause of airflow vibrato.

Study 2 provides the airflow results for the production of normal vibrato, bleat (adductory gesture), and external epigastric pumping (Ps gesture) produced by four non-professional highly trained amateur singers.

RQ4. Does airflow vibrato rate differ from airflow bleat rate and external epigastric pumping rate in male and female singers? Study 2 found that the airflow vibrato rates were statistically significantly slower than the airflow bleat rates. The range of airflow vibrato rates was 5.07 – 6.17 Hz, and was similar to Study 1 (4.5 – 6.0 Hz). The airflow bleat rates ranged from 9.03 – 12.05 Hz for the singing tasks and 8.19 – 11.94 Hz for the speaking tasks. Airflow modulation rates of bleat and vibrato were not affected by changes in pitch and loudness level. During conditions of whisper + heavier bleat, the rates were slightly slower than the bleating rates with phonation, and this was only due to difficulty in bleating heavily with whisper.

Titze et al. (2008) found that PCA and LCA/TA are primarily involved in giggle, a phenomenon similar to trillo and bleat. The repeated voice onsets and offsets were generated by alternate raising and lowering the activity of the PCA and LCA/TA muscles. Figure 1 in Titze et al.'s study showed that the activation of PCA is in line with relaxation of TA, and vice-versa. This showing that they are out of phase. They mentioned that the faster rates of giggle were matched closely with twitch activation times of these intrinsic laryngeal muscles.

The findings for bleat in this study, where the bleat frequency can be approximately double that of normal vibrato, suggest that the bleat-like activity attributed to adductory-abductory movement may account for variations in the airflow vibrato seen in Study 1 where there are double pulses seen within the airflow vibrato cycle. See for example Figures 10, 11, and 13, where there are two pulses within the airflow vibrato cycle. In these kinds of cases, the primary variation of airflow that defines airflow vibrato appears to be supplemented with a secondary source, and the adductory-oriented bleat-like phenomenon may be the cause, even though it is not heard as a bleat-produced sound.

The external epigastric pumping was used with the assumption that it essentially directly causes changes in subglottal pressure which further causes changes in F0, intensity, and airflow. The airflow modulation rates during external epigastric pumping were created by the rates provided by the experimenter as she pushed on the subject's epigastric region, and ranged from 5.49 – 7.37 Hz. Thus, the rate per se does not differentiate subglottal pressure as a source of the variations of airflow vibrato during a vibrato cycle.

RQ5. Does F0 vibrato rate differ from F0 bleat rate and F0 external epigastric (upper abdominal) pumping rate in males and females? Like the airflow vibrato rates, the F0 vibrato rates were statistically significantly slower than the F0 bleat rates. The range of F0 vibrato rates was 5.05 – 6.13 Hz, similar to Study 1 (4.5 – 6.0 Hz). The F0 bleat rates ranged from 9.0 – 12.35 Hz for both speaking and singing tasks, and were similar to airflow bleat rates. The F0 vibrato and bleat rates were not affected by change in pitch and loudness level. The faster rates of F0 and airflow in bleat were most likely due to involvement of the adductory-abductory mechanism of intrinsic laryngeal muscles primarily. The F0 and airflow vibrato rates were similar in range and their correlation was moderate to strong ($R^2=0.67$) which was lower than observed in Study 1 ($R^2=0.75$). This may indicate that professional singers have a better correlation between airflow and F0 during vibrato than in non-professional singers, but it is again mentioned that a limitation of rate measures is the small number of cycles used to obtain the measure, and for a more irregular signal such as the airflow vibrato, it is more difficult to make a valid measure. The correlation between airflow and F0 rate during bleat and external epigastric pumping showed strongest correlations (R^2=0.86 for bleat and R^2=0.87 for external epigastric pumping). This indicates that the strongest correlation exists between F0 and airflow vibrato rates if the source of production is either primarily Ps or glottal adduction.

RQ6. Does airflow vibrato extent differ from airflow bleat extent and airflow external epigastric (upper abdominal) pumping extent in males and females? Airflow vibrato extents were statistically significantly lower than airflow bleat extents during phonation and whisper, and airflow external epigastric pumping extents during whisper. The airflow external epigastric pumping extents during phonation were observed to be similar or slightly higher than airflow vibrato extents. Because of the similarities between the external epigastric pumping extents and airflow vibrato extents, the resulting suggestion would be that lung pressure variations may be sufficient to produce the airflow vibrato extents seen in both Study 1 and Study 2, supporting the lung pressure hypothesis for vibrato production.

Both males and females had similar airflow vibrato extents in Study 2, whereas females showed statistically significantly higher airflow vibrato extents than males in Study 1. In Study 2, the airflow vibrato extents were not significantly affected by change in pitch and loudness levels, whereas in Study 1, although increase in loudness level did not affect the airflow vibrato extent, the higher pitch had statistically significantly larger airflow vibrato extents compared with low pitch in both males and females. The average airflow vibrato extents at higher pitch were seen to be statistically significantly larger in professional singers (Study 1; for P2, females- 94 cm^3/s, males- 75 cm^3/s) compared with non-professional singers (Study 2; for P2, females- 29 cm^3/s, males- 33 cm^3/s). Thus, the level of training may affect the airflow vibrato extent, where more training and experience may move the extent to greater values on higher pitches.

The largest airflow modulation extents were seen for whisper and bleat (about 380 cm^3/s). Regarding bleat, these extents were undoubtedly created by greater adductory-abductory changes (predominantly PCA and LCA/TA). Thus, very large alterations in airflow vibrato extent may be caused by, again, posteriorly-located changes in glottal area.

During external epigastric pumping also, whisper tasks were seen to have larger airflow modulation extents, and this again indicates the participation of lung pressure to cause greater fluctuations in airflow during vibrato or simulated vibrato. Also, during external epigastric pumping the deeper pumping had larger airflow modulation extents compared with shallow pumping, suggesting that greater subglottal pressures will cause greater airflow vibrato extents. It would suggest, then, that the professional singers may have been using higher lung pressures and greater posterior glottal activity during vibrato production compared with the non-professional singers. The airflow vibrato extents were smaller in the latter, but similar to fluctuations created by shallow pumping, indicating again that the potential source for the shallower extents also could be lung pressure variations.

RQ7. Does F0 vibrato extent differ from F0 bleat extent and F0 external epigastric (upper abdominal) pumping extent in males and females? The F0 modulation extents for bleat, external epigastric pumping, and vibrato showed similar ranges from 0.5 – 2.6 ST, and there was no statistical significant differences observed among these three sub-tasks. In study 2, males had higher F0 modulation extents than females and were statistically significant in bleat, EEP, and low pitch vibrato tasks. The F0 vibrato extents were not affected by increase in loudness levels, but were statistically significantly higher at low pitch than high pitch in males.

In Study 1, the F0 vibrato extents were seen to be statistically significantly higher in females, especially for the high pitch (about 2.24 ST). This indicates that a relatively greater increase in CT muscle activity may have been used by the professional soprano singers to increase their F0 vibrato extents. In Study 2, slightly higher F0 vibrato extents were observed in non-professional sopranos compared to the males but not statistically significantly so. In Study 2, the non-professional male singers had statistically significantly higher F0 vibrato extents at lower pitch compared with higher pitch (about 2.38 ST), whereas in Study 1, the professional male singers showed higher F0 vibrato extents at high pitch compared with low pitch (about 1.7 ST from 1.51 ST), but was not statistically significant.

During external epigastric pumping, F0 modulation extents were seen to be higher with deeper pumping than in shallow, and was statistically significant in males (up to 2.8 ST). This indicates the dependence of F0 modulation extents on subglottal pressure, increasing with greater subglottal pressure, especially for males. At the same time, increases in intensity during vibrato were not significantly associated with the F0 vibrato extents. Therefore, because of intensity's dependence on subglottal pressure, increasing Ps apparently is not enough to explain F0 vibrato extents.

During speaking tasks with bleating (prolonging a vowel with bleating), the heavier bleat had higher F0 modulation extents than lighter bleat conditions. This indicates greater glottal adduction also increases the F0 modulations. During singing tasks of bleating (with straight tone)prolonging a sung vowel with bleating), the F0 bleat extents increased from lighter to heavier bleat at low pitch, and decreased at high pitch. The variables which might increase the F0 modulation extents would therefore appear to be an increase in subglottal pressure, greater glottal adduction variation, and CT activity (more stretching and contraction).

RQ8. Do intensity extent, subglottal pressure, average airflow, and percent airflow of vibrato differ from bleat and external epigastric pumping in males and females? Oral pressures (equivalent to subglottal pressures) were measured for all levels of sub-tasks for bleat and vibrato. Overall, the highest oral pressures were seen in the heavier bleat productions at high pitch conditions and vibrato at high pitch forte (about 16 cm of H_2O) followed by straight tone at high pitch forte (about 14 cm of H_2O). In straight tones and vibrato, oral pressures increased with increase in loudness level and pitch. But the range of oral pressures was higher in Study 1 (5 – 24 cm of H_2O) than in Study 2 (4 – 17.5 cm of H_2O). In Study 1, males tended to have larger subglottal pressures than the females, whereas in Study 2, although they were in a similar range, females tended to have slightly higher pressures than the males, especially at low pitch. During speaking tasks using bleat, phonation tasks tended to have greater subglottal pressures than in whisper. Within phonation and whisper tasks, heavier bleats had statistically significantly higher pressures than lighter ones. During singing tasks of bleating, high pitch (P2) heavier bleat had statistically significantly higher oral pressures than lighter bleats at P1 and P2, and heavier bleat at P1. Thus, from a functional point of view, the subjects of the two studies appear to use higher subglottal pressures in general for greater loudness, higher pitch, and heavier bleat, suggesting the typical findings for increased subglottal pressure and/or increased respiratory effort. In addition, the professional singers tended to use more subglottal pressure in singing than the amateur singers.

Average airflows (cm^3/s) were seen to be similar in both males (144 cm^3/s) and females (138 cm^3/s) while producing vibrato. Similarly, in Study 2 (Table 35), males (155 cm^3/s) and females (145 cm^3/s) showed similar average airflow values (cm^3/s). During vibrato, there was no significant change in average airflows due to change in pitch and loudness level. In Study 1, in general, average airflows did not increase significantly as the loudness and pitch increased (Table 4).

Percent airflows in Study 2 were highest in males due to larger airflow modulation extents and a similar range of average airflows compared with females. Therefore, for the amateur singers, there may be a difference in how the males varied their airflow vibrato compared to the females. In Study 1, females tended to have larger airflow vibrato extents and a similar range of average airflows compared with males, and so higher percent airflows were seen in the female subjects. Differences in the results could be due to differences in duration of vocal/singing training experiences in the subjects of Study 1 and Study 2. In general, males may tend to have higher average airflows due to larger larynges (Holmberg et al., 1989; 1988).

