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Velopharyngeal Port Opening in Western Classical and Musical Theater Treble Singers in the Transition from Middle to Upper Voice (Secondo Passaggio)

by

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B.A., B.S., University of California, Davis, 2014

M.M., University of Colorado Boulder, 2023

A thesis submitted to the
Faculty of the Graduate School of the
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of the requirement for the degree of

Doctor of Musical Arts

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Velopharyngeal Port Opening in Western Classical and Musical Theater Treble Singers in the Transition from Middle to Upper Voice (Secondo Passaggio)

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Abstract

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Velopharyngeal Port Opening in Western Classical and Musical Theater Treble Singers in the Transition from Middle to Upper Voice (Secondo Passaggio)

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The role of velopharyngeal port opening (VPO) in the middle to upper voice transition in treble singers remains unclear, with conflicting evidence regarding its aerodynamic and acoustic effects. Empirical studies are limited and rarely compare Western Classical (WC) and Musical Theater (MT) singing. This study investigates changes in acoustic strategy, F0-nasalance, and nasal DC airflow during pitch glides on the vowel [a] using non-invasive, real-time physiological and acoustic measures. Nineteen treble undergraduate and graduate singers during the WC task used a statistically significant acoustic strategy in which the second harmonic (2fo) exceeded the fundamental (1fo) for the low pitch (C5), with the relationship reversing at the high pitch (G5). Fifteen participants during the MT task (Ab4 to Eb5) demonstrated a variety of acoustic approaches, including the WC strategy and two 2fo-dominant strategies. F0-nasalance and nasal DC airflow decreased significantly from low to high pitch for the WC task, whereas no significant trends were observed for the MT task. These findings suggest that singers may employ VPO differently depending on singing style during the middle to upper voice transition, likely reflecting the differing acoustic strategies characteristic of WC and MT performance. Also significant was the discovery of a previously undocumented limitation to the Glottal Enterprises OroNasal 2-Chamber CV Mask used for the F0-nasalance and nasal DC flow measurements. While this limitation likely effected the F0-nasalance measurements for this study, the nasal DC flow measurements are unaffected. Future research will explore a correction factor for the mask, as well as obtain additional data for the MT task.

VELOPHARYNGEAL PORT OPENING IN WESTERN CLASSICAL AND MUSICAL THEATER TREBLE SINGERS DURING THE TRANSITION FROM MIDDLE TO UPPER VOICE (SECONDO PASSAGGIO)

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Del Simone, Alice Jeanne (D.M.A, Voice Performance and Pedagogy, College of Music)
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A quick acknowledgement that I used ChatGPT-5.3 for grammar and sentence structure refinement. All substantive ideas and research findings presented in this dissertation remain my own original work, and I take full responsibility for the final text.

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Table of Contents

<u>Chapter 1: Introduction</u>

1.1 Rationale and Aims

Developing a sustainable technique for singing high notes is a central concern for performers, teachers, and students of voice. Most undergraduate and graduate students of voice are treble voice types (sopranos and mezzo-sopranos).[1] Accordingly, voice science research should prioritize questions that benefit this population. Navigating the transition from middle to upper voice is a foundational skill for treble singers across styles. In Western Classical (WC) singing, the goal is to make this transition imperceptible, whereas in Musical Theater (MT) singing, maintaining a strong belt technique for high notes is required for many of the roles in popular MT repertoire.[2] Expanding the scientific literature on efficient approaches to this transition would serve both voice teachers and treble singers.

One physiological mechanism that may influence this transition is velopharyngeal port opening (VPO). The velopharyngeal port is the opening between the soft palate (velum) and the posterior pharyngeal wall, serving as the gate between the nasal passages and the oral cavity.[3] VPO refers to the degree of velar lowering or raising that regulates airflow from the oral cavity into the nasal passages.[4] Debate about the role of VPO in singing is complicated by confusion surrounding the perceptual effects of nasal airflow during phonation. Some voice teachers and

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[1] Dana Lynne Varga, "Supply and Demand: Gender Disparity in Opera (Part 1)," The Empowered Musician, accessed March 17, 2026, https://www.theempoweredmusician.com/articles/gender-disparity-part1; Dana Lynne Varga, "Gender Disparity in Opera, Part Two," Classical Singer Magazine, March 1, 2018, accessed March 17, 2026, https://www.csmusic.net/content/articles/gender-disparity-in-opera-part-two/.

[2] Donald Miller, *Resonance in Singing* (Princeton, NJ: Inside View Press, 2008), 88.

[3] Johan Sundberg, *The Science of Singing* (Dekalb, Ill: Northern Illinois Univ. Press, 1987), 9.

[4] Nicholas Perna, "Nasality Deconstructed," *Journal of Singing* 76, no 4 (2020): 430.

singers associate nasal involvement with bright, forward-focused timbre.[5] However, this quality, often described as *twang*, is more accurately attributed to epilaryngeal or pharyngeal narrowing.[6] By contrast, VPO is more likely to produce a perceptually "honky" or muffled quality.[7]

Despite its physiological and acoustic relevance, the functional role of VPO in singing remains unclear. This raises a central question: does VPO provide an advantage or disadvantage for treble singers in the middle to high voice transition? Existing research offers conflicting perspectives on this question, particularly regarding its aerodynamic versus acoustic effects. Some researchers link VPO to increased vocal fold stabilization, which may assist singers in traversing this acoustically unstable region.[8] However, others note that the acoustic effects of VPO may conflict with certain resonance strategies used in this transition.[9] The utility of VPO likely depends on the resonance strategy employed and may differ between WC and MT singers. This stylistic distinction is particularly relevant given the differing target sounds in WC and MT singing.

However, empirical data addressing this question, particularly across different singing styles, remains limited. Only four studies examined trained treble singers traversing the *secondo*

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[5] Ingo Titze, "Nasality in Vowels," *The NATS Journal* 43, no. 3 (1987): 34.

[6] Perna, "Nasality Deconstructed," 430.

[7] Ian Howell, *Hearing Singing* (Lanham: Rowman & Littlefield, 2025): 196; Vennard, *SINGING: The Mechanism and the Technic* (New York: Carl Fischer, 2018), 93.

[8] Berton Coffin, *Overtones of Bel Canto* (Metuchen, N.J: Scarecrow Press, 1980), 37, 42-43; Nicholas Perna, "Nasalance and the Tenor Passaggio," *Journal of Singing* 70, no. 4 (2014): 409; Matthias Echternach et al., "The Effect of Nasalance on Vocal Fold Oscillation Patterns During the Male Passaggio," *Journal of Voice* 32, no. 3 (2019): 500.e13-500.e15, https://doi.org/10.1016/j.jvoice.2019.09.013.

[9] Titze, "Nasality in Vowels," 35; Johan Sundberg et al., "Experimental Findings on the Nasal Tract Resonator in Singing," *Journal of Voice* 21, no. 2 (2007): 127; Brian Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing," *Journal of Voice* 34, no. 3 (2018), 350-351, https://doi.org/10.1016/j.jvoice.2018.11.014.

passaggio.[10] Of those studies, three collected real-time data about treble and non-treble voice at the same time using a variety of equipment. Jennings & Kuehn used equipment they note is unlikely to give accurate readings above 750 Hz (~F#5) and Yanagisawa et al. used visual inspection of VPO that required invasive equipment placed in the nose.[11] Birch et al. used the same equipment as Yanagisawa et al. for visual inspection, but found that those results did not correspond with the results obtained using airflow measurements with a non-invasive mask. They suggested that the use of visual inspection equipment changed the way the participants sang.[12] The fourth study, Vampola et al., used a computer model based on one treble singer.[13] Of the four, only one, Yanagisawa et al., investigated VPO in treble singers attempting an MT task.[14] There are other VPO studies that may have captured data about treble singers transitioning through their *secondo passaggio*, but it is difficult to know what pitch range was being studied because the authors did not record the fundamental frequencies participants sang.[15] The present

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[10] Peer Birch et al. "Velum Behavior in Professional Classic Operatic Singing," *Journal of Voice* 16, no. 1 (2002), 61-71 https://doi.org/10.1016/S0892-1997(02)00073-5; Jori Jennings and David Kuehn, "The Effects of Frequency Range, Vowel, Dynamic Loudness Level, and Gender on Nasalance in Amateur and Classically Trained Singers," *Journal of Voice* 22, no. 1 (2008): 75-89, https://doi.org/10.1016/j.jvoice.2006.08.017; Tomáš Vampola et al. "Finite element modeling of the effects of velopharyngeal opening on vocal tract reactance in female voice," *The Journal of the Acoustical Society of America* 150, no. 3 (2021): 2154-2162, https://doi.org/10.1121/10.0006370; Eiji Yanagisawa et al., "Supraglottic Contributions to Pitch Raising: Videoendoscopic Study with Spectroanalysis," *Annals of Otology, Rhinology & Laryngology* 100, no. 1 (1991): 19-30, https://doi.org/10.1177/000348949110000104.

[11] Jennings & Kuehn, "The Effects of Frequency Range, Vowel, Dynamic Loudness Level, and Gender on Nasalance in Amateur and Classically Trained Singers," 87; Yanagisawa et al., "Supraglottic Contributions to Pitch Raising," 19–20.

[12] Birch et al., "Velum Behavior in Professional Classic Operatic Singing," 68.

[13] Vampola et al., "Finite element modeling of the effects of velopharyngeal opening on vocal tract reactance in female voice," 2154-2162.

[14] Yanagisawa et al., "Supraglottic Contributions to Pitch Raising: Videoendoscopic Study with Spectroanalysis," 19-30.

[15] Stephen Austin, "Movement of the velum during speech and singing in classically trained singers," *Journal of Voice* 11, no. 2 (1997): 212-221; Linda Fowler and Richard Morris, "Comparison of Fundamental Frequency Nasalance between Trained Singers and Nonsingers for Sung Vowels," *Annals of Otology, Rhinology & Laryngology* 116, no. 10 (2007): 739-746, https://doi.org/10.1177/000348940711601005; Kristine Tanner et al.,

study addresses the gaps in the literature by examining VPO in treble singers during the middle to high voice transition using non-invasive, real-time physiological and acoustic measures, and by directly comparing WC and MT singing tasks to investigate how VPO interacts with style-dependent acoustic strategies.

"Velopharyngeal Port Status During Classical Singing," *Journal of Speech, Language, and Hearing Research* 48, no. 6 (2005) 1311-1324, https://doi.org/10.1044/1092-4388(2005/091).

1.2 Research Questions

The research questions for this study were:

1. Will the sound pressure level (SPL) for the first harmonic minus the second harmonic (or H1-H2) significantly change from the low to the high pitch?
    a. For the WC task, the low pitch was C_5 and the high pitch was G_5.
    b. For the MT task, the low pitch was $A^b{}_4$ and the high pitch was $E^b{}_5$.
2. Will F0-nasalance significantly change from the low to the high pitch?
3. Will nasal DC airflow significantly change from the low to the high pitch?

1.3 Hypotheses

For Question 1 our hypotheses were:

- For the WC task, we hypothesized that participants would significantly increase H1-H2 and that H1-H2 would be negative on the low pitch and positive on the high pitch.[16]
- For the MT task, we hypothesized that H1-H2 would be negative on both pitches.[17]

For Questions 2 & 3 our hypotheses were:

- For the WC task, we hypothesized that F0-nasalance and nasal DC flow would significantly decrease from the low pitch to the high pitch.[18]
- For the MT task, we hypothesized that F0-nasalance and nasal DC flow would significantly increase from the low to the high pitch.[19]

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[16] Richard Lissemore, "Articulatory Activity of the Tongue, Jaw, and Lips During the Second Passaggio Transition of the Soprano Voice," (PhD diss., The City University of New York, 2024), iv–vi.

[17] Flynn et al., “Acoustic Comparison of Lower and Higher Belt Ranges in Professional Broadway Actresses,” *Journal of Voice* 34, no. 3 (2020): 412, https://doi.org/10.1016/j.jvoice.2018.10.006.

[18] Austin, “Movement of the velum during speech and singing in classically trained singers,” 212-221; Fowler and Morris, “Comparison of Fundamental Frequency Nasalance between Trained Singers and Nonsingers for Sung Vowels,” 739-746; Shelby Martell, Natalia Lastowiecka, and Youkyung Bae, “Task-Dependent Velopharyngeal Timing in Singers with Classical Training,” *Journal of Voice* 39 (2023): 1696.e33 - 1696.e42, https://doi.org/10.1016/j.jvoice.2023.06.026; GJ Troup et al., “On velum opening in singing,” *Journal of Research in Singing* 13 (1989): 35-39.

[19] Perna, “Velopharyngeal Opening Variability in Collegiate Treble Singers,” (unpublished fellowship application, Van L. Lawrence Fellowship, 2024), 1-2.

1.4 Terminology

Absolute Spectral Tone Color (ASTC): Any individual sound frequency can be perceived as having a specific vowel-like quality or color. For example, high frequencies (C_7 and above) have an [~i]-like or bright quality, while low frequencies (C_5 and below) have an [~u]-like or dark quality. Vowels are perceived as a combination of the ASTCs of the harmonics being boosted by the first and second resonances of the vocal tract.[20]

Auditory roughness: A buzzy percept in a sound caused by the presence of harmonics greater than $5f_o$ closely clustered together.[21]

Close timbre: A vocal quality or acoustic register achieved when $2f_o$ rises above f_{R1}. $2f_o$ crossing f_{R1} is called "turning over."[22]

Cricothyroid muscles (CT): Paired intrinsic muscles of the larynx that connect from their origin at the anterior arch of the cricoid cartilage to both the thyroid lamina and the inferior cornu of the thyroid cartilage. The CT muscles are the primary muscles for changing pitch.[23]

Formant: A spectral peak in the radiated sound spectrum that is generated by a resonance of the vocal tract. Formants are notated as F_1, F_2, F_3…etc.[24]

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[20] Howell, *Hearing Singing*, 130-133.

[21] Howell, *Hearing Singing*, 29.

[22] Kenneth Bozeman, *Practical Vocal Acoustics* (New York: Bloomsbury Academic, 2025), 47.

[23] Ingo Titze, *Principles of Voice Production* (Iowa City, IA: National Center for Voice and Speech, 2000), 11-12.

[24] Ingo Titze et al., "Toward a consensus on symbolic notation of harmonics, resonances, and formants in vocalization," *The Journal of the Acoustical Society of America* 137, no. 5 (2015): 3005-3007, https://doi.org/10.1121/1.4919349.

Fundamental frequency ($1f_o$): The lowest harmonic in the radiated sound spectrum. Roughly equivalent to the perceived pitch and measured in Hz.[25]

Harmonic: A frequency component of periodic sound. The first harmonic is called the fundamental frequency ($1f_o$) and all harmonics after it are integer multiples of $1f_o$. Harmonics are labeled $1f_o$, $2f_o$, $3f_o$…etc and sometimes H1, H2, H3…etc.[26]

Inertance/inertive reactance: In the vocal tract, inertance/inertive reactance is the tendency of the air column in the vocal tract to resist changes in airflow. This produces a phase relationship in which supraglottal pressure assists vocal fold opening during increasing flow and assists closing during decreasing flow, thereby supporting self-sustained oscillation.[27]

Nasalance: The ratio of the nasal to oral airflow (F0-nasalance) or the ratio of nasal to oral acoustic energy (F1-nasalance.)[28]

Open timbre: A vocal quality that occurs when two or more harmonics are positioned at or below f_{R1}. The more harmonics that lie below f_{R1}, the more open the perceived vocal timbre.[29]

Passaggio: A zone of instability in a singer's range that may necessitate a change in registration.[30]

Primo passaggio: A zone of instability often identified for treble singers near the pitch F_4.[31]

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[25] Howell, *Hearing Singing*, 31; Titze, *Principles of Voice Production*, 170-178.

[26] Titze, *Principles of Voice Production*, 170-178; Titze et al. "Toward a consensus on symbolic notation of harmonics, resonances, and formants in vocalization," 3005-3007.

[27] Titze, *Principles of Voice Production*, 99-102.

[28] Martin Rothenberg, "A New Method for the Measurement of Nasalance—Mask Based Nasometry," accessed October 9, 2025, http://www.rothenberg.org/Nasalance/Nasalance.htm.

[29] Bozeman, *Practical Vocal Acoustics*, 45.

[30] Titze, *Principles of Voice Production*, 293-299.

[31] Titze, *Principles of Voice Production*, 293-299.

Resonance: A term whose meaning is context dependent. Generally, resonance refers to the tendency of a system to oscillate with greater amplitude at specific frequencies when driven by an external force. In the context of voice, vocal tract resonances refer to the natural frequencies of the vocal tract at which acoustic energy is selectively amplified, resulting in peaks in the radiated spectrum. Vocal tract resonances are labeled f_{R1}, f_{R2}, f_{R3}…etc.[32]

Secondo passaggio: A zone of instability for treble singers between middle and high voice often identified as occurring between C_5 and F_5.[33]

Spectral slope: The rate at which harmonic amplitude decreases as frequency increases, often expressed in dB per octave.[34]

Thyroarytenoid muscles (TA): Paired intrinsic muscles of the larynx that connect from their origin at the thyroid cartilage to the arytenoid cartilage. The TA muscles form the bulk of the vocal folds. Contracting the TA muscles shortens and thickens the vocal folds.[35]

Twang: Refers to both a bright percept of sound and the pharyngeal narrowing and increased closed quotient that create that sound.[36]

Velopharyngeal port (VP): The passage between the soft palate (velum) and the posterior pharyngeal wall. It serves as the gate between the nasal passages and the oral cavity.[37]

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[32] Titze, *Principles of Voice* Production, 153-158. Titze et al., "Toward a consensus on symbolic notation of harmonics, resonances, and formants in vocalization," 3005-3007.

[33] Barbara M. Doscher, *The Functional Unity of the Singing Voice*, 2nd expanded ed., with John Nix (Lanham: Rowman & Littlefield, 2023), 182.

[34] Titze, *Principles of Voice Production*, 283-285.

[35] Titze, *Principles of Voice Production*, 11.

[36] Perna, "Nasality Deconstructed," 430.

[37] Sundberg, *The Science of Singing*, 9.

Velopharyngeal port opening (VPO): VPO is the degree by which the velum is relaxed/lowered or engaged/raised to control airflow from the oral cavity into the nasal passages.[38]

Whoop coupling / whoop timbre: A vocal timbre achieved when $1f_o$ reaches f_{R1} for the vowel being sung. This timbre is perceived as "hooty" or "pure." A singer may continue whoop timbre above the f_{R1} of the vowel through vowel modification that raises f_{R1} so it can continue to track $1f_o$ as it increases. Whoop timbre is associated with WC treble singing.[39]

Yell coupling: A type of open timbre where a singer, through vowel modification, raises f_{R1} to track $2f_o$ above the normal f_{R1} location for the vowel being sung. Yell coupling is associated with MT belt timbre.[40]

[38] Perna, "Nasality Deconstructed," 430.

[39] Bozeman, *Practical Vocal Acoustics*, 47-48.

[40] Bozeman, *Practical Vocal Acoustics*, 45.

Chapter 2: Review of Literature

2.1 Organization

This chapter includes a limited discussion of registration events and a comprehensive review of the scientific literature on velopharyngeal port opening (VPO) in singing. This discussion will focus on the voices of Western Classical (WC) sopranos, mezzo-sopranos and contraltos, and Musical Theater (MT) and Contemporary Commercial Music (CCM) treble singers, especially belters between the pitches B_4 and G_5. It also examines selected strategies used to traverse this portion of the vocal range. In this document, the term "WC trebles" excludes countertenors.

The organizational structure of the chapter is outlined below:

2.5 Scientific Research on VPO in Singing

2.5.1 The Terminology Problem

2.5.2. Studies that Explore the Perceptual Qualities of Nasality

2.5.3 Studies of VPO on One Note

2.5.3.1 General Studies of VPO in Unspecified Vowels

2.5.3.2 Studies that Assess VPO Using Different Vowels

2.5.3.3 Studies that Compare VPO in Speech and Singing

2.5.3.4 Studies that Address the Acoustic Effects of VPO

2.5.4 Studies of VPO on Changing Pitches

2.5.5 Studies of the Use of VPO during Register Transitions

2.6 Conclusion

The registration discussion will draw on a limited number of significant and/or recent pedagogues who address registration events in treble voices between B_4 and G_5. The discussion will be further divided into three groups: authors who discuss registration without reference to style, those who discuss registration in WC singing only, and those who discuss registration in MT and Contemporary Commercial Music (CCM) singing only. A limited overview of strategies used to balance the WC and MT/CCM treble middle and high voice will follow. These strategies will be organized into three categories: Acoustic Strategies, Integrated Strategies, and Velopharyngeal Port Opening (VPO) Strategies. Withing each category, the discussion will be further organized by the style (WC, CCM, or both) for which the author proposes the strategy.

The comprehensive review of VPO research will follow the targeted discussion of registration. This review will begin with a Discussion of Terminology section focusing on the terms “nasal resonance,” “VPO,” “nasalance,” “twang,” and “nasality.” Following the terminology discussion, a summary of study results will be presented. This summary will be organized into four sections: (1) Studies that Explore the Perceptual Qualities of Nasality, (2) Studies of VPO on One Note, (3) Studies of VPO on Changing Pitches, and (4) Studies of the Use of VPO during Register Transitions.

This chapter will conclude with a brief overview of the information contained in this review of literature displayed in concise tables. A final section will then discuss how findings of this review of literature informed the methodology used in the study of VPO in treble singers discussed in later chapters of this document.

2.2 Limitations and Exclusions

The topic of this document combines two pedagogical questions: first, the existence and location of registration events in the treble voice; and second, velopharyngeal port behavior during singing. Given the vast quantity of writing on the topic of registration, this section is limited to the opinions and research of a few significant pedagogues from before the year 2000 and a summary of selected more recent authors on the topic. The selection criteria for the authors presented in the registration section attempts to offer a variety of perspectives from pedagogues of different genders and working in different musical styles (specifically WC and CCM styles.) However, it is important to note that this is not a complete discussion of registration and that the selection criteria employed was subjective and did not follow a rigorous process. Sources for this section were limited to English language or English translation and focus mostly on the authors' writing about the treble voice between B_4 and G_5.

For the section on velopharyngeal port behavior in singing, the author utilized the databases ProQuest and CU Boulder One Search. The lack of unified nomenclature on this topic necessitated the use of many search terms. The search terms used were:

- “nasalance”
- “nasalance” AND “singing OR voice OR vocal”
- “OroNasal System”
- “velopharyngeal port” AND “voice”
- “velopharyngeal port” AND “singing”
- “nasal airflow” AND “singing”
- “nasal resonance” AND “singing”
- “nasality” AND “singing.”

These searches yielded over 4000 results. In addition to the database searches, the author also consulted the bibliographies of papers closely related to the topic. From these sources, 25 were deemed sufficiently related for inclusion because they addressed velopharyngeal port behavior during singing. There is a large body of work addressing velopharyngeal port behavior during speaking that is of great use to professionals working with patients with voice disorders, but these studies were excluded from this review because they did not involve singing tasks. Sources were also limited to English language or English translations. The review includes sources relating to any style of singing; however, most sources focus on WC singing.

2.3 Registration in Treble Singers

2.3.1 Registration without Reference to Style

Registration is a contentious topic eliciting strong opinions from almost every pedagogue who has ever written a treatise or book. There are three large schools of thought among the pedagogues who acknowledge the existence of registers: (1) registers are laryngeal events, (2) registers are acoustic events caused by vocal tract shaping, and (3) registers are a combination of laryngeal and acoustic events. Again, this discussion will focus primarily on what pedagogues have to say about registration in the treble voice between B_4 and G_5. Also, it is important to note that although many of these authors do not mention style, most research conducted on singing prior to this millennium did not consider MT and CCM styles.

In his 1987 book *The Science of* Singing, Johan Sundberg discusses registers from the laryngeal perspective and summarizes the confounding and conflicting research about voice source muscular activity through a singer's range.[41] He states, "register difference must refer to voice source difference."[42] However, he also illuminates a novel variable for describing the behavior of the voice source: vocal fold vibratory pattern. Sundberg states that the pattern with which the vocal folds open and close has a profound effect on the radiated sound spectrum from the mouth, or, in other words, vocal timbre. For example, he cites research in men showing that a longer closed phase of the glottis corresponds to modal register.[43] Sundberg argues that the contribution of the vocal folds to registration involves both the length and depth of vocal fold contact and the duration of the closed phase of the glottis. While this may seem to put Sundberg squarely in the camp of laryngeal registration, he later acknowledges the role of acoustics in registration saying,

> a change in an articulatory parameter, which really should influence only the vocal tract shape, and hence the formant frequencies, may sometimes affect the voice source as well. Singers often experience difficulties in the continuity of phonation; the voice timbre changes automatically, as it were, just because the pitch or the vowel is changed, or, in other word, just because the frequency relationship between the fundamental and the formants changed… resonance phenomena in the subglottic airways may also have this effect.[44]

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[41] Sundberg, *The Science of the Singing Voice*, 54–56.

[42] Sundberg, *The Science of the Singing Voice*, 69.

[43] Sundberg, *The Science of the Singing Voice*, 63–64, 88.

[44] Sundberg, *The Science of the Singing Voice*, 91.

Sundberg recognizes that registration events are created by a complex set of factors.

Ingo Titze examines the effect of subglottic resonances on registration in more detail. He proposes two hypotheses for the cause of involuntary register transition, the first of which involves these resonances. He states that the resonances of the trachea below the vocal folds, "contribute, constructively or destructively, to the intraglottal driving pressures of the vocal folds."[45] He clarifies: "positive reinforcement of vocal fold vibration is achieved when the [subglottal] formant pressure is positive during [glottal] opening and negative during closing. In particular, when the bottom portions of vocal folds are moving outward, a positive pressure should help to push them outward."[46] This describes the constructive role of subglottic tracheal resonances, but a destructive arrangement is also possible. In that situation, negative formant pressure would be exerted during the opening phase and positive during the closing phase, making self-sustaining vocal fold oscillation more difficult, especially with a large vertical phase of vocal fold contact.[47] Titze notes that there are specific frequencies where the constructive or destructive feedback is predicted to occur. One frequency range where destructive feedback is predicted is A_5 – C_5, which Titze suggests may partially explain why maintaining vertical fold contact in this range is difficult. He also points to another zone between D_5 and $F^{\#}_5$ where destructive feedback from subglottic tracheal formants may signal another register transition.[48] Both the C_5 and $F^{\#}_5$ locations roughly align with other pedagogues' predictions for WC singing.

[45] Titze, *Principles of Voice Production*, 295.

[46] Titze, *Principles of Voice Production*, 295–96.

[47] Titze, *Principles of Voice Production*, 295–96.

[48] Titze, *Principles of Voice Production*, 298.

In his description of the first hypothesis, Titze mentions a large vertical phase of vocal fold contact. He links this configuration to "modal" or "chest" register. He cites research that shows that in this register, the TA muscle is active which "bulges the vocal fold medially below the level of the vocal processes."[49] He includes a useful diagram explaining two different modes of vocal fold vibration which is included below (see Figure 2.1). The ability of the TA to

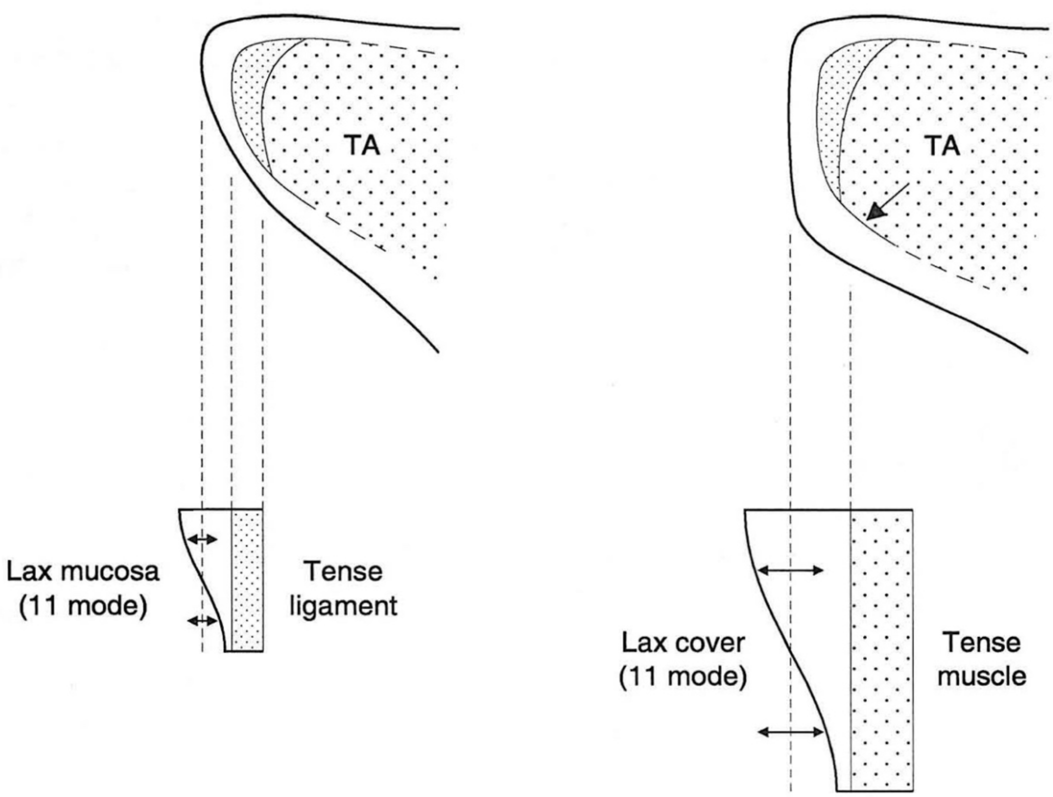

Figure 2.1 Vocal fold configuration in coronal section for falsetto register and modal register. In the transition from falsetto to modal register, the thyroarytenoid (TA) muscle contracts, which bulges out the inferior portion of the fold. Vibration in the mucosa and ligament changes to vibration in the cover and body. Diagram by Ingo Titze in Principles of Voice Production: Second Printing (Iowa City, IA: National Center for Voice and Speech, 2000), 291.

maintain the deep fold contact mode is dictated by its maximum active stress. Titze's second hypothesis for involuntary register changes states that when the TA reaches its maximum active

[49] Titze, *Principles of Voice Production*, 291.

stress, there will be a sudden physiological switch from the tense TA muscle mode to the tense ligament mode which Titze links to “falsetto” register. Titze notes that the pitch location of this switch had not been determined in 2000 when he wrote *Principals of Voice Production*, but supposes that it could be around F_4, C_5, or F_5 depending on the singer.[50] Titze proposes that, in order to avoid the involuntary transition caused by reaching the physiological limits of the TA, trained singers instead gradually release TA activity at lower pitches while increasing CT activity.[51] He summarizes this theory with a muscle activation plot showing the wide range of TA and CT activities that can create the same pitch (see Figure 2.2).

[50] Titze, *Principles of Voice Production*, 301.

[51] Titze, *Principles of Voice Production*, 300–301.