Because professional Western classical singers can produce good quality vibrato, the characteristics of their vibrato might be considered relatively standard. They have larger airflow vibrato extents compared to non-professionals singers (Study 2). They also showed higher lung pressures than the latter. As discussed above, the larger extents in professional singers could be due to larger subglottal pressure variations, more glottal adduction variation, and potential participation of the posterior glottis (a combination of external epigastric pumping and bleat), whereas in non-professional singers, the airflow vibrato extents might be primarily respiratory (as seen in airflow external epigastric pumping extents).

Intensity vibrato extents were found to be in the range of 0.66 – 3.05 dB. They were not affected by changes in pitch and loudness level. During speaking phonation and singing bleat tasks, typically the intensity modulation extents decreased from lighter to heavier conditions. This suggests that an increase in glottal adduction decreased the intensity modulation extents. Although relative intensities within each subject were lower in whisper, intensity extents were found to be highest during whisper bleat and whisper external epigastric pumping. The heavier bleat with whisper produced the highest intensity extents, ranging from 6.7 – 13.0 dB. The combination of whisper and bleat produced the largest airflow vibrato extents, as well.

Physiologically, rapid contraction and relaxation of the CT muscles along with posterior glottal area involvement are hypothesized to produce large airflow and intensity modulation extents. During external epigastric pumping, the intensity modulation extents were found to be higher in whisper than in phonation. Also, deeper pumping generated higher intensity modulation extents compared to shallow, especially in males. This again indicates greater lung pressures, higher airflows, and airflow modulation extents produce higher intensity modulation extents.

These results support the laryngeal level and respiratory level intensity modulations produced during vibrato and / or simulated vibrato (Large et al., 1971; 1970; Smith, 1970; Zemlin, 1968; Shipp et al., 1980; Rothenberg et al., 1988; Dromey et al., 2009; 1992). The intensity modulation extents during vibrato in Study 1 ranged from 0.9 – 3.8 dB and was in a similar range seen in Study 2. Yet the quality of the vibrato produced by the professional singers might be considered to be better than the non-professional singers. This would indicate the potential importance of F0 and airflow modulations along with greater lung pressures during vibrato which were found to be highest in the former (trained, experienced) group. All these findings give strong indications to posterior glottis activity along with CT muscle action, subglottal pressure, and laryngeal flow resistance.

Other observations in terms of regularity, waveform shape, and phase. The phase differences among F0, airflow, and intensity modulation cycles were found to be less or almost in-phase during external epigastric pumping. Therefore, when there exists a nearly in-phase relationship among F0, intensity, and airflow undulations during vibrato singing, the phenomenon suggests subglottal pressure as a primary source of vibrato generation.

During vibrato, in Study 1 and 2, a wide range of phase differences were produced between airflow and F0, where airflow leads F0 predominantly. Similarly, during bleat, the phase differences varied broadly especially during whisper, and predominantly airflow lead F0 and intensity. There were a few conditions where airflow and F0 modulations were in anti-phase.

One of the distinguishing features of bleat from vibrato is in terms of the consistency of the waveforms. Bleat is highly variable in the airflow, F0, and intensity of its waveforms, as well as in the phase relation among those variables (Figure 26-29). However, most often the F0 modulations during bleat were more inconsistent and irregular in waveshape, whereas the airflow bleat was more consistent and regular.

Vocal tract constriction changes. Vocal tract constriction changes were studied in order to see the changes in F0, airflow, and intensity during articulatory narrowing (consonant /l:/) and widening (vowel /a/) of the oral cavity. During the /al:al:a.../ productions, the difference in intensity between vowel and consonant was about 4.0 dB during phonation, and 8 dB during whisper, considerably large changes. This indicates that intensity modulation extents can be highly affected by vocal tract changes. The airflow changes between the phonated production of the vowel and consonant was only about 13 cm^3/s, whereas during whisper, it was about 60 cm^3/s. This indicates that airflow during singing (phonation) might not be affected significantly due to vocal tract constriction changes unless the constriction is extremely narrow (or, of course, full occlusion of the vocal tract). The differences in F0 between the /a/ vowel and the /l:/ consonant production was negligible, thus suggesting that F0 vibrato is a phenomenon that is primarily laryngeally-mediated rather than vocal tract related for non-fully-occluded sounds. The non-professional amateur singers in Study 2 had shorter airflow and F0 vibrato extents than the professionals in Study 1, but had similar intensity vibrato extents compared to the professional singers of Study 1. This might indicate a slight assistance of the vocal tract (oral structures especially) to produce amplitude modulations in intensity in the non-professional group. Oscillations of the vocal tract synchronous to vibrato were observed by Hirano (1988). Hirano hypothesized that if the oscillatory movements of the vocal tract are moderate, that could be helpful to avoid tightness or rigidity of the vocal tract adjustment. Hirano observed negligible F0 and significant amplitude modulations due to vocal tract oscillations. The oral cavity variation studied here was to attempt to identify changes due to that variation, but the study here did not assume that during the experiment that the subjects of either study moved articulators to any identifiable extent, and thus the results for this portion of the overall study do not pertain to seeking sources of airflow vibrato characteristics.

Possible sources of airflow and F0 modulation extents. Figure 38 shows the possible sources of generation that were hypothesized based on results obtained from Study 1 and Study 2. Three possible sources were hypothesized. The first one was primarily CT muscle action which could alone cause F0 vibrato extents. Changes in CT muscle action may lead to small changes in glottal area and glottal flow resistance. Therefore, small changes in airflow vibrato extents would also be expected due to CT contraction variation alone. The portion with the blue dashed line in Figure 38 shows the modulation extents if CT is a primary source. The second source hypothesized was subglottal pressure, Ps. A triangle with green dashed lines is drawn based on results obtained from external epigastric pumping, as the primary source of modulation is change in subglottal pressure. In Study 2, the range of F0 and airflow vibrato extents obtained were 0.5 – 3.0 ST and 20 – 150 cm^3/s, respectively. The third potential source hypothesized was glottal adduction. A rectangle with red dashed line is drawn based on results obtained from bleating, as the primary source of modulation is change in glottal adduction. In Study 2, the range of F0 and airflow vibrato extents obtained were 0 – 1.5 ST and 50 – 150 cm^3/s, respectively.

Figure 38 graphs the airflow vibrato extents versus the F0 vibrato extents for the eight subjects of this study. The figure shows that the sopranos S1 and S2 from Study 1 might be using primarily Ps as the source of production of vibrato modulation extents, rather than using glottal adduction or even CT contraction. They showed the highest airflow and F0 vibrato extents. The tenor T of Study 1 is seen in the figure to be using glottal adduction as his primary source of vibrato modulation extents (hypothetically). He showed higher airflow vibrato extents but smaller F0 vibrato extents. The remaining singers, the baritone (B) from Study 1 and all four singers from Study 2, were essentially in the overlap region of CT and Ps. These five singers showed higher F0 vibrato extents but smaller airflow vibrato extents.

Figure 39 shows the coefficient of variation of F0 vibrato extent and the coefficient of variation of airflow vibrato extent for all eight singers in Study 1 and 2. The coefficient of variation (COV) is the standard deviation divided by the mean. The lower the COV value is, the more regular and consistent are the vibrato cycles relative to the mean. The two sopranos S1 and S2 from Study 1 showed relatively low COV values for both F0 and airflow vibrato extents. This might suggest that if the singers produced F0 and airflow vibrato extents by primarily using Ps as the source, the resulting hypothesis would be that the Ps source provides relatively regular variations in both F0 and airflow vibrato. The tenor T from Study 1 showed the highest COV for F0 vibrato extent and an average COV (about 0.3) for airflow vibrato extents. This might suggest that if glottal adduction were used primarily for the production of F0 and airflow modulations during vibrato, the resulting hypothesis would be that the adduction source provides relatively large F0 variations, or F0 instability, due to irregular adduction motions, compared to the mean. The remaining singers, the baritone from Study 1 and all four singers in Study 2, have COV values for F0 vibrato in the middle of the scale and slightly high COV values for airflow vibrato. The resulting hypothesis would be that the CT source provides relatively normal F0 vibrato variation but somewhat irregular airflow vibrato, compared to the mean. These results and conjectures suggest that regular and consistent airflow vibrato cycles may need predominantly Ps control, but that control is not consistent among both professional and amateur singers.

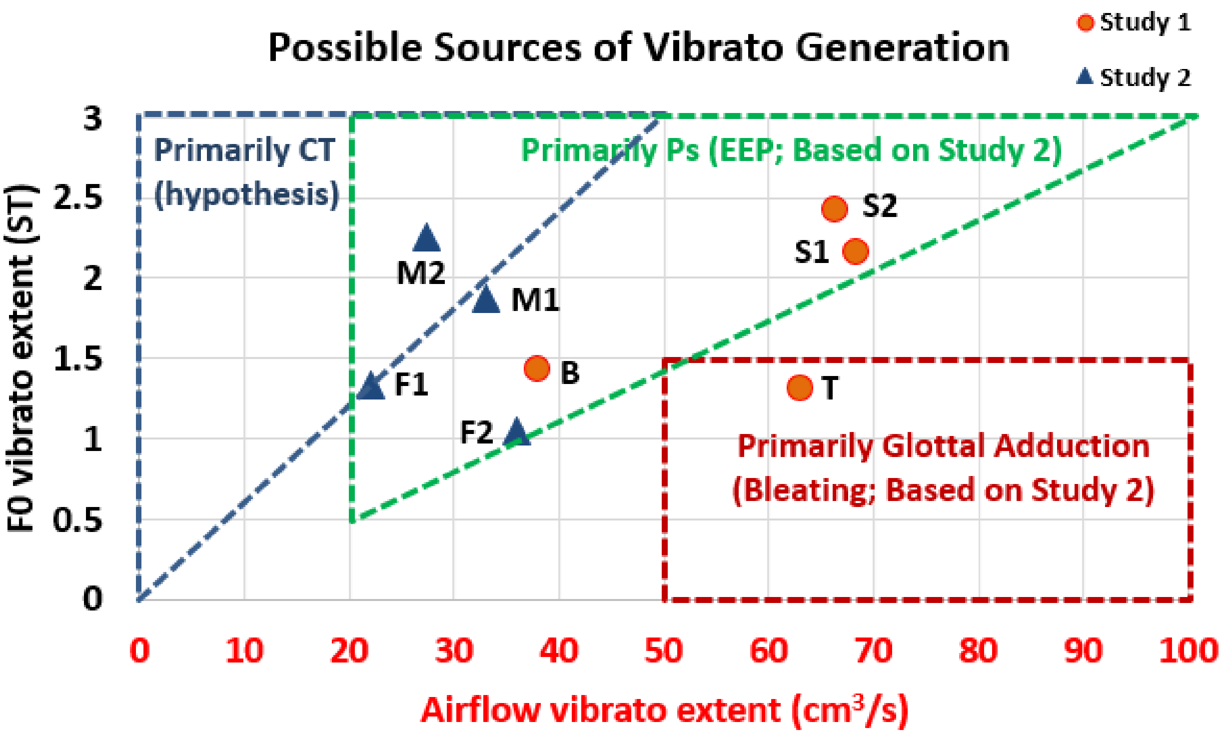

Figure 38. Possible sources of airflow and F0 vibrato extents under three categories: primarily CT (based on assumption; portion with dashed blue triangle), primarily Ps (based on results obtained from external epigastric pumping data; portion with dashed green triangle), and primarily glottal adduction (based on results obtained from data on bleating; portion with dashed red rectangle). The filled circles represent the data from Study 1, and the filled triangles the data from Study 2. S1 and S2, sopranos; B, baritone; T, tenor; M1 and M2, male subjects; F1 and F2, female subjects.

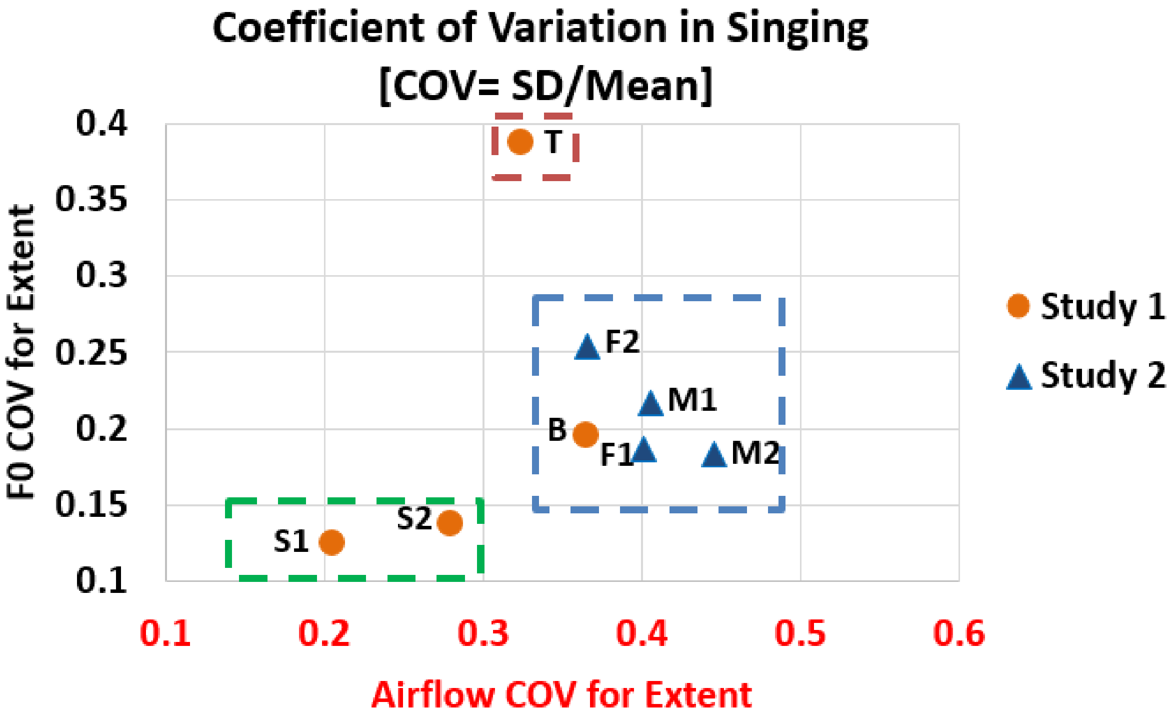

Figure 39. Coefficient of variation (COV) of airflow and F0 vibrato extents for all the eight singers in Study 1 and 2. COV is standard deviation of vibrato extent divided by mean of vibrato extent. The filled circles represent the data from Study 1, and the filled triangles the data from Study 2. S1 and S2, sopranos; B, baritone; T, tenor; M1 and M2, male subjects; F1 and F2, female subjects.

Spectral measures. A string of vibrato cycles in this study ranged from quite sinusoidal looking to quite complex in waveshape, with multiple magnitude variations within a vibrato cycle, more so for airflow vibrato than for F0 vibrato. The question arises, how should the complexity be measured or described? One approach is spectral. The section offers examples of what this would look like for the waveforms of this study, but is not exhaustive. Figures 40-43 show (on the left) spectra of airflow vibrato for three cases. If a spectrum has only one component, it means that the signal is sinusoidal. If the spectrum has multiple components, then the signal is not sinusoidal. Figures 40 and 41 show the spectra for the airflow vibrato for soprano-1 singing at high pitch piano and mezzoforte conditions, respectively. The harmonics are indicated by red vertical lines. The airflow vibrato in each figure is fairly regular and consistent, but not entirely sinusoidal. Figure 40 shows inharmonic components, but more importantly that the intensity level difference between the first and second harmonic was about 29.8 dB, suggesting that the highly dominant harmonic was the first, suggesting a nearly-sinusoidal pattern for the airflow vibrato, as can be seen in the figure to the right in Figure 40. Figure 41shows that the airflow vibrato was highly harmonic, but importantly the intensity level difference between first and second harmonic was 17.3 dB, suggesting that the second harmonic was significantly greater for that utterance than for the one shown in Figure 40. This is confirmed by seeing a little more non-sinusoidal waveform shape in Figure 41.

Figure 42 and 43 show the spectra of baritone singing at low pitch piano and mezzoforte conditions. The airflow vibrato is irregular and inconsistent, indicating more complicated airflow vibrato waveshapes. Figure 42 shows stronger second and third harmonics than shown in Figures 40 and 41. Therefore, the intensity level difference between first and second harmonic, and first and third harmonic was only 7.5 dB and 10.7 dB, which is much less in comparison with the more regular airflow vibrato waveforms of Figures 40 and 41. Figure 43 shows the intensity level difference between the first and second harmonic, and first and third harmonic of 14.5 dB and 9.8 dB, respectively. Higher intensities for H2 and H3 indicate the frequencies of multiple components for the airflow vibrato. Every F0 vibrato cycle corresponds with 2-3 airflow vibrato cycles. Therefore, the intensity level differences were less, and the intensity of H3 is higher than H2 in Figure 43.

Thus, intensity level differences between H1 and H2, and H1 and H3 were significantly different between the regular and irregular airflow vibratos. The intensities of H2 and H3 would be higher in irregular airflow vibratos when compared with regular airflow vibratos. Thus, the spectral measure suggested to describe the complexity of the airflow vibrato waveforms is taking the difference between the acoustic levels of the harmonics, especially between the level of H1 and the levels of the subsequent harmonics. In addition, a measure of the non-harmonic components should be considered.

In addition to these spectral considerations, a harmonic-to-noise measure of the airflow waveforms, and a cepstral analysis, would be appropriate.

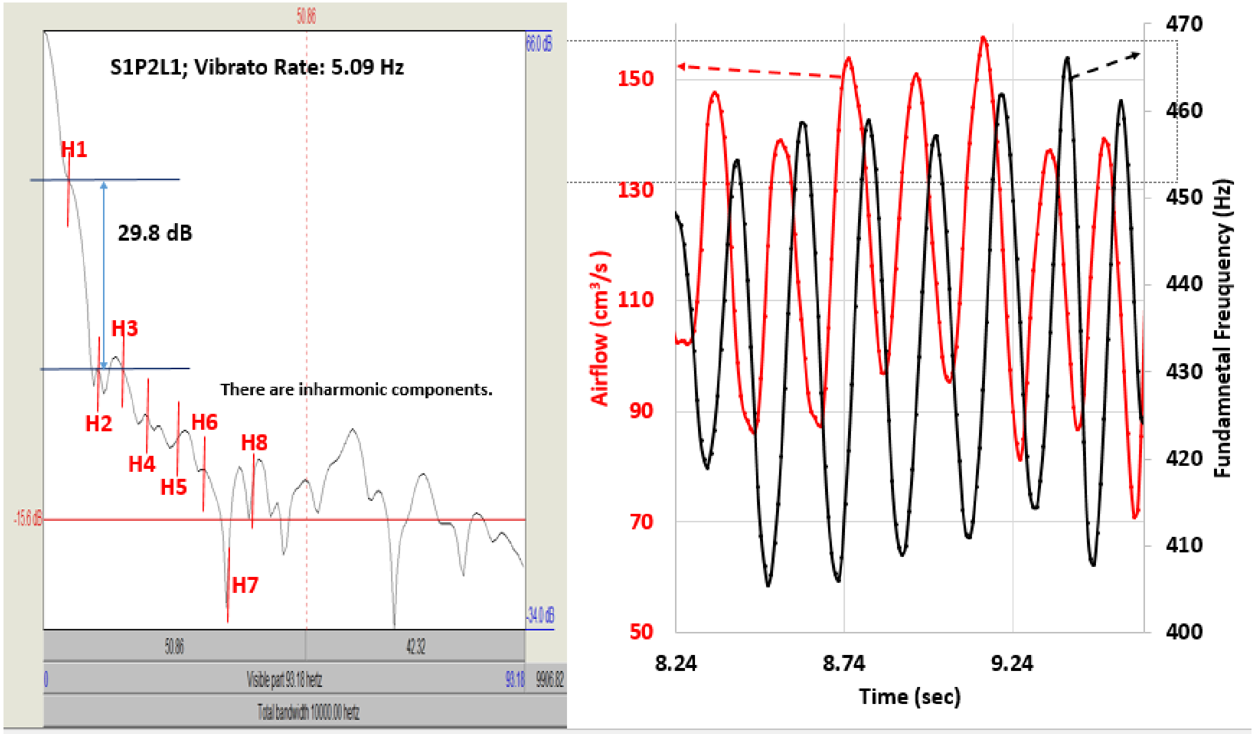

Figure 40. Airflow vibrato of soprano1 singing at high pitch piano condition. The left panel shows the spectrum of the airflow vibrato given on right side. The harmonics were indicated by red vertical lines. The intensity level difference between harmonic1 and harmonic2 was 29.8 dB. The rate of airflow vibrato is 5.09 Hz.