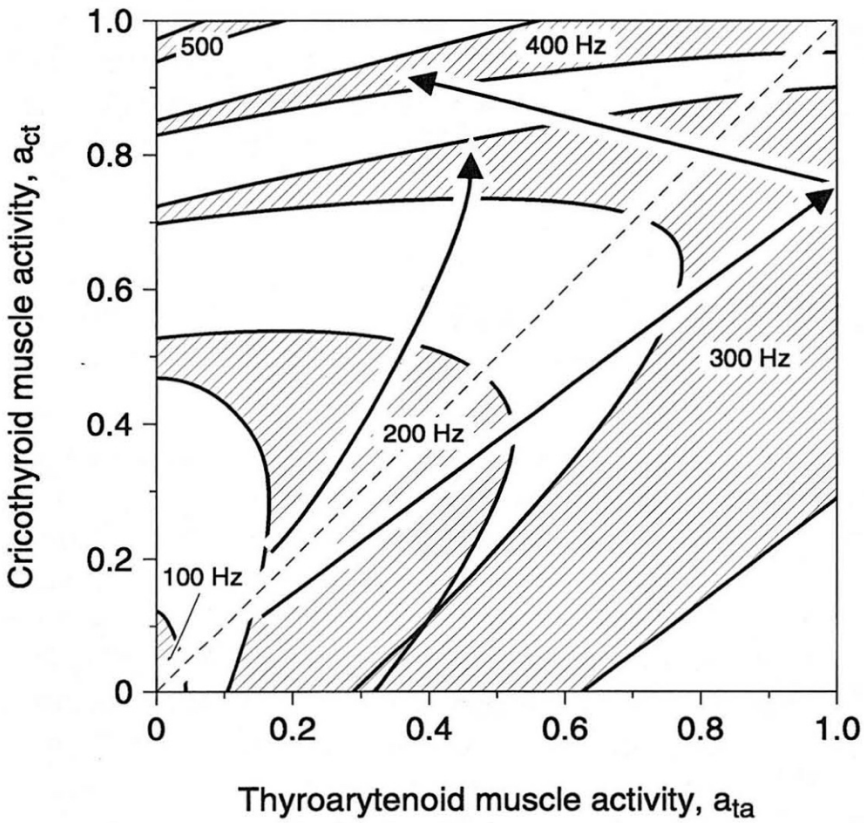

Figure 2.2 Muscle activation plot (MAP) showing abrupt register transition (two straight arrows) and gradual transition (curved arrow). Diagram by Ingo Titze in Principles of Voice Production: Second Printing (Iowa City, IA: National Center for Voice and Speech, 2000), 300.

Titze provides both a laryngeal and acoustical explanation of registers, reflecting a trend, also seen in Sundberg's work, towards acknowledging that both laryngeal muscles and acoustical phenomena play a role in registration.

While the acknowledgement of the complex interaction underlying registration events is becoming more widespread, some researchers focus more deeply on the laryngeal or acoustic aspects individually. Two research teams that published landmark papers on laryngeal behavior are Roubeau, Henrich, and Castellengo in 1993, 2001 and 2009, and Herbst, Švec and Ternström in 2009 and 2014.[52]

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[52] Bernard Roubeau, Nathalie Henrich, and Michèle Castellengo, "Laryngeal Vibratory Mechanisms: The Notion of Vocal Register Revisited," *Journal of Voice* 23, no. 4 (2009): 425–38, https://doi.org/10.1016/j.jvoice.2007.10.014.; Christian T. Herbst and Jan G. Švec, "Adjustment of Glottal

Roubeau et al. introduce a model that incorporates four modes of laryngeal vibratory mechanisms. Mechanism 0 (M0) is associated with short and relaxed vocal folds, a high closed quotient and an irregular vibratory cycle when compared to other modes.[53] Mechanism 1 (M1) is characterized by a greater mass and deeper layers of the vocal folds participating in vibration than in Mechanism 2 (M2). During M1 phonation, the vocalis muscle is involved in vibrations. M1 also has a shorter and more abrupt closing phase of the glottal cycle than M2. M2 is characterized by its comparison to M1 and by only the superficial layer of the vocal folds participating in vibration.[54] Mechanism 3 (M3) is the least well studied mode by this research team. During M3 phonation, the vocal folds are tightly stretched and very thin. The authors suggest that it is possible that there is no contact between the vocal folds during phonation, but they note that electroglottographs (EGGs) do not measure M3 phonation well. When they do get EGG signal, the glottal cycle is similar to M2's longer and less abrupt closing phase.[55] The authors are careful to distinguish their model from previous work on registration, providing a clear definition of how they see their work fitting into the body of literature:

> Laryngeal vibratory mechanisms are the different configurations of the glottal vibrator that allow the production of the entire frequency range of the human voice.
> The mechanisms, four in all, are classified from low to high and numbered from zero to three.
> The sounds produced by one and the same mechanism can present great variations in timbre and intensity. The modification of timbre and the proprioceptive sensations with which they are associated contribute to the determination of the registers. On the basis of these definitions, the notions of registers and of mechanisms are different, even though sometimes they may be considered as synonymous. The same mechanism can contribute to the production of several registers.

Configurations in Singing," *Journal of Singing* 70, no. 3 (2014): 301-307.; Christian Herbst, Sten Ternström, and Jan Švec, "Investigation of Four Distinct Glottal Configurations in Classical Singing—A Pilot Study," *The Journal of the Acoustical Society of America* 125, no. 3 (2009): EL104–9, https://doi.org/10.1121/1.3057860."

[53] Roubeau et al., "Laryngeal Vibratory Mechanisms," 430.

[54] Roubeau et al., "Laryngeal Vibratory Mechanisms," 426–28.

[55] Roubeau et al., "Laryngeal Vibratory Mechanisms," 429–30.

It is easy to establish a correspondence between the terminology of registers and the laryngeal mechanisms associated with their production, but only if one observes great rigor in the use of each of the two terms: "mechanisms" and "registers", because each one has its own specific definition.[56]

Christian Herbst and Jan Švec investigate additional nuances of laryngeal registration in their landmark 2009 study "Investigation of four distinct glottal configurations in classical singing – A pilot study." They argue for four distinct glottal configurations that influence the

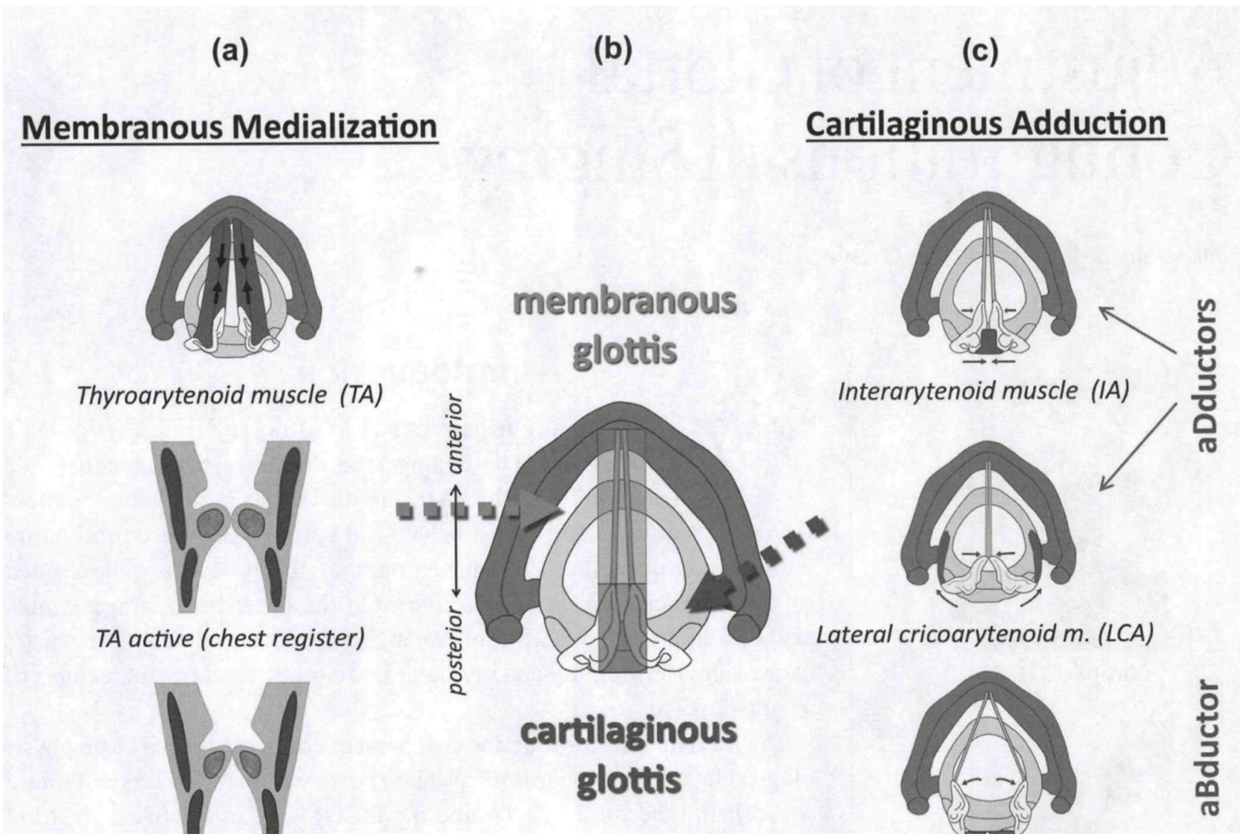

Figure 2.3 Schematic illustration of two types of glottal adduction: (a) membranous medialization, middle and bottom graph: coronal section through the larynx, showing the effect of TA muscle contraction; (b) conceptual separation of glottis into membranous and cartilaginous portion; (c) cartilaginous adduction. From Herbst and Švec, "Adjustment of Glottal Configuration in Singing," Journal of Singing 70, no. 3 (January/February 2014), 302.

perceived register. They designate falsetto register and chest register in the same way as Titze with the TA muscle active (or membranous medialization present) in chest and relaxed (membranous medialization not present) in falsetto. They also introduce another variable of

[56] Roubeau et al., "Laryngeal Vibratory Mechanisms," 437.

glottal behavior: cartilaginous adduction. The authors provide a diagram demonstrating these two variables (see Figure 2.3). From the two glottal behavior variables, Herbst and Švec denote four phonation types used by singers: abducted falsetto, adducted falsetto, abducted chest and adducted chest. They display the glottal behavior in a helpful chart (see Figure 2.4).

Voice quality	Cartilaginous adduction	Membranous medialization
aBducted falsetto	—	—
aDducted falsetto	++	—
aBducted chest	—	++
aDducted chest	++	++

Figure 2.4 Table showing four distinct phonation types, as created by different degree of cartilaginous adduction and membranous medialization. From Herbst and Švec, "Adjustment of Glottal Configuration in Singing," Journal of Singing 70, no. 3 (January/February 2014), 304.

While these two research teams focus on laryngeal behavior, other individuals and teams focus on the relationships between the harmonics in the radiated sound spectrum and the resonances of the vocal tract. Their results will be covered in the following two sections on registration in WC singing and registration in MT and CCM styles because much of the research focusses on specific couplings of harmonics and resonances for style-specific target sounds. However, Joseph Talia points out another important consideration that is style agnostic: "while scientists tend to approach the study of vocal registers as mechanical problems, and voice scientists as an acoustical study, singers are concerned whether the sound is of equal quality and intensity throughout the entire range of pitches."[57] This suggests an avenue for understanding registers that ignores the mechanics and highlights the results: the sounds we hear.

Titze alludes to this avenue of understanding when he discusses register transitions above vocal fry (Roubeau et al.'s M0) as "spectral slope transitions" that are heard as "an abrupt quality change that results from an abrupt acoustic change, specifically from the sudden loss or gain of high-frequency sound energy at the source."[58] He notes that a shallow spectral slope has many harmonics and sounds brassy, while a steep spectral slope has fewer harmonics and sounds flute-like. Titze argues that spectral slope steepness is dependent on changes in prephonatory glottal closure. He argues that an abduction quotient (Q_a) less than 0.5 produces a shallower spectral slope, which is perceived as a "richer" timbre. Q_a greater than 0.5 produces a steep spectral slope associated with less "rich" timbre. Abduction quotient is determined by prephonatory glottal half width (ξ_0) and amplitude of vibration (A) with the equation $Q_a = \xi_0/A$. The equation predicts that if the glottis is closed before phonation, the abduction quotient will be less than or equal to zero, resulting in a shallow spectral slope. Conversely, if the glottis is open before phonation, the opposite is true and a steeper spectral slope is predicted.[59] In other words, Titze argues that the brassiness or flutiness of a sung sound is highly influenced by glottal behavior.

Howell also supports a definition of registration that is based on the listener's perception of the sound radiated from the mouth. He argues that "chest" register is identified by a "buzzy" sound quality caused by the presence of high harmonics, while "head" register is identified by a

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[57] Joseph Talia, *Vocal Science for Elite Singers* (Bowen Hills: Australian Academic Press, 2018), 152.

[58] Titze, *Principles of Voice Production*, 284.

[59] Titze, *Principles of Voice Production*, 289–90.

lack of buzziness.[60] He notes that increasing buzziness, also called auditory roughness, can be achieved through laryngeal or vowel changes, but regardless of its source, it is the auditory roughness itself that characterizes the register.[61] This perception-based definition alleviates some of the challenges of register nomenclature by being inclusive of all laryngeal or acoustical sources of register changes.

Aside from auditory roughness, Howell introduces a way to quantify the brightness or darkness of a particular pitch. He argues that simple sine wave tones with the same frequency will "share a common tone color percept."[62] He calls this "absolute spectral tone color" or ASTC and argues that it is an inherent quality of every specific pitch that can be "only expressed or masked" in a complex sound.[63] These fixed tone colors can be related to vowel-like sounds which are displayed in Howell's figure below (see Figure 2.5).

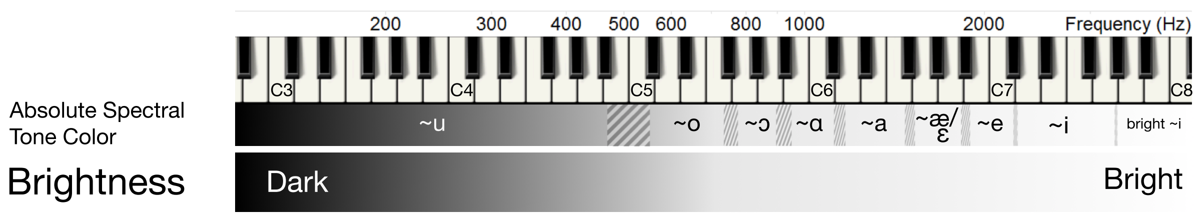

Figure 2.5 Frequency locations of vowel color transitions according ASTC. Diagram by Ian Howell in Hearing Singing: A Guide to Functional Listening and Voice Perception (Lanham, MD: Rowman & Littlefield, 2025), 132.

Howell stresses that ASTC arises from "non-vowel-defining portions of any spectrum…[or] energy below F_1 and above F_2" for the vowel being sung, but notes that the ASTC locations assigned to vowels in his figure are derived mostly from the F_2 locations of those vowels.[64] Most

[60] Howell, *Hearing Singing*, 103.

[61] Howell, *Hearing Singing*, 105.

[62] Howell, *Hearing Singing*, 130.

[63] Howell, *Hearing Singing*, 131.

[64] Howell, *Hearing Singing*, 132.

important for this discussion, however, are the locations at which ASTC shifts in vowel-like qualities. These shifts occur at locations where other research recognizes registration shifts, [~u] to [~o] around C_5, [~o] to [~ɔ] around $F^{\#}_5$, and [~ɔ] to [~ɑ] around C_6. Howell notes this and suggests that "these particular registration points rest on a significant psychoacoustic component as well. The expectation of how a vowel percept will change as pitch rises may then be a combination of perceptual and physical consideration."[65] In other words, the registration transitions we notice in treble singers around C_5 and $F^{\#}_5$ may be influenced by the change in ASTC of that fundamental frequency, and, for the singer, how they navigate these transitions may be influenced both by the need for physiological changes in laryngeal musculature and their own perception of the sound.

Titze and Howell remind us that the existence of registration events can be confirmed by timbral changes that the listener hears. It is also important to acknowledge that the changes experienced by singers as they move through their range give important information about the location and impact of registration events. Several theories for the pitch locations of registration events have already been presented in this section, and additional theories will be discussed in subsequent sections. However, as Kari Ragan notes in her textbook *A Systematic Approach to Voice: The Art of Studio Application*, "the sensory experience of registration events is very individual and multifaceted across gender, genre, voice type, and training."[66] Beyond the categories that Ragan lists, Wendy LeBorgne and Marci Daniels Rosenberg acknowledge that in the singer's experience of registration, "the other 'wildcard'… is the unique individual

[65] Howell, *Hearing Singing*, 156–57.

[66] Kari Ragan, *A Systematic Approach to Voice: The Art of Studio Application* (San Diego, CA: Plural Publishing, Inc., 2020), 32.

anatomical and physiologic differences that result in one singer's natural ability (or perhaps combined vocal folds and vocal tract shape) to easily navigate registers while another singer with a different anatomy may struggle on the exact same passages."[67] When studying registers, one must acknowledge that any theory presented may not resonate with the experience of every singer. In practice, studying and teaching registration often involves making informed or educated guesses.

2.3.2 Registration in WC Trebles

Two eminent pedagogues from around the turn of the 20th century demonstrate that different schools of thought about the causes of registration have existed for over a century, at least. Giovanni Battista Lamperti, transcribed by his student William Earl Brown, stated "the height and depth of perpendicular vibration is the same for all tones. The voice changes only its resonance, thereby causing the so-called 'registers.'"[68] Here, Lamperti alludes to the acoustic nature of registers through his use of the word 'resonance' and implies that laryngeal vibrations are the same throughout the range. As we will see, considerable empirical evidence supports the presence of laryngeal changes throughout a singer's range; however, Lamperti did not consider these to be significant contributors to registration events in the voice.

García argues the opposite – that register events are dictated by changes in vocal fold vibration. He calls the section of the voice from F_4 to C_5 "medium" register and argues that in "medium" register the vocal folds vibrate along both the membranous and cartilaginous glottis, while in "head" register only the membranous glottis vibrates. He also notes that in both

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[67] Wendy DeLeo LeBorgne and Marci Daniels Rosenberg, *The Vocal Athlete*, 2nd ed. (San Diego, CA: Plural Publishing, 2021), 179.

[68] Giovanni Battista Lamperti, *Vocal Wisdom*, enl. ed., 12th print, ed. Lillian Strongin, trans. William Earl Brown (New York: Taplinger, 1957), 103.

"medium" and "head" register only the top of the vocal folds vibrate, while in "chest" register the full perpendicular length of the vocal folds vibrate. His arguments stem from his own observations of the vocal folds using dental mirrors.[69] García introduces the idea that the vocal folds can change vibratory behavior in both horizontal (length) and perpendicular (depth) directions. Further, as a point that is significant for the present discussion, García also acknowledges that the transition from "medium" to "head" register can occur over a range of notes from $C^{\#}_5$ to E_5.

As the second half of the 20th century begins, the dialogue around registration increasingly incorporates new scientific research. Specifically, pedagogues identify the balance of activity between the cricothyroid (CT) and thyroarytenoid (TA) muscles as an important indicator of registration.[70] William Vennard describes this muscular interaction as a "dynamic balance" and attributes vocal "breaks" to excessive rigidity in either muscle.[71] Vennard does not prescribe specific pitch ranges for registers. However, he notes that in the treble voice the challenge of the "middle voice" is a very real experience for singers because there are many options for TA-CT activity balances in that range. He further states that "the upper limit of this register is reached when the limit of [TA] muscular strength has been reached."[72]

Like Vennard, Cornelius Reid also refers to TA and CT action when describing the source of registers. His proposal for the locations of registration events allows for a large overlap in the different registers he names. He identifies F_5 as the upper limit of the "Coordinated Chest

[69] Manuel García, *Treatise on the Art of Singing* (London: Leonard & Co., 1924), 8–10.

[70] Vennard, *SINGING*, 58; Cornelius L. Reid, *The Free Voice: A Guide to Natural Singing*, 50th anniversary ed., with George Shirley (New York, NY: Oxford University Press, 2018), 40.

[71] Vennard, *SINGING*, 58.

[72] Vennard, *SINGING*, 66–67.

Register" and E_5 as the upper limit of "The Falsetto," but suggests that these same notes reside in the center of the "Coordinated Head Register."[73] Reid indicates that singers have a variety of choices for how to produce the same note. He argues that register always has a vocal fold component but also acknowledges that vowels have an impact as well.[74] By mentioning the impact of vowels, Reid is adding an acoustic aspect to registration since changes in vowels are created by changes in vocal tract position which influence the acoustic properties of the sound radiated from the mouth. Thus, Reid can be placed in the third camp of pedagogues who maintain that both laryngeal and acoustic factors play a role in registration events.

A variety of terms have already been used to describe different registers, including head, chest, medium, and middle. It is important to note that the primary source of confusion when comparing pedagogical perspectives on registration is the lack of unified terminology. A dizzyingly wide variety of terms are used in voice studios and pedagogical writing, and this discussion will attempt, as much as possible, to align these terms with note ranges. Please refer to Table 2.1 which compiles the terms used by the authors considered in this chapter to describe registers in treble voices and their corresponding note ranges, where available.

Table 2.1 Treble Voice Registration Terms and Corresponding Ranges by Author

Author	**Publication and First Publication Date**	**Registration Terms Used for Treble Voices**	**Note Range**
Manuel García II	Hints on Singing (1894)[75]		
		Chest Voice	~ E_3 – B_4
		Medium Register	C_4 – D^b_5
		Head Register	$C^\#_5$ – C_6

[73] Reid, *The Free Voice*, 46.

[74] Reid, *The Free Voice*, 38, 40, 44.

[75] García, *Hints on Singing*, 9–10.

William Vennard	Singing the Mechanism and Technic (1967)[76]		
		Chest Voice/Heavy Mechanism	Up to F_4
		Middle	Not specified[77]
		Head Voice/Light Mechanism	
Berton Coffin	Overtones of Bel Canto (1980)[78]		
		Contralto	
		3 Chest	Up to D_4
		2 Middle (Upper)	E_3 – A_4
		1.5 Mixed	A_3 – D^b_5
		1 Vowel Register	D^b_4 – A_5
		.67 Head Mix (Flute)	B4 – C_6
		.5 Whistle	E_5 – E^b_6
		.33 Super Whistle	B_5 and above
		Mezzo Soprano	
		3 Chest	Up to E^b_4
		2 Middle (Upper)	F_3 – B^b_4
		1.5 Mixed	B^b_3 – E^b_5
		1 Vowel Register	D_4 – B^b_5
		.67 Head Mix (Flute)	C_5 – $C^\#_6$
		.5 Whistle	F_5 – E_6
		.33 Super Whistle	C_6 and above
		Lyrico-Spinto Soprano	
		3 Chest	Up to E_4
		2 Middle (Upper)	$F^\#_3$ – B_4
		1.5 Mixed	B_3 – E_5
		1 Vowel Register	$D^\#_4$ – B_5
		.67 Head Mix (Flute)	$C^\#_5$ – D_6
		.5 Whistle	$F^\#_5$ – F_6
		.33 Super Whistle	$C^\#_6$ and above
		Lyric Soprano	
		3 Chest	Up to F_4
		2 Middle (Upper)	G_3 – C_5
		1.5 Mixed	C_4 – F_5
		1 Vowel Register	E_4 – C_6
		.67 Head Mix (Flute)	D_5 – $D^\#_6$
		.5 Whistle	G_5 – $F^\#_6$
		.33 Super Whistle	D_6 and above

[76] Vennard, *SINGING*, 73.

[77] Vennard, *SINGING*, 78. Vennard writes "I prefer not to locate specific notes upon which a voice will change, because this tends to make the student self-conscious when he sees these notes in songs."

[78] Coffin, *Overtones of Bel Canto*.

		Coloratura Soprano	
		3 Chest	Up to $F^{\#}_4$
		2 Middle (Upper)	$G^{\#}_3 – C^{\#}_5$
		1.5 Mixed	$C^{\#}_4 – F^{\#}_5$
		1 Vowel Register	$F_4 – C^{\#}_6$
		.67 Head Mix (Flute)	$D^{\#}_5 – E_6$
		.5 Whistle	$G^{\#}_5 – G_6$
		.33 Super Whistle	$D^{\#}_6$ and above
Cornelius Reid	The Free Voice (1986)[79]		
		Pure Chest Register	$D_2 – F_3$
		Coordinated Chest Register	$F_2 – F_5$
		Break	$D_4 – F_4$
		The Falsetto	$E_4 – E_5$
		Coordinated Head Register	$F_3 – F_5$
Johan Sundberg	The Science of Singing (1987)[80]		
		Chest Register	Up to G_4
		Middle Register	$G_4 – E_5$[81]
		Head Register	Above E_5
Richard Miller	Training Soprano Voices (2000)[82]		
		Soprano	
		Chest	$G_3 – E^{b}_4$
		Lower Middle	$B^{b}_3 – C_5$
		Upper Middle	$C^{\#}_5 – F^{\#}_5$
		Upper	$G_5 – C_6$ ($C^{\#}_6$)
		Flageolet	$D_6 – A_6$
		Mezzo-soprano	
		Chest	E_3 (F_3) – E_4 (F_4)
		Lower Middle	$C_4 – B^{b}_4$ (B_4)
		Upper Middle	$B_4 – E_5$ (F_5)
		Upper	F_5 ($F^{\#}_5$) – B^{b}_5 (B_5)
		Flageolet	C_6 and above
		Contralto	
		Chest	$D_3 – G_4$ (A_4)

[79] Reid, *The Free Voice*, 46.

[80] Sundberg, *The Science of the Singing Voice*, 50–51.

[81] Sundberg, *The Science of the Singing* Voice, 51. Sundberg writes "These ranges of register overlap, and the register boundaries vary substantially among individuals." He also notes that he "wants to state explicitly that he does not favor any particular terminology: rather, he was forced to choose one and then try to be consistent." Science of Singing 51

[82] Richard Miller, *Training Soprano Voices* (New York: Oxford University Press USA, 2000), 25.

		Lower Middle	F_4 – A_4
		Upper Middle	B^{b}_{4} – D_5
		Upper	E^{b}_{5} – A^{b}_{5}
		Flageolet	A_5 and above (seldomly developed)
Ingo Titze	Principles of Voice Production (2000)[83]		
		Transition 1	Around F_3[84]
		Transition 2	Around $G^{\#}_{3}$
		Transition 3	Around E_4
		Transition 4	Around G_5
Donald Miller	Registers in Singing (2000)[85]		
	Chest Registers	*Chest*	F_3 – F_4
		Belting Extension	F_4 – D_5
	Falsetto Registers	*Middle*	C_4 (and below) – F_5
		Upper	D_5 – C_6
		Flageolet	B_5 – F_6
Roubeau et al.	Laryngeal Vibratory Mechanisms: The Notion of Vocal Register Revisited (2009)[86]		
		Mode 0 (M0)	Below M1. No overlap with M1, except in very low AMAB voices
		Mode 1 (M1)	E^{b}_{2} – $F^{\#}_{4}$
		Mode 2 (M2)	F_3 – F_5
		Mode 3 (M3)	Lacking sufficient data but produces the highest sounds. Likely overlap with M2 range possible.
Ian Howell	Hearing Singing (2025)[87]		
	Absolute Spectral Tone Color Transitions	/~u/ to /~o/	C_5
		/~o/ to /~ɔ/	$F^{\#}_{5}$
		/~ɔ/ to /~ɑ/	C_6

83 Titze, *Principles of Voice Production*, 293.

84 Titze, *Principles of Voice* Production, 298. Titze notes singers have different length tracheas which would change the location of constructive and destructive feedback by two-three semitones, 298.

85 Donald Miller, *Registers in Singing: Empirical and Systematic Studies in the Theory of the Singing Voice*, with Rijksuniversiteit Groningen (Groningen: Rijksuniversiteit, 2000), 47.

86 Roubeau et al., "Laryngeal Vibratory Mechanisms," 428–30.

87 Howell, *Hearing Singing*, 156.

While Reid espouses a registration model that is flexible enough to encompass all voice types, Richard Miller finds value in a more granular breakdown of register differences among treble voices. He believes that the location of registration events is indicative of voice type between sopranos, mezzo-sopranos, and contraltos. He introduces six register terms to describe treble voices: chest, lower middle, upper middle, upper and flageolet. The transition from upper middle to upper takes place somewhere between B^{b}_{4} and $F^{\#}_{5}$ for all treble voice types according to R. Miller.[88] He also notes that the end of the lower middle "correlates with the upper limit of the singer's occasional speech-inflected range."[89] When describing the cause of registration events, Miller fits into the laryngeal and acoustical causes camp. He writes,

> It is the relationship of vocalis-muscle tension to passive tension in the vocal ligament that produces the subtle changes involved in transitions among chest, mixed, head and flageolet timbres. Ability to use the colors of registration stems from habituated tonal concepts originating in the musicianly mind, not from conscious attempts at directed mechanical control. As an acoustic filter device, the vocal tract (from glottis to the lips) reacts to the altering laryngeal source with corresponding resonance responses…Vocal registration, then, is neither solely laryngeal nor purely supraglottic, but both. It is also dependent on subglottic pressure and airflow ratios.[90]

Like many other authors, Miller acknowledges that there are likely many contributors to registration events. His novel idea is that the location of these events is consistent and prescriptive for voice type.

Berton Coffin also argues for a view of registration that is specific to voice type. However, his most notable contribution to the discourse on registers is his acknowledgment and detailed investigation of the role different vowels play in facilitating or complicating registration. He describes registers as carriable by vowel, and he notes that resonance, or the positioning of

[88] Miller, *Training Soprano Voices*, 25.

[89] Miller, *Training Soprano Voices*, 116.

[90] Miller, *Training Soprano Voices*, 28.

the vocal tract, plays a role in the self-sustaining oscillation of the vocal folds.[91] His *Chromatic Vowel Chart for Voice Building and Tone Placing* will be discussed later in this chapter as a strategy for negotiating register transitions; however, it also reveals his ideas about the location of registers. For Coffin, two to four registers can overlap at any particular pitch and what distinguishes the register is the vowel sound the singer targets.[92] This places Coffin in the acoustic events camp of registration, while acknowledging that vocal tract positioning effects the behavior of the vocal folds.

While the trend towards a more inclusive explanation of registers continues, some pedagogues devote their work to a better understanding of the acoustic or laryngeal mechanisms individually. Donald Miller is a pedagogue who researched acoustic causes of registration events, focusing on relationships among harmonics in the radiated sound spectrum from the mouth, and the influence of different vowels on those relationships. He notes that a registration shift from treble middle to upper voice occurs when the singer switches from a resonance strategy where the second resonance of the vocal tract (f_{R2}) tracks the second ($2f_o$) or third ($3f_o$) harmonic to a strategy where the first resonance of the vocal tract (f_{R1}) tracks the fundamental frequency ($1f_o$). This switch occurs at different pitch locations for different vowels due to their formant locations. According to Miller, for open vowels with a high first formant (F_1), the switch occurs in the range of A_4 – $E^b{}_5$, but for closed vowels with a low F_1, the switch occurs around F_5. He asserts that these strategy changes constitute register transitions that do not involve laryngeal changes.[93]

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[91] Coffin, *Overtones of Bel Canto*, 23, 26.

[92] Coffin, *Overtones of Bel Canto*.

[93] Miller, *Resonance in Singing*, 70, 77.

The effects of different vowels on the location of acoustic registration events may explain some of the challenges in pinning down exact pitches where register changes occur.

Kenneth Bozeman takes D. Miller's ideas a step further and creates terms for different resonance tracking strategies. He describes acoustic registration events as separate from laryngeal registration events and defines the acoustic events as a change in timbre that occurs every time a voice source harmonic passes through the first resonance of the vocal tract.[94] Bozeman outlines two timbres: open and close. Open timbre occurs when the first resonance of the vocal tract (f_{R1}) is below two or more harmonics, and close timbre occurs when f_{R1} is below the second harmonic.[95] Within these two timbres are two distinct resonance tracking strategies that Bozeman identifies frequently used by WC singers. Within open timbre there is "Yell coupling" which occurs when f_{R1} tracks the second harmonic ($2f_o$) higher than the normal first formant (F_1) for the vowel being sung.[96] The other strategy Bozeman identifies is "Whoop coupling" (also called whoop timbre) within close timbre. Whoop coupling occurs when f_{R1} tracks the fundamental frequency ($1f_o$).[97] Since these different timbres and strategies depend on the frequency of the first formant of the vowel being sung, those frequencies will determine where acoustic passaggi occur for each vowel. Bozeman provides a diagram of the approximate

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[94] Bozeman, *Practical Vocal Acoustics*, 13, 15.