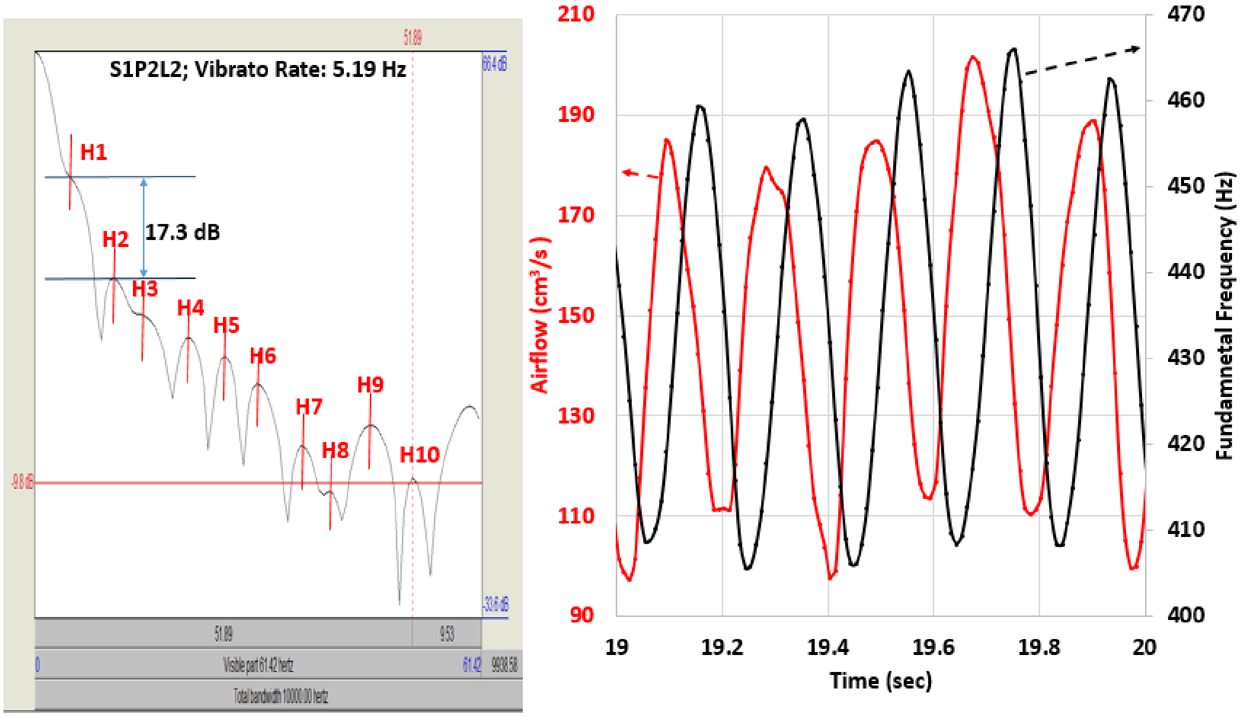

Figure 41. Airflow vibrato of soprano1 singing at high pitch mezzoforte condition. The left panel shows the spectrum of the airflow vibrato given on right side. The harmonics were indicated by red vertical lines. The intensity level difference between harmonic1 and harmonic2 was 17.3 dB. The rate of airflow vibrato is 5.19 Hz.

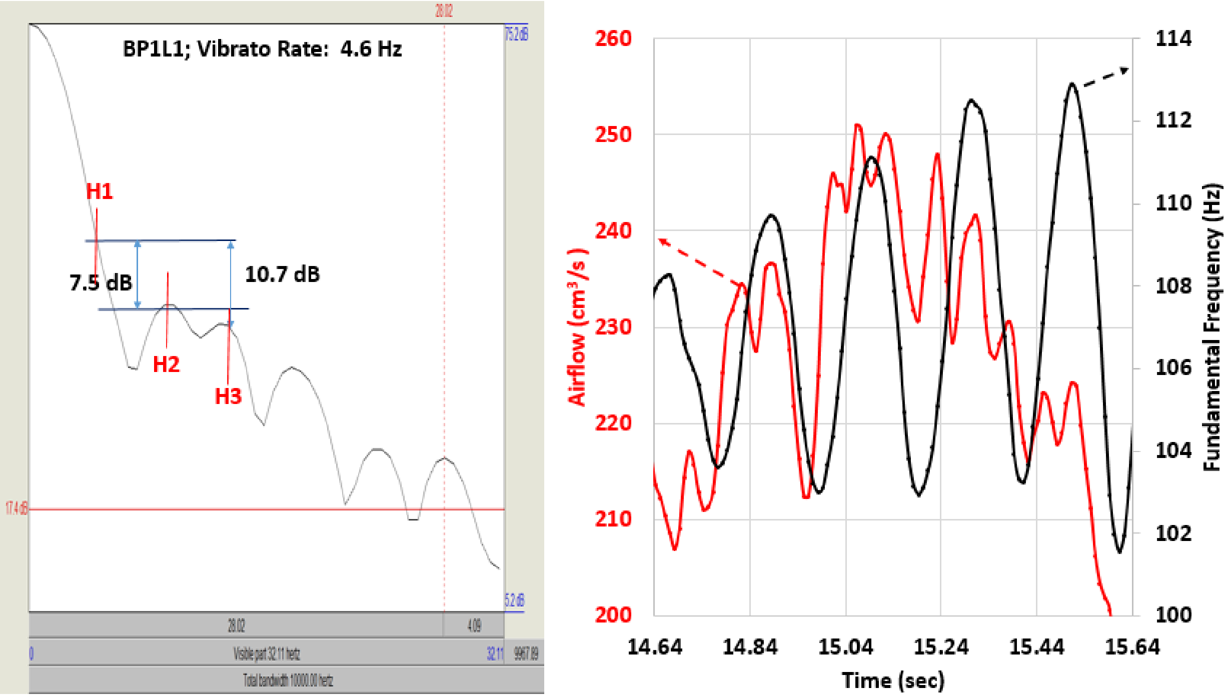

Figure 42. Airflow vibrato of baritone singing at low pitch mezzoforte condition. The left panel shows the spectrum of the airflow vibrato given on right side. The harmonics were indicated by red vertical lines. The intensity level difference between harmonic1 and harmonic2 was 7.5 dB, and 10.7 dB for harmonic1 and harmonic3. The rate of airflow vibrato was 4.6 Hz.

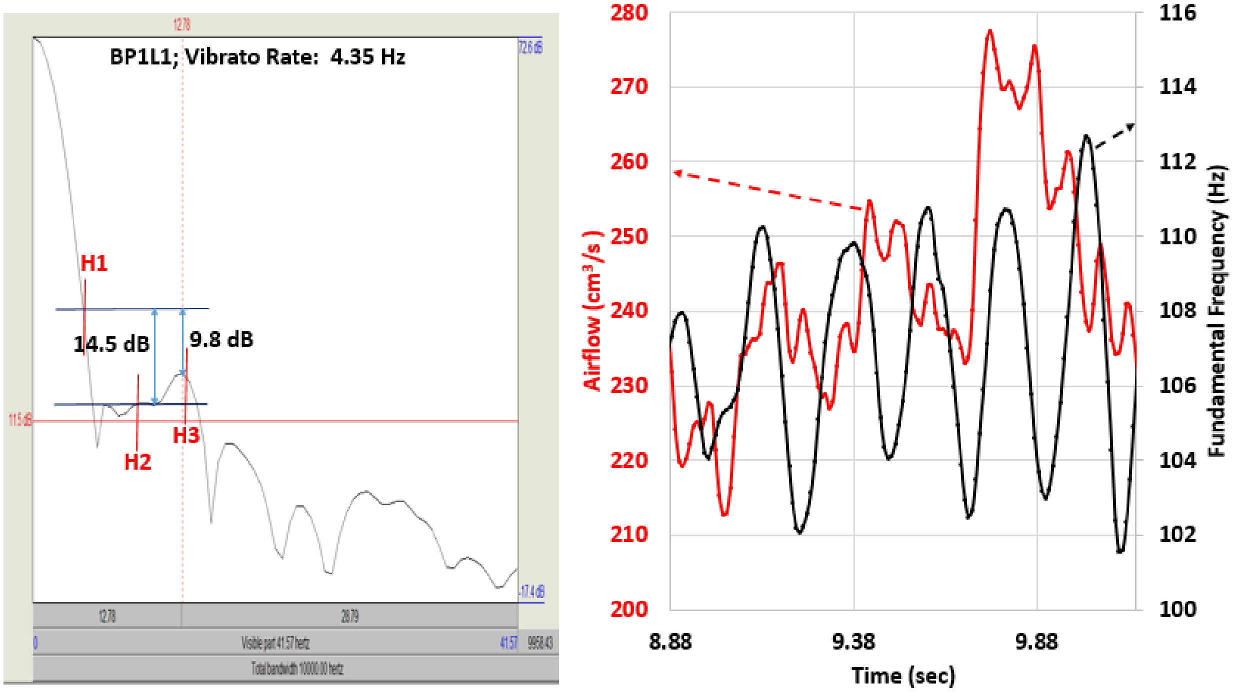

Figure 43. Airflow vibrato of baritone singing at low pitch piano condition. The left panel shows the spectrum of the airflow vibrato given on right side. The harmonics were indicated by red vertical lines. The intensity level difference between harmonic1 and harmonic2 was 14.5 dB, and 9.8 dB for harmonic1 and harmonic3. The rate of airflow vibrato is 4.35 Hz.

CHAPTER V. CONCLUSIONS

The purpose of this study was to gain an understanding of the production of airflow vibrato, a phenomenon without a scientific basis up to this time. Two studies were run, the first to examine observations of airflow vibrato (rate, extent, relationship with fundamental frequency vibrato, intensity variation), and the other to study more specifically potential sources of the creation of airflow vibrato (by specifically manipulating glottal adduction and subglottal pressure). The results should give deeper insights into phonation in general and the aerodynamics of phonation specifically, and begin a greater focus on an understudied area of research that can be called “the aerodynamics of laryngeal modulations”. The first study with professional singers demonstrated the obvious existence of airflow vibrato, and as such expands the categories of vibrato classification. That is, the three classic vibrato descriptors, frequency vibrato, intensity vibrato, and timbre vibrato, now can be accompanied by a fourth, airflow vibrato.

Study 1: Airflow Vibrato in Four Professional Singers

The results from studying four professional singers suggest that airflow vibrato varies in an overall similar manner with F0 vibrato, usually leading F0 vibrato, but can be much more complex in waveshape than F0 vibrato. Because airflow in general is related strongly to laryngeal flow resistance, it might be assumed that airflow vibrato is strongly related to glottal adduction and subglottal pressure. In this study, however, adduction (suggested by the EGGW measure) and subglottal pressure (suggested by loudness) did not have obvious causative relations with airflow vibrato. Airflow vibrato did have a strong relation with pitch, however, having a wider airflow vibrato extent with higher pitch. In addition, the two female singers tended to have greater vibrato extents than the two male singers. This study lead to the second study that attempted to study possible sources of airflow vibrato more specifically.

Study 2: Sources of Airflow Vibrato

Airflow vibrato was compared to airflow variations during bleat (primarily glottal adductory changes) and external epigastric pumping (primarily subglottal pressure changes) in order to attempt to uncover potential sources of airflow vibrato. Males tended to have higher F0 vibrato extents than females, but similar airflow vibrato extents were seen in both males and females, which was contrary to the results of Study 1. The epigastric pumping portions of the study suggest that subglottal pressure variations may have a strong influence on the vibrato characteristics. The non-professional singers showed smaller airflow vibrato extents similar to the airflow variations during shallow abdominal pumping. Larger airflow vibrato extents in professional singers compared to amateur singers suggest greater glottal adduction variation (presumably of the posterior glottis) along with higher lung pressure variations.

F0 modulation extents were seen to be in a similar range as bleat, external epigastric pumping, and vibrato. But higher F0 modulation extents were seen when higher subglottal pressures were involved, i.e., during deep abdominal pumping. Therefore, singers who show higher F0 vibrato extents are potentially using higher lung pressure variations along with CT contraction alterations. Laryngeally mediated intensity extents were also seen to be higher along with larger airflow extents, when the posterior glottis activity (during whisper) was involved.

This leads to an hypothesis that highly experienced professional singers develop a skill of increased posterior glottal activity along with CT muscle function and higher lung pressures during vibrato production, whereas in newly trained or less experienced singers, vibrato production involves the anterior glottis primarily by CT and vocalis coordination, with potentially less respiratory involvement.

Observation of Regularity of Airflow and F0 Modulations

F0 modulations were smoother, more consistent, and quasi-sinusoidal compared to airflow modulations during vibrato production. Airflow vibrato presented with a variety of waveform shapes and a wide range of regularity. The results for bleating conditions suggest that the primary airflow vibrato shaping is most likely due to adductory and subglottal pressure variations, whereas the finer variations superimposed on the airflow vibrato waveshape may be due to superimposed bleat-like variations of the glottis (up to two times the undulation frequency).

The phase differences among F0, intensity, and airflow occurred over a wide range. The ranges were relatively consistent within each subject, emphasizing the individual style of producing vibrato. During bleat productions, the phase differences among F0, intensity, and airflow also occurred over a wide range. The striking phenomenon that was seen for bleat was smoother, consistent, and quasi-sinusoidal airflow modulations with simple to complex (multiple components and inconsistent) F0 modulations. During external epigastric pumping, very regular and consistent modulated waveforms of intensity, F0, and airflow were seen. The phase differences among them were almost zero, and was more highly correlated in deep abdominal pumping than in shallow pumping. Thus, combining the results for bleat and epigastric pumping, since both sources of variation resulted in smooth waveforms and relatively predictable relationships, they cannot be the full cause of airflow vibrato, since airflow vibrato showed a relatively wide range of shapes and irregularities.

Combining the results of Study 1 and Study 2 (especially when viewing Figures 38 and 39) suggests that a few hypotheses can be generated relative to the sources of airflow vibrato and its relation to F0 vibrato. For example, relative to airflow vibrato extent and F0 vibrato extent, the two sopranos of Study 1 appear to use subglottal pressure variation as a primary source (undoubtedly also with CT variations), the tenor primarily glottal adduction variations, and the baritone and the 4 amateur singers both CT and Ps variations. Also, the two sopranos had relatively consistent extents of both F0 and airflow vibrato that were small relative to the average extents, suggesting that subglottal pressure variation may provide relatively regular variations of both F0 and airflow vibrato. The results for the tenor suggest the hypothesis that a primarily adductory source provides relatively low F0 vibrato extent and moderately high airflow vibrato extent, but with a relatively inconsistent extent especially of the F0. For the rest of the subjects (the baritone and the four subjects of Study 2), the hypothesis is that a primarily CT-governed source may result in moderate F0 vibrato extent and relatively low airflow vibrato extent, but a moderate level of inconsistency for the F0 extent and a higher level of inconsistency to the airflow extent. These are hypotheses to test in future studies.

Limitations and Future Directions

The airflow vibrato measures such as extent and rate were sometimes difficult to measure due to the complex nature of the airflow vibrato waveforms. During the more complex waveform conditions, prominent and/or most approximate values were considered for the measurement. The EGG measures did not show significant changes in adduction when peaks and valleys of the airflow vibrato were compared, suggesting that possible countering aspects are involved with those measures.

For most of the conditions, airflow vibrato lead F0 vibrato. The current study could not discover the probable reason behind this observation. The airflow and F0 vibrato extents were significantly affected with increase in pitch in both Study 1 and Study 2, but were unaffected by increase in loudness levels. As Ps increased, the average airflow was expected to increase. But the average airflows along with F0 and airflow vibrato extents did not change significantly with increase in loudness levels for all eight subjects. This might indicate the there was an increase in glottal flow resistance in order to maintain similar ranges of glottal airflows. But the current study could not give a convincing explanation of F0 and airflow vibrato extents unaffected by loudness levels.

A critically important future study is to use flexible fiber-optic high-speed imaging of vocal fold vibration simultaneously with laryngeal EMG, direct measures of subglottal pressure using a tracheal puncture technique, and measures of airflow using the airflow mask system, while the singer is producing vibrato. Such a study would help answer many of the questions that are unanswered in the current study, because viewing the larynx would give the important information about glottal size and shape variation during singer. Comparing the results obtained from different possible sources of Study 2 along with this future physiological study should give a more complete understanding of F0, airflow, and intensity vibrato, and most importantly the complexity of the waveform shape in airflow vibrato. If there exists a difference in regularity of airflow vibrato waveform shape between professional and non-professional singers that should suggest that there may be a target behavior in laryngeal aerodynamics as the airflow corresponds to some favorable physiological coordination that increases with professional experience.

The studies of production and control of airflow vibrato should direct the clinical investigation of airflow variation relative to vocal tremors and other abnormal neuromuscular activities as seen in spasmodic dysphonia, muscle tension dysphonia, and neurogenic stuttering. By doing so, a deeper understanding of how the body produces these disorders will be gained.

From the results of airflow and F0 modulation characteristics of possible sources (primarily adductory and primarily Ps) obtained from Study 2, a basic understanding of these phenomena was presented. This should help the clinician to therapeutically focus on target behavior. For example, if the airflow and F0 modulation cycles were exactly in phase, the possible source most likely would be respiratory (results obtained from external epigastric pumping). This would suggest to the clinician to plan one of the therapy goals on respiratory muscle strengthening, training, and control. Whereas, if the airflow and F0 modulation cycles were not in phase and varied widely in phase difference, the possible source may be laryngeal (results obtained from bleating and the corresponding adductory gesture). This indirectly suggests that the clinician might focus on phonatory strengthening through different vocal functioning exercises to improve muscle strength, functioning, and control.

In addition, the regularity and waveform shapes of F0 and airflow vibrato should be extensively studied. The wide range of waveshapes of the airflow vibrato of this study was remarkable, and the sources for such variability are still not fully understood.

The relationship between airflow vibrato and perceptual attributes should also be pursued. A perceptual study should be done by categorizing the airflow vibrato samples based on the levels of complexity (regularity, consistency, and multiple components and peaks). The complexity of the airflow vibrato should be measured using cycle to cycle short-term perturbation measures similar to jitter and shimmer, as well as longer-term measures such as the coefficient of variation, harmonics to noise ratio, and spectral methods. Qualitative measures should be used such as CAPE-V and perceptual judgement of quality of vibrato from expert singers or singing teachers.

It is anticipated that eventually there will be sufficiently complex and valid computer models that could be used to include not only the aerodynamic and acoustic aspects of complex vibrato production, but also the corresponding effects of the individual intrinsic and extrinsic laryngeal muscles involved with production of vocal vibrato (e.g., Titze's *VoxInSilico* software).

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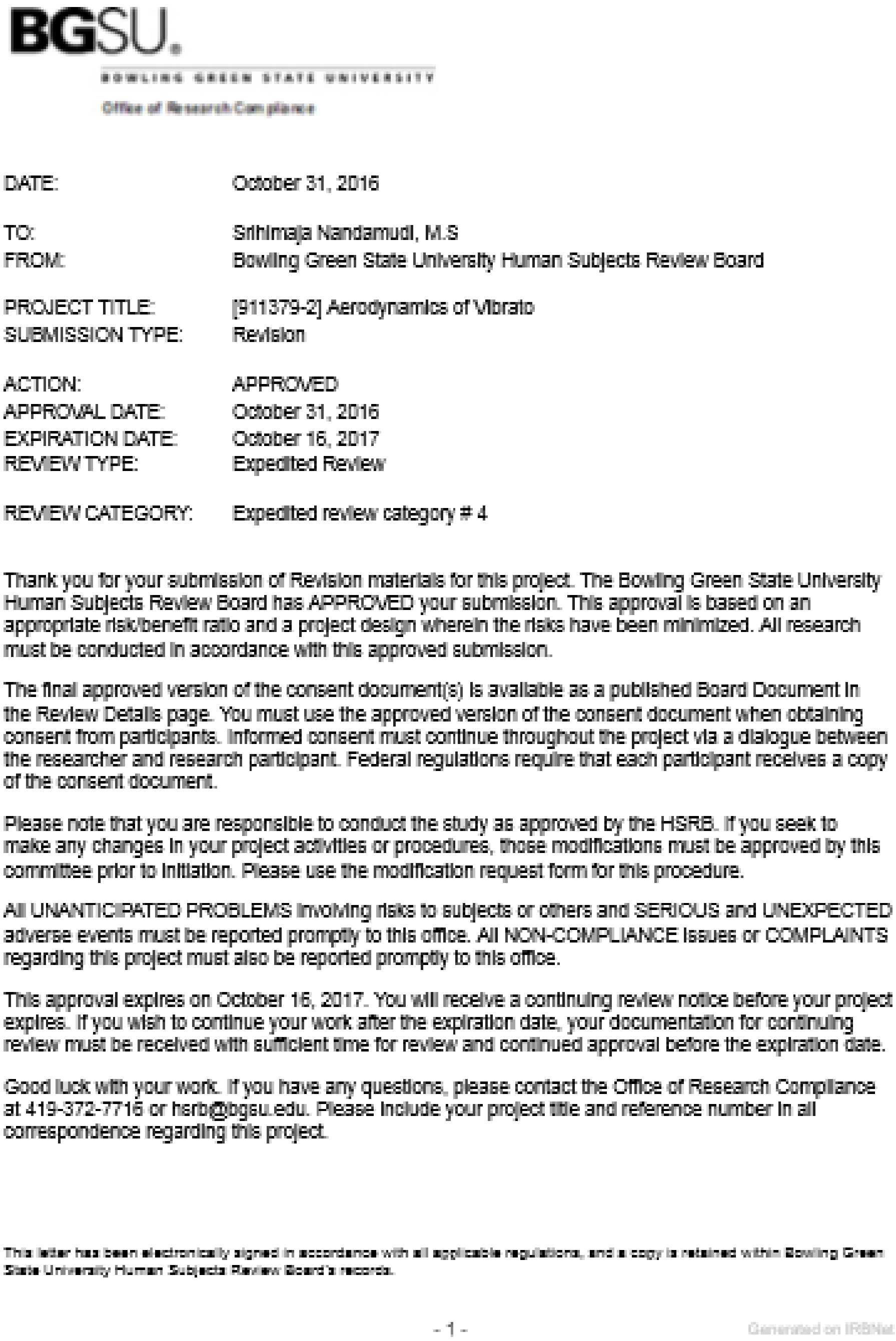
APPENDIX A