[95] Bozeman, *Practical Vocal Acoustics*, 21, 23.

[96] Bozeman, *Practical Vocal Acoustics*, 21.

[97] Bozeman, *Practical Vocal Acoustics*, 23.

F_1 locations for sopranos and mezzo sopranos (see Figure 2.6). The acoustic registration events

Figure 2.6 Approximate first formant locations with turning/closing pitches below for treble voices. Diagram by Bozeman, 2013. http://www.kenbozeman.com/resources/1stFormantLocationsImage.jpg.

for all vowels except [i] and [u] occur approximately between B_4 and F_5. The events for [i] and [u] occur between approximately E_4 to B_4. Bozeman argues that in WC singing it is these acoustic registration events that listeners perceive, not laryngeal events.[98]

Howell describes the effect of f_{R1} tracking the fundamental frequency ($1f_o$) based on the perceived radiated sound. He says this acoustic strategy "favors the warmer, pure regions of the spectrum," and elaborates that it is used "to generate a high-intensity, perceptually pure F_1 [sound]."[99] For Howell, the benefit of f_{R1} tracking $1f_o$ comes from its attenuation of high harmonics and steep spectral slope which creates a sound that is easily identifiable as "pure-sounding."

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[98] Kenneth Bozeman, *Kinesthetic Voice Pedagogy: Motivating Acoustic Efficiency* (Gahanna, OH: Inside View Press, 2017), 71.

[99] Howell, *Hearing Singing*, 160–61.

Unlike Bozeman, Herbst and Švec conducted detailed research into laryngeal behavior, as discussed earlier. They describe the different phonation types used in different styles of singing. Adducted falsetto, or cartilaginous adduction combined with a lack of membranous medialization, is the phonation type they suggest WC treble singers use (see Figures 2.3 and 2.4).[100] Their suggestions for other styles of singing will be included later in this chapter.

2.3.3 Registration in MT and CCM Treble Singers

Considerably less research exists on registers in MT and CCM styles alone, and most serious studies on these styles have been conducted in the twenty-first century. There is a long history of belting being considered a faulty technique that could even be dangerous for vocal health.[101] This perception led to a lack of research into styles that continue to be immensely popular worldwide. The authors selected for this section treat belting as a legitimate singing artform worthy of scientific study and, in many cases, challenge the assumption that belting is inherently harmful for the vocal folds.

Authors writing about MT and CCM styles generally accept the model that there are many commercially viable choices for singers when it comes to registration. In 2000, D. Miller presented an MT and CCM registration model that incorporates both laryngeal and vocal tract adjustments for different styles. His table includes vocal fold adjustment, larynx position, subglottal pressure and the appropriate frequency range (see Figure 2.7). Further, the table

[100] Herbst and Svec, "Adjustment of Glottal Configurations in Singing," 304.

[101] J. Ruhl, "Is Singing a Dying Art?" *NATS Bulletin* 42 (1986): 31–33; Conrad L. Osborne, "The Broadway Voice: Just Singin' in the Pain," *High Fidelity* 29, no. 1979 (1979): 64; Cornelius L. Reid, *A Dictionary of Vocal Terminology: An Analysis* (New York: Joseph Patelson Music House, 1983).

	vocal fold adjustment	larynx position*	subglottal pressure	frequency range
pop	'falsetto'	intermediate to high	moderate	low to middle
legit	'falsetto'	low to intermediate	moderate	middle to high
belt	'chest'	high to very high	high	middle
classical chest	'chest'	low to intermediate	moderate	low

Note *. This parameter could be more directly designated 'first formant frequency,' of which larynx position is merely the most determinative factor on open vowels. Other factors (mouth opening, pharynx width) are also operative in determining F1.

Figure 2.7 Table "Physiological and acoustical parameters characterize four types of treble voice production." From D. Miller "Registers in Singing: Empirical Studies in the Theory of the Singing Voice," PhD Thesis, University of Groningen (2000), 91.

acknowledges that changes in laryngeal position significantly affect the acoustical properties of the sung sound, and that other vocal tract adjustments may influence these properties as well.

Similarly, twenty years later, Kari Ragan summarizes registration as "both a physiological laryngeal source occurrence and an acoustic occurrence that cannot be easily separated."[102] She represents registration as a slide rule with a laryngeal and a resonance, or

[102] Ragan, *A Systematic Approach to Voice: The Art of Studio Application*, 86.

vocal tract position, component (see Figure 2.8).[103] Ragan identifies a "*secondo passaggio*" for treble voices between $B^{b}{}_{4}$ and G_5.[104]

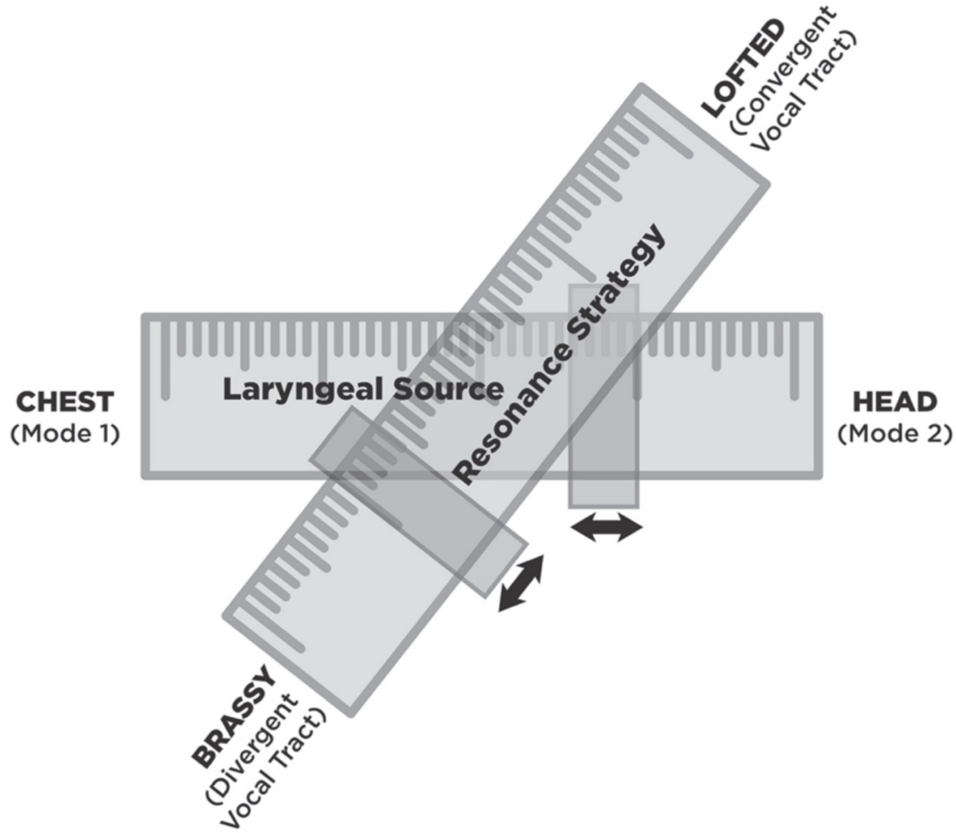

Figure 2.8 Registration slide rule. Diagram by Ragan in A systematic approach to voice: the art of studio application (San Diego, CA: Plural Publishing, 2020), 87.

LeBorgne and Rosenberg state that "musical theater register shifts are often noted to be abrupt, noticeable transitions with distinct vocal quality and timbre changes."[105] This may occur for many reasons, but difference in resonance strategies may play a role in the timbral changes. D. Miller describes a first resonance of the vocal tract tracking the second harmonic (f_{R1}:$2f_o$) strategy present in some recordings of belters. He predicts that this strategy cannot extend much

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[103] Ragan, *A Systematic Approach to Voice: The Art of Studio Application*, 90.

[104] Ragan, *A Systematic Approach to Voice: The Art of Studio Application*, 95.

[105] LeBorgne and Rosenberg, *The Vocal Athlete*, 183.

beyond D_5 and that using this strategy precludes a smooth, unnoticeable transition to the f_{R1}:1f_o strategy favored by WC trebles in the upper range.[106] However, D. Miller admits that, as of 2008, insufficient research existed on MT and CCM styles to properly quantify their resonance strategies. He suspects that there are many combinations of vocal fold closed quotient and resonance strategy that would produce commercially viable sounds in these styles.[107]

In 2011, Amy Lebowitz and R. J. Baken conducted a study specifically analyzing closed quotient and resonance strategy in professional Broadway treble actors. They found no significant differences in closed quotient (CQ) between the two Broadway singing styles of legit and belt, both exhibiting a CQ below 50%. However, they did find a significantly large speed quotient (contacting time divided by decontacting time) in belting compared to legit singing. They also, as D. Miller predicted, did not find a unified resonance strategy. For some singers, 2f_o was the strongest harmonic, but for others 1f_o was the strongest. Their study used an excerpt from the song "Maybe This Time" that reached C_5 as the top note, so they do not provide data for acoustical or laryngeal strategies for higher notes in these styles.[108] Lebowitz & Baken echo Miller when describing the limitations of their study saying: "belting remains a vaguely defined phenomenon with potentially infinite variation…it is, therefore, possible that any investigation of the acoustics of the belt voice will face inherent limitations of external validity."[109] A wider variety of sounds and techniques appear to exist in MT and CCM singing, requiring further study to determine the positive or negative effects on singers who these strategies.

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[106] Miller, *Resonance in Singing*, 88.

[107] Miller, *Resonance in Singing*, 94.

[108] Amy Lebowitz and R. J. Baken, "Correlates of the Belt Voice: A Broader Examination," *Journal of Voice* 25, no. 2 (2011): 161-64, https://doi.org/10.1016/j.jvoice.2009.10.014.

[109] Lebowitz and Baken, "Correlates of the Belt Voice," 165.

Amanda Flynn et al. further demonstrated the variety of acoustic strategies used by MT singers in their 2018 study "Acoustic Comparison of Lower and Higher Belt Ranges in Professional Broadway Actresses." Unlike Lebowitz and Baken, they did not observe professional Broadway treble belters using a fundamental dominant strategy. Instead, they observed either $2f_o$ or $3f_o$ dominance in all but three of their thirty samples.[110] They examined climatic belted notes from repertoire on C_5, $E^b{}_5$ and F_5.[111] However, they noted that the $2f_o$ and $3f_o$ dominance was stronger in the low belt (C_5) samples. In the higher belt examples, energy was "more evenly-distributed…across the first three peaks…relative to the lower belt," and "in the higher belt range, there was less variability between peaks, in many cases including a relatively strong fundamental."[112] While their participants did not use $1f_o$ as the dominant harmonic, in higher belted notes, $1f_o$ was not as weak relative to other harmonics as it was in lower notes. This suggests that belting higher notes may require an acoustic strategy that emphasizes a stronger fundamental compared to lower notes. Flynn et al. acknowledge that their study did not control for the vowels of the climatic belt notes because they occurred on different words ("gun" for C_5, the first syllable of "ev'ry" for $E^b{}_5$, and the second syllable of "defying" for F_5.)[113] This suggests that different vowels may influence the acoustic strategy used. However, like Lebowitz and

[110] Flynn et al., "Acoustic Comparison of Lower and Higher Belt Ranges in Professional Broadway Actresses," 412.

[111] Flynn et al., "Acoustic Comparison of Lower and Higher Belt Ranges in Professional Broadway Actresses," 411.

[112] Flynn et al., "Acoustic Comparison of Lower and Higher Belt Ranges in Professional Broadway Actresses," 412–13.

[113] Flynn et al., "Acoustic Comparison of Lower and Higher Belt Ranges in Professional Broadway Actresses," 411, 414.

Baken, Flynn et al. conclude that "the production of commercially viable belt sounds is far more variable than previous acoustic studies have indicated."[114]

Apart from differences in acoustic strategies used, Herbst et al. argue that there are differences in laryngeal configuration between the way that WC and MT trebles produce sound in their higher range. As mentioned earlier, Herbst et al. predict that WC trebles use adducted falsetto to produce notes higher in their range. They predict that MT trebles use adducted chest instead.[115] This means that for treble belt singing the team believes that there is deeper vertical fold contact than in WC singing.

These authors suggest that flexibility is key to registration in MT and CCM styles. Kevin Wilson echoes this point in his article "Practical Approaches In Coordinating Registration for the Cis-Gender Female Musical Theatre Singer."[116] He presents several different frameworks for teaching registration to MT and CCM singers that will be discussed in a later section. In his frameworks, Wilson acknowledges, based on his personal experience, that MT and CCM artists produce sounds differently below B_4 and above C_5.[117] Although scientific research has not yet determined the cause of these differences, they nonetheless have real-world effects on singing artists.

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[114] Flynn et al., "Acoustic Comparison of Lower and Higher Belt Ranges in Professional Broadway Actresses," 413.

[115] Herbst et al., "Investigation of Four Distinct Glottal Configurations in Classical Singing—A Pilot Study," 304.

[116] Kevin Wilson, "Practical Approaches in Coordinating Registration for the Cis-Gender Female Musical Theatre Singer," *Journal of Singing* 80, no. 2 (2023): 185, https://doi.org/10.53830/WKDK2451.

[117] Wilson, "Practical Approaches In Coordinating Registration for the Cis-Gender Female Musical Theatre Singer," 186.

2.4 Register Blending Strategies in the Treble Middle to High Voice Transition

2.4.1 Acoustic Registration Strategies in WC Trebles

Pioneers in acoustic voice science research began exploring acoustic strategies for singers in the 1960s.[118] However, increased interest in the field can be linked to D. Miller's presentation of his new software *VoceVista* at the 1995 NATS National Convention in St. Louis.[119] This software could be easily downloaded onto a personal computer and provided increased access to the technological tools that allowed researchers and voice teachers analyze sound spectrogram data in real-time. As more users examined these spectrograms, the began noticing recurring patterns. From these observations, researchers and teachers developed various applications that informed and shaped their own vocal pedagogies.

In 2000, D. Miller identified a resonance challenge when moving from treble middle voice into high voice. In the middle voice, $2f_o$ can be stronger than the fundamental, and D. Miller observed many singers using an f_{R2} tracking $2f_o$ strategy in that part of their range. However, in order to move to the high voice, this strategy must be exchanged for the f_{R1} tracking $1f_o$ strategy, which many pedagogues identified as the most efficient and commonly used approach for a WC high voice sound.[120] The question then becomes, how does a singer successfully achieve this strategy transition?

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[118] Miller, *Resonance in Singing, i-iii*.

[119] "The 90s | National Association of Teachers of Singing," accessed January 28, 2026, https://www.nats.org/The_90s.html.

[120] Miller, *Registers in Singing*, 53–54.

One answer to this question is the use of vowel modification. A substantial body of research that links changes in articulator position to corresponding changes in f_{R1} and f_{R2}.[121] Altering the first and second resonances of the vocal tract can also influence the perceived identity of the vowel, since vowels are associated with characteristic ranges of first and second formant values as illustrated in the diagrams below (see Figures 2.9 and 2.10). Therefore,

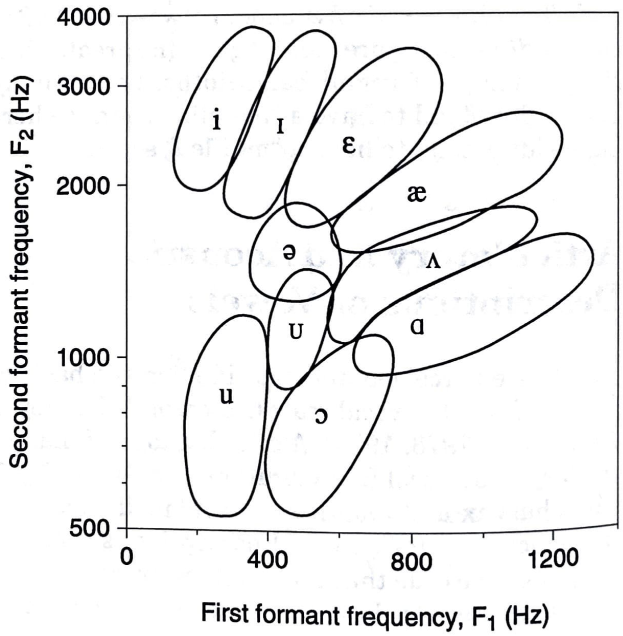

Figure 2.9 F_1 and F_2 chart for various vowels. Diagram by Ingo Titze in Principles of Voice Production: Second Printing (Iowa City, IA: National Center for Voice and Speech, 2000), 162.

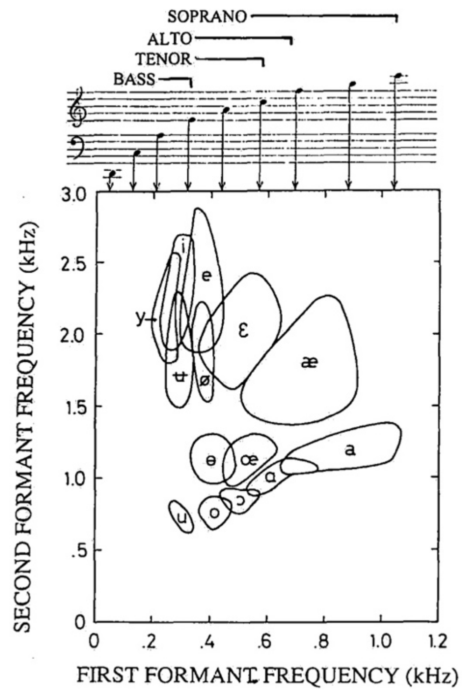

Figure 2.10 F_1 and F_2 chart for various vowels. From Sundberg and Skoog "Dependence of Jaw Opening on Pitch and Vowel in Singers." Journal of Voice 11, no. 3 (1997), 302

through the careful vowel modification, singers can adjust vocal tract resonances to track specific harmonics and target vowels.

A pioneer in the use of vowel modification for register transitions in WC singing is Berton Coffin. He developed a system of granular control over vowel modification that he

[121] Johan Sundberg and Jöorgen Skoog, "Dependence of Jaw Opening on Pitch and Vowel in Singers," *Journal of Voice* 11, no. 3 (1997): 301–3, https://doi.org/10.1016/S0892-1997(97)80008-2; Titze, *Principles of Voice Production*, 162–70.

believes creates seamless registration transitions. Coffin describes “15 usable degrees of [vowel] opening” and cautions—the uppercase letters are his—“DO NOT SUPERIMPOSE SOME SET SPACE CONCEPT ON THE THROAT…a voice with a set position is out of tune and out of resonance.”[122] For Coffin, varying the openness of a vowel is not just helpful, but essential for proper voice production throughout a singer’s range.

Coffin describes registers as variable by vowel and voice part. In his well-known vowel chart, he suggests specific vowel modifications for each pitch, guiding singers toward vowel targets that maximize resonance and help avoid audible register transitions. He groups target vowels into four categories: (1) front vowels: [i], [e], [ɛ], [æ] and [a]; (2) neutral vowels: [ə], [ʊ], [ʌ] and [ɑ]; (3) back vowels: [u], [o], [ɔ], [ɒ], and [ɑ]; and (4) umlaut vowels: [y], [ø], [œ] and [a]. The order of the vowels goes from lowest F_1 to highest in each category; hence, the inclusion of the same vowels in multiple categories. Then, for each category he includes a piano illustration of all the vowel options for each pitch in each register (see Table 2.1 for a complete list of names of registers from Coffin’s chart). The chart is color coded to make sense of which vowel has ideal resonance for a particular pitch. The colors are Red: “dangerously open. Spread. Vocal tract formation interferes with vocal cord vibration. Sing vowel on diagonal below;” Yellow: “open. Bright. Metallic quality;” Green: “Moderately open. Safe resonance;” and Blue: “closed. Low dynamic level.”[123] In practice, the chart provides guidance that helps singers pick effective vowels based on the pitch, vowel, and dynamic level they want to sing. For example, if a mezzo soprano is challenged by singing the front vowel [i] on an F_5, Coffin’s chart suggests that [e] is the green—safe resonance—vowel for that pitch. [i] itself is colored blue, so might be

[122] Coffin, *Overtones of Bel Canto*, 24, 26.

[123] Coffin, *Overtones of Bel Canto*.

an appropriate vowel for a piano dynamic on F_5, and [æ̃] (a nasalized [æ] vowel) is yellow and could be used for a bright sound, if desired. Learning to use Coffin's chart takes study, but, once

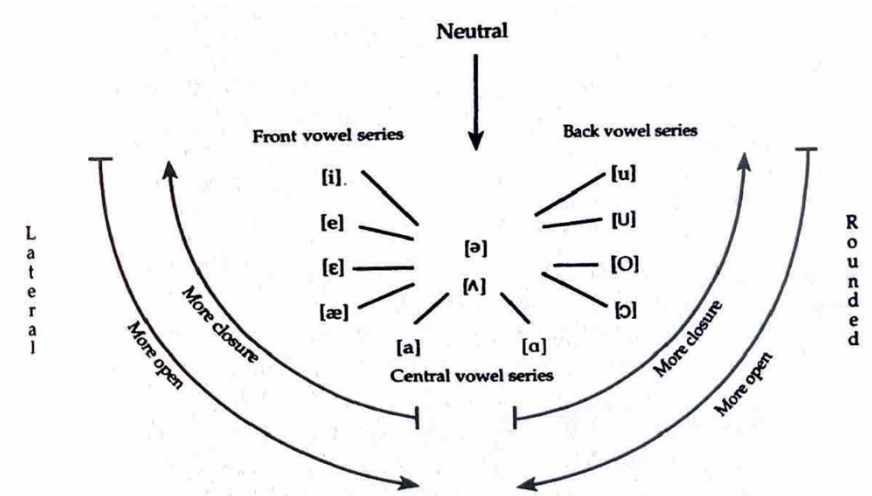

Figure 2.11 Vowel modification (aggiustamento) chart. Diagram by R. Miller in Training Soprano Voices (New York: Oxford University Press, 2000), 125.

understood, it gives singers and teachers useful vowel modification options if the target vowel of a word is presenting a challenge on a particular note.

R. Miller presents his own similar strategy in his book *Training Soprano Voices*. He suggests, like Coffin, that vowels should be opened in sequence and provides two diagrams, shown below, to describe how this should be done (see Figures 2.11 and 2.12).

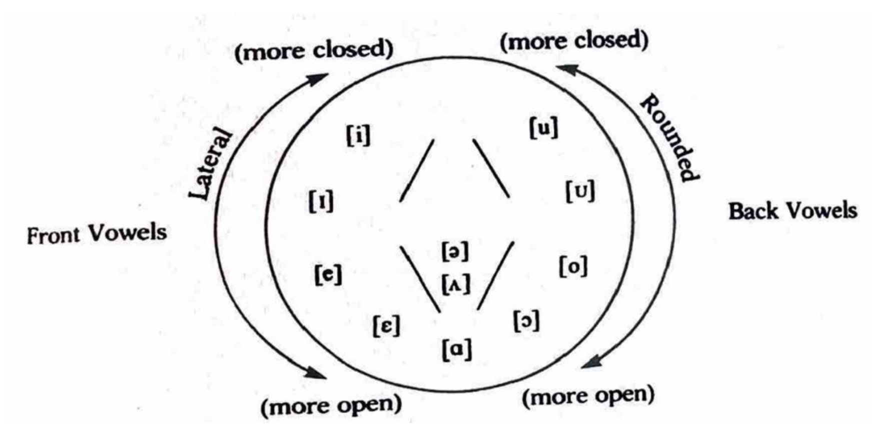

Figure 2.12 Modification of front vowel series, central vowel series, and back vowel series. Diagram by R. Miller in Training Soprano Voices (New York: Oxford University Press, 2000), 125.

In the first diagram, R. Miller categorizes many vowels according to two properties: closed v. open and rounded v. lateral. In the second diagram, he presents the same information, but arranges the vowels in sequences that progress from open to closed across different vowel series. For example, for the front vowels, the diagram recommends that as a treble singer increases in pitch through the *secondo passaggio*, the vowel should be modified from [i] (the most closed front vowel) to [e], then to [ɛ], then to [æ], and finally to [a]. The *secondo passaggio*, according to R. Miller, occurs between D_5 and G_5 depending on the singer's voice type.[124] While this strategy is explicit about the vowels to be used, it lacks the granular specificity found in Coffin's approach.

Barbara Doscher, in her 1994 book *The Functional Unity of the Singing Voice*, supplies a similar suggestion for the use of vowel modification for upper register transitions in treble voices. However, she does not go into as much detail as Coffin or R. Miller. Doscher cites García in identifying $C^{\#}_5$ – E_5 as a critical transition range for treble voices.[125] She also introduces a practical application of the f_{R1} tracking $1f_o$ strategy observed by many researchers of WC singing saying, "the vowels must open to match the fundamental."[126] Like Coffin and R. Miller, Doscher identifies vowel opening as pitches ascend as a critical strategy for effective vowel modification, linking this adjustment to raising the f_{R1} to match $1f_o$. However, she also recommends "slight rounding" when passing through the *secondo passaggio*, which she identifies as F_5 – G_5. Doscher

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[124] Miller, *Training Soprano Voices*, 23.

[125] Doscher, *The Functional Unity of the Singing Voice*, 180.

[126] Doscher, *The Functional Unity of the Singing Voice*, 181.

supports this suggestion with evidence drawn from years of applying the strategy with students in her voice studio.[127]

Two studies conducted in 1997 and 2010 explore jaw opening as a specific articulator adjustment to raise f_{R1} so that it tracks the fundamental. Johan Sundberg and Jörgen Skoog in 1997 tested the vowels [a], [ɑ], [o], [u], and [e] using motion capture technology. They found that jaw opening was the primary strategy for raising f_{R1} as $1f_o$ approaches f_{R1} for [a] and [ɑ]. However, for the other vowels, jaw opening was not used until pitches higher than the lowest F_1 associated with the given vowel. Sundberg and Skoog hypothesized that, for the other vowels, reducing tongue constriction was a more convenient strategy for raising f_{R1} as $1f_o$ approached the lowest F_1 required for vowel intelligibility. In this model, jaw opening was used later, after tongue constriction was eliminated.[128] Echternach et al. in 2010 looked only at an [a] vowel using MRI and found similar results. Singers opened their jaws and widened lips when $1f_o$ approached 750 Hz, the typical F_1 of an [a] vowel. However, the study also revealed that singers used a range of strategies involving the other articulators that they studied (tongue dorsum height, jaw protrusion, pharynx width, and uvula vertical position).[129] These two studies suggest that jaw opening is an effective strategy to raise f_{R1} to track the fundamental, especially for [a] and [ɑ] and very high pitches, but that singers use a wide variety of other strategies to achieve the same resonance adjustment.

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[127] Doscher, *The Functional Unity of the Singing Voice*, 182.

[128] Sundberg and Skoog, "Dependence of Jaw Opening on Pitch and Vowel in Singers," 306.

[129] Matthias Echternach, Johan Sundberg, Susan Arndt, Michael Markl, Martin Schumacher, and Bernhard Richter, "Vocal Tract in Female Registers—A Dynamic Real-Time MRI Study," *Journal of Voice* 24, no. 2 (2010): 136, https://doi.org/10.1016/j.jvoice.2008.06.004.

Ken Bozeman in *Practical Vocal Acoustics* and *Kinesthetic Voice Pedagogy 2* explores combinations of articulator adjustments to traverse the treble transitions from middle to high voice. He calls this transition "turning to whoop" (whoop timbre is defined as f_{R1} tracking $1f_o$) and identifies three strategies.[130] First, singers can actively modify vowels to lower f_{R1} and achieve whoop timbre lower in their range by closing the vowel.[131] This approach would likely involve closing the jaw and fronting the tongue. Second, singers can maintain vocal tract shape and rely on passive vowel modification as the pitch rises.[132] Passive modification results in a perceptual change in the vowel quality. According to Bozeman, "the back vowels [ɑ ɔ ʊ o] will move toward a closer neighbor [and] the front vowels [æ ɛ e I] will both close and round or neutralize slightly."[133] [u] and [i] are exceptions to passive vowel modification because their F_1 frequencies are already low. Bozeman suggests that they need specific active modifications that keep the tongue high in the mouth.[134] The final strategy is active vowel modification that raises f_{R1} to delay entering whoop timbre. This strategy requires increased the jaw opening to raise f_{R1} so that it remains well above $1f_o$ but still below $2f_o$. Bozeman concludes that WC treble singers most often employ the first two strategies.[135] Taken together, these strategies combine acoustic observations with practical articulatory adjustments, offering flexible, science-informed approaches for singers and teachers to apply.

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[130] Bozeman, *Practical Vocal Acoustics*, 52.

[131] Bozeman, *Practical Vocal Acoustics*, 52.

[132] Bozeman, *Practical Vocal Acoustics*, 53; Bozeman, *Kinesthetic Voice Pedagogy*, 49.

[133] Bozeman, *Kinesthetic Voice Pedagogy*, 49.

[134] Bozeman, *Kinesthetic Voice Pedagogy*, 50–51.

[135] Bozeman, *Practical Vocal Acoustics*, 53–54.

Another researcher seeking to link acoustic phenomena to articulatory behavior during the transition from middle to upper soprano voice is Richard Lissemore. In his 2024 dissertation, he examines the relative radiated sound pressure level (SPL) of the fundamental and the second harmonic, determines the relationship produced by "techniqued" WC sopranos, and assesses the articulatory changes the "techniqued" singers make to achieve those acoustic results.[136] Lissemore defines "techniqued" singers through his own auditory assessment, but confirms this assessment via a perceptual experiment using eight experienced voice teachers.[137] For an [ɑ] vowel, the "technique" sopranos consistently demonstrated $2f_o$ SPLs higher than $1f_o$ on pitches below 600 Hz (around D_5-$D^{\#}_5$). Above that frequency, however, $1f_o$ exceeded $2f_o$.[138] Lissemore describes this relationship using the metric L_1-L_2, defined as the radiated SPL of $1f_o$ minus the radiated SPL of $2f_o$.[139] Using this measure, "technique" sopranos switched from negative to positive L_1-L_2 values around 600 Hz.[140]

Lissemore used a combined ultrasound and optical tracking system called HOCUS to track eight distinct articulatory measurements: lip aperture, palate to jaw, palate elbow to highest tongue point, anterior palate to anterior tongue, anterior oral cavity pentagon, Triangle 1 (anterior palate point to the jaw to the anterior point of the tongue contour), Triangle 2 (anterior palate point to the jaw to palate elbow), and Triangle 3 (the anterior palate point to the palate elbow to

[136] Lissemore, *Articulatory Activity of the Tongue, Jaw, and Lips During the Second Passaggio Transition of the Soprano Voice*, iv–vi.

[137] Lissemore, *Articulatory Activity of the Tongue, Jaw, and Lips*, 130–35.

[138] Lissemore, *Articulatory Activity of the Tongue, Jaw, and Lipse*, 178–79.

[139] Lissemore, *Articulatory Activity of the Tongue, Jaw, and Lips*, 25.

[140] Lissemore, *Articulatory Activity of the Tongue, Jaw, and Lips*, iv–vi.

the anterior point of the tongue contour).[141] From analysis of this complex set of articulatory adjustments, Lissemore found that the increase in the area of Triangle 3 resulted in a larger difference between $1f_o$ and $2f_o$, or, using his mathematical model, a larger positive value of L_1-L_2. Lissemore summarizes his articulatory findings: "though our research also revealed that a lowered mandibular position was indeed an important element of a successful acoustic transition, we concluded that the position of the anterior tongue relative to the hard palate was the factor that best distinguished our groups of most and least techniqued singing."[142] Lissemore's conclusions challenge the models suggested by Sundberg & Skoog and Echternach et al. by introducing an additional important articulatory action beyond jaw opening.