HSRB Approval Letter



BGSU.
BOWLING GREEN STATE UNIVERSITY
Office of Research Compliance

DATE: October 31, 2016

TO: Srihimaja Nandamudi, M.S
FROM: Bowling Green State University Human Subjects Review Board

PROJECT TITLE: [911379-2] Aerodynamics of Vibrato
SUBMISSION TYPE: Revision

ACTION: APPROVED
APPROVAL DATE: October 31, 2016
EXPIRATION DATE: October 16, 2017
REVIEW TYPE: Expedited Review

REVIEW CATEGORY: Expedited review category # 4

Thank you for your submission of Revision materials for this project. The Bowling Green State University Human Subjects Review Board has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a project design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

The final approved version of the consent document(s) is available as a published Board Document in the Review Details page. You must use the approved version of the consent document when obtaining consent from participants. Informed consent must continue throughout the project via a dialogue between the researcher and research participant. Federal regulations require that each participant receives a copy of the consent document.

Please note that you are responsible to conduct the study as approved by the HSRB. If you seek to make any changes in your project activities or procedures, those modifications must be approved by this committee prior to initiation. Please use the modification request form for this procedure.

All UNANTICIPATED PROBLEMS involving risks to subjects or others and SERIOUS and UNEXPECTED adverse events must be reported promptly to this office. All NON-COMPLIANCE issues or COMPLAINTS regarding this project must also be reported promptly to this office.

This approval expires on October 16, 2017. You will receive a continuing review notice before your project expires. If you wish to continue your work after the expiration date, your documentation for continuing review must be received with sufficient time for review and continued approval before the expiration date.

Good luck with your work. If you have any questions, please contact the Office of Research Compliance at 419-372-7716 or hsrb@bgsu.edu. Please include your project title and reference number in all correspondence regarding this project.

APPENDIX B

Recruitment Script

Singers are invited to participate in a study on ‘aerodynamics of vibrato’. Speech and singing data will be collected to determine acoustic and aerodynamic aspects of vibrato. The purpose of this study is to understand glottal airflow changes while speaking and singing. Participation is voluntary, and if you decide to withdraw from the experiment at any time, you can do so without any kind of penalty. You will be given a $15 gift card as a token of appreciation for your participation. This study will be conducted by Srihimaja Nandamudi, M.S, doctoral student in Voice and Speech Sciences (nandas@bgsu.edu ; 419-372-4320) and Dr. Ronald C. Scherer, Ph. D., Distinguished Research Professor (ronalds@bgsu.edu ; 419-372-7189) in the Department of Communication Sciences and Disorders, College of Health and Human Services, Bowling Green State University.

The study includes one session which will take about two hours. The study will take place at The Voice Laboratory, Health and Human Services Building. During the study, you will be asked to fill out a consent form (which includes a complete description of the protocol) and a confidential health & voice form. You will be acquainted with the environment and recording procedures. You will be asked to perform relatively familiar speech and singing tasks with convenient breaks of 5-10 minutes whenever necessary.

If you are interested in hearing more about this study and are considering participating, please write to me, Sri Nandamudi, at the email address nandas@bgsu.edu ; please include your contact information. Thank you.

APPENDIX C

Study 1 Consent Form

I. Purpose

You are invited to participate in a research project on *"Flow Vibrato in Singers"*. You will be asked to sing a variety of sounds in different pitches and loudness levels. The speech and singing tasks, which will include a combination of repeated tones, scales, arpeggios, vocalises (musical exercises), and musical excerpts from the vocal literature, are normally encountered in your daily voice use as a singer and performer.

This project is descriptive in nature. The results may help us in better understanding vocal function. A copy of this consent form will be given to you. This project will be part of a research project in the Department of Communication Science and Disorders.

II. Procedures

The utterances you will be expected to perform are representative of your everyday singing activities. The tasks will include repeated tones, scales, arpeggios, and vocalises (vocal exercises) performed at different pitch, loudness levels and registers. In addition, you will be expected to perform musical excerpts from the vocal literature.

You will sit or stand (depend on your convenience) while performing the speech and singing tasks in a sound-treated booth in the Voice Physiology Laboratory at the College of Health and Human Services. The dimensions of the booth are approximately 4 foot by 6.33 foot by 6.5 foot. You will be asked to become accustomed to the booth and it's furnishings by being in the booth 10 minutes before the actual recording begins, or longer, until you indicate that you are comfortable with the environment.

For most utterances, you will be asked to place a mask on your face. This mask is made of clear plastic and has holes in it. It will measure the airflow you use during voicing (singing and speech). You will hold the mask to your face; the soft seal of the mask prevents air escape around the edges. There is a sterile tube that extends from a pressure transducer on the inside of the mask to the inside corner of your mouth. This tube has no sharp edges. It is used to measure the air pressure in your mouth. The only mask discomfort known is the presence of the mask on the face.

You will wear an electroglottography electrode band on your neck. This will indirectly record aspects of vocal fold motion. This device is non-invasive. The only known problem is irritation to metal contact. Please let me know if you are allergic to metal contact. There will be a microphone and a sound level meter placed in front or to the side of you.

The recording session is anticipated to take place on one occasions lasting approximately 60 minutes. On the day of the recording, you will be asked to fill out a Health and Voice History Form to make sure that you are in sufficiently good condition physically and vocally. If you think that your physical condition is interfering with your singing production, the recording session will be canceled and re-scheduled to a later date at your convenience. You will be given approximately 10 minutes to get used to the booth before the recording of the tasks begins. You may take a break or stop the session anytime you like (due to any reason). You have the right to discontinue any task that is uncomfortable to you.

A video camera placed outside the booth will record the experiment for archival and trouble-shooting purposes.

III. Risks:

There are no known risks involved in this project. As mentioned above, the only known problem is a potential irritation to metal contact while using the electroglottography (EGG). Please let me know if you are allergic to metal contact.

IV. Benefits:

The current research project is significant pedagogically. It may help singing teachers in understanding the functional changes associated with pitch, loudness, and register variations in singing.

You may benefit from the findings and procedures of the experiment as a teacher of singing and voice pedagogy. Potential benefits include:

1) Acquiring a better understanding of the scientific basis of pitch, loudness, and register variations in singing training;

2) Acquiring a better understanding of the objective measurements used in voice science research and their application to voice pedagogy;

3) Hands-on experience of instrumentation techniques frequently mentioned in singing and voice science journals.

You will not be paid for participating in the study.

V. Confidentiality:

The recorded samples and data to which only members of the research team have access, will be stored in password protected files in the Voice Physiology Laboratory, College of Health and Human Services at Bowling Green State University. The recordings made in this study will be kept for a minimum of 10 years for further reference, analysis, investigation, and inclusion in other research projects.

You, as a collaborator in this project will be anonymous as a subject relative to all reports and presentations.

VI. Participation:

Your participation in this study is completely voluntary. Participating or not participating will have no effect on your relationship with BGSU. If you decide to withdraw from the experiment at any time, you may do so without penalty of any kind.

VII. Contact Information:

Please contact me, Srihimaja Nandamudi (419) 378-0280 (cell), or Dr. Ronald C. Scherer (419) 372-7189 (work phone), at any time concerned this study. Also, if you have questions regarding the conduct of this study or about your rights as a research participant, you may contact the Chair of Bowling Green State University's Human Subjects Review Board at (419) 372-7716 (hsrb@bgnet.bgsu.edu). This research project may involve participating students from the Department of Communication Sciences and Disorders; and possibly from other departments of the BGSU campus, including your own department.

VIII. Agreement:

I have read the above statement and am familiar with the procedures, risks, and benefits of the experiment. I declare that I am older than 18 years of age. I agree to be a subject in this research project. I further agree that I can withdraw from this experiment at any time, and that I can contact the Principal Investigator or the Human Subjects Review Board concerning any aspect of this project and my reactions to it.

Name: ________________________________ Date: ___________________

APPENDIX D

Study 2 Consent Form

I. Purpose

You are invited to participate in a research project on “Aerodynamics of Vibrato”. You will be asked to speak and sing at different levels of loudness, pitch, and register within your comfort levels. The speech and singing tasks will include a combination of repeated tones (straight tones and vibratos), scales, and bleat with phonation and whisper. This project is descriptive in nature. The results may help us in better understanding vocal function. A copy of this consent form will be given to you. This study is part of a research project in the Department of Communication Sciences and Disorders.

II. Procedures

The utterances you will be expected to perform are representative of your everyday singing activities. The tasks will include phonation and whispering of sustained vowels, repeated productions of /l/ (“el”) sounds, and scales performed at different pitches, loudness levels, and registers. In addition, you will be asked to use a bleat with both phonation and whisper.

One of the tasks includes externally gently pumping your epigastrium (upper abdominal region) while you are phonating or whispering the /a/ vowel. The researcher gently moves his or her fingers back and forth on the region just below the chest (sternum), above the “belly button”, while you are producing the vowel /a/ or singing a straight tone using the vowel /a/.

You will perform three trials of the above mentioned speech and singing tasks in a single session of approximately two hours in a sound-treated booth in the Voice Laboratory in the Health and Human Services Building.

For some utterances, you will be asked to place a sterilized mask on your face that covers your mouth and nose. This mask is made of see-through clear plastic and has holes in it. It will measure the airflow you use during the tasks. You will hold the mask to your face; the soft seal of the mask prevents air escape around the edges. There is a sterile tube that extends from a pressure transducer on the outside of the mask to the inside corner of your mouth. This tube has no sharp edges. It is used to measure the air pressure in your mouth. The only mask discomfort known is the presence of the mask on the face.

You will wear an electroglottographic electrode band on your neck. This will indirectly record aspects of vocal fold motion. This device is non-invasive. The only known problem is irritation to metal contact. Please indicate if you are allergic to metal contact. There will be a microphone and a sound level meter placed in front or to the side of you.

The recordings will take place in one session which will take about two hours. On the day of recording, you will be asked to fill out a Health and Voice History Form to make sure that you are in sufficiently good condition physically and vocally. If you think that your physical condition is interfering with your singing production, the recording session will be canceled and re-scheduled to a later date at your convenience.

The recording session is in three parts. The first part is to acquaint you with the environment and recording procedures. This will be followed by a 10 minute break. The second and third parts will involve recording the various tasks of the experiment, with another 10 minute break between the two parts. You may take a break or stop the session anytime you like (due to any reason).

III. Risks:

There are no known risks involved in this project. As mentioned above, the only known problem is a potential irritation to metal contact while using the electroglottograph. Please indicate if you are allergic to metal contact.

IV. Benefits:

The current research project may be significant pedagogically. It may help singing teachers in understanding the functional changes associated with pitch, loudness, and register variations in singing, and help confirm, support, and justify the usefulness of agility exercises in singer training.

You will be rewarded a $15 gift card as a token of appreciation for participation.

V. Confidentiality:

The recorded samples and the data will be stored in password protected files in the Voice Physiology Laboratory, College of Health and Human Services at Bowling Green State University. The recordings made in this study will be kept for a minimum of 10 years for further reference, analysis, investigation, and inclusion in other research projects. Paper copies of your signed consent form, associated health form, and other documents will be locked in a confidential file drawer in the Voice laboratory at the department of communication sciences and disorders. The data will be associated with your name, but no data, writing, or presentation will associate any information with your name.

VI. Participation:

Your participation in this study is completely voluntary. If you decide to withdraw from the experiment at any time, you may do so without penalty of any kind. As a BGSU student, your withdrawal from the participation will not impact your grades or any association with BGSU.

VII. Contact Information:

Please contact me, Srihimaja Nandamudi (419) 378-0280 (Cell), or Dr. Ronald C. Scherer (419) 372-7189 (work phone), at any time concerned this study. Also, if you have questions regarding the conduct of this study or about your rights as a research participant, you may contact the Chair of Bowling Green State University's Human Subjects Review Board at (419) 372-7716 (hsrb@bgnet.bgsu.edu).

VIII. Agreement:

I have read the above statement and am familiar with the procedures, risks, and benefits of the experiment. I agree to be a subject in this research project. I further agree that I can withdraw from this experiment at any time, and that I can contact the Principal Investigator or the Human Subjects Review Board concerning any aspect of this project and my reactions to it.

Name: ________________________________ Date: __________________

APPENDIX E

Study 1 Health and Voice History Form

Date: ________________

Name: _________________________ .Date of Birth: _________________ .Age: __________

I. Do you have or currently experience any of the following?

_______ Allergies

_______ Respiratory problems

_______ Hearing loss

_______ Menstrual cycle difficulties

_______ Neurological problems

_______ Endocrine/Hormone problems

_______ Sinus problems

_______ Premenstrual syndrome

If any of the conditions apply, please explain the effect on your voice and singing performance.

II. Do you currently have any voice difficulties such as laryngeal discomfort, huskiness, pitch range change, etc., and if so, what is the effect (if any) on your speaking and singing?

III. Do you have or have you ever had any of the following?

_______ Laryngeal surgery or injury

_______ Head surgery or injury

_______ Appendectomy

_______ Stroke

_______ Heart surgery _______ Injury to the neck

_______ Chest surgery _______ Chemical exposure or inhalation

_______ Thyroid surgery _______ Gastroesophageal reflux disease

_______ Tonsillectomy _______ Other surgeries or injuries

If you checked any of these, please discuss when it occurred and other details. How do they affect your current voice and singing performance?

IV. Do you:

_______ Smoke (tobacco or other substances)

How much? _______________

_______ Drink alcoholic beverages (beer, wine, other alcoholic substances)

How much? _______________

_______ Take any medication regularly

If so, list all current medications and doses (including aspirin, birth control pills, And vitamins).

IV. Are there any other current or past conditions or situations that may negatively affect your vocal production today?

APPENDIX F

Study 2 Health and Voice History Form

Date: ________________

Name: _________________________ Date of Birth: _________________ Age: __________

Circle the appropriate option

I am a: Bass Baritone Tenor Alto Mezzo-soprano Soprano

Number of years of singing voice training:

Number of years of speaking voice training:

Describe your professional performance experiences:

I. Do you have or currently experience any of the following?

_______ Allergies

_______ Respiratory problems

_______ Hearing loss

_______ Menstrual cycle difficulties

______ Swallowing problems

_______ Neurological problems

_______ Endocrine / hormone problems

_______ Sinus problems

_______ Premenstrual syndrome

_______ Dry tissue (mouth, throat, etc.)

If any of the conditions apply, please explain the effect on your voice and singing performance.

II. Have you ever had or currently undergoing voice and / or speech therapy? If so, please discuss.

III. Do you currently have any voice difficulties such as laryngeal discomfort, vocal roughness, strained voice, abnormal pitch, , reduced pitch range, weak voice, shaky voice, difficulty singing high notes. If so, please discuss.

III. Do you have or have you ever had any of the following?

_______ Laryngeal surgery or injury

_______ Head surgery or injury

_______ Heart surgery

_______ Chest surgery

_______ Thyroid surgery

_______ Tonsillectomy

_______ Appendectomy

_______ Stroke

_______ Injury to the neck

_______ Chemical exposure or inhalation

_______ Gastroesophageal reflux disease

_______ Other surgeries or injuries

If you checked any of these, please discuss when it occurred and other details. How do they affect your current voice and singing performance?

IV. Do you:

_______ Smoke (tobacco or other substances)?

How much? _______________

_______ Drink alcoholic beverages (beer, wine, other alcoholic substances)?

How much? _______________

_______ Take any medication regularly?

If so, list all current medications and doses (including aspirin, birth control pills, and vitamins).

IV. Are there any other current or past conditions or situations that may negatively affect your vocal production today?

APPENDIX G

Flow Mask Calibration

Purpose

The purpose was to calibrate the adult size aerodynamic flow mask used in the Glottal Enterprises model MSIF 2 S/N 2049S system.

Equipment

The equipment used for this purpose consisted of a) a sweeper (Simplicity, Model S14CL) to generate airflows, b) a calibrated pneumotachograph (Rudolph 3788, Lot#980890), c) a Validyne pressure transducer (MP45-16-871, S/N 119473), d) two voltmeters, e) a Glottal Enterprises large flow mask (MSIF-2 S/N 2049S), and f) a mold that the flow mask fits onto. Pictures of the arrangement are shown below (Figure A1 and A2).

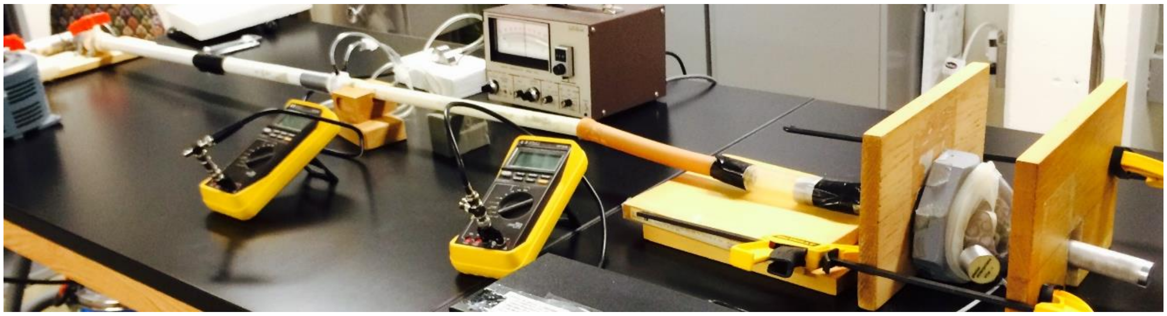


Figure A1: Flow calibration of Pneumotach mask

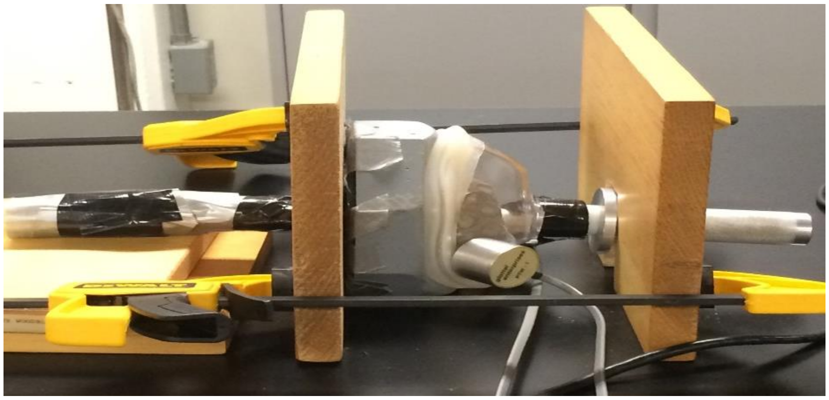


Figure A2: Closer view of flow mask along with the mold that fits onto.

Equipment settings

The settings on the Validyne pressure transducer system were as follows.

Sensitivity Gain: 15 mV/V

Sensitivity Vernier: 5.0

Filter: 10 Hz

Suppression: off

R Balance range: High

The R balance on the zero balance and the zeroing knob on the GE pressure transducer were adjusted until the voltmeter read zero prior to the calibration.

Procedure

The equipment was set as shown in Figures A1 and A2. A two-way sweeper that can push or pull air was used. Air was forced away from the sweeper through a calibrated Rudolph pneumotach and then through the mold into the flow mask. The amount of airflow was controlled by a line valve and a bleed valve between the sweeper and the pneumotach. The amount of flow through the pneumotach corresponded to the voltage output of pressure transducer-1 (Validyne MP45). The amount of pressure drop across the mask, which related linearly to the flow through the mask (Glottal Enterprises – MSIF 2), corresponded to the voltage shown on Voltmeter-2. The amount of airflow from the sweeper was manually adjusted in such a way that the voltage increments of approximately 0.5 volts were made between 0 and 11.5 volts. The voltage readings were noted simultaneously from the two voltmeters. The same procedure was repeated with the air reversed, i.e., pulled through the mask in the other direction (toward the sweeper) in the ingressive direction using the suction end of the sweeper. The voltage values were again noted from the two voltmeters simultaneously.