Lissemore also challenges the idea that raising f_{R1} to track $1f_o$ through jaw opening alone fully explains soprano high voice acoustic strategies. He proposes that an increase in Triangle 3 results in a decrease in f_{R2} that discourages the f_{R2} tracking $2f_o$ strategy often used in the middle voice. The change allows sopranos to switch to f_{R1} tracking $1f_o$ at a lower point in the range. Lissemore also suggests that increased glottal airflow may raise the SPL of $1f_o$ which would constructively contribute to a strong $f_{R1}/1f_o$ resonance strategy.[143] Like Echternach et al., Lissemore only studied one vowel, so his results would need to be replicated for other vowels. Nevertheless, his work contributes an important perspective on the complexity of articulatory adjustments that can influence acoustic registration strategies.

[141] Lissemore, *Articulatory Activity of the Tongue, Jaw, and Lips*, 180.

[142] Lissemore, *Articulatory Activity of the Tongue, Jaw, and Lips*, 181.

[143] Lissemore, *Articulatory Activity of the Tongue, Jaw, and Lips*, 181–86.

2.4.2 Acoustic Registration Strategies in MT/CCM Trebles

A growing number of authors are studying acoustic strategies in MT singing. As discussed earlier, it is likely that treble MT singers are using variety of acoustic strategies for their belted notes. D. Miller identifies an f_{R1} tracking $2f_o$ strategy, and Lebowitz & Baken present data that supports this strategy in a limited way. Both studies only look at belted notes D_5 and below.[144] Flynn et al. describe a more complex set of acoustical options for notes C_5 to F_5 including $2f_o$ or $3f_o$ tracking f_{R1}. They observe that in these higher belted notes, while $1f_o$ is not the highest energy harmonic, it is higher in high belted notes than in lower belted notes.[145] While it is not clear that the harmonic strategy used in high belting is uniform across singers, some authors suggest ways singers can alter their articulators to utilize some of these strategies.

D. Miller suggests that belters should maintain a high larynx to encourage f_{R1} tracking $2f_o$, especially on open vowel with a high F_1.[146] He also recommends that belters minimize the space in the back of the mouth to maximize the ability to raise f_{R1} using jaw opening.[147] Bozeman suggests a similar strategy of high larynx, narrow pharynx and widened mouth, and calls this shape "divergent resonator" or "megaphone" shape. Like D. Miller, he argues that "megaphone" shape allows for more efficient f_{R1} tracking $2f_o$ an acoustic strategy he calls "yell timbre."[148] For higher belt sounds, Bozeman acknowledges that even when using "megaphone" shape f_{R1} must eventually pass above $2f_o$, He compares this sound to WC close timbre or a

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[144] Miller, *Resonance in Singing*, 90; Lebowitz and Baken, "Correlates of the Belt Voice," 161–65.

[145] Flynn et al., "Acoustic Comparison of Lower and Higher Belt Ranges," 413.

[146] Miller, *Registers in Singing*, 88.

[147] Miller, *Registers in Singing*, 91.

[148] Bozeman, *Practical Vocal Acoustics*, 46.

"turning over," though occurring at higher pitch level with a brighter quality than typically would be used by a WC.[149] In their textbook *The Vocal Athlete*, Wendy D. LeBorgne and Marci Daniels Rosenberg argue that, for treble MT singers to create belt sounds without increasing closed quotient, (or the time the vocal folds are in direct contact), the use of f_{R1} tracking $2f_o$ can be a potentially less injurious strategy. They identify several articulatory adjustments that may help raise f_{R1} so that it can match $2f_o$ as long as possible, including a raised larynx, narrowed pharynx when compared to WC treble singers, and widened jaw and widen lips.[150]

While the authors in the previous paragraph all suggest similar articulatory changes to raise f_{R1}, Howell writes that vowel modification can also be used to create belt sounds. He suggests that modifying towards brighter vowels like [e] and [æ] "facilitates the impression of chest voice's buzzy brightness without the TA engagement that would only work in a lower pitch range."[151] Like LeBorgne and Rosenberg, Howell acknowledges that increases closed quotient at higher pitches is one way to create a belt sound, but that at high pitches, that strategy is increasingly risky for vocal injury in some singers. He highlights that an acoustic adjustment via vowel modification can create the same sound without additional risk.

2.4.3 Integrated Registration Strategies without Reference to Style

While it may be useful to discuss acoustic strategies separately from other processes that influence registration choices, many pedagogues discuss teaching registration using integrated approaches. These approaches often mention some combination of acoustic, laryngeal, aero-dynamic and sensory strategies. Ragan includes a practical summary of acoustic, laryngeal, and

[149] Bozeman, *Kinesthetic Voice Pedagogy*, 106.

[150] LeBorgne and Rosenberg, *The Vocal Athlete*, 165, 182.

[151] Howell, *Hearing Singing*, 105.

sensory interactions in the introduction to her chapter on exercises to teach registration. She writes that within a register, "the pattern of vocal fold vibration (vertical phase difference, amplitude of vibration, open and closed quotient, and length and stiffness of the vocal folds) [are] the same…and the quality of sound within the adjacent pitches hav[e] the same essential timbre." She continues, "registration is both a physiological laryngeal source occurrence and an acoustic occurrence that cannot be easily separated."[152] She also acknowledges that "the sensory experience of registration events is very individual and multifaceted across gender, genre, voice type, and training."[153] From this perspective, the process of teaching registration involves the intersection of three systems: the balance of laryngeal muscle action, the positioning of the vocal tract, and the body's sensory feedback.

Titze adds another system to this list: the respiratory system. He summarizes registration research to show that laryngeal muscle balance combined with lung pressure results in many combinations that can create the same perceived pitch. This research is illustrated in the graph below which shows a band that encompasses all the CT or TA activities (labeled a_{ct} and a_{ta}

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[152] Ragan, *A Systematic Approach to Voice: The Art of Studio Application*, 86.

[153] Ragan, *A Systematic Approach to Voice: The Art of Studio Application*, 118.

respectively) and lung pressures (P_L) that can create the same pitch (see Figure 2.13). The variety of choices mirror the complexity of options for a singer when making registration choices.

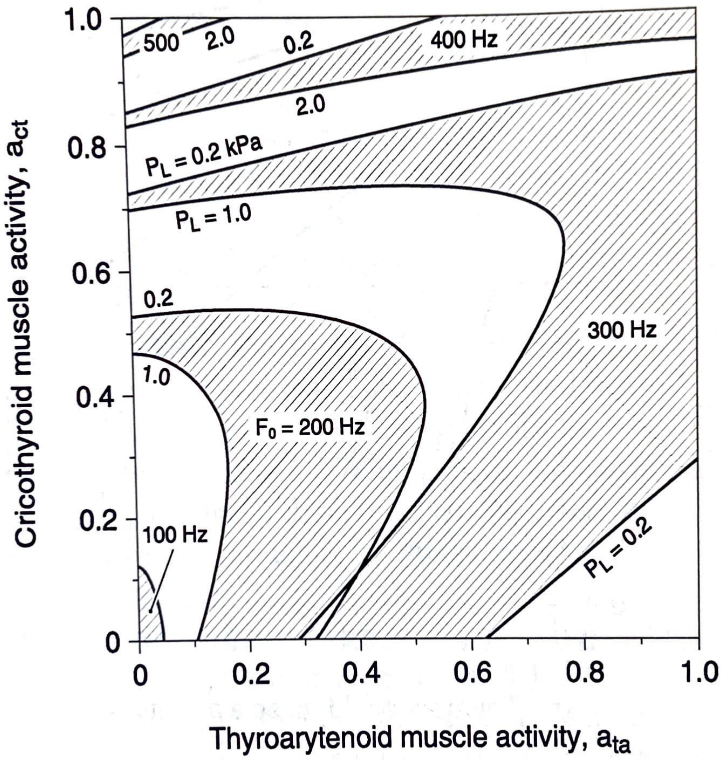

Figure 2.13 Muscle activation plot (MAP) with constant F_o bands for the body-cover model that includes lung pressure. Diagram by Ingo Titze in Principles of Voice Production: Second Printing (Iowa City, IA: National Center for Voice and Speech, 2000), 233.

2.4.4 Integrated Registration Strategies in WC Trebles

Integrated strategies suggested specifically for WC trebles involve a combination of acoustic, aerodynamic, laryngeal, or sensory adjustments. Vennard, Doscher and Titze all propose integrating aerodynamics, acoustics, and laryngeal activity to help singers navigate vocal registers. Vennard prioritizes breathing stating that, "the aerodynamic aspect of voice production should never be ignored."[154] Drawing on both his own teaching experience and the scientific knowledge of the day, he examines the WC treble middle voice and concludes that

[154] Vennard, *SINGING*, 59.

there are only two laryngeal options, heavy or light production. However, Vennard suggests that singers can navigate the whole range without voice breaks by adjusting intensity, determined by breath pressure, and quality of the target sound, determined by vocal tract shape.[155] Doscher echoes these three interacting factors but proposes a more flexible model of laryngeal behavior. She writes, "there is no doubt that breath management, laryngeal adjustments, and acoustical factors work together in endless combinations to produce changes in tone quality which are called registers."[156] Like Vennard, she also emphasizes that mastery of the balance among these three systems enables effective register blending in WC singing.[157]

Along with his muscle activation plot that incorporates lung pressure, Titze also includes scientific discoveries in acoustics into his suggestions for register navigation. He notes that the f_{R1}:1f_o tracking strategy commonly used by WC trebles creates constructive feedback at the vocal folds, which help sustain their oscillation.[158] Returning to his theories on subglottic resonances, Titze also suggests that vocal tract adjustments may partially counteract the destructive feedback from subglottic formants. However, he believes that the balance of vocal fold muscle tensions is likely more significant.[159] When suggesting how singers should learn to manage registration transitions, Titze points to Coffin's vowel modification strategies, but remarks that they need to be updated to include information about subglottic resonances.[160]

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[155] Vennard, *SINGING*, 77.

[156] Doscher, *The Functional Unity of the Singing Voice*, 191.

[157] Doscher, *The Functional Unity of the Singing Voice*, 193.

[158] Titze, *Principles of Voice Production*, 303.

[159] Titze, *Principles of Voice Production*, 304.

[160] Titze, *Principles of Voice Production*, 304.

Reid, D. Miller and R. Miller all propose pedagogical strategies that integrate aerodynamics, laryngeal mechanics, acoustics, and sensory feedback. Although they incorporate sensory information in different ways, each pedagogue identifies it as playing a primary role either as immediate feedback during phonation or as a guide toward an intended target sound. R. Miller emphasizes the latter approach. He writes, "ability to use the colors of registration stems from habituated tonal concepts originating in the musicianly mind, not from conscious attempts at directed mechanical control."[161] Later, he states, "vocal registration…is neither solely laryngeal nor purely supraglottal, but both…it is also dependent on subglottic pressure and airflow ratios."[162] For R. Miller, the control of vocal registers originates in the singer's mental conception of sound. The imagined target sound guides production, but achieving it requires systematic practice. Through training, singers learn to coordinate the balance of laryngeal muscle tensions, air flow requirements, and vocal tract and articulator positions needed to make the desired sound.

Reid proposes the *messa di voce*, an exercise in which a singer executes a crescendo followed by a decrescendo on one note, to train registration blending. He selects this exercise because it promotes laryngeal muscle balance through variations in dynamic levels which are controlled by aerodynamic activities. As Reid explains, "because register participation *responds* to intensity, its activity can be *controlled* by intensity."[163] He also acknowledges that vowels have an impact on registration.[164] Like R. Miller, Reid notes the importance of the target sound

[161] Miller, *Training Soprano Voices*, 28.

[162] Miller, *Training Soprano Voices*, 28.

[163] Reid, *The Free Voice*, 31, 52.

[164] Reid, *The Free Voice*, 52.

imagined by the singer. However, he extends this idea by explaining that sensory feedback, including the singer's proprioceptive and vibratory experience as well as auditory perception, prompts further adjustments in the larynx and vocal tract as the singers works to match the target sound.[165] In his own words:

> Tone is initiated by the mental concept. The vocal organs respond, and the character of the response, with its consequent determination of quality and texture, reflects the overall efficiency of the coordinative process. In this process a physical impression is experienced to which the body relates by means of sensory perception. The experience of the bodily organs is then telegraphed through the nervous system to the hearing mechanism, finally to record once again on the mind as a concrete impression. The total impression recorded becomes a subjective reality, but this reality does not necessarily agree objectively with the original concept.[166]

Reid's description of the process that creates sound is especially informative for training singers because it depicts the level of complexity required to create different vocal colors via registration. His suggestion of the use of *messa di voce* provides an exercise that combines all these complex processes into one task while offering singers a clear set of target sounds to guide their practice.

D. Miller also explores the practical sensory experience of the singer as they train registration tasks. Like Titze, he investigates the role of f_{R1}:1f_o tracking in singers during the transition from middle to upper voice, which he believes must occur by F_5 in WC trebles.[167] He summarizes his own study that examined how f_{R1}:1f_o tuning affects the pressure differential between sub and supra-glottal pressures. He found that with a well-tuned vowel, or a vowel where the vocal tract has been modified to match f_{R1} to 1f_o, it is possible for the peak supraglottal pressure to occur while the glottis is closing. This timing creates a negative transglottal pressure

[165] Reid, *The Free Voice*, 33, 66.

[166] Reid, *The Free Voice*, 66.

[167] Miller, *Registers in Singing*, 106.

that aids in bringing the vocal folds together.[168] D. Miller calls this a "back pressure phenomenon" and relates it to the singer's experience during the middle to upper transition. He suggests that this phenonenon "contributes to a subjective impression of ease in the upper range" and reduces the average airflow needed to sing the target pitch.[169] He also describes the singer's experience when vocal tract or laryngeal muscle balance adjustments are not made:

> If this same adjustment is maintained while the subject sings progressively higher pitches, the normal result, certainly for the untrained singer, is an increase in subglottal pressure, glottal resistance, and intensity of sound. If this is continued into the upper Fo [$1f_o$] range, the singer either 1) maintains the initial adjustment, resulting in somewhat forced upper notes, [or] 2) 'breaks' to a 'lighter' register, sacrificing continuity.[170]

To avoid these outcomes that can be judged both by a listener and through the singer's own sensory experience, D. Miller recommends vowel modification as the method to balance all the complex factors involved in registration.

2.4.5 Integrated Registration Strategies in MT/CCM Trebles

MT and CCM approaches to integrated registration strategies emphasize flexibility and experimentation. Like studies of WC singing, the limited experimental evidence published in studies of MT and CCM treble registration demonstrates a complex and variable combination of vocal tract adjustments and laryngeal behaviors that can lead to similar sounds. This topic requires further study, however, the evidence available supports voice studio strategies that are easily adjustable and customizable to each individual singer.

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[168] Miller, *Registers in Singing*, 104.

[169] Miller, *Registers in Singing*, 106–7.

[170] Miller, *Registers in Singing*, 44.

Two recent studies on MT/CCM registration examine the vocal tract and laryngeal behavior of a small number of professional MT/CCM singers, both treble and non-treble, as they sing throughout their vocal range. Rudisch et al. used MRI data to assess vocal tract adjustments in healthy professional singers producing a variety of vocal qualities required in their repertoire. The study's goal was to establish a baseline of adjustments that could be used to diagnose pathological singing.[171] They investigated five vocal qualities: traditional/legit, neutral belt, warm belt, brassy belt, and rock belt; and numerous anatomical measures which they condense into six significant measures: lip opening, jaw opening, oropharynx opening, larynx height, jaw

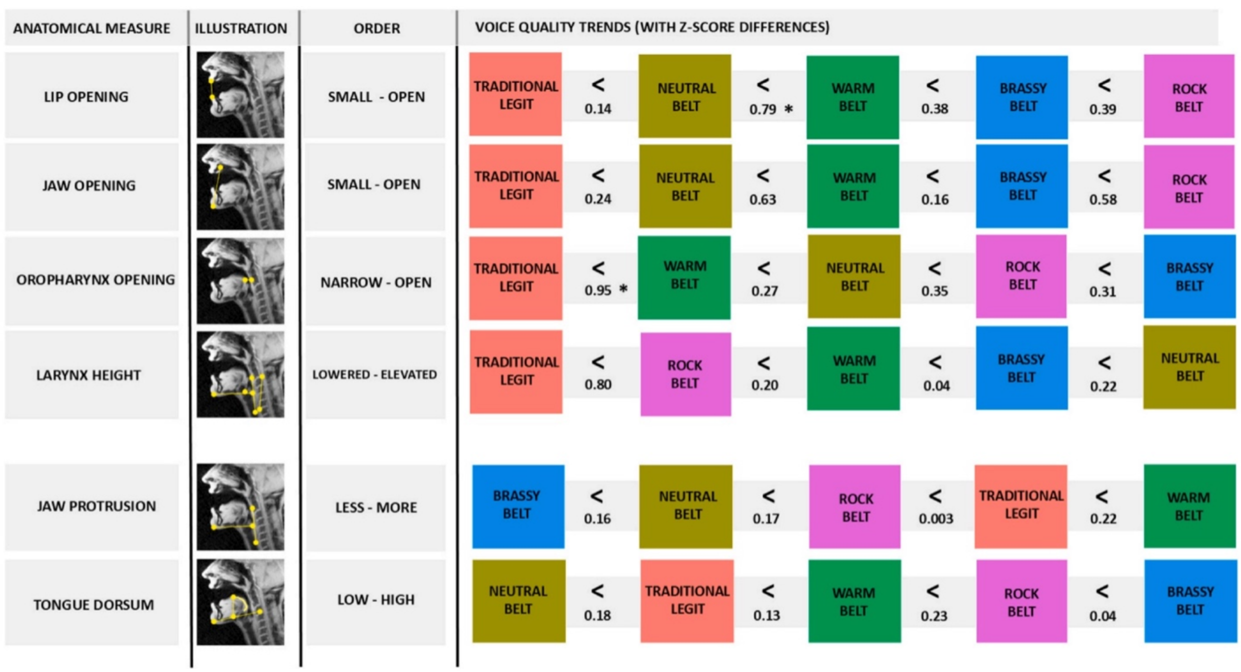

Figure 2.14 Visualization of significant findings for voice qualities and anatomical measures organized by estimates and trends. Asterisk indicates statistical significance between adjacent voice qualities. From Rudisch et al. "Investigating Vocal Tract Configurations Across Different Belting Qualities in Female and Male Musical Theater Singers Using Real-Time Dynamic MRI," Journal of Voice In Press (2025), 8.

[171] Denis Michael Rudisch et al., "Investigating Vocal Tract Configurations Across Different Belting Qualities in Female and Male Musical Theater Singers Using Real-Time Dynamic MRI," *Journal of Voice*, May 2025, in press, 2-3, https://doi.org/10.1016/j.jvoice.2025.04.021.

protrusion and tongue dorsum height.[172] Their findings are usefully summarized in a table (see Figure 2.14).

Rudisch et al. identify several notable trends. They found that the results were largely similar between treble and non-treble singers, suggesting that these techniques are not frequency dependent. In general, the legit style was the most closed style and rock belt the most open.[173] Lip opening, jaw opening, oropharyngeal opening, and laryngeal height showed the most variation across styles; however, the authors identify lip opening, jaw opening, and oropharyngeal opening as the most significant variables affecting acoustic quality.[174] Finally, Rudisch et al. propose an addition to Bozeman's model which characterizes MT singing as employing a divergent resonator.[175] Their data suggests that rock belt style is achieved with increased opening both at the lips and in the oropharynx, which the study authors call a "tube-like" shape. In contrast, legit, the style most similar to WC singing analyzed in the study, appeared "hourglass" shaped instead of the inverted megaphone shape proposed in Bozeman's model.[176] Because study participants' vocal tract adjustments remained similar across the frequency range studied, the findings provide limited guidance for strategies specific to navigating the treble voice around C_5 and F_5. However, the results do suggest that any vocal tract adjustments used to navigate these challenging areas in MT/CCM styles would not require radical changes to the configurations already used to produce the target vocal quality.

[172] Rudisch et al., "Investigating Vocal Tract Configurations," 3, 8.

[173] Rudisch et al., "Investigating Vocal Tract Configurations," 9.

[174] Rudisch et al., "Investigating Vocal Tract Configurations," 9–10.

[175] Bozeman, *Practical Vocal Acoustics*, 46–48.

[176] Rudisch et al., "Investigating Vocal Tract Configurations," 10.

The second recent study examining professional MT/CCM singers navigating throughout their vocal range was conducted by Mathais Aaen and Marek Frič to analyze the Complete Vocal Technique (CVT) framework. CVT describes four vocal modes: Neutral, Curbing, Overdrive and Edge; identified primarily by two parameters: *metal* and *density*, as well as other perceptual characteristics.[177] *Metal* refers to the amount of "perceptual brassiness, ring, and brilliance" and *density* to "auditory-perceptual weight" or "filling in of the note."[178] Within this framework, the four vocal modes are briefly described as follows: (1) *Neutral* contains 0% *metal* and between 1% and 100% *density* and "represents clear, open and soft phonation;" (2) *Curbing* contains 1% to 50% *metal* and an undefined amount of *density* described as "restrained" or "held-back" phonation; (3) *Overdrive* contains 1% to 100% *metal* and 1% to 100% *density* and represents "yell-like" and "clear, open and calling-like" phonation; (4) *Edge* contains 1% to 100% *metal* and 1% to 100% *density* but is characterized by a "clear, open, and distinctly twanged" phonation.[179]

For their study, Aaen and Frič asked two professional singers, one treble and one non-treble, both of whom were also Authorized CVT teachers, to sing every note in their respective range for 2-3s increments in each of the four CVT vocal modes. The treble participant sang from C_3 to D_6, while the non-treble participant sang from C_2 to C_6.[180] Aaen and Frič found that the participants could not produce every vocal mode across their entire range. *Overdrive* exhibited

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[177] Mathias Aaen and Marek Frič, "Going Beyond the Register—Vocal Mode Categorization Across Four Octaves in Professional Male and Female Singing Voice Using Voice Range Profile, EGG, Acoustic, and Vibroacoustic Measurements: Double-Case Study," *Journal of Voice*, July 2025, 22-23, https://doi.org/10.1016/j.jvoice.2025.06.003.

[178] Aaen and Frič, "Going Beyond the Register" 22.

[179] Aaen and Frič, "Going Beyond the Register," 22–23.

[180] Aaen and Frič, "Going Beyond the Register" 3–4.

the smallest range excursion, while *Neutral* and *Edge* demonstrated the largest range for the treble singer.[181] Across the pitch ranges in which each vocal mode could be produced, the authors observed an incremental change in *metal* and *density* rather than abrupt perceptual changes at any of the traditional passaggi locations described in previous studies of WC singing. They summarize that "the singers maintained systematically and statistically significantly different phonation coordination without registration shifts."[182] This conclusion supports the authors' call for a "more fluid and multidimensional" idea of vocal registers in order to "[afford] the singer and singing teacher more artistic freedom and possibilities…[and] genre-independent technical ability that gives versatility and options for changing expression according to different roles and performances demands."[183]

Kevin Wilson is also a proponent of the freedom offered by a flexible approach to registration in MT and CCM singing. He identifies three models he uses in his voice studio to teach registration: "The Neutral Voice", "The Binary Voice", and "The Flexible Voice". All three models rely on students identifying and experiencing a variety of specific sounds and then receiving coaching on how to incorporate those sounds into their performance repertoire. "The Neutral Voice" model, relies on the singer's ability to identify a vocal sound that is "centered around speech patterns, maintaining a balanced laryngeal position and pharyngeal resonance qualit[y] similar to projected speech."[184] Wilson suggests cultivating this type of sound with a treble student through the range of A_3 – E_5 and splits the range into "unweighted speech

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[181] Aaen and Frič, "Going Beyond the Register" 5.

[182] Aaen and Frič, "Going Beyond the Register" 16.

[183] Aaen and Frič, "Going Beyond the Register" 21.

[184] Wilson, "Practical Approaches In Coordinating Registration," 186.

qualities" (A_3 – B_4) and "child-like or juvenile qualities akin to Disney princess voice" (C_5 – E_5).[185] From this foundation, he introduces a Five Voice model to expand the student's understanding of resonance choices across their range. He describes the Five Voices as follows:

> **Voice 1** – should have a bright timbre, increased nasality, a neutral jaw (fingers distance between teeth), and a higher larynx. This will be a horizontal alignment.
>
> **Voice 2** – should have a very bright timbre but should be able to be produced with the nostrils pinched.
>
> **Voice 3** – should be very similar to the student's natural speech voice placement, neutral of speech-like larynx which can be found by swallowing and noting where the larynx rests after swallowing.
>
> **Voice 4** – should have a chiaroscuro balance synonymous with classical voice/opera voice.
>
> **Voice 5** – should have an absence of nasalance, replicate the hoot of a stuffy nose, and have a lowered larynx. This will be a vertical alignment.[186]

He then suggests assigning target "voices" to different parts of the range encouraging exploratory practice in which singers intentionally use the opposite "voice" from the target voice. This process allows students to expand their understanding of which vocal tract positions are most and least conducive to different parts of their range.[187]

His next model, "The Binary Voice," relies on a student experiencing laryngeal registration changes. Wilson suggests the use of purposeful yodels to "reinforce the release of extrinsic laryngeal muscular tension, allowing for laryngeal flexibility."[188] He also recommends incorporating physical gestures that track the singer's experience of what is happening to their

[185] Wilson, "Practical Approaches In Coordinating Registration," 186.

[186] Wilson, "Practical Approaches In Coordinating Registration," 187.

[187] Wilson, "Practical Approaches In Coordinating Registration," 187.

[188] Wilson, "Practical Approaches In Coordinating Registration," 188.

soft palate and larynx.[189] Wilson's final model is "The Flexible Voice." In this approach, he proposes the idea of registration as a continuum and provides the image of a pendulum as a guide.[190] He describes this model as "a non-linear approach to balancing laryngeal and acoustic registration events."[191] When using this model with students, Wilson advocates for exploration of how both vowel modification and emotional affects influence registration navigation. With regard to vowel modification, he references Justin Moniz's article "Regulating Vocal Load in High Impact Production" which supports closing vowels between E_4 – $B^b{}_4$ to transfer energy load from the vocal folds to resonance energy.[192] Regarding emotional affect, Wilson provides a table of emotions and intensities for singers to explore as a means of investigating how expressive intention can influence registration strategies (see Figure 2.15).

INTENSITY	HAPPY	SAD	ANGRY	AFRAID	ASHAMED
HIGH	Elated Excited Ecstatic	Distressed Hurt Sorrowful	Furious Enraged Disgusted	Terrified Fearful Panicked	Disgraced Mortified Sorrowful
MEDIUM	Cheerful Relieved Satisfied	Depressed Somber Broken Hearted	Upset Frustrated Betrayed	Frightened Threatened Apprehensive	Apologetic Guilty Embarrassed
LOW	Content Pleased Glad	Upset Disappointed Unhappy	Annoyed Irritated Touchy	Nervous Timid Anxious	Uncomfortable Regretful Ridiculous

Figure 2.15 Table of primary emotions at three intensity variations. From Wilson "Practical Approaches In Coordinating Registration for the Cis-Gender Female Musical Theatre Singer," Journal of Singing vol. 80, no. 2 (2023), 191.

[189] Wilson, "Practical Approaches In Coordinating Registration," 188.

[190] Wilson, "Practical Approaches In Coordinating Registration," 189.

[191] Wilson, "Practical Approaches In Coordinating Registration," 189.

[192] Wilson, "Practical Approaches In Coordinating Registration," 189. Justin Moniz, "Regulating Vocal Load in High Impact Production," *Journal of Singing* 78, no. 5 (2022): 601–7, https://doi.org/10.53830/OMOO7954.

Wilson notes that “emotional play can be beneficial in instigating energies for registration navigation and assessing functional efficiency in the voice for storytelling.[193] His incorporation of acting tasks into vocal technique represents an important throughline in MT and CCM voice training. While this integration of acting and vocal function is widely practiced in many studios, it has not yet been extensively examined in empirical research.

Overall, the demerging research surrounding registration in MT and CCM singing suggests that flexible pedagogical approaches are likely the most effective for achieving the wide variety of target sounds required for these nuanced and varied singing styles. Such approaches integrate laryngeal behavior, vocal tracts shaping and other physiological and acoustic factors, often encouraging experimentation and playful exploration as singers develop the coordination necessary to navigate their range while maintaining stylistic authenticity.

2.4.6 VPO Registration Strategies in WC Singing

The remainder of this section on register blending strategies in treble middle to high voice transition will address VPO strategies for register blending. Research studies on VPO during register transitions will be discussed later in the chapter; therefore, this section provides only a brief overview of pedagogical writings on the topic. Two authors, previously discussed in this chapter, address VPO as a registration strategy in WC singing. Berton Coffin, a proponent of the use of VPO, writes that it “is of great value to male and female singers in their upper passaggios and allows them to shift from the resonance used in the center of their voices to that of their higher notes.”[194] Later, he continues,

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[193] Wilson, “Practical Approaches In Coordinating Registration,” 190.

[194] Coffin, *Overtones of Bel Canto*, 33.

> this opening facilitates the high notes, is necessary for the French Nasals and in sotto voce when the vowel tract is reduced in size. Hold hand over the mouth long enough to hear and feel the high vibration in the turbinates then remove hand, keeping that memory of vibration in the tone. This is education of the soft palate.[195]

Coffin also suggests yodeling between an open and closed velopharyngeal port to train the E_5 – F_5 register transition in a variety of other exercises.[196] He links this technique to Mathilde Marchesi via the writing of John Stratton, who described her students as producing a "compressed blown tone."[197] Coffin suggests that the usefulness of VPO in register transition may come from the reduction in breath pressure he believes it provides, and its ability to attenuate the first formant of the vowel being produced which he implies would assist in the transition to higher notes.[198] His rationale for why reduction in breath pressure would assist the transition is that "this helps the voice spin," while his explanation for attenuating F_1 is that "if even one of the nasal passages is obstructed there is a cul de sac sound which makes passaggio notes difficult."[199] It is clear that Coffin views the use of VPO in the *secondo passaggio* transition as a beneficial strategy; however he offers only descriptions of its effect on the resulting sound as evidence.

On the other hand, Bozeman suggests that VPO may be less useful for register transitions. He writes, "historic bel canto pedagogy has generally maintained the goal of complete closure of the nasal port. After all, the nasal cavity is not an effective resonator, tending instead to reduce the intensity of higher partials. There may however be other benefits to slight

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195 Coffin, *Overtones of Bel Canto*, 37.

196 Coffin, *Overtones of Bel Canto*, 37, 42–43.

197 John Stratton, "Operatic Singing Style and the Gramophone," *Journal of the British Institute of Recorded Sound*, July 1966, 57-59."

198 Coffin, *Overtones of Bel Canto*, 47, 88.

199 Coffin, *Overtones of Bel Canto*, 47, 88.

nasalance. Future studies will have to resolve this question definitively."[200] Bozeman, like Coffin, notes that allowing air through the nose attenuates part of the singer's acoustic output; however, he does not view this effect as advantageous. He does note that there may be benefits to VPO, but concludes that there is not enough evidence to confirm its usefulness for WC singing.

2.4.7 VPO Registration Strategies in MT/CCM Singing

There is limited information on VPO in MT/CCM pedagogical writing. Bozeman also addresses VPO in MT/CCM singing. For these styles, he believes VPO is a useful strategy for mix belt singing because it "can reduce the pressure difference across the glottis (the difference between breath pressure below and above the glottis), moderating the vocal load."[201] This is similar to Coffin's suggestion for WC singing that a reduction in breath pressure could make singing through a transition zone easier. Wilson, however, takes a more nuanced view on the use of VPO. He recommends instead,

> 'Behind the nose, not in the nose' is a helpful statement to the student new to tones created by the effect of what we currently know as the anteromedial movement of the pharyngeal walls which can increase acoustic energy from 2800-4300hz. Simply pinching the nose is a sufficient check-in to reassure the student that the nasalance values are balanced; when too much air is present in the nasal cavities and the nose is pinched, the tone will stop, but reassuring the tone is not 'nasal' provides a bit of comfort to students making the wide variety of noises in 'mixed' registration.[202]

Wilson's reference to "balanced" nasalance values, suggests that limited nasal airflow may be helpful, but that too much will negatively influence the sound.

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[200] Bozeman, *Kinesthetic Voice Pedagogy*, 68.

[201] Bozeman, *Kinesthetic Voice Pedagogy*, 107.

[202] Wilson, "Practical Approaches In Coordinating Registration," 190.

2.5 Scientific Research on VPO in Singing

2.5.1 The Terminology Problem

Before detailing the scientific research that has been conducted on VPO in singing, it is important to acknowledge the inconsistency in the terminology used to describe the effect or role of the nose in singing. This section draws much of its structure from Nicholas Perna's 2020 *Journal of Singing* article "Nasality Deconstructed" which provides a useful summary of the terms that are often associated with VPO, and the variety of meanings that have been ascribed to them.[203] The five terms that will be discussed here are *nasal resonance*, *nasalance*, *VPO*, *twang*, and *nasality*. Nasality will be addressed last because it is the most controversial in its meaning within the literature. Broadly speaking, the effect or role of the nose in singing can be divided into two rough categories: (1) the perceptual effect of opening the velopharyngeal port to allow air to pass through the nose while singing, and, (2) the perceptual effect of vibrations or narrowings in the vocal tract that are associated with the nose, but that may or may not be associated with air actually passing through the nose.

The term *nasal resonance* is most often used to describe the perceptual effect of allowing air to pass through the nose while singing. In 1967, Vennard writes: "the quality of tone as resonated by the nose is well known even to the layman. It is a "honky," muffled sound, which should not be confused with that which is sometimes called 'nasal twang.'"[204] By making this distinction explicit, Vennard indicates that confusion in terminology has existed around this topic for some time. Although further discussion of *twang* will follow, for Vennard the term *nasal*

[203] Perna, "Nasality Deconstructed."

[204] Vennard, *SINGING*, 93.

resonance refers specifically to the perceptual quality of the voice when air passes through the nose. Howell echoes this distinction writing, "the nose itself generates a dopey and dull sound as a resonator rather than a bright edgy sound."[205] LeBorgne and Rosenberg offer a more complex definition of *nasal resonance*. They describe it as "resulting in an additional acoustic tube…the consequence…is that it produces resonance frequencies independent of the oral cavity. As a result, the combined oral-nasal cavities produce oral formants, nasal formants, and nasal anti-formants… [which combine] to produce a complex spectral output, resulting in spectral envelops with deep valleys and increased higher frequencies."[206] This definition frames *nasal resonance* in terms of its acoustic interaction with the resonances of the vocal tract. It also acknowledges that the combined effect of nasal and oral resonances may obscure the "honky" or "dopey" sounds described by Vennard and Howell. However, LeBorgne and Rosenberg also illustrate the ongoing challenge of terminology by presenting this definition of *nasal resonance* under the section heading "Nasality in Commercial Music Singing," thereby referring to *nasality* without clearly defining the term.[207]

Nasalance is more easily defined. It is a calculable ratio; however there are two different ratios are referred to as *nasalance* in the literature. These can be distinguished by the type of equipment used to measure them. Martin Rothenberg, inventor of the Glottal Enterprises OroNasal System, helpfully distinguishes these two versions on his website.[208] His equipment measures what he calls "F0-nasalance" defined as "the ratio of nasal-to-oral airflow volume

[205] Howell, *Hearing Singing*, 196.

[206] LeBorgne and Rosenberg, *The Vocal Athlete*, 164.

[207] LeBorgne and Rosenberg, *The Vocal Athlete*, 163.

[208] Rothenberg, "A New Method for the Measurement of Nasalance."

velocity at the voice fundamental frequency."[209] F0-nasalance can be expressed as a percentage using the following equation: [A_{1fon}/(A_{1foo} + A_{1fon}) x 100] where A_{1fon} equals the nasal airflow volume velocity at the voice fundamental frequency ($1f_o$) and A_{1foo} equals the oral airflow volume velocity at $1f_o$. The second type of nasalance Rothenberg calls "First Formant Nasalance" or "F1-nasalance."[210] F1-nasalance is measured using a Nasometer, which measures acoustic energy at the mouth and at the nostrils. It can be expressed by the following equation: [A_n/(A_o + A_n) x 100] where A_n equals the nasal acoustic energy and A_o equals the oral acoustic energy.[211] Rothenberg argues that F0-nasalance is less susceptible to measurement error because it is not effected by the vowel or pitch frequency being produced.[212] A Nasometer measuring F1-nasalance has two band pass filters that attenuate energy below 300 Hz and above 750 Hz. As pitch and vowel change, especially if pitch frequency and/or vowel formant frequencies fall outside this range, the F1-nasalance measurement may be affected.[213]

All definitions of *VPO* relate to the activity of the velum and whether it is relaxed/lowered to allow exhaled air to pass into the nose, or engaged/raised to block exhaled air from entering the nose. Perna offers a simple definition: "VPO is a measurement of the nasal airflow."[214] Similar to LeBorgne and Rosenberg in their description of *nasal resonance*, Perna also summarizes research describing the acoustic effect of *VPO* as a "dampening of sound via

[209] Rothenberg, "A New Method for the Measurement of Nasalance."

[210] Rothenberg, "A New Method for the Measurement of Nasalance."

[211] Rothenberg, "A New Method for the Measurement of Nasalance."

[212] Rothenberg, "A New Method for the Measurement of Nasalance."

[213] Rothenberg, "A New Method for the Measurement of Nasalance."

[214] Perna, "Nasality Deconstructed," 430.

attenuation of spectral peaks especially f_{R1} (300-800 Hz)."[215] However, as R. Miller discusses, *VPO* and sensations of vibration in the nose or "mask" are often conflated, and singers' proprioceptive awareness of *VPO* can vary widely.[216]

Twang is a property of vocal sound that can be described both mechanically and by its acoustic effect. Perna summarizes that *twang* is "the brightness…that comes from pharyngeal narrowing leading to increased energy in the 4-7 kHz range."[217] LeBorgne and Rosenberg rely on the research of Sundberg and Thalen in defining the term. They write that "twang is used in the CCM context to describe an acoustic result of a longer closed quotient during the vibratory cycle, H1-H2 [$1f_o$-$2f_o$] is smaller than neutral singing, F_1-F_2 is higher, and F_3 and F_5 are lower in twang as compared to neutral singing."[218] These two definitions are not necessarily in conflict. Instead, they show that both the acoustic properties and the mechanical origins of *twang* are complex, but that they appear unrelated to air passing through the nose.

The use of the word *nasality* in the literature is inconsistent and demonstrates a basic confusion about how the nose contributes either to the perceived sound or the singer's proprioceptive experience of that sound. Titze illuminates this misunderstanding well, saying,

> from the singer's standpoint, there seems to be a perceptual equivalence between nasality and brilliance (ring) in the tone produced. In both cases the perceptual focus of sound production is away from the larynx and toward the face.[219]

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215 Perna, "Nasality Deconstructed," 430.

216 Richard Miller, "The Velopharyngeal (Palatopharyngeal) Port During Singing," *Journal of Singing* 53, no. 1 (1996): 28.

217 Perna, "Nasality Deconstructed," 429.

218 Johan Sundberg and Margareta Thalén, "What Is 'Twang'?" *Journal of Voice* 24, no. 6 (2010): 659–60, https://doi.org/10.1016/j.jvoice.2009.03.003; LeBorgne and Rosenberg, *The Vocal Athlete*, 164.

219 Titze, "Nasality in Vowels," 34.

From this description, it can be inferred that he uses *nasality* to mean VPO as he later describes *nasality* as "acoustic leakage through the nose," a phenomenon associated with nasalized vowels, which are produced by lowering the velum to open the velopharyngeal port.[220] Like definitions of *twang*, Titze specifies that the brilliance/ring he is referring to is created via epilaryngeal narrowing.[221] Titze further explains that both *VPO* and epilaryngeal narrowing create a similar spectral pattern: "in particular, the ratio of the peak energy in the high-frequency portion of the spectrum (2 kHz to 4 kHz) to the peak energy in the low frequency portion (0 kHz – 1 kHz) is increased."[222] However, the mechanisms producing this spectral change differ. Epilaryngeal narrowing increases the prominence of the high-frequency peak in relation to the low-frequency peak, whereas *VPO* reduces the low-frequency peak in relation to the high-frequency peak by expanding the energy distribution in the first formant region.[223] In other words, epilaryngeal narrowing creates a spikier high-frequency peak, while VPO creates a wider low-frequency peak. Titze summarizes the causes and effects as follows:

> In one case [VPO] we lower the low-frequency prominence of the oral (and pharyngeal) resonance by creating an acoustic leakage through the nose; in the other [epilaryngeal narrowing], we raise the high-frequency prominence of the oral (and pharyngeal) resonance by creating an additional resonator in the larynx.[224]

He notes that he has not tested these mechanisms experimentally in human subjects, but suggests that epilaryngeal narrowing is likely the more efficient method for producing the facial vibrations

[220] Titze, "Nasality in Vowels," 34–35.

[221] Titze, "Nasality in Vowels," 34.

[222] Titze, "Nasality in Vowels," 34.

[223] Titze, "Nasality in Vowels," 34–35.

[224] Titze, "Nasality in Vowels," 35.

associated with resonant voice therapies.[225] Tanner et al. echo this conclusion in their human study on resonant voice therapy.[226]

Titze explains why the perceptual effect of *VPO* and epilaryngeal narrowing is similar. However, the lack of clarity in the literature often arises when authors refer to *nasality* without identifying the mechanical cause, while simultaneously using other related terms discussed above. For example, Doscher quotes Vennard in her book *The Functional Unity of the Singing Voice* writing:

> Vennard says that the velopharyngeal closure by means of the soft palate should be complete and that nasal resonance is of negligible value. At the same time, he acknowledges the need for come "twang" in a tone…and believes that the use of "twang" in the upper range encourages "focus" and a strong singing formant.[227]

In this passage, *VPO* and an increase in the high-frequency singer's formant range appear to be linked. However, according to Titze, the two mechanisms produce different acoustic effects: VPO reduces low-frequency peaks, whereas epilaryngeal narrowing increases high-frequency peaks (a phenomenon often associated with definitions of *twang*.)[228] Doscher further oberserves: "many singing teachers decry even a hint of nasality in the tone, but calmly accept and even advocate what they call "head resonance" or "nasal resonance." Is the difference between the two terms a purely semantic one?"[229] Her question gets to the heart of the confusion. Since *VPO* and epilaryngeal narrowing can produce similar changes in the ratio of high to low frequency partials, and, because both may create a sensation of resonance focused toward the face,

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[225] Titze, "Nasality in Vowels," 35.

[226] Tanner et al., "Velopharyngeal Port Status During Classical Singing," 1312.

[227] Doscher, *The Functional Unity of the Singing Voice*, 120.

[228] Titze, "Nasality in Vowels," 35.

[229] Doscher, *The Functional Unity of the Singing Voice*, 121.

distinguishing between the two mechanisms from the perspective of singers, listeners, or teachers is a difficult task. Doscher also notes that the existence of different degrees of VPO, ranging from "a pure murmur [to] a nasalized vowel, such as French ones, or some intermediate sound," further complicates the task of identifying *nasality*.[230]

Other authors also acknowledge the complexity of the concept of *nasality* in their writing. McKinney introduces the new terms "postnasality" and "nasal honk" to describe the sound of a voice produced with the velopharyngeal port open. He contrasts these with "forced nasality" and "nasal twang," which he argues can be produced with or without VPO.[231] He suggests that the later phenomena can obscure the former, writing that "if the nasal port is open, postnasality (nasal honk) may be present,… but if so, it will tend to be covered up by the characteristic penetrating quality of nasal twang [caused by a constriction somewhere in the pharynx], in which the nose is forced to vibrate."[232] Here, McKinney acknowledges that two distinct mechanisms, VPO and pharyngeal constriction, can produce different sounds associated with the nose. He further suggests, without citing a scientific source, that the sound created by epilaryngeal narrowing may be perceptually more dominant. McKinney concludes that "the test of excessive nasal resonance must remain a subjective one for the individual listener."[233] However, this statement illustrates the same terminological difficulty discussed above, as the term *nasal resonance* is used without a clear mechanical definition.

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[230] Doscher, *The Functional Unity of the Singing Voice*, 148.

[231] James C. McKinney, *The Diagnosis & Correction of Vocal Faults: A Manual for Teachers of Singing & for Choir Directors* (Long Grove, IL: Waveland Press, Inc., 2020), 134–35.

[232] McKinney, *The Diagnosis & Correction of Vocal Faults*, 134–35.

[233] McKinney, *The Diagnosis & Correction of Vocal Faults*, 135.

The distinction between the perceptual effects of epilaryngeal narrowing and VPO is not universally acknowledged in writings on the topic of *nasality*. Jean Westerman Gregg, in an effort to define the contribution of the VP to singing technique, claims that the VP does not need to be "train[ed] to stay open or closed."[234] He continues, "it would appear that if the sound is a nasal one to the listener, the amount of tone sent into the nose exceeds that capable of being released by the nostrils."[235] In this statement, he does not define what constitutes a "nasal" sound, making it difficult to discern which tonal quality he attributes to VPO. He further states that "unless a truly prominent nasality in the sound can be detected by the listener, it would probably be best to let the velopharyngeal mechanism do its thing without interference."[236] Once again, without knowing what he means by *nasality*, it is difficult to understand what he hopes to improve in the sound by not interfering with the velopharyngeal port's activity.

Some discussions of *nasality* omit the contribution of epilaryngeal narrowing entirely. R. Miller links *nasality* to VPO when he suggests having a singer plug their nose to avoid *nasality*.[237] Marilee David makes the same link when she writes, "excessive nasality indicates inadequate velopharyngeal closure."[238] R. Miller does suggest that using nasal consonants as an exercise can help singers feel vibrations in the face and that "these sensations assist the singer in achieving desirable relationships between the fundamental pitch and its harmonic partials."[239] As

[234] Jean Westerman Gregg, "On the Velopharyngeal Port," *Journal of Singing: The Official Journal of the National Association of Teachers of Singing* 56, no. 1 (1999): 43.

[235] Gregg, "On the Velopharyngeal Port," 44.

[236] Gregg, "On the Velopharyngeal Port," 44–45.

[237] Miller, *Training Soprano Voices*, 96.

[238] Marilee David, *The New Voice Pedagogy*, 2nd ed. (Blue Ridge Summit: Scarecrow Press, 2008), 85.

[239] Miller, *Training Soprano Voices*, 94.

Titze explains, VPO can increase the ratio of high to low frequency partials by attenuating energy in the low frequency range. R. Miller's suggestion, therefore, may be useful for some singers.[240] Nevertheless, ignoring the potential role of epilaryngeal narrowing fails to capture the full complexity of what is described as *nasality*.

LeBorgne and Rosenberg attempt to clarify the definition of *nasality* by stating that "nasality and twang are unique entities."[241] They later describe *nasality* writing,

> The addition of the nasal resonance changes the interaction of the resonance tubes resulting in some degree of formant tuning, which ultimately attenuates the first formant and enhances the higher partials (i.e., gives more brilliance, not nasality, to the voice.)[242]

This description is similar to that offered by Titze. However, in his account, opening the velopharyngeal port results primarily in attenuation of lower frequency energy rather than an increase in higher frequency energy. In his explanation, epilaryngeal narrowing, or *twang*, is responsible for increasing the prominence of high energy partials.[243] LeBorgne and Rosenberg, however, suggest that the brilliance that results from the acoustic effect of VPO should not be described as *nasality*. This implies that they define *nasality* according to a different, unspecified, perceptual quality. Consequently, defining *nasality* solely in terms of the acoustic effects of VPO may not fully capture the way the term is used in the broader literature.

In his article, Perna concludes that "nasality is a percept that arises when multiple conditions, which have yet to be definitively determined, are met simultaneously."[244] This definition captures both the lack of clarity in the literature and the complexity of the types of

240 Titze, "Nasality in Vowels," 35.

241 LeBorgne and Rosenberg, *The Vocal Athlete*, 164.

242 LeBorgne and Rosenberg, *The Vocal Athlete*, 399.

243 Titze, "Nasality in Vowels," 35.

244 Perna, "Nasality Deconstructed," 431.

sounds that listeners may perceive as nasal. He further suggests that the term *nasal resonance* should be avoided because resonance "can be defined as amplification and enrichment" whereas passing air through the nose does neither.[245] Instead it attenuates low frequencies.[246] He also argues that "*twang* [is] most likely is not nasality, even though it might sound nasal to some listeners."[247] This assertion reflects the similar acoustic ratio change in the ratio of high to low frequency energy produced by VPO and epilaryngeal narrowing as described by Titze, while acknowledging the mechanical differences between the two mechanisms.[248] Perna also notes that both *VPO* and *nasalance* "might be nasality but may not perceptually sound nasal."[249] This observation reflects the perceptual confusion that surrounds both the bright *twang* quality and the "dopey" tone quality often associated with the nasal sounds, combined with the similar changes in the ratio of high to low frequency energy discussed above.[250] Overall, the inconsistencies in terminology demonstrate that there is no broad consensus regarding the meaning of the term *nasality* in the context of singing. In the following discussion, efforts will be made to clarify terminology where possible.

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[245] Perna, "Nasality Deconstructed," 430.

[246] Titze, "Nasality in Vowels," 35.

[247] Perna, "Nasality Deconstructed," 430.

[248] Titze, "Nasality in Vowels," 35.

[249] Perna, "Nasality Deconstructed," 430.

[250] Howell, *Hearing Singing*, 196.

2.5.2 Studies that Explore the Perceptual Qualities of Nasality

The remainder of this chapter is devoted to a comprehensive review of studies that address nasality or VPO. Some studies will be discussed in multiple categories due to their relevance to more than one aspect of the topic.

The first group of studies examining the role of the nose in singing attempts to determine the contribution of the nasal passages and sinuses to the perceived sound of the singing voice. W. B. Wooldridge in his 1954 dissertation, "The nasal resonance factor in sustained vowel tone in the human voice" and Vennard in his 1964 article "An experiment to evaluate the importance of nasal resonance in singing," both investigate whether filling the nasal passages produces a discernable difference in vowel quality in singers.[251] Wooldridge filled the nasal passages of six professional singers with cotton gauze, while Vennard filled the nasal passages and nasopharynx of five professional males singers with gauze and filled their maxillary sinuses with water.[252] Both researchers presented recordings of the singers performing vocalises on non-nasal vowels, both with and without these treatments, to expert listeners. In both studies, listeners generally did not perceive a significant difference in vowel quality between the conditions.[253] However, Vennard found that listeners were able to perceive a difference on the [i] vowel when the singer was using falsetto production.[254] He also asked the singers to perform two phrases containing consonants and found that the listeners could distinguish between the conditions when

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[251] W. B. Wooldridge, "The Nasal Resonance Factor in Sustained Vowel Tone in the Human Voice" (PhD diss., Indiana University, 1954).

[252] Wooldridge, "The Nasal Resonance Factor in Sustained Vowel Tone," 39; William. Vennard, "An Experiment to Evaluate the Importance of Nasal Resonance in Singing," *Folia Phoniatrica et Logopaedica* 16, no. 2 (1964): 148, https://doi.org/10.1159/000262995.

[253] Wooldridge, "The Nasal Resonance Factor in Sustained Vowel Tone," 39; Vennard, "An Experiment to Evaluate the Importance of Nasal Resonance," 150.

[254] Vennard, *SINGING*, 150.

consonants were present.[255] Both authors ultimately concluded that the terms ‘nasal resonance’ and ‘sinus resonance’ are “without validity in describing the quality of the singing voice.”[256] Vennard additionally observed that nasal consonants cannot be produced without the nasal passages being open, and that the pronunciation of all consonants was altered to some extent by the treatment.[257]

In his article, Vennard also references a nineteenth century experiment in which tubes of varying cross-sectional areas were inserted through the VP. In this experiment, conducted by Passavant and later recorded in 1924 by Rousselot, the results demonstrated that a tube with a cross-sectional area of 12 sq. mm had no effect of vowel quality, whereas a tube measuring 28 sq. mm did produce a perceptible change. Vennard interprets these findings as evidence that different degrees of VPO can have different effects on the perceived nasality of the voice.[258]

Antje Boschmann conducted a pilot experiment with a goal like that of Vennard and Wooldridge, namely, to assess the role of the nasal passages in perceived nasality. However, instead of physically blocking off the nasal passages, Boschmann asked the two participants (one treble, one non-treble, and both classically trained) to vary their degree of VPO to produce dopey, twangy, and neutral sounds on the vowel [æ]. The non-treble participant performed the task on D_3, while the treble participant performed it on F_4 and D_5. F0-nasalance was measured using the Glottal Enterprises DualView System, and acoustic recordings were collected using a Countryman H60W6LXLR H6 microphone.[259] The nasality of the recorded sound examples was

[255] Vennard, *SINGING*, 149–50.

[256] Vennard, “An Experiment to Evaluate the Importance of Nasal Resonance,” 151–52.

[257] Vennard, “An Experiment to Evaluate the Importance of Nasal Resonance,” 152.

[258] Vennard, *SINGING*, 94.

[259] Antje Boschmann, “A Pilot Study: Effects of Nasalance on Nasality,” *NEC VSAL*, February 2022, 9.

then evaluated by eleven voice graduate students. No correlation was found between F0-nasalance and perceived nasality.[260]

Perna found results like those reported by Boschmann. In his study, he presented seven recordings of ascending and descending five note scales with known F1-nasalance values to twenty-five expert listeners, defined as collegiate professors or published voice teachers.[261] Two notable findings emerged from the study. First, listeners' evaluations did not correspond to the known F1-nasalance values. Second, inter-listener ratings of nasality showed considerable variation. Based on these findings, Perna concludes "that within the voice pedagogy community, the sound of nasality is not clearly defined or agreed upon."[262]

The final two studies that explore the perceptual qualities of nasality were conducted by Peer Birch et al. and Thirunavukkarasu Jayakumar et al. as part of larger investigations of VPO. The VPO results will be discussed in the next section. Birch et al. studied seventeen professional opera singers (three high sopranos, three sopranos, two mezzo-sopranos, three tenors, two baritones, two bass-baritones, and two basses), while Jayakumar et al. studied fifteen female professional Carnatic singers and twenty-five female non-singers.[263] Both teams used the Glottal Enterprises DualView System to measure F0-nasalance, and Jayakumar et al. also used a Kay-PENTAX Nasometer II to measure F1-nasalance.[264] Both studies also recorded audio tokens that

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[260] Boschmann, "A Pilot Study: Effects of Nasalance on Nasality," 9.

[261] Nicholas Perna, "Nasality: Do You Hear What I See?" *VoicePrints*, October 2015, 6.

[262] Perna, "Nasality: Do You Hear What I See?," 6.

[263] Birch et al., "Velum Behavior in Professional Classic Operatic Singing," 62; Thirunavukkarasu Jayakumar et al., "Nasalance, Nasal Airflow and Perceived Nasality in Carnatic Singers and Non-Singers," *Indian Journal of Otolaryngology and Head & Neck Surgery* 76, no. 1 (2024): 6, https://doi.org/10.1007/s12070-023-03994-w.

[264] Birch et al., "Velum Behavior in Professional Classic Operatic Singing," 62; Jayakumar et al., "Nasalance, Nasal Airflow and Perceived Nasality," 6.

were judged for perceived nasality by expert listeners: six teachers of singing in the Birch et al. study and five speech language pathologists in the Jayakumar et al. study.[265] Once again, both studies found no correlation between nasalance measurements and perceived nasality.[266]

Table 2.2 Studies that Explore the Perceptual Qualities of Nasality

Reference (Citation)	Participants	Methods	Main Finding of Study
Vennard, 1967[267] (translation and summary of Rousselot, 1924 referencing Passavant in the nineteenth century)	1 singer, gender not specified	Inserting tubes of different cross-sectional areas into the nose and through VP.	12 sq. mm cross-sectional area had no effect on vowel quality, 28 sq. mm changed vowel quality.
Wooldridge, 1954[268]	6 professional singers (gender not specified)	Participants sang [i, e, a, o, u] on unspecified pitches with and without nasal passages filled with cotton gauze. Jury of expert listeners assessed the change in vowel quality between filled and unfilled conditions.	No perceptual change in vowel quality observed between nasal passages filled with gauze and without gauze.
Vennard, 1964[269]	5 male trained singers	Participants sang vocalises on the vowels [i, a, u] in chest and falsetto register and on two phrases from repertoire with normal conditions, and with the maxillary sinuses filled with water while the nasal passages and nasopharynx were packed with gauze. One X-ray of	No difference observed between sounds with and without nasal passages and sinuses filled on vowels, except for the [i] vowel produced with falsetto production. On the phrases from

[265] Birch et al., "Velum Behavior in Professional Classic Operatic Singing," 63; Jayakumar et al., "Nasalance, Nasal Airflow and Perceived Nasality," 7.

[266] Birch et al., "Velum Behavior in Professional Classic Operatic Singing," 69; Jayakumar et al., "Nasalance, Nasal Airflow and Perceived Nasality," 16.

[267] Vennard, *SINGING*, 94.

[268] Wooldridge, "The Nasal Resonance Factor in Sustained Vowel Tone," 39.

[269] Vennard, "An Experiment to Evaluate the Importance of Nasal Resonance in Singing," 146–53.

		each subject was taken. The X-rays were taken on different vowels for each subject. 111 expert listeners judged difference in sound between the conditions.	repertoire, differences were observed.
Birch et al., 2002[270]	17 professional opera singers: 3 high sopranos, 3 sopranos, 2 mezzo-sopranos, 3 tenors, 2 baritones, 2 bass-baritones, 3 basses	Participants sang the words 'panta' 'pinti' and 'puntu' at 3 dynamic levels on an A major triad throughout their range. Measurements were taken by nasofiberscope (visual inspection of VPO) and Glottal Enterprises DualView System (F0-nasalance). 6 teachers of singing also judged the perceived nasality of the recorded singing examples.	No correlation between nasal airflow or VPO and perceived nasality.
Perna, 2015[271]	25 expert listeners (collegiate professors or published voice teachers)	Expert listeners evaluated 7 five note ascending and descending scales performed in a comfortable pitch range and rated recordings as (1) increasing in nasopharynx resonance, (2) decreasing in nasopharynx resonance, (3) constant nasopharynx resonance, as pitch increased. Listener ratings were compared to F1-nasalance values recorded at the same time as the audio recordings.	No correlation observed between F1-nasalance values and rater evaluations. Very little inter-rater correlation.
Boschmann, 2022[272]	1 WC trained female singer, 1 WC trained male singer	Female participant sang F_4 and D_5, male participant sang D_3 on [ae] with dopey, twangy, and neutral sounds and the sound examples (recordings were made using a Countryman H60W6LXLR H6 microphone) were played	No correlation between F0-nasalance and perceived nasality.

[270] Birch et al., “Velum Behavior in Professional Classic Operatic Singing.”

[271] Perna, “Nasality: Do You Hear What I See?”

[272] Boschmann, “A Pilot Study: Effects of Nasalance on Nasality.”

		for 11 voice graduate students to rank perceived nasality. F0-nasalance was measured using the Glottal Enterprises DualView System.	
Jayakumar et al., 2024[273]	15 female professional Carnatic singers (minimum 10 years of training) and 25 non-singers of the same age range	Participants sang two sets of tasks: (1) 10s sustained on vowels [a], [i], and [u] at low (240 Hz), medium (360 Hz) and high (482 Hz) pitches; (2) [pa:va], [pi:va], [pu:va] & [ma:va], [mi:va], [mu:va] with ascending pitches at low, medium and high pitches. Data collected using Glottal Enterprises DualView System (F0-nasalance), and Nasometer II (F1-nasalance). Perceived nasality judged by 5 SLPs using a visual analog scale.	No correlation between F0-nasalance, F1-nasalance and perceived nasality.

2.5.3 Studies of VPO on One Note

This section includes studies that assess VPO on a single sustained pitch. Although many of the studies include more than one pitch, the measurements focus on what happens while a singer sustains one note at a time rather than what happens when they sing more than one pitch at a time in a single breath. VPO is evaluated through a variety of methods including visual inspection, nasalance measurements, and nasal airflow measurements. The studies discussed in this section break down into four categories: (1) general studies of VPO on unspecified vowels; (2) studies that assess VPO using different vowels; (3) studies that compare VPO in speech and singing; and (4) studies that address the acoustic effects of VPO.

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[273] Jayakumar et al., "Nasalance, Nasal Airflow and Perceived Nasality."

2.5.3.1 General Studies of VPO on Unspecified Vowels

In 1989, Troup et al. used xeroradiographic images to visually assess velum behavior in singers. They studied nine professional WC sopranos singing an unspecified vowel on E_3, E_4, E_5, C_6, and E_6. Visual inspection of the xeroradiographic images showed a variety of velum behaviors with a general trend of a decrease in VPO as pitch increased. However, the study authors reported variability across participants. VPO was observed in three of the nine singers on the pitch C_6, but in five of the nine singers on the pitch E_6.[274] The authors concluded that "total velum closure is language dependent, education dependent, style dependent, pitch dependent and anatomically dependent" suggesting that velum behavior does not follow a single, consistent pattern across singers.[275]

2.5.3.2 Studies that Assess VPO a Using Different Vowels

The five studies in this section use a variety of methods to assess VPO in different vowels. Some studies also combine changes in vowel with changes in pitch. Scotto di Carlo & Autesserre used xeroradiographic images and nasal endoscopy to visually inspect velum behavior in six professional WC singers of all voice types. However, the authors only reported results from one participant, a professional soprano who sustained the vowels [i] and [ɑ̃] on a low and a high pitch (pitch frequencies are unspecified). VPO was observed for both pitches with both vowels; however different patterns emerged depending on the vowel. For the nasal vowel

[274] Troup et al., "On Velum Opening in Singing," 37.

[275] Troup et al., "On Velum Opening in Singing," 39.

[ɑ̃], VPO decreased as pitched increased, whereas for [i] the opposite pattern was observed, with VPO increasing as pitch increased.[276]

In 1995, McIver & R. Miller studied the effects of different vowels on VPO, as well as the effect of combining different vowels with the nasal consonant [m]. They used a Nasometer to measure F1-nasalance during the tasks. The participants were thirty undergraduate vocal performance majors between the ages of 18 and 23; fifteen sopranos or mezzo-sopranos and fifteen tenors or baritones/basses.[277] Each participant performed three tasks on a comfortable middle voice pitch (sopranos – B^b_4, mezzo-sopranos – G_4, tenors – B^b_3, basses – F_3): (1) singing [i], [e], [a], [o], [u] with a pause after each vowel; (2) [mi], [me], [ma], [mo], [mu]; (3) [im], [em], [am], [om], [um].[278] The results showed a variety of F1-nasalance values across participants with several noteworthy trends. In the first task (vowels only), the authors reported differences between the soprano/mezzo-soprano group and the tenor/baritone group. The sopranos/mezzo-sopranos recorded higher F1-nasalance values for the back vowels [a] and [o], whereas the tenors/baritones recorded higher F1-nasalance values for the front vowel [i].[279] For the tasks in which vowels that were preceded by or followed by [m] (tasks 2 and 3), the tenors/baritones recorded higher F1-nasalance values than the sopranos/mezzo-sopranos.[280] McIver & R. Miller concluded that these results demonstrated differences in how treble and non-

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[276] D. Autesserre and N. Scotto di Carlo, "Movements of the Velum in Singing," *Journal of Research in Singing* 11, no. 3 (1987): 7, 12.

[277] William McIver and Richard Miller, "A Brief Study of Nasality in Singing," *Journal of Singing* 52 (1995): 22.

[278] McIver and Miller, "A Brief Study of Nasality in Singing," 21–22.

[279] McIver and Miller, "A Brief Study of Nasality in Singing," 23.

[280] McIver and Miller, "A Brief Study of Nasality in Singing," 24.

treble voices used VPO in their singing technique.[281] However, they did not acknowledge that the participants sang different pitches, nor did they consider the potential influence of fundamental frequency on these results.