The data are shown in Table A1. Figure A3 shows the flow mask voltage (volts) on the abscissa and the flow (cm^3/s) on the ordinate. A best-fit line was constructed and the slope and regression values were obtained. The equation that was used to convert the voltage to pressure was pressure $P = 5.0552*V – 0.3991$, P in cm of H_2O. The equation to convert the mask system voltage was Flow $F= 739.49*V – 50.231$, F in cm^3/s.

Table A1

Data for Glottal Enterprises Flow Mask Calibration

Temperature: 74.3 degrees; Humidity: 24%; Pressure: 29.26 in Hg

Exhaling / Blowing Direction			**Inhaling / Sucking Direction**		
Validyne Voltage (V)	**GE Voltage (V)**	**Validyne Flow (cc/s)**	**Validyne Voltage (V)**	**GE Voltage (V)**	**Validyne Flow (cc/s)**
0.53	0.466	396.9267758	0.499	-0.435	-374.505895
1.003	0.892	727.6358237	1.012	-0.868	-733.7292212
1.5	1.334	1053.848213	1.495	-1.269	-1050.666325
2.008	1.774	1367.495638	1.984	-1.655	-1353.086313
2.534	2.218	1674.211314	2.506	-2.087	-1658.295809
3.006	2.641	1936.393184	3.042	-2.484	-1955.952473
3.496	3.042	2198.072573	3.517	-2.866	-2209.086758
3.98	3.449	2448.528001	3.97	-3.235	-2443.417301
4.49	3.898	2706.552783	4.5	-3.64	-2711.570738
4.99	4.3	2956.403015	5.03	-4.08	-2976.340368
5.46	4.69	3190.906647	5.45	-4.39	-3185.904716
5.98	5.16	3452.74886	6.03	-4.86	-3478.166308
6.53	5.58	3735.73099	6.47	-5.27	-3704.450668
7.02	6.04	3995.961637	6.93	-5.68	-3947.466069
7.48	6.4	4249.60912	7.49	-6.06	-4255.240177
7.96	6.85	4526.287172	7.96	-6.5	-4526.287172
8.48	7.39	4842.618628	8.58	-7	-4905.678784
9	7.81	5179.2039	9.06	-7.41	-5219.483359
9.5	8.28	5524.803613	9.52	-7.83	-5539.114795
10.02	8.75	5910.039851	10.08	-8.18	-5956.320616
10.56	9.2	6341.200683	10.5	-8.59	-6291.623888
10.97	9.54	6691.816183	10.95	-9.08	-6674.220926
8.24	6.97	4694.288706	8.2	-6.7	-4669.965305
5.23	4.37	3076.043873	5.22	-4.23	-3071.056444
2.246	1.925	1508.363737	2.248	-1.828	-1509.532381

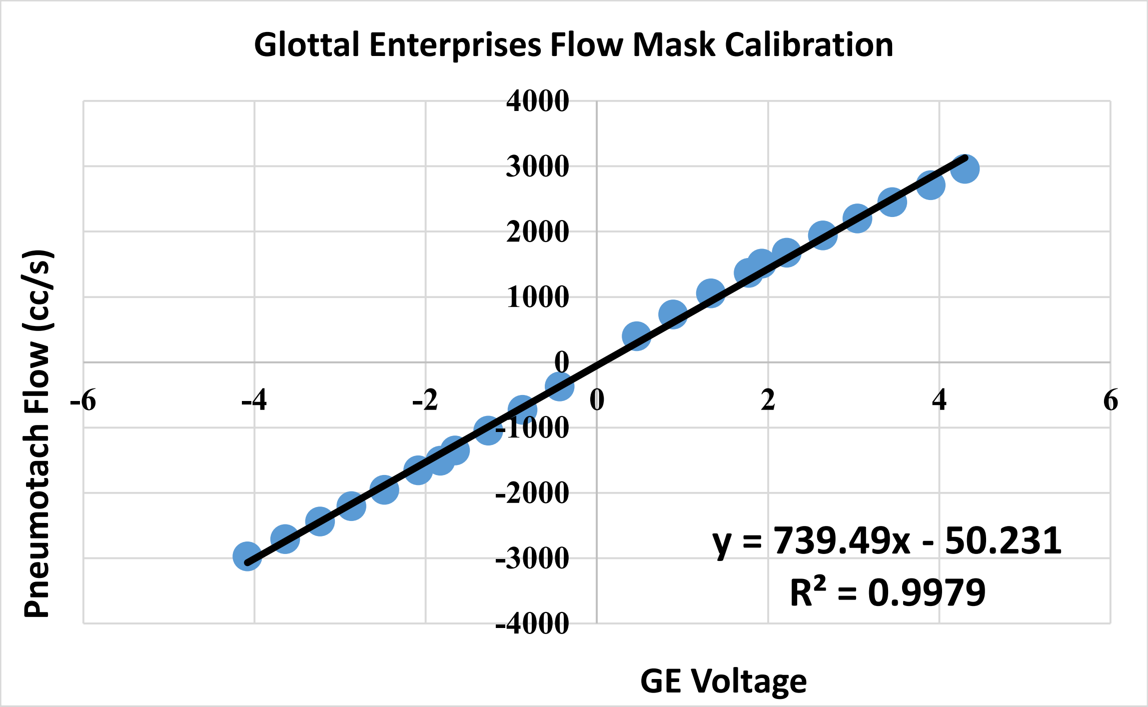


Figure A3. Flow Mask Voltage vs. Flow Volume for GE MSIF-2 Flow Mask Calibration

APPENDIX H

Pneumotach Mask: Oral Pressure Calibration

Purpose

The purpose was to calibrate the oral pressure transducer (PTL 116) of the GE flow mask.

Equipment

The equipment used for this purpose was a) Oral pressure Transducer (PTL 116), b) pressure tubing, c) a U-tube manometer, and d) DATAQ digital oscilloscope. The equipment was connected as shown in the schematic Figure A4.

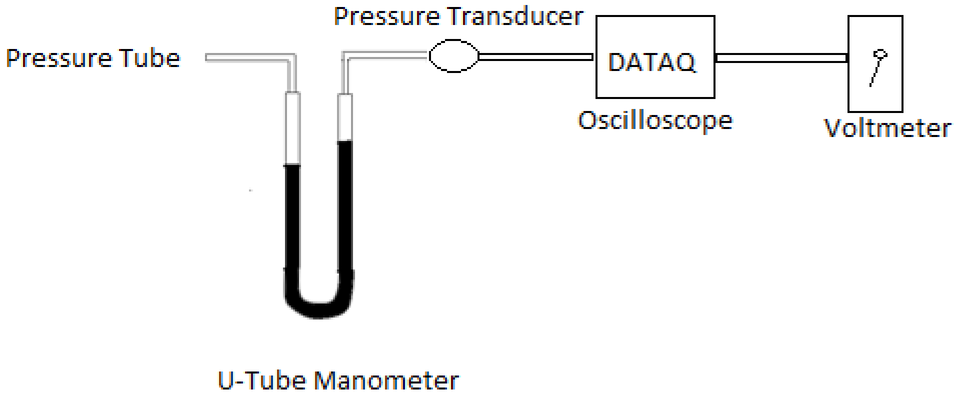


Figure A4. Set up for calibration of oral pressure transducer

Procedure

The pressure transducer was connected to a pressure tube, and a U-tube manometer. A digital oscilloscope (DATAQ) was connected to the transducer. The pressure induced in the tube created an equal amount of pressure in both the transducer and the manometer. The positive and negative pressures were given by blowing air into, and sucking air from the pressure tube, respectively, which is connected to a manometer. This procedure was followed until the output voltage reached the above mentioned saturation points, here until 9.65 V. An equation between voltage and pressure was obtained for these data, oral pressure P = 5.0552*V – 0.3991. The data are given in Table A2 and Figure A5.

Table A2

Oral Pressure Calibration for GE Aerodynamic Flow Mask through Pressure Transducer (PTL 116)

Pressure mm(left)	**Pressure mm(right)**	**Voltage(V)**	**Pressure difference (cm of H2O)**
-29	-29	-0.011	0
-57	0	1.176	5.7
-82	24	2.188	10.6
-98	41	2.85	13.9
-116	59	3.589	17.5
-140.5	84.5	4.58	22.5
-159	102	5.3	26.1
-180	123.5	6.12	30.35
-196	139.5	6.73	33.55
-217	161	7.56	37.8
-237	182	8.33	41.9
-260	205	9.19	46.5
-276	220	9.65	49.6
-293	280	9.65	57.3

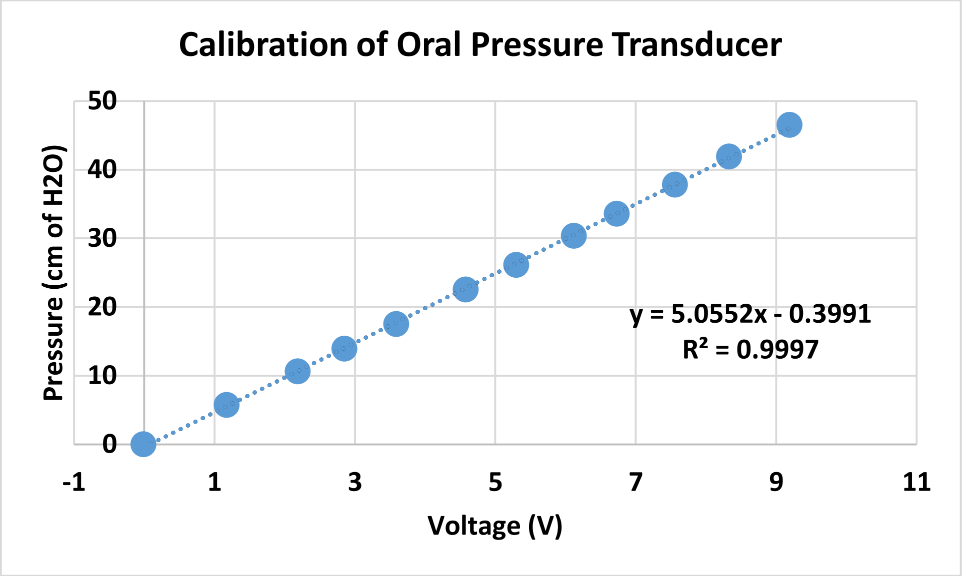


Figure A5. Flow mask voltage vs. Oral pressure for GE MSID-2 mask calibration