In addition to the perceived nasality results discussed previously, Birch et al. also examined the effect of vowel and pitch on VPO using the visual inspection data from their nasofiberscopies and F0-nasalance measurements collected with the Glottal Enterprises DualView System. Visual inspection showed three shapes the VP created when it was open. These shapes were described as coronal (an oval expanded side to side), sagittal, (an oval expanded vertically), and constricted (a small circular opening).[282] The authors propose that "these varying VPO shapes suggest that singers may use a VPO to fine-tune vocal timbre."[283] They also reported that the F0-nasalance data did not consistently correspond with the visually observed VPO. In some samples, the F0-nasalance measurement suggested no nasal airflow, while the visual inspection showed an open VP. Birch et al. attribute these discrepancies to methodological factors, noting that the measurements were taken at different times using different equipment, and that the equipment could have influenced the way participants sang.[284] The authors summarize their overall findings writing, "clear evidence of a VPO was found for all singer classifications, at least under some conditions. The VPO was observed for the vowels [a] and [u] and one of the tenors also showed a VPO on the vowel [i]…All tenors showed that a VPO was near their passaggio."[285]

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[281] McIver and Miller, "A Brief Study of Nasality in Singing," 24025.

[282] Birch et al., "Velum Behavior in Professional Classic Operatic Singing," 66.

[283] Birch et al., "Velum Behavior in Professional Classic Operatic Singing," 70.

[284] Birch et al., "Velum Behavior in Professional Classic Operatic Singing," 68.

[285] Birch et al., "Velum Behavior in Professional Classic Operatic Singing," 70.

Fowler & Morris also examined how differences in pitch and vowel affect VPO, and whether vocal training influenced a singer's use of VPO. The researcher studied thirty-six WC trained and thirty-six untrained female participants. Each participant sustained the vowels [i], [æ], [u], [ɑ] for six seconds at three frequency levels (25%, 50% and 75% of their comfortable vocal range, which was determined by a preliminary test at the beginning of the session.) The Glottal Enterprises DualView System was used to measure F0-nasalance and a cassette tape recorder was used to record audio samples. The authors found no significant differences in VPO use between the trained and untrained groups, so they combined the groups for their statistical analyses of pitch and vowel effects.[286] They note that the results were 'likely more related to neuromuscular function that to training."[287] The analyses showed that the front vowels [i] and [æ] demonstrated significantly higher F0-nasalance values than the back vowels [u] and [ɑ], and that F0-nasalance decreased as pitch increased.[288] However, the authors note that "high nasalance scores were generated by some participants from both groups for all vowel sounds and frequency levels sampled."[289] They propose that, "the wide range of nasal acoustic energy levels may help explain why the controversy regarding the use of VPO during singing remains unsolved. This result implies that differences in morphology probably dictate VP [port] behavior during singing."[290]

Similarly to Fowler & Morris, Jayakumar et al. examined the effects of training, vowel, and pitch on VPO. However, unlike Fowler & Morris, they studied singers trained in Carnatic

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[286] Fowler and Morris, "Comparison of Fundamental Frequency Nasalance," 742.

[287] Fowler and Morris, "Comparison of Fundamental Frequency Nasalance," 744.

[288] Fowler and Morris, "Comparison of Fundamental Frequency Nasalance," 742, 744.

[289] Fowler and Morris, "Comparison of Fundamental Frequency Nasalance," 744.

[290] Fowler and Morris, "Comparison of Fundamental Frequency Nasalance," 744–45.

singing, not WC singing. Their methods are explained in the previous section. The results showed a significant effect for training, with trained singers using more nasal airflow than untrained participants.[291] For the trained singers, F0-nasalance decreased significantly as pitch increased for the vowel [i] only.[292] When contrasted with the results of Fowler & Morris, these findings support the hypothesis that singing style may influence the use of VPO.

2.5.3.3 Studies that Compare VPO in Speech and Singing

Three studies compare velum behavior in singing to velum behavior in speaking. Austin 1997 uses a photodetector to measure VPO, while Tanner et al. and Martell et al. both used the PERCI-SAR System to measure nasal airflow, nasal pressure, and oral pressure. Austin's photodetector system utilized two fiber optic wires; one inserted in the nose and positioned above the VP, and one inserted in the mouth and positioned below the VP. His participants were four WC trained professional female singers.[293] Participants performed two tasks: (1) speaking three sentences in English designed to elicit the normal speech sounds of [n], [v], and [k]; (2) singing the sustained vowels [a], [e], [i], [o], [u]. Each task was repeated five times in four conditions: (1) normal speech; (2) low singing range; (3) middle singing range; (4) high singing range. The specific pitches selected for low, middle and high ranges were not specified.[294] Overall, the singers demonstrated greater VP closure during singing than during speech.

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[291] Jayakumar et al., "Nasalance, Nasal Airflow and Perceived Nasality," 15.

[292] Jayakumar et al., "Nasalance, Nasal Airflow and Perceived Nasality," 8.

[293] Austin, "Movement of the Velum during Speech and Singing," 213.

[294] Austin, "Movement of the Velum during Speech and Singing," 213–14.

Additionally, as pitch increased during the singing tasks, the amount of time that the VP was open decreased.[295]

Tanner et al. studied ten soprano graduate students with extensive performance experience. Participants sang and spoke the nonsense words [hɑmpɑ], [himpi], and [humpu] at high, comfortable, and low pitches and at loud, comfortable, and soft dynamics. The PERCI–SAR System was used to measure nasal airflow, nasal pressure, and oral pressure. The device uses tubes inserted into the nose and mouth.[296] The authors found that nasal airflow was influenced by phonetic context, and that mean nasal airflow was significantly higher in singing than in speech.[297] Nasal airflow increased with pitch and loudness, particularly for the [m] and [p] consonants, while nasal airflow varied across the vowels varied depending on pitch and loudness.[298] Among the vowels, nasal airflow was highest on [ɑ] compared to [i] and [u] at all pitches levels.[299] Overall, nasal airflow on the vowels was greater at the low and comfortable dynamic levels.[300] The authors also calculated an estimate of the VPO area and found that it was significantly larger in singing than in speech, though that it "never exceeded normative values for VP adequacy."[301] Tanner et al. summarize their findings as follows:

> This investigation confirmed that trained sopranos regularly permit transnasal airflow through the VP port during classical singing. The magnitude of this flow varied by phonetic context…any amount of nasal airflow was shunted through a very small gap in the VP port…In general, the singers in the present investigation allowed nasal airflow in the

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[295] Austin, "Movement of the Velum during Speech and Singing," 217.

[296] Tanner et al., "Velopharyngeal Port Status During Classical Singing," 1313–14.

[297] Tanner et al., "Velopharyngeal Port Status During Classical Singing," 1315, 1319–20.

[298] Tanner et al., "Velopharyngeal Port Status During Classical Singing," 1316, 1320–21.

[299] Tanner et al., "Velopharyngeal Port Status During Classical Singing," 1316.

[300] Tanner et al., "Velopharyngeal Port Status During Classical Singing," 1322.

[301] Tanner et al., "Velopharyngeal Port Status During Classical Singing," 1319, 1322.

> following sequence: anticipatory flow during the vowel ([ɑ] only), maximum flow on *m*, carryover flow on *p*, and return to baseline during the following vowel.[302]

Tanner et al.'s results demonstrate that studying VPO on isolated vowels does not fully capture how singers use VPO when singing text.

Martell et al. also investigated VPO in speech and singing within the context of vowel and consonant combinations. They studied eight soprano undergraduate and graduate voice students between the ages of 21 and 31.[303] Participants spoke and sang the phrase "I will say hamper" at C_4 and C_5 and at three degrees of loudness. Intraoral and nasal pressure data was collected using the PERCI-SAR System.[304] The authors used these pressure measurements to investigate how participants coordinated VPO timing to produce the [mp] consonant cluster. They found that the velum was raised more quickly in singing than in speaking and that, in singing, the velum was raised more quickly at C_5 than at C_4.[305] These results reinforce that the dictional context of a sung phrase can influence the velum behavior.

2.5.3.4 Studies that Address the Acoustic Effects of VPO

The final two studies in this section address the acoustic effects of VPO. Sundberg et al. 2007 use a computational model to predict acoustic behavior, while Gill et al. analyze acoustic data collected from multiple participants. In Sundberg et al., models based on CT scans of the vocal tract and nasal cavity system of a single baritone participant producing the vowel [a] were created and analyzed. The results indicate that, in this model of the vowels [a], [i] and [u], VPO lowers peak SPL and widens the bandwidth of first formant of the vowel being produced. This

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[302] Tanner et al., "Velopharyngeal Port Status During Classical Singing," 1322.

[303] Martell et al., "Task-Dependent Velopharyngeal Timing in Singers," 1696.e34.

[304] Martell et al., "Task-Dependent Velopharyngeal Timing in Singers," 1696.e34.

[305] Martell et al., "Task-Dependent Velopharyngeal Timing in Singers," 1696.e39-1691.e40.

change increases the relative strength of the singer's formant, reinforcing assertions made by Titze.[306] The authors recognize that their model is based on only one participant and that:

> it seems likely that singers' differing VPO shapes reflect attempts to tune the resonance characteristics of their nasal and vocal tracts such that a desirable timbral effect is obtained. It also seems likely that the effect of a VPO will show inter-individual differences depending on the shape of the nasal resonance system, known to vary substantially between persons. In other words, the same VPO may lead to different timbral effects in different singers, even if F0 [$1f_o$] and formant frequencies are identical.[307]

This acknowledgement that morphological differences can influence the acoustic effect of VPO echoes the conclusions drawn by Troup et al. and Fowler & Morris.[308]

Gill et al. investigated the spectral effects of varying degrees of VPO using seven voice graduate students (four sopranos, one tenor, two baritones) between the ages of 27 and 39. Participants sang the vowel sequence [i-e-æ-a-o-u] on several pitches. Sopranos sang E_4, G_4, $B^b{}_5$, $D^b{}_5$ and E_5; tenor 2 sang G_3, $B^b{}_3$, $D^b{}_4$, E_4, G_4, B_4; baritone 1 sang G_2, E_3, G_3, $B^b{}_3$, $D^b{}_4$, E_4; and baritone 2 sang D_3, F_3, $A^b{}_3$, B_3, D_4). Each pitch was recorded three times under three different VPO conditions: none, slight/narrow, much/wide). Oral and nasal air flows were measured using the Glottal Enterprises DualView System to assess how successfully participants produced the intended VPO conditions. Sounds samples were captured using a head-mounted omnidirectional electret microphone.[309] Measurements of nasal-oral radiated sound level and nasal DC flow confirmed that the participants were able to appropriately vary their VPO as instructed.[310]

306 Sundberg et al., "Experimental Findings on the Nasal Tract Resonator in Singing," 127; Titze, "Nasality in Vowels," 35.

307 Sundberg et al., "Experimental Findings on the Nasal Tract Resonator in Singing," 134.

308 Troup et al., "On Velum Opening in Singing," 39; Fowler and Morris, "Comparison of Fundamental Frequency Nasalance," 744–45.

309 Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing," 347.

310 Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing," 348–50.

Acoustic analysis revealed clear differences among the three VPO conditions. Compared to the no-VPO condition, the much/wide VPO condition produced a weaker fundamental frequency, attenuated energy peaks below 1 kHz, and increased energy in the 2 – 4 kHz range.[311] Slight/narrow VPO, in contrast, did not alter the energy level of $1f_o$ or the strongest peak below 1 kHz, but still produced an increase in energy in the 2 – 4 kHz range without requiring an increase in subglottic pressure.[312] The authors conclude that the acoustic effect of the slight/narrow VPO condition "should be favorable with regard to spectral balance [and] could be regarded as advantageous for singers."[313]

Table 2.3 Studies of VPO on One Notes

Reference (Citation)	Participants	Methods	Main Finding(s) of Study
General Studies of VPO on Unspecified Vowels			
Troup et al., 1989[314]	9 professional sopranos	Participants sang an unspecified vowel on the pitches E_3, E_4, E_5, C_6, and E_6. Xeroradiographic images were collected while participants sang.	Results showed a variety of VP behavior with a general trend of fewer singers using VPO as pitch increased.
Studies that Assess VPO Using Different Vowels			
Scotto di Carlo & Autesserre, 1987[315]	6 professional singers (all voice types represented)	Participant spoke and sang on a sustained pitch the vowels [i], [a], [u], and [ɑ̃] on a low, a middle and a high pitch (exact pitches unspecified.) Xeroradiographic images were collected, as well as nasal endoscopy.	For the professional soprano, VPO observed at all pitches and for both vowels. For [ɑ̃] VPO decreased with increase in pitch. The opposite was observed for [i].

311 Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing," 350.

312 Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing," 350.

313 Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing," 351.

314 Troup et al., "On Velum Opening in Singing," 35–39.

315 Autesserre and Scotto di Carlo, "Movements of the Velum in Singing," 3–13.

McIver & R. Miller, 1995[316]	30 vocal performance majors ages 18-25 from Oberlin University (15 male, 15 female, unknown breakdown of voice types)	Participants sang three tasks on one pitch (sopranos – B^b_4, mezzo-sopranos – G_4, tenors – B^b_3, basses – F_3): (1) [i], [e], [a], [o], [u]; (2) [mi], [me], [ma], [mo], [mu]; (3) [im], [em], [am], [om], [um]. A Nasometer was used to measure F1-nasalance during the tasks.	Results show variation in F1-nasalance among the different vowels in all tasks.
Birch et al., 2002[317]	17 professional opera singers: 3 high sopranos, 3 sopranos, 2 mezzo-sopranos, 3 tenors, 2 baritones, 2 bass-baritones, 3 basses	Participants sang the words 'panta' 'pinti' and 'puntu' at 3 dynamic levels on an A major triad throughout their range. Measurements were taken by nasofiberscope (visual inspection of VPO) and Glottal Enterprises DualView System (F0-nasalance). 6 teachers of singing also judged the perceived nasality of the recorded singing examples.	Some VPO observed in most singers, but which vowels and which parts of the vocal range varied between singers. Three different types of VPO (coronal, sagittal, constricted) were observed.
Fowler & Morris, 2007[318]	36 trained female singers and 36 non-trained female participants from ages 19-51	Participants sang sustained vowels ([i], [æ], [u], [ɑ]) for 6 seconds at 3 frequency levels (25%, 50% and 75% of comfortable vocal range determined by a test at the beginning of the session.) The Glottal Enterprises DualView System was used to measure F0-nasalance and a cassette tape recorder was used to record audio samples.	For both trained and untrained participants overall, F0-nasalance decreased as pitch increased. However, variation within both groups existed.
Jayakumar et al., 2024[319]	15 female professional Carnatic singers (minimum 10 years of training)	Participants sang two sets of tasks: (1) 10s sustained on vowels [a], [i], and [u] at low (240 Hz), medium (360 Hz) and high (482 Hz) pitches; (2)	On [i] singers significantly decreased nasalance as pitch increased. Singers used significantly higher

316 McIver and Miller, "A Brief Study of Nasality in Singing."

317 Birch et al., "Velum Behavior in Professional Classic Operatic Singing."

318 Fowler and Morris, "Comparison of Fundamental Frequency Nasalance."

319 Jayakumar et al., "Nasalance, Nasal Airflow and Perceived Nasality."

	and 25 non-singers of the same age range	[pa:va], [pi:va], [pu:va] & [ma:va], [mi:va], [mu:va] with ascending pitches at low, medium and high pitches. Data collected using Glottal Enterprises DualView System (F0-nasalance), and Nasometer II (F1-nasalance). Perceived nasality judged by 5 SLPs using a visual analog scale.	nasal air flow than non-singers.
Studies that Compare VPO in Speech and Singing			
Austin, 1997[320]	4 Western classically trained professional female singers	Participants performed two tasks: (1) speak three sentences in English designed to elicit normal speech pronunciation of [n], [v], and [k]; (2) sing [a], [e], [i], [o], [u]. Each task was repeated five times in four conditions: (1) normal speech; (2) low singing range; (3) middle singing range; (4) high singing range. The pitches selected for low, middle and high were not specified. Tasks were performed with a photodetector comprised of two fiber optic wires, one inserted in the nose and positioned above the VP and one inserted in the mouth and positioned below the VP.	VP was closed more in singing that in speaking. VP was closed more in the middle and high range sung tasks.
Tanner et al., 2005[321]	10 soprano graduate students with extensive performance experience	Participants sang and spoke the nonsense words [hɑmpɑ], [himpi], and [humpu] at high, comfortable and low pitches and at loud, comfortable and soft dynamics. The PERCI–SAR System was used to measure nasal airflow, nasal pressure, and oral pressure. The devise uses tubes inserted in the nose and mouth.	*Nasal airflow is dependent on phonetic context.* Mean nasal airflow was greater in singing than in speech. Nasal airflow increased with pitch and loudness for [m] and [p] especially. Nasal airflow and sung pitch varied across the vowels. Nasal

[320] Austin, "Movement of the Velum during Speech and Singing."

[321] Tanner et al., "Velopharyngeal Port Status During Classical Singing."

			airflow was highest on [ɑ] compared to [i] and [u].
Martell et al., 2023[322]	8 soprano undergraduate and graduate students of singing age 21 – 31	Participants spoke and sang the phrase "I will say hamper" at C_4 and C_5 and at three degrees of loudness. Intraoral and nasal pressure data was collected using the PERCI-SAR System.	Velum was raised more quickly in singing than in speaking. Velum rose faster at C_5 than at C_4. Loudness had no effect on velum timing.
Studies that Address the Acoustic Effects of VPO			
Sundberg et al., 2007[323]	1 baritone	Models based on CT scans of the vocal tract and nasal cavity system of the participant executing an [a] vowel were created and analyzed.	VPO lowers the f_{R1} peak SPL and widens its bandwidth. The later may contribute to perceived nasality. VPO increases vocal track resistance.
Gill et al., 2018[324]	7 voice graduate students (4 sopranos, 1 tenor, 2 baritones) age 27 – 39	Participants sang [i-e-æ-a-o-u] on different pitches (sopranos sang E_4, G_4, $B^b{}_5$, $D^b{}_5$ and E_5; tenor sang G_3, $B^b{}_3$, $D^b{}_4$, E_4, G_4, B_4; baritone 1 G_2, E_3, G_3, $B^b{}_3$, $D^b{}_4$, E_4; baritone 2 D_3, F_3, $A^b{}_3$, B_3, D_4). Each pitch was recorded three times with three different VPO conditions (none, slight/narrow, much/wide). Oral and nasal air flows were collected using the Glottal Enterprises DualView System and sounds samples were captured using a head-mounted omnidirectional electret microphone.	When compared to none, wide VPO resulted in lower $1f_o$ SPL peak, attenuated energy peaks below 1 kHz and a boost in otherwise low levels in the 2 – 4 kHz range. Slight VPO, compared to none, did not alter highest peak below 1 kHz but did display the boost in the 2 – 4 kHz range.

322 Martell et al., "Task-Dependent Velopharyngeal Timing in Singers with Classical Training."

323 Sundberg et al., "Experimental Findings on the Nasal Tract Resonator in Singing."

324 Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing."

2.5.4 Studies of VPO on Changing Pitches

Four studies investigated VPO using tasks in which participants changed notes in one breath. Volo et al. studied two professional WC baritones who performed two tasks: (1) singing [ɑ], [e], [i], [o], [u] on an ascending and descending perfect fifth in a key of their choosing; and (2) singing the same vowels on a two-octave arpeggio also in a key of their choosing. Xeroradiographic images were collected while the participants sang and were visually inspected to assess velum behavior. In the sustained fifth task, no VPO was observed; however, VPO was observed during the arpeggio task.[325] These results suggest that VPO use may depend, in part, on the size of intervals being performed.

Yanagisawa et al. also used visual inspection to assess velum behavior during singing tasks in which participants changed notes in one breath. They studied nine professional singers (four male, five female) and two untrained male participants.[326] Participants performed two tasks: (1) a siren on "ng" sliding as high and as low as possible; (2) a siren over the same range using as many of the following vocal styles as desired: speech, falsetto, cry/sob, twang, belting, and opera. Instead of xeroradiographic imaging, the researchers used simultaneous fiberscopic and telescopic nasoendoscopy to observe vocal tract and velum behavior during the tasks.[327] Two notable findings regarding velum behavior were reported. First, during the "ng" task, VPO decreased as $1f_o$ increased, and there was no VPO present at the highest pitches. Second, the sung tasks revealed different patterns of VP closure depending on vocal style. For the falsetto and cry/sob styles, the VP closure is described as "sphincteric," whereas for the speech and opera

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325 M. Volo et al., "A Pilot Study of Nasal Aerodynamic Flow in Singing," *Quaderni del Centro di Studio per le Ricerche di Fonetica del C.N.R.* 5 (1986): 395–404.

326 Yanagisawa et al., "Supraglottic Contributions to Pitch Raising," 19.

327 Yanagisawa et al., "Supraglottic Contributions to Pitch Raising," 19–20.

styles, closure is described as "trapdoor-like."[328] These results suggest, similarly to the findings of Sundberg et al. 2007 and Birch et al. 2002, that velum behavior is adaptable and flexible and may vary depending on many factors including pitch and vocal style.[329]

The final two studies in this section used Nasometers to collect F1-nasalance data to explore VPO in sung passages with changing notes. Jennings & Kuehn studied two groups of participants: Group 1 consisted of twenty-five voice performance majors (eight sopranos, five mezzo-sopranos, six tenors, six baritones) aged 18-42, and Group 2 consisted of 21 amateur singers (eleven females, ten males) aged 18-58. Participants completed three tasks. First, they read the Zoo Passage (a passage of text without nasal consonants to assess for hypernasality) two to three times. Second, they sang 30 five note scales ascending and descending legato and in a single breath. Each vowel ([ɑ], [e], [i], [o], [u]) was sung on the scale six times: twice in each of three pitch ranges (low, mid and upper), first at *mf* and second at *p*. Third, participants repeated the second task but took a breath between each note of the scale. For sopranos and mezzo-sopranos, the pitch ranges were A_3-E_4 (low), F_4-C_5 (mid), C_5-G_5 (upper). The pitch ranges for tenors and baritones were one octave lower. A KayPENTAX Nasometer II 6400 was used to obtain F1-nasalance measurements.[330]

The results showed a variety of significant effects. No significant differences in F1-nasalance were observed between soprano/mezzo-soprano and tenor/baritone participants. However, training had a significant effect: Group 2 (amateurs) produced significantly higher

[328] Yanagisawa et al., "Supraglottic Contributions to Pitch Raising," 28.

[329] Sundberg et al., "Experimental Findings on the Nasal Tract Resonator in Singing," 134; Birch et al., "Velum Behavior in Professional Classic Operatic Singing," 70.

[330] Jennings and Kuehn, "The Effects of Frequency Range, Vowel, Dynamic Loudness Level, and Gender on Nasalance," 79–80.

overall F1-nasalance than Group 1 (voice majors).[331] Pitch changes did not significantly affect F1-nasalance, but vowel did. The vowel [i] produced significantly higher F1-nasalance than any other vowel, while [ɑ] and [e] had produced significantly higher values than [o] and [u].[332] Dynamics also significantly influenced F1-nasalance, with significantly higher values observed in *p* tasks compared to *mf* tasks.[333] Jennings & Kuehn also identified an important limitation of their data related to the bandwidth of the Nasometer. As Rothenberg mentions in his argument for the use of F0-nasalance as opposed to F1-nasalance, the upper range scale for the soprano and mezzo-soprano participants ended at G_5 (784 Hz) which is exceeds the Nasometer's bandwidth of 750 Hz.[334] As a result, the F1-nasalance data for the sopranos/mezzo-sopranos in their upper range likely contains measurement errors.[335]

The second study using F1-nasalance data was conducted by Santoni et al. They studied 20 non-trained participants (ten male, ten female) aged 18-35 who completed four tasks: (1) speaking a sentence from the non-nasal Zoo Passage; (2) speaking the nasal consonant filled sentence "Mamma made some lemon jam;" (3) speaking the first paragraph of the Rainbow Passage; and (4) singing a song with the range of F_3 – D_4 that contained both oral and nasal phonemes. Participants completed each task twice: once using a forward focus and once using a

331 Jennings and Kuehn, "The Effects of Frequency Range, Vowel, Dynamic Loudness Level, and Gender on Nasalance," 80–81.

332 Jennings and Kuehn, "The Effects of Frequency Range, Vowel, Dynamic Loudness Level, and Gender on Nasalance," 81.

333 Jennings and Kuehn, "The Effects of Frequency Range, Vowel, Dynamic Loudness Level, and Gender on Nasalance," 81.

334 Rothenberg, "A New Method for the Measurement of Nasalance"; Jennings and Kuehn, "The Effects of Frequency Range, Vowel, Dynamic Loudness Level, and Gender on Nasalance," 87.

335 Jennings and Kuehn, "The Effects of Frequency Range, Vowel, Dynamic Loudness Level, and Gender on Nasalance," 87.

backward focus. Participants were trained in the two focus conditions through demonstrations provided by one of the study's authors. A KayPENTAX Nasometer 6450 headset was used to measure F1-nasalance.[336] Two significant results emerged from the singing tasks. First, male participants displayed significantly higher overall F1-nasalance than female participants. Second, the backward focus condition resulted in significantly lower F1-nasalance for all participants.[337] These findings further contribute to the body of evidence suggesting that multiple vocal adjustments can influence VP behavior.

Table 2.4 Studies of VPO on Changing Pitches

Reference (Citation)	**Participants**	**Methods**	**Main Finding(s) of Study**
Volo et al., 1986[338]	2 professional baritones	Participants sang two tasks: [ɑ], [e], [i], [o], [u] on (1) an ascending and descending perfect fifth in a key of their choosing; (2) a two-octave arpeggio in a key of their choosing. Xeroradiographic images were collected while participants sang for visual inspection of velum behavior.	No VPO observed in sustained note changes. VPO observed in arpeggios.
Yanagisawa et al., 1991[339]	9 professional singers (4 male, 5 female) and 2 male untrained participants	Participants performed two tasks: (1) siren on "ng" as high and as low as possible; (2) siren as high and as low as possible on as many of the following styles of singing as desired: speech, falsetto, cry/sob, twang, belting, and opera. A simultaneous fiberscopic and telescopic	For the "ng" task, as $1f_o$ increased, velum elevated and closed VP in the highest notes. Different qualities of VP closure observed – "sphincteric" for falsetto and cry/sob, and "trapdoor" for speech and opera.

[336] Charlene Santoni et al., "Influence of Voice Focus Adjustments on Oral-Nasal Balance in Speech and Song," *Folia Phoniatrica et Logopaedica* 72, no. 5 (2020): 353-4, https://doi.org/10.1159/000501908.

[337] Santoni et al., "Influence of Voice Focus Adjustments on Oral-Nasal Balance in Speech and Song," 355, 357.

[338] Volo, M et al., "A Pilot Study of Nasal Aerodynamic Flow in Singing," 395–404.

[339] Yanagisawa et al., "Supraglottic Contributions to Pitch Raising," 19–30.

		velolaryngeal endoscopy was performed on the participants while they performed the tasks.	
Jennings & Kuehn, 2008[340]	*Group 1:* 25 voice performance majors (8 soprano, 5 mezzo-soprano, 6 tenor, 6 baritone) ages 18-42. *Group 2:* 21 amateur singers (11 female, 10 male) ages 18-58.	Participants performed three tasks: (1) reading the Zoo Passage (a passage of text without nasal consonants to assess for hypernasality) 2-3 times; (2) singing 3 five note scales up and down, legato and in one breath. Each vowel ([ɑ], [e], [i], [o], [u]) was sung on the scale six times, twice at in each of low, mid and upper range – the first time *mf* the second time *p*; (3) repeat the second task but take a breath between each note of the scale. For sopranos and mezzo-sopranos the pitch ranges were A_3-E_4 (low), F_4-C_5 (mid), C_5-G_5 (upper). Pitch ranges for tenors and baritones were an octave lower. A KayPENTAX Nasometer II 6400 was used to obtain F1-nasalance measurements.	No differences in F1-nasalance observed between soprano/mezzo-soprano and tenor/baritone participants. Group 2 (amateurs) used significantly more F1-nasalance overall than Group 1 (voice majors). No significant differences in F1-nasalance due to pitch change. [i] had significantly more F1-nasalance than any other vowel. [ɑ] and [e] had significantly more F1-nasalance than [o] and [u]. There was significantly more F1-nasalance in *p* tasks compared to *mf* tasks.
Santoni et al., 2019[341]	20 non-trained participants (10 male, 10 female) ages 18-35	Participants performed four tasks: (1) spoke a sentence from the non-nasal Zoo Passage; (2) spoke the nasal consonant filled sentence “Mamma made some lemon jam;” (3) spoke the first paragraph of the Rainbow Passage; (4) sang a song with the range of F_3 – D_4 that contained both oral and nasal	For the song, male participants had significantly higher F1-nasalance than female participants in the forward focus tasks. For the song, all participants significantly reduced F1-nasalance for the backward focus.

340 Jennings and Kuehn, “The Effects of Frequency Range, Vowel, Dynamic Loudness Level, and Gender on Nasalance,” 75–89.

341 Santoni et al., “Influence of Voice Focus Adjustments on Oral-Nasal Balance in Speech and Song,” 351–62.

		phonemes. Participants completed each task twice, once with forward focus and once with backward focus. The focuses were learned via demonstration by one of the study authors. A KayPENTAX Nasometer 6450 headset was used to measure F1-nasalance.	

2.5.5 Studies of the Use of VPO during Register Transitions

Three studies have specifically examined the effect of VPO during register transitions. The first two focus on the *primo passaggio* transition around $E_4 – F_4$ in tenors and baritones, while the third explores the effect of VPO on treble voices and how it might influence their register transitions. Perna 2014 studied seven professional tenors. Participants performed three tasks: (1) they sang the nonsense words [pinti], [panta] and [puntu] separately on the pitches $B^b{}_3$, F_4 and $B^b{}_4$; (2) they repeated task (1) but produced vocal fry after each word without changing the position of the vocal tract; (3) they sang a B^b major scale on [i], [a], and [u] starting on $B^b{}_3$. F1-nasalance data were collected using the Glottal Enterprises divided mask.[342] The results showed that for all but one participant, F1-nasalance increased on [a] between F_4 and G_4. This increase in F1-nasalance corresponded to a change in acoustic strategy. For the other vowels, results were less consistent but mostly followed a similar pattern. Perna concludes that "adding a slight increase in nasalance as tenors prepare to "turn over" may be a useful pedagogic tool while training tenors."[343] The author is careful to limit these conclusions to WC tenors, the population he studied.

342 Perna, "Nasalance and the Tenor Passaggio," 404–5.

343 Perna, "Nasalance and the Tenor Passaggio," 409.

Echternach et al. 2019 studied VPO use during the *primo passaggio* transition in both tenors and baritones. The participants were six tenors and two baritones all trained in the WC tradition. Participants performed two tasks on the vowel [i]: (1) singing a pitch glide from A_3 to A_4 at comfortable loudness while transitioning from modal voice to falsetto; (2) singing the same pitch glide but transitioning from modal voice to how they would perform the note on stage (SVaP).[344] F0-nasalance data were collected using the Glottal Enterprises DualView System. High-speed videoendoscopy was performed to visualize vocal fold behavior, with the camera inserted through a small hole in the DualView mask. Electroglottophic (EGG) signals were recorded using the Glottal Enterprises EG2-PCX2. The [i] vowel was selected because it provided a favorable tract configuration for observing vocal fold behavior. Audio samples were recorded using a Behringer ECM-8000 microphone.[345] Participants demonstrated significantly greater F0-nasalance in falsetto compared to the SVaP condition.[346] In the SVaP condition, individual differences were observed in whether F0-nasalance increased during the passaggio transition around F_4; however, five out of eight subjects displayed increased F0-nasalance during or above the passaggio. For these subjects, F0-nasalance corresponded with stabilization of vocal fold activity.[347] The authors infer that these results suggest that "nasalance could be used for stabilization during the male passaggio [primo passaggio] avoiding a register shift to falsetto."[348]

[344] Echternach et al., "The Effect of Nasalance on Vocal Fold Oscillation Patterns," 500.e10-500.e11.

[345] Echternach et al., "The Effect of Nasalance on Vocal Fold Oscillation Patterns," 500.10-500.11.

[346] Echternach et al., "The Effect of Nasalance on Vocal Fold Oscillation Patterns," 500.e12.

[347] Echternach et al., "The Effect of Nasalance on Vocal Fold Oscillation Patterns," 500.e13-500.e15.

[348] Echternach et al., "The Effect of Nasalance on Vocal Fold Oscillation Patterns," 500.e15.

They also note, however, that other strategies such as epilaryngeal narrowing may contribute to stabilizing the *primo passaggio* register transition, and that more study is needed.[349]

Vampola et al. 2021 is the only study in this review of literature that examines the effect of VPO during register shifts in treble voices. For their study, the authors created a computerized tomography-based finite element model using CT scans of one participant's vocal tract and nasal cavities (a female amateur singer and speech trainer). The model was used to assess the effect of VPO on acoustical parameters and vocal tract inertance for the vowels [a], [i] and [u] across the vocal range of a treble singer.[350] The model produced several inferences. First, for all three vowels, VPO raised the frequency of f_{R1}, while lowering its peak amplitude.[351] In addition, VPO improved inertance conditions for the vocal tract by decreasing the extreme negative inertance values and shortening the frequency range of negative inertance following f_{R1}.[352] Negative inertance hinders the vocal fold oscillation, whereas positive inertance facilitates it.[353] Thus, raising the frequency of f_{R1} and changing the inertance conditions of the vocal tract may aid in passaggio transitions. Specifically, VPO positioned f_{R1} for [i] and [u] within a frequency interval of positive inertance (approximately 209–391 Hz) during the *primo passaggio* transition (329–349 Hz), and positioned f_{R1} for [a] within a positive inertance frequency interval (500–610 Hz) during the *secondo passaggio* (622–698 Hz.)[354] However, the authors note,

> the female singer may prefer smoothing the register transition from lower to high pitches (at the second passaggio, at about 500 Hz) by decreasing adduction before it would

[349] Echternach et al., "The Effect of Nasalance on Vocal Fold Oscillation Patterns," 500.e14.

[350] Vampola et al., "Finite Element Modeling of the Effects of Velopharyngeal Opening," 2155–56.

[351] Vampola et al., "Finite Element Modeling of the Effects of Velopharyngeal Opening," 2157.

[352] Vampola et al., "Finite Element Modeling of the Effects of Velopharyngeal Opening," 2159.

[353] Titze, *Principles of Voice Production*, 99–102.

[354] Vampola et al., "Finite Element Modeling of the Effects of Velopharyngeal Opening," 2160.

necessarily decrease (due to the change to a lighter register with a larger open quotient). The female singer may also avoid nasalance, since it would damp [f_{R1}], and females rely on strong [f_{R1}] (tuning [f_{R1} to $1f_o$]) for loudness and projection.[355]

Overall, Vampola et al.'s findings support the idea that VPO may be one of several strategies a treble singer could employ to traverse vocal passaggi. The authors also acknowledge an important limitation: the model employed in this study did not account for changes in oral vocal tract geometry, although those changes would inevitably occur in a live singer.[356]

Table 2.5 Studies of the Use of VPO during Register Transitions

Reference (Citation)	Participants	Methods	Main Finding(s) of Study
Perna, 2014[357]	7 professional operatic tenors	Participants performed three tasks: (1) sing the nonsense words [pinti], [panta] and [puntu] separately on the pitches $B^b{}_3$, F_4 and $B^b{}_4$; (2) repeat task (1) but after each word vocal fry without changing the position of the vocal tract; (3) sing a B^b major scale on [i], [a], and [u] starting on $B^b{}_3$. F0-nasalance data were collected using the Glottal Enterprises divided mask.	For all but one participant, F1-nasalance increased on [a] between F_4 and G_4, and the increase in nasalance corresponded to a change in acoustic strategy. For the other vowels, results were less consistent but mostly followed a similar pattern.
Echternach et al., 2019[358]	8 professionally trained Western Classical singers (6 tenors, 2 baritones) ages 24-47	Participants performed two tasks on an [i] vowel: (1) sing a pitch glide from A_3 to A_4 at comfortable loudness transitioning from modal voice to falsetto; (2) sing the same pitch glide but transitioning from modal voice to how they would perform the note on	Participants demonstrated significantly more F0-nasalance in falsetto compared to SVaP. There were individual differences in whether F0-nasalance increased during the passaggio transition around F_4, but 5 out of 8 subjects

[355] Vampola et al., "Finite Element Modeling of the Effects of Velopharyngeal Openin," 2160–61.

[356] Vampola et al., "Finite Element Modeling of the Effects of Velopharyngeal Opening," 2161.

[357] Perna, "Nasalance and the Tenor Passaggio," 403–10.

[358] Echternach et al., "The Effect of Nasalance on Vocal Fold Oscillation Patterns," 500.e9-500.e16.

		stage (SVaP). F0-nasalance data was collected using the Glottal Enterprises DualView System. A high-speed videoendoscopy was performed to visualize vocal fold behavior. The camera was inserting through a small hole in the DualView mask. Electroglottophic (EGG) signals were recorded using the Glottal Enterprises EG2-PCX2. Audio samples were recorded using a Behringer ECM-8000 microphone.	displayed greater F0-nasalance during the modal to SVaP transition during the passaggio or above it. For those subjects, F0-nasalance corresponded to stabilization of vocal fold activity.
Vampola et al., 2021[359]	1 female trained amateur singer and speech trainer	A computerized tomography finite element model was created using CT scans of the participant's vocal tract and nose. The model was used to assess the effect of VPO on acoustical parameters and vocal tract reactance for the vowels [a], [i] and [u].	For all three vowels, VPO raises the first resonance of the vocal tract, but lowers its peak amplitude. VPO creates beneficial positive vocal tract inertance conditions that support vocal fold oscillation. The raised first resonances of the vocal tract create more inertive vocal tract conditions for passaggi transitions: 209-391 Hz for [i] and [u] (primo passaggio E_4-F_4 – 329-349 Hz) and 500-610 Hz for [a] (*secondo passaggio* is between D#5 and F5 – 622-698 Hz.) Authors note that other strategies may be more effective for treble singers.

[359] Vampola et al., "Finite Element Modeling of the Effects of Velopharyngeal Opening," 2154–62.

2.6 Conclusion

Registration and the strategies to achieve stylistically appropriate register transitions has been a topic of considerable discussion and debate since the first treatises on singing were published. This review of literature focuses on a small subset of diverse vocal pedagogues, their perspectives, and selected studies that have examined strategies for managing register transitions. The contents of this discussion are summarized in the two tables below (see Tables 2.6 and 2.7). The first table outlines selected ideas regarding the causes of registration events, while the second summarizes the selected strategies discussed in this review of literature for navigating those events.

Table 2.6 Summary of Causes of Registration

Reference	Proposed Cause of Registration Events
Register Events Are Caused by Laryngeal Behavior	
García, 1894[360]	The combination of membranous and/or cartilaginous glottis vibrations defines registers.
Vennard, 1967[361]	The dynamic balance of TA and CT muscle action define registers.
Sundberg, 1987[362]	Vocal fold vibratory patterns define registers.
Titze, 2000[363]	The vertical phase of vocal fold contact defines registers.
Titze, 2000[364]	The TA maximum active stress defines where in the singer's range a register event happens.
Roubeau et al., 2009[365]	There are four identifiable modes of laryngeal vibration that may or may not align with definable registers.

[360] García, *Hints on Singing*.

[361] Vennard, *SINGING*, 58–67.

[362] Sundberg, *The Science of the Singing Voice*, 54–64.

[363] Titze, *Principles of Voice Production*, 291.

[364] Titze, *Principles of Voice Production*, 300–301.

[365] Roubeau et al., "Laryngeal Vibratory Mechanisms," 425–38.

Herbst & Švec, 2014[366]	There are four distinct phonation types created by different combinations of cartilaginous adduction and membranous medialization of the vocal folds that may or may not align with definable registers.
Registration Events Are Acoustical Events Caused by the Shape of the Vocal Tract	
Lamperti, 1931[367]	The behavior of the vocal folds remains the same throughout the singing range, only changes in resonance occur.
Coffin, 1980[368]	The vowel being sung distinguishes the register, but changes in vocal tract position do affect vocal fold behavior.
Titze, 2000[369]	The resonances of the subglottal vocal tract influence the location of registration events.
D. Miller, 2008[370]	The relative frequencies of the resonances of the vocal tract and the harmonics of the radiated sound spectrum define the location of register events. Since vowels have different formant frequencies, singing different vowels will result in different resonances of the vocal tract. Thus, registration events will occur at different frequencies for different vowels.
Bozeman, 2013[371]	Different relative relationships between the frequency of vocal tract resonances and harmonics of the radiated sound spectrum create identifiable timbres such as yell timbre, whoop timbre, open timbre and close timbre.
Howell, 2025[372]	The perceived darkness or brightness of a pitch is due to the vowel-like quality of the acoustic information of the radiated sound spectrum outside of the vowel defining part of the spectrum. This quality of a tone is called absolute spectral tone color (ASTC) and remains constant for a single pitch no matter what vowel is being sung. The frequencies where ASTC changes roughly align with defined registration events.
Registration Events Are Caused by a Combination of Laryngeal Behaviors and Acoustical Events/Vocal Tract Shape	
Reid, 1968[373]	There are many combinations of TA-CT muscle activity balances that can produce the same note. The balance will affect the perceived register. Vowels also play a role in perceived register.

366 Herbst and Svec, "Adjustment of Glottal Configurations in Singing," 301–8.

367 Lamperti, *Vocal Wisdom*, 103.

368 Coffin, *Overtones of Bel Canto*, 23–26.

369 Titze, *Principles of Voice Production*, 295–96.

370 Miller, *Resonance in Singing*, 70–77.

371 Bozeman, *Practical Vocal Acoustics*, 43–57.

372 Howell, *Hearing Singing*, 130–32.

373 Reid, *The Free Voice*, 38–46.

R. Miller, 2000[374]	Laryngeal behavior, vocal tract shape, subglottic pressure and airflow ratios all play a role in perceived register. Register transition locations are prescriptive of vocal fach.
Titze, 2000[375]	Changes in spectral slope influence the perception of register transitions. These changes are a result of prephonatory glottal behavior.
Ragan, 2020[376]	Singers can vary both laryngeal behavior and resonance strategies at the same time to achieve a wide variety of sounds on the same pitch. This variation can be represented by a slide rule,
Lebowitz & Baken, 2011[377]; Flynn et al., 2018[378]	Human subject studies demonstrate a wide variety of combinations of laryngeal behaviors and acoustic strategies in MT singers.

Table 2.7 Summary of Registration Strategies

Reference	**Strategy**
No Specific Style	
Titze, 2000[379]	Combine laryngeal muscle balance choices with lung pressure.
Western Classical Singing	
Acoustic Strategies	
Coffin, 1980[380]	"Chromatic Vowel Chart for Voice Building and Tone Placing" as well as accompanying vocal exercises.
Doscher, 1994[381]	Open vowels to track the fundamental frequency of the pitch being sung but maintain a slight rounding.
R. Miller, 2000[382]	Vowel modifications using the "Vowel modification (aggiustamento)" chart and the "Vowel modification of front vowel series, central vowel series and back vowel series" chart.
Bozeman, 2013 & 2021[383]	Three different vocal tract adjustments to enter whoop timbre for WC treble singers.

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374 Miller, *Training Soprano Voices*, 25–28.

375 Titze, *Principles of Voice Production*, 84–90.

376 Ragan, *A Systematic Approach to Voice: The Art of Studio Application*, 90–95.

377 Lebowitz and Baken, "Correlates of the Belt Voice," 159–65.

378 Flynn et al., "Acoustic Comparison of Lower and Higher Belt Ranges in Professional Broadway Actresses," 410–14.

379 Titze, *Principles of Voice Production*, 233.

380 Coffin, *Overtones of Bel Canto*.

381 Doscher, *The Functional Unity of the Singing Voice*, 180–82.

382 Miller, *Training Soprano Voices*, 125.

383 Bozeman, *Practical Vocal Acoustics*, 27–29; Bozeman, *Kinesthetic Voice Pedagogy*, 49–51.

Sundberg & Skoog, 1997[384]; Echternach et al., 2010[385]; Lissemore, 2024[386]	Studies reveal various articulator adjustments used by WC treble singers traversing their *secondo passaggio* (ca. D_5 – G_5).
Integrated Strategies	
Vennard, 1967[387]; Doscher, 1994[388]; Titze, 2000[389]	Singers should use a combination of aerodynamic (breath), vocal tract and laryngeal behavior adjustment to execute appropriate register transitions.
Reid, 1968[390]; D. Miller, 2000[391]; R. Miller, 2000[392]	Singers should use a combination of aerodynamic (breath), vocal tract, acoustic strategy and sensory feedback adjustments to execute appropriate register transitions.
VPO Strategies	
Coffin, 1980[393]	Singers can use nasalized vowels as notated in the "Chromatic Vowel Chart for Voice Building and Tone Placing" and accompanying exercises to execute appropriate register transitions.
MT/CCM Singing	
Acoustic Strategies	
Bozeman, 2013[394]	Use of divergent resonator/megaphone shape to maintain a stylistically appropriate timbre.
D. Miller, 2008[395]; Lebowitz & Baken, 2011[396]; Flynn et al., 2018[397]	Studies reveal various strategies for matching resonances of the vocal tract to harmonics of the radiated sound spectrum appropriate for achieving belt timbre and the various articulator changes singers use to achieve them.

[384] Sundberg and Skoog, "Dependence of Jaw Opening on Pitch and Vowel in Singers," 301–6.

[385] Echternach et al., "Vocal Tract in Female Registers," 133–39.

[386] Lissemore, *Articulatory Activity of the Tongue, Jaw, and Lips*.

[387] Vennard, *SINGING*, 59.

[388] Doscher, *The Functional Unity of the Singing Voice*, 191–93.

[389] Titze, *Principles of Voice Production*, 303–4.

[390] Reid, *The Free Voice*, 31–33, 52, 66.

[391] Miller, *Registers in Singing*, 104–7.

[392] Miller, *Training Soprano Voices*, 28.

[393] Coffin, *Overtones of Bel Canto*.

[394] Bozeman, *Practical Vocal Acoustics*, 22.

[395] Miller, *Resonance in Singing*, 90.

[396] Lebowitz and Baken, "Correlates of the Belt Voice," 159–65.

[397] Flynn et al., "Acoustic Comparison of Lower and Higher Belt Ranges," 410–14.

Howell, 2025[398]	Use of vowel modification to achieve belt timbre.
Integrated Strategies	
Wilson, 2023[399]	Center flexibility and experimentation when exploring register transitions with MT/CCM treble singers.
Rudisch et al., 2025[400]; Aaen & Frič, 2025[401]	Studies reveal flexible approaches to MT/CCM registration strategies.
VPO Strategies	
Bozeman, 2021[402]	VPO may reduce the pressure different across the glottis in belting which would reduce vocal effort while making register transitions.

Overall, the discussion of registration reveals a variety of potential laryngeal and/or acoustical causes for perceivable differences among registers. The preponderance of evidence suggests that transitions in timbre occur throughout a singer's range and that a successful singer must develop strategies for approaching these transitions. Teachers of singing and voice science researchers have long investigated methods for navigating register transitions, and the proposed solutions are varied and occasionally contradictory. One strategy among many is the use of VPO during registration transitions. Coffin and Bozeman suggest that it may be useful in certain situations, while others argue that it is detrimental in all cases.[403]

To better understand the role of VPO in singing, researchers have conducted a limited number of studies. The results of those studies are summarized below:

Among seven studies that evaluated perceived nasality and its relationship to VPO or air flowing into the nasal passages, no significant correlations were observed. The authors used a

[398] Howell, *Hearing Singing*, 105.

[399] Wilson, "Practical Approaches In Coordinating Registration" 185–92.

[400] Rudisch et al., "Investigating Vocal Tract Configurations Across Different Belting Qualities."

[401] Aaen and Frič, "Going Beyond the Register."

[402] Bozeman, *Kinesthetic Voice Pedagogy*, 68, 107.

[403] Coffin, *Overtones of Bel Canto*, 33–47; Bozeman, *Kinesthetic Voice Pedagogy*, 68, 107; Nasal Resonance: Fact or Fiction?" *Journal of Singing* 57, no. 2 (2000): 46.

variety of methods to evaluate VPO, including blocking nasal airflow by filling nasal passages with materials, allowing participants to independently control of VPO, and measuring nasalance. All methods returned the same result: no correlation between perceived nasality and VPO. However, as discussed in the terminology section, definitions of *nasality* are not uniform. As a result, it is unclear whether the acoustic qualities evaluators used to judge perceived nasality were consistent across studies, or even among evaluators within individual studies.

Eleven studies investigated VPO on one sustained note at a time. Their results support the following general conclusions:

1. Singers vary their VPO with changes in vowel. (Jayakumar et al. 2024, Fowler & Morris 2007, Tanner et al. 2005, Birch et al. 2002, McIver & R. Miller 1995, Scotto di Carlo & Autesserre 1987)
2. VPO is influenced by phonetic context. (Martell et al., 2023, Tanner et al., 2005)
3. Variation in the morphology of a singer's oropharynx and nasal cavities may result in variation in both the use and acoustic effects of VPO. (Sundberg et al. 2007, Fowler & Morris 2007, Troup et al. 1989)
4. For most vowels, as fundamental frequency increases, VPO likely decreases. (Jayakumar et al. 2024, Martell et al. 2023, Fowler & Morris 2007, Austin 1997, Troup et al. 1989, Scotto di Carlo & Autesserre, 1987)
5. The use of VPO attenuates energy peaks below 1 kHz. (Gill et al. 2018, Sundberg et al. 2007, Vampola et al. 2021)

Four studies examined VPO during pitch changes within a single breath. They yield a range of results and provide further evidence of the complex influences of vowel, pitch, style, and morphology on VPO use in singing.

Finally, only three studies focused specifically on the role of VPO in facilitating smooth register transitions. Their findings suggest that VPO may be helpful, especially for tenors navigating their *primo passaggio* around F_4, but also indicate other strategies for achieving smooth transitions exist and may be preferred by some singers.

Across the literature on VPO, study authors call for further investigation into its role in singing. Birch et al. write, "the benefit of a well-controlled VPO for vocal timbre and its relevance to vocal pedagogy remains unclear, requiring future investigation."[404] Gill et al. simply emphasize the need for additional research noting that "despite evidence of VPO of different shapes and sizes, it is still controversial whether singers benefit from it."[405] Bozeman echoes this perspective:

> Historic bel canto pedagogy has generally maintained the goal of complete closure of the nasal port. After all, the nasal cavity is not an effective resonator, tending instead to reduce the intensity of higher partials. There may however be other benefits to slight nasalance. Future studies will have to resolve this question definitively.[406]

Important questions remain regarding the use of VPO in singing, particularly its role in register transitions. Of the three studies that examined VPO during register transitions, only one specifically investigated its effect in treble singers. That study, Vampola et al., examined only a single participant, and did so by creating a computerized model instead of collecting data from singers in a live setting. In their discussion, the authors note that studies of tenor, baritone and bass singers reveal an increase in VPO around E_4 and above, whereas two studies of treble singers (Austin and Tanner et al.) observed decreases in VPO as pitch increases. Despite this contrast, Vampola et al. found evidence suggesting a possible benefit of VPO during the treble

[404] Birch et al., "Velum Behavior in Professional Classic Operatic Singing," 70.

[405] Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing," 346.

[406] Bozeman, *Kinesthetic Voice Pedagogy*, 68.

secondo passaggio around E_5. They write, "this discrepancy in findings between the present study and the previous ones needs to be studied further."[407] Later, they add that "a further…study is warranted to investigate the effects of VPO on stabilizing vocal fold vibration in pitch glides."[408]

The study conducted by the present author and the Berton Coffin Voice Lab will provide a second investigation of VPO during register transitions in WC treble singers. It will focus on the *secondo passaggio* transition using a pitch glide from C_5 to G_5 and will use live participants. This design allows for investigation into whether the potential benefits of VPO predicted by Vampola et al. are utilized by treble singers or whether singers employ alternative strategies.

The current study will assess VPO by collecting F0-nasalance data using the Glottal Enterprises DualView System. The DualView system was selected because of its previous use by Birch et al. and Gill et al. for treble singers.[409] As Rothenberg as well as Jennings & Keuhn note, collecting F1-nasalance data using a Nasometer is likely to produce errors for frequencies above 750 Hz; therefore, that method would not be suitable for this study.[410]

This study was conducted in tandem with a study by Dr. Nicholas Perna which will collect data from MT treble singers performing a pitch glide from $A^b{}_4$ to $E^b{}_5$. Preliminary data from that study will be presented in this document with permission. Leborgne & Rosenberg note the need for further research on VPO in MT singers, writing:

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407 Vampola et al., "Finite Element Modeling of the Effects of Velopharyngeal Opening," 2160.

408 Vampola et al., "Finite Element Modeling of the Effects of Velopharyngeal Opening," 2161.

409 Birch et al., "Velum Behavior in Professional Classic Operatic Singing," 62; Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing," 347.

410 Rothenberg, "A New Method for the Measurement of Nasalance"; Jennings and Kuehn, "The Effects of Frequency Range, Vowel, Dynamic Loudness Level, and Gender on Nasalance," 87.

> Because of the limited data on nasalance scores, further research on normative ranges for both classical singers and belters needs to be completed in order to determine if belters display a higher degree of nasality in singing than their classical counterparts,[411]

Yanagisawa et al. is the only existing study that examines VPO in MT singing.[412] Therefore, additional studies of VPO in MT singers are urgently needed. By creating a link between a study of WC and MT trebles singers using the same equipment and similar tasks, useful comparisons can be made between the two singing styles.

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[411] LeBorgne and Rosenberg, *The Vocal Athlete*, 399.

[412] Yanagisawa et al. "Supraglottic Contributions to Pitch Raising," 19-30.

Chapter 3: Method

3.1 Institutional Review Board Approval

This human subject study was conducted with approval from the IRB of the University of Colorado Boulder (Protocol Number 21-0588.) It was conducted in parallel with another CU Boulder approved study (Protocol Number 24-0656) that shares the same methods but focusses on MT singers. Data collection for Protocol Number 21-0588 is complete, while data collection for Protocol Number 24-0656 is ongoing as a part of Dr. Nicholas Perna's Van L. Lawrence Fellowship. See Appendix 1 for IRB approval letters.

3.2 Participants

Study participants were 21 soprano and mezzo-soprano undergraduate or graduate vocal majors from the CU Boulder between the ages of 18 and 35 studying WC, MT and/or CCM singing. More detailed information about the participants is available in Table 3.1.

Table 3.1 Participant Survey Results

Subject Number	Western Classical Task	Musical Theater Task	Voice Type	Style Most Often Performed	Years of Training
S01	Yes	Yes	Soprano	Classical/Opera	4-6
S02	Yes	No	Soprano	Classical/Opera	>6
S03	Yes	Yes	Mezzo-soprano	Musical Theater	>6
S04	Yes	No	Mezzo-soprano	Classical/Opera	>6
S05	Yes	No	Soprano	Classical/Opera	>6
S06	Yes	Yes	Soprano	Classical/Opera	>6
S07	No	Yes	Mezzo-soprano	Musical Theater	4-6

S08	Yes	Yes	Mezzo-soprano	Musical Theater	4-6
S09	Yes	Yes	Soprano	Classical/Opera	>6
S10	Yes	Yes	Mezzo-soprano	Musical Theater	>6
S11	Yes	Yes	Soprano	Classical/Opera	>6
S12	Yes	Yes	Soprano	Classical/Opera	>6
S13	Yes	Yes	Mezzo-soprano	Musical Theater	>6
S14	Yes	Yes	Mezzo-soprano	Classical/Opera	4-6
S15	Yes	Yes	Soprano	Classical/Opera	>6
S16	Yes	No	Soprano	Classical/Opera	4-6
S17	No	Yes	Mezzo-soprano	Musical Theater	>6
S18	Yes	No	Mezzo-soprano	Classical/Opera	4-6
S19	Yes	Yes	Soprano	Musical Theater	4-6
S20	Yes	Yes	Mezzo-soprano	Classical/Opera	>6
S21	Yes	No	Soprano	Classical/Opera	1-3

3.3 Experimental Hardware

Two different data collection set ups were used during the experimental protocol. The first, depicted in Figure 3.1, was used to collect audio and electroglottograph signals simultaneously. Audio signals were recorded in Audacity (Muse Group, Limassol, Cyprus) using an omnidirectional measurement microphone (Earthworks M30; Earthworks, Milford, NH) routed through an audio interface (Focusrite Clarett 4Pre, Focusrite Audio Engineering Ltd., High Wycombe, United Kingdom) to a MacBook Air. Electroglottographic (EGG) signals (EG2-PCX2; Glottal Enterprises, Syracuse, NY) were recorded in Audacity and routed through the same Focusrite Clarett 4Pre audio interface. EGG signals were routed through the right channel and audio signals through the left channel.

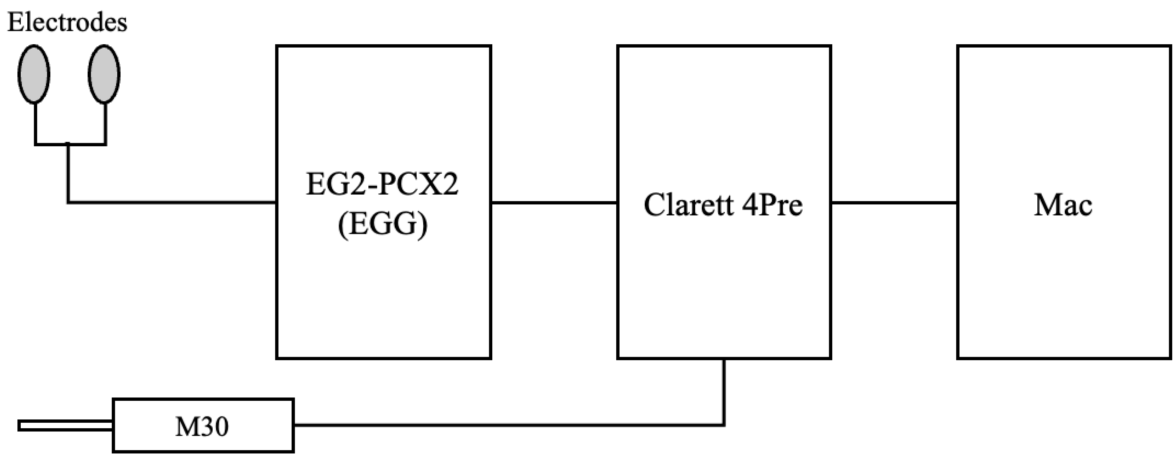


Figure 3.1 Equipment set up for the collection of audio and EGG data

The second set up, depicted in Figure 3.2, was used to collected nasal and oral air flows simultaneously with electroglottographic signals. The electroglottographic signals were collected

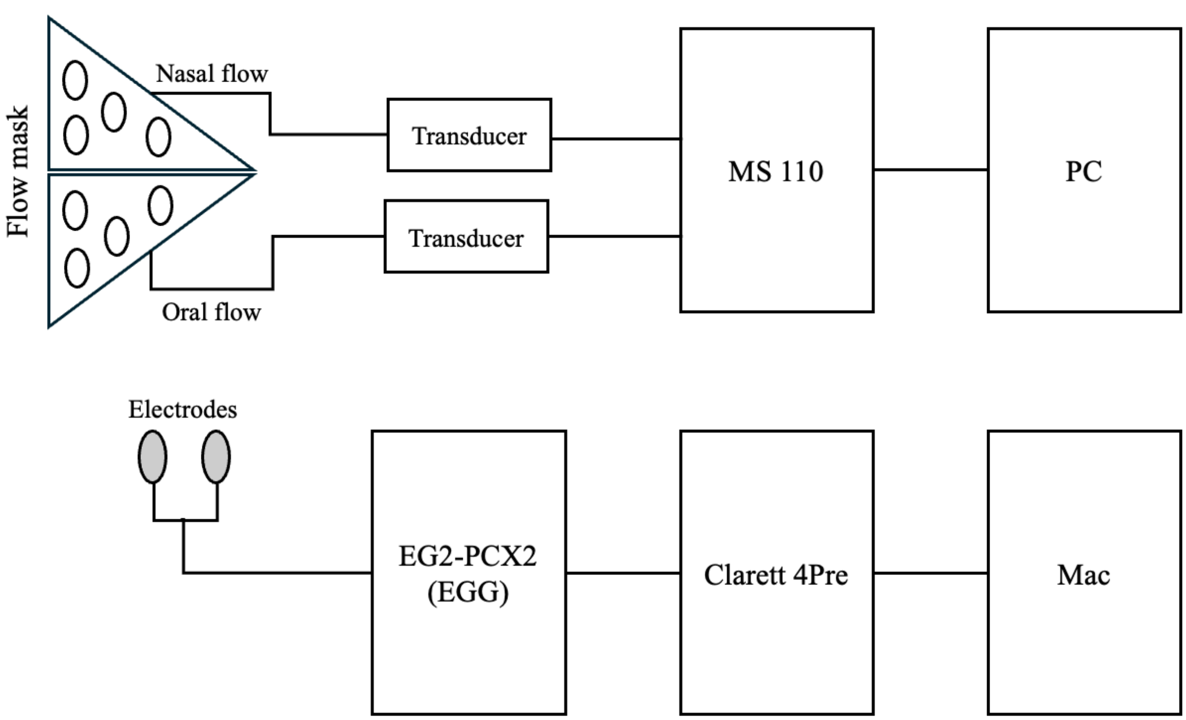


Figure 3.2 Experimental set up for the collection of oral and nasal airflow and EGG data.

with the same process as the first set up. Nasal and oral air flows were recorded using a mask with a plastic divider on the upper lip to separate the nasal and oral flows (OroNasal 2-Chamber CV Teen-Adult Mask with Screen Rings; Glottal Enterprises, Syracuse, NY.) The flows were transferred through a pressure transducer (PT-2E Pressure Transducer; Glottal Enterprises, Syracuse, NY) which was transferred through a transducer and analog data computer interface (MS-110; Glottal Enterprises, Syracuse, NY) to a PC computer. These set ups are similar to Gill et al. 2018.[413]

3.4 Experimental Protocol

Before the protocol, informed consent was obtained from participants via a paper or electronic consent form. Participants completed a brief questionnaire. Questions are included in Table 3.2, also see Appendix 2.

Table 3.2 Participant Questionnaire

Questions
What is your voice type?
What type of singing do you perform most often? Options: Classical/Opera, Musical Theater, CCM (Pop, Rock, R&B, etc.), Other
What other types of singing do you perform?
Number of years of singing instruction Options: <1, 1-3, 4-6, >6

The participants were asked a randomizing question to determine whether they would perform the audio or air flow collection first. Participants were instructed about the vocal task. The task required participants to sing an ascending [a] vowel pitch glide from C_5 to G_5 for the Western Classical task. If they performed the Musical Theater task, they would sing an ascending [a] vowel pitch glide from $A^b{}_4$ to $E^b{}_5$ or A_4 to E_5. Then electrode gel (Spectra 360 Electrode Gel;

[413] Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing," 347.

Parker Laboratories, Inc., Fairfield, NJ) was applied to the EGG electrodes and the participants were instructed on how to position the EGG electrodes on their own neck. For the airflow data, participants were instructed on how to position the divided mask and then asked to perform to the vocal task to set appropriate gain levels. After the gain levels were determined, calibration was performed and then the task was recorded three times. If they were performing both the Western Classical and Musical Theater tasks, then each task was recorded three times for a total of six times. For the audio data, participants were given a 15 cm ruler and instructed to position themselves 12 cm from the microphone and perpendicular to it. Then each task was recorded three times for a total of three or six times. For a detailed protocol process, see Appendix 3.

3.5 Data Analysis Protocol

Three types of data were collected during this protocol: (1) nasal and oral airflow data; (2) acoustic signal data; (3) EGG signal data. The original files were separated into low and high pitch samples. All data was then analyzed with Praat (Paul Boersma & David Weenink, Amsterdam, The Netherlands,) and the Praat scripts (Audio script Boulder.praat; EML Nasalance airflow cal script v 3.praat, EML EGG Tools v1_06.praat) used to process the data were coded by Dr. Ian Howell (Embodied Music Lab, Ann Arbor, Michigan.) During the Praat analysis of the EGG signals, the decision was made to exclude that data from the present study due to insufficient signal in many of the participants. This decision to exclude EGG results is like Gill et al.[414]

For the statistical analysis, three categories of data were considered: F0-nasalance (%,) nasal DC airflow (L/s,) and the difference between the sound pressure level (SPL) of the

[414] Gill et al., “Spectrum Effects of a Velopharyngeal Opening in Singing,” 346-351.

fundamental minus the SPL of the second harmonic measured in dB ($1f_o$-$2f_o$ or H1-H2.) Each subject had data from three trials for each category, and averages of the three trials were calculated before statistical analyses were performed. Using RStudio (Posit PBC, Boston, Massachusetts), paired t-tests were used to compare the mean values for each data category of the lower note to that of the higher note. Effect size was analyzed using Cohen's d.

Four study personnel also used a five-point Likert scale to rate the MT task audio recordings based on how well they represented a contemporary MT sound. See Appendix 4 for expert listener survey.

Chapter 4: Results

4.1 Acoustic Results

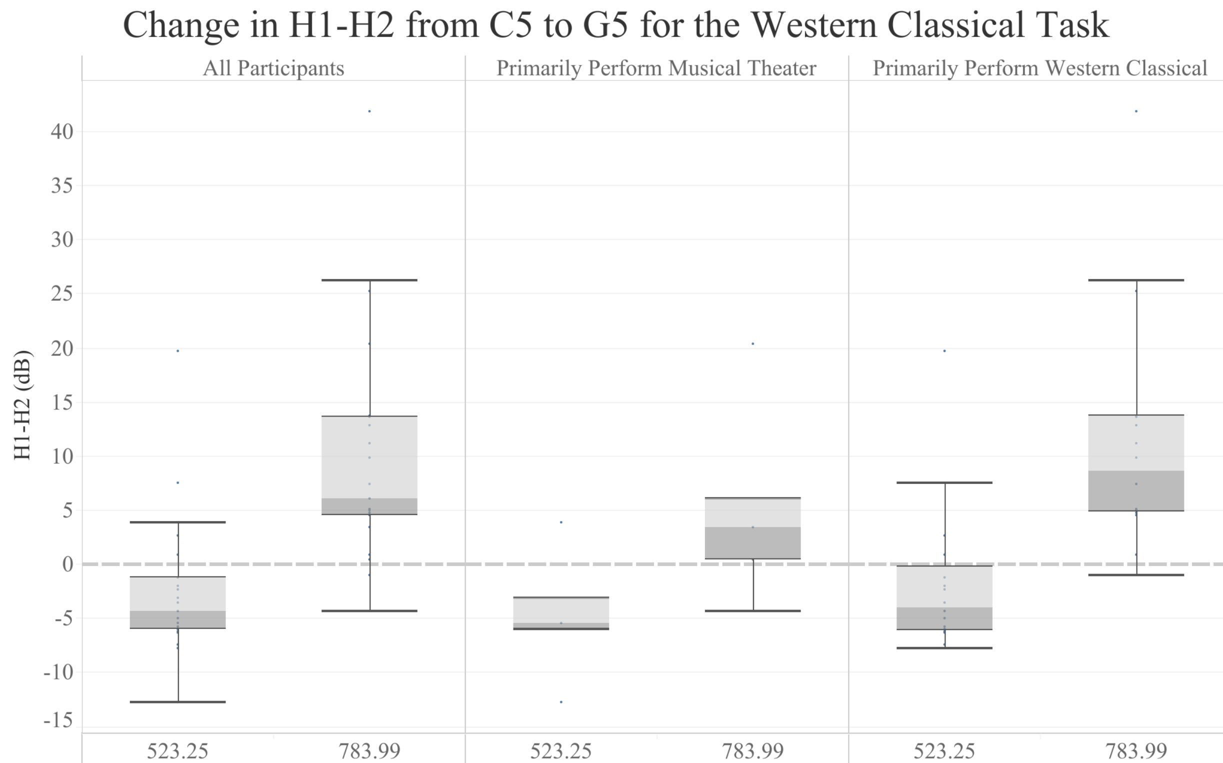
4.1.1 Western Classical Task Acoustic Results

19 participants completed the classical acoustics task. Of those participants, 14 reported in the survey that they mostly perform WC vocal music, while 5 reported performing mostly MT vocal music. All groups show similar results: H1-H2 ($1f_o$-$2f_o$) is significantly higher for the high pitch (C_5) when compared to the low pitch (G_5) (p-value < 0.05.) H1-H2 for the low pitch is negative, or, in other words, the second harmonic has a higher SPL than the fundamental. For the high pitch H1-H2 was positive, so the fundamental has a higher SPL than the second harmonic. The numerical data is displayed in Table 4.1 and the graphical results are displayed in Figure 4.1.

Table 4.1 H1-H2 Numerical Results

	Western Classical Task			Musical Theater Task		
	All Participants	Primarily Perform WC	Primarily Perform MT	All Participants	Primarily Perform MT	Primarily Perform WC
Mean H1-H2 low pitch	-1.90	-0.92	-4.66	-8.31	-7.46	-8.80
Mean H1-H2 high pitch	11.00	13.06	5.21	1.92	3.59	5.19
Standard deviation low pitch	6.94	7.19	5.99	3.35	2.87	4.14
Standard deviation high pitch	11.01	11.02	9.30	15.01	16.72	12.13
p-value	7.45e-5*	0.0011*	0.0098*	0.020*	0.15	0.032*
Cohen's d	1.17	1.12	2.07	0.63	0.62	0.94

(*) denotes a statistically significant result.



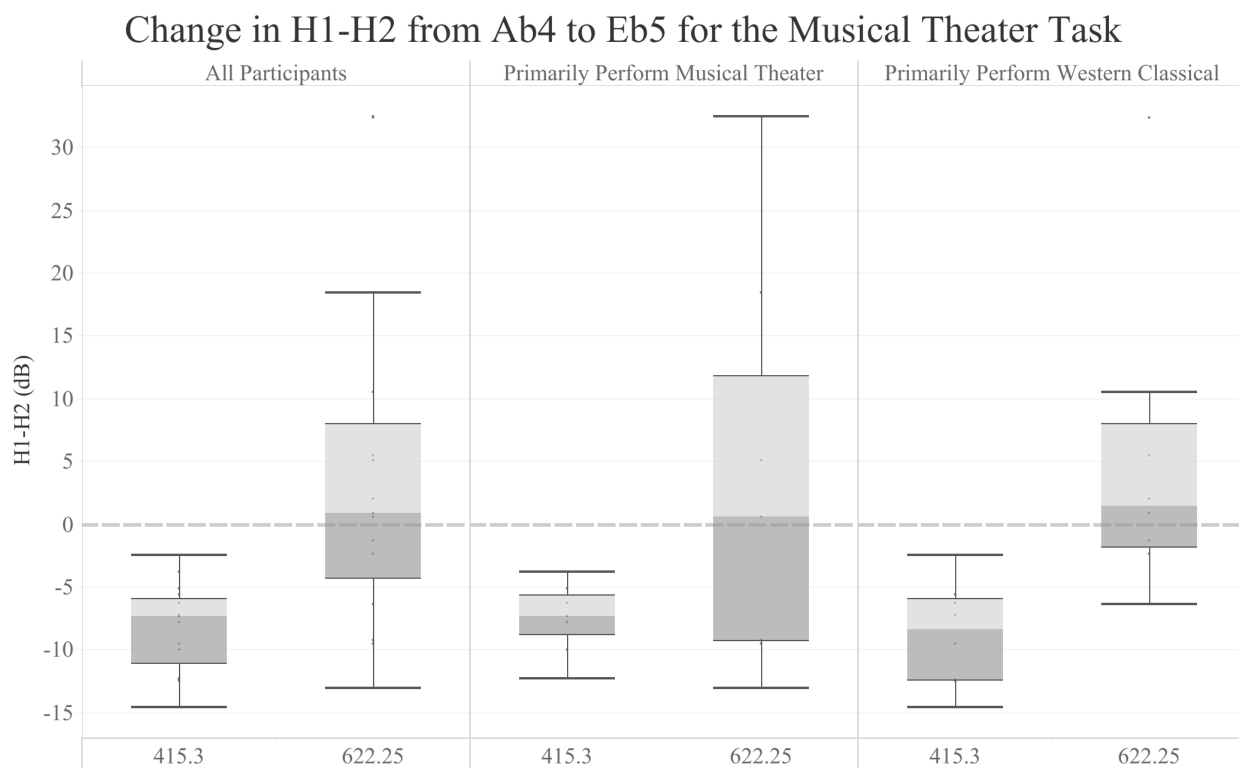
H1-H2 (dB) for each Frequency (Hz) broken down by participant category for the Western Classical task.

Figure 4.1 The box and whisker plot shows the H1-H2 results for the WC task. All trends are statistically significant (p-value < 0.05.)

The effect size of the change in pitch on acoustic strategy is large for all participants (1.17), those that mostly perform WC (1.12) and those who mostly perform MT (2.07.) The effect size is largest for participants that mostly perform MT.

4.1.2 Musical Theater Task Acoustic Results

15 participants completed the MT acoustics task. 7 reported mostly performing MT vocal music and 8 reported mostly performing WC vocal music. Numerical results data are displayed in Table 4.1. All three groups displayed a similar trend: H1-H2 was negative on the low pitch ($A^b{}_4$) and positive for the high pitch ($E^b{}_4$.) The trends were statistically significant for all participants and for the participants who reported mostly performing WC music (p-value < 0.05.) The trend was not statistically significant for the participants who reported mostly performing MT (p-value = 0.15.) Graphical results are displayed in Figure 4.2.



H1-H2 (dB) for each Frequency (Hz) broken down by participant category for the Musical Theater task.

Figure 4.2 The box and whisker plot shows the H1-H2 results for the MT task. The trends for "All Participants" and "Primarily Perform WC" are statistically significant (p-value < 0.05.) The trend for "Primarily Perform MT" is not statistically significant (p-value > 0.05.)

The effect size is moderate for all participants (0.63) and those who mostly perform MT music (0.62.) The effect size is large for participants who mostly perform WC music (0.94.)

4.2 Considerations for Interpreting F0-Nasalance and Nasal DC Airflow Results

Data was collected and analyzed using methodology obtained from Birch et al. 2002, Gill et al. 2018, and Echternach et al. 2019.[415] After data collection and analysis were complete, communications with Glottal Enterprises revealed an undocumented limitation of the OroNasal 2-Chamber CV Mask used to collect the data. The mask relies on a 50 Hz lowpass filter to remove the AC acoustic flow component from the DC airflow component. For $1f_o$ values above

[415] Birch et al., "Velum Behavior in Professional Classic Operatic Singing," 61-71; Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing." 346-351; Echternach et al., "The Effect of Nasalance on Vocal Fold Oscillation Patterns," 500.e9-500.e16.

400 Hz, singers produce a stronger glottal flow pulse which likely creates a large AC acoustic flow component relative to the DC airflow component. As a result, the low pass filter is no longer able to remove the AC acoustic flow component and, instead, reports the AC flow with the DC flow as an artificially large DC flow. This limitation of the mask likely affects the oral channel and not the nasal channel because, due to the VP being at least partially closed, the oral channel experiences larger acoustic airflow oscillations than the nasal channel. Since the F0-nasalance is calculated by the equation,

$$Nasalance(\%) = \frac{Nasal\ DC\ flow}{Oral\ DC\ flow + Nasal\ DC\ flow} \times 100$$

an artificially high oral DC flow would result in an artificially low F0-nasalance. Thus, the nasal DC airflow results will be more accurate than the F0-nasalance results.[416]

4.3 F0-Nasalance Results

4.3.1 Western Classical Task F0-Nasalance Results

19 participants completed the F0-nasalance classical task at the same time as they completed the acoustics task: 14 mostly perform WC vocal music and 5 mostly perform MT vocal music. One participant who primarily performs MT (S03) was excluded as an outlier for this task. All participants and those who primarily perform WC show similar results: F0-nasalance significantly decreases from the low pitch (C_5) to the high pitch (G_5) (p-values < 0.05.) For the 4 participants who mostly perform MT, a decrease in F0-nasalance was observed, but it is not statistically significant (p-value > 0.05.) Numerical results can be found in Table 4.2.

Table 4.2 F0-Nasalance Numerical Results

	Western Classical Task	Musical Theater Task

[416] "Roy Thompson, email message to Berton Coffin Lab personnel, March 14 & 20, 2026."

	All Participants	Primarily Perform WC	Primarily Perform MT	All Participants	Primarily Perform MT	Primarily Perform WC
Mean F0-nasalance low pitch (%)	0.20	0.18	0.28	0.23	0.27	0.18
Mean F0-nasalance high pitch (%)	0.043	0.038	0.060	0.20	0.26	0.14
Standard deviation low pitch	0.13	0.12	0.087	0.15	0.20	0.082
Standard deviation high pitch	0.046	0.047	0.020	0.094	0.069	0.076
p-value	4.46e-6*	6.70e-5*	0.069	0.44	0.89	0.21
Cohen's d	1.46	1.54	1.39	0.22	0.071	0.54

(*) denotes a statistically significant result.

The effect size is large for all groups (1.46 for all participants, 1.54 for those who mostly perform WC singing, and 1.39 for those who mostly perform MT singing.) The effect size is largest for the singers who mostly perform WC singing. Graphical results displayed in Figure 4.3.

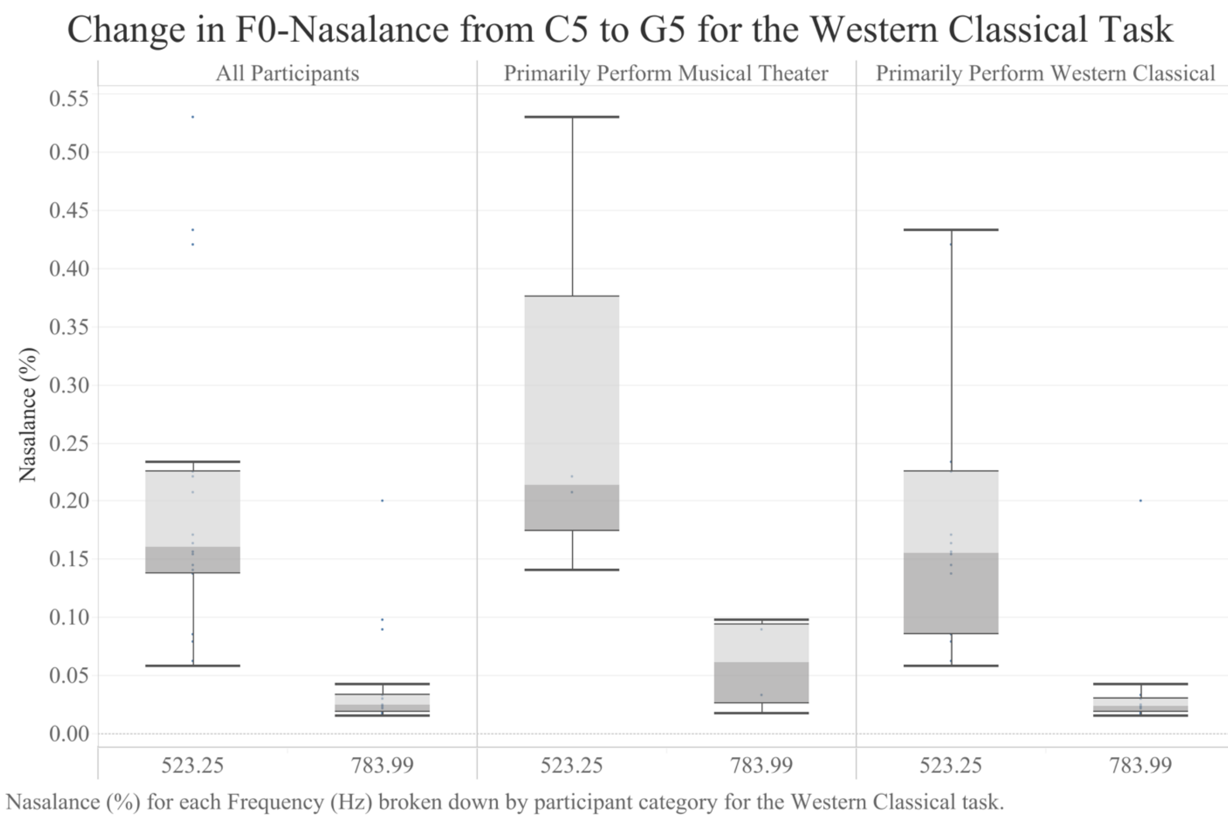
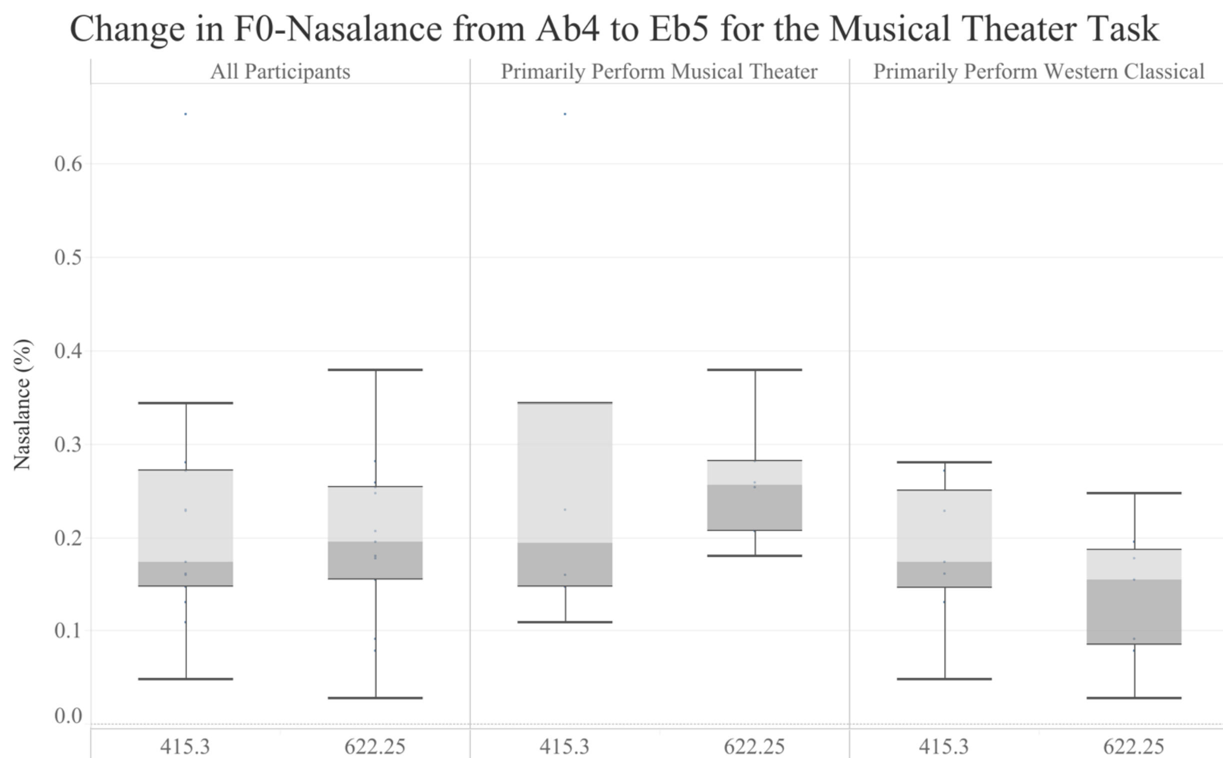


Figure 4.3 The box and whisker plot shows the F0-nasalance results for the WC task. The trends for "All Participants" and "Primarily Perform WC" are statistically significant (p-values < 0.05.) The trend for "Primarily Perform MT" is not statistically significant (p-value > 0.05.)

4.3.2 Musical Theater Task F0-Nasalance Results

15 participants (7 mostly perform MT, 8 mostly perform WC) completed the MT F0-nasalance task at the same time as completed the MT acoustics task. Two participants' data (S17 and S20) were excluded as outliers. S17 primarily performs MT, and S20 primarily performs WC. For all the groups there is no significant change in F0-nasalance between the two pitches (p-value > 0.05.) Effect size is small for all participants (0.22) and those who mostly perform MT

(0.071.) The effect size is medium for those who mostly perform WC (0.54.) Graphical results displayed in Figure 4.4 and numerical results in Table 4.2.



Nasalance (%) for each Frequency (Hz) broken down by participant category for the Musical Theater task.

Figure 4.4 The box and whisker plot shows the F0-nasalance results for the MT task. All trends are not statistically significant (p-values > 0.05.)

4.4 Nasal DC Airflow Results

4.4.1 Western Classical Task Nasal DC Airflow Results

19 subjects completed the WC task. The same participant (S03) was excluded as an outlier for the nasal DC flow analysis. All the groups showed a significant decrease in nasal DC flow from the low pitch (C_5) to the high pitch (G_5) (p-values < 0.05.) Numerical results can be found in Table 4.3.

Table 4.3 Nasal DC Airflow Numerical Results

	Classical Task			Musical Theater Task		
	All Participants	Primarily Perform WC	Primarily Perform MT	All Participants	Primarily Perform MT	Primarily Perform WC
Mean nasal DC airflow low pitch (L/s)	0.16	0.17	0.13	0.13	0.14	0.13
Mean nasal DC airflow high pitch (L/s)	0.072	0.075	0.061	0.13	0.15	0.11
Standard deviation low pitch	0.084	0.094	0.028	0.058	0.038	0.074
Standard deviation high pitch	0.039	0.041	0.032	0.091	0.085	0.10
p-value	0.00056*	0.0040*	0.032*	0.87	0.73	0.62
Cohen's d	1.00	0.93	1.90	0.047	0.15	0.20

(*) denotes a statistically significant result.

The effect of changing notes from the low to high pitch on nasal DC flow was large for all groups (1.00 for all participants, 0.93 for primarily WC, and 1.90 for primarily MT.) It was largest for the participants who mostly perform MT. Graphical results are displayed in Figure 4.5.

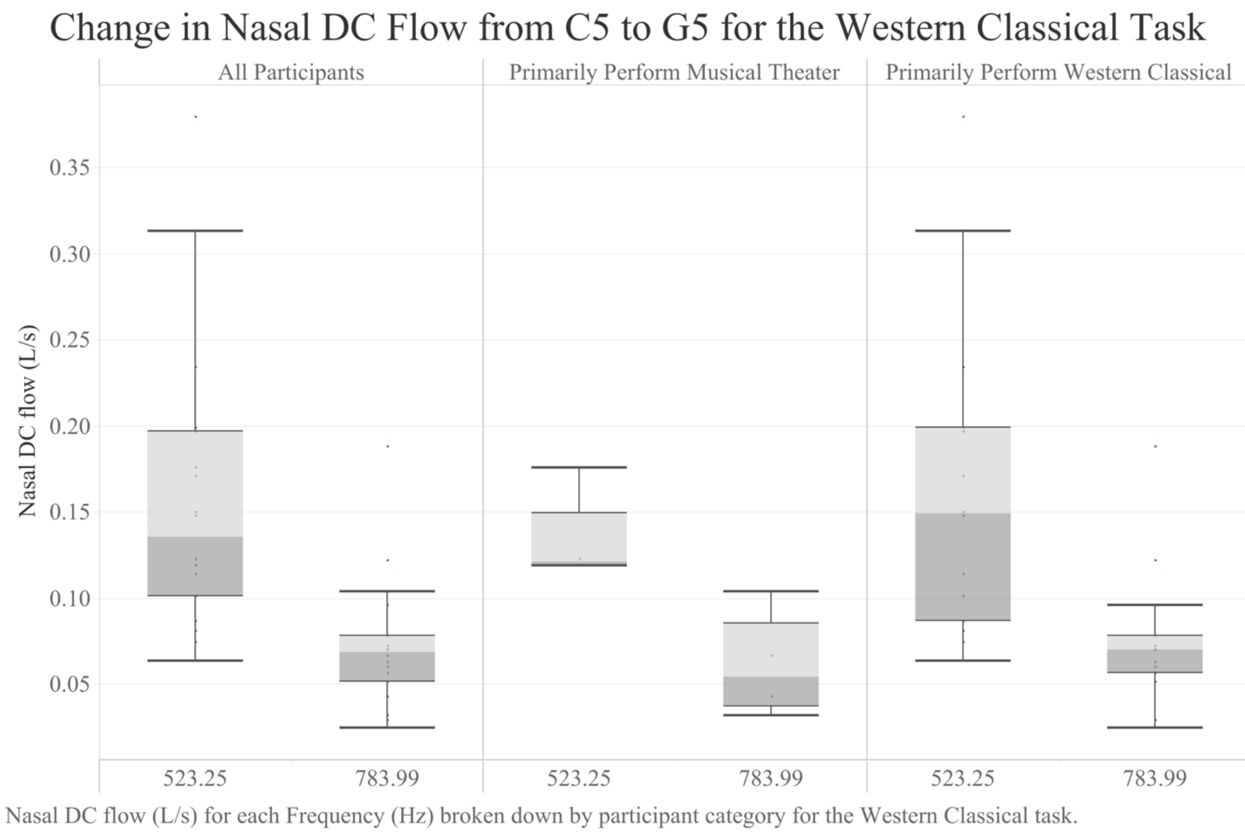


Figure 4.5 The box and whisker plot shows the nasal DC flow results for the WC task. All trends are statistically significant (p-values < 0.05.)

4.4.4 Musical Theater Task Nasal DC Airflow Results

Of the 15 participants who completed the MT task, the same two (S17 and S20) were excluded as outliers for the nasal DC flow analysis. No group showed a significant change in nasal DC flow from the low (A^{b}_{4}) to the high (E^{b}_{5}) pitch (p-values > 0.05.) Numerical results can be found in Table 4.3. The effect size of changing pitch on nasal DC flow is small for all groups (0.047 for all participants, 0.15 for primarily MT, and 0.20 for primarily WC.) Graphical results displayed in Figure 4.6 and numerical results in Table 4.3.

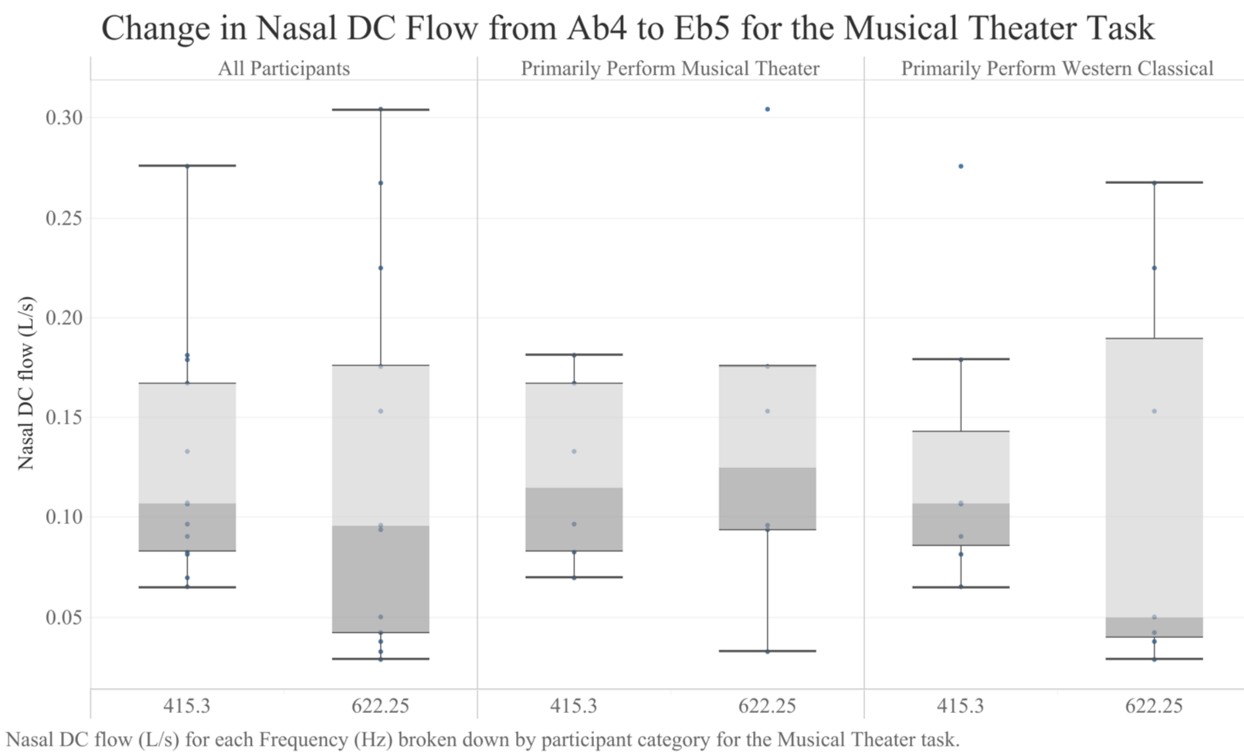


Figure 4.6 The box and whisker plot shows the nasal DC flow results for the MT task. All trends are not statistically significant (p-values > 0.05.)

Chapter 5: Discussion

5.1 Sample Size

This study examined 19 participants for the WC task and 15 for the MT task. It is relevant to note that of the studies on which this study's methodology was built, only one, Birch et al. had a similar sample size (n = 17.)[417] Gill et al. (n = 7) and Echternach et al. (n = 8) had smaller samples sizes.[418] However, Birch et al. and Gill et al. studied treble voices along with non-trebles, so their sample sizes for treble voices were smaller than this study's (n = 4 for Gill et al., n = 6 for Birch et al.)[419] Thus, the current study represents the largest study of this kind on treble voices.

5.2 Acoustic Findings

Across the MT and WC tasks, four acoustics strategies are observed. The spectrogram images of these strategies are displayed in Figure 5.1. Strategy 1 is labeled "Transitioning to Whoop Timbre" after Bozeman's terms.[420] For this strategy singers demonstrated a negative H1-H2 for the low pitch and a positive H1-H2 for the high pitch. In other words, $2f_o$ had a higher SPL than the fundamental for the low pitch and that order is reversed for the high pitch. D. Miller describes this strategy as the important acoustic register shift in WC treble voices from middle to upper voice and notes that it happens on different pitches for different vowels.[421]

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[417] Birch et al., "Velum Behavior in Professional Classic Operatic Singing," 62.

[418] Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing," 347; Echternach et al., "The Effect of Nasalance on Vocal Fold Oscillation Patterns," 500.e10-500.e11.

[419] Birch et al., "Velum Behavior in Professional Classic Operatic Singing," 62; Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing," 347.

[420] Bozeman, *Practical Vocal Acoustics*, 13-23.

[421] Miller, *Resonance in Singing*, 70, 77.

Bozeman discusses this strategy in *Practical Vocal Acoustics* suggesting that treble singers can maintain intensity through the middle voice by clustering f_{R1} and f_{R2} to boost $2f_o$, and then switching to f_{R1} tracking $1f_o$ (whoop timbre) once the pitch rises above the first formant of the vowel being sung.[422] For the sung /a/ vowel, the first formant is predicted to occur between B_4 and G_5 (see Figure 2.6.) Therefore, we hypothesized that participants, especially for the WC task, would employ this well-documented strategy.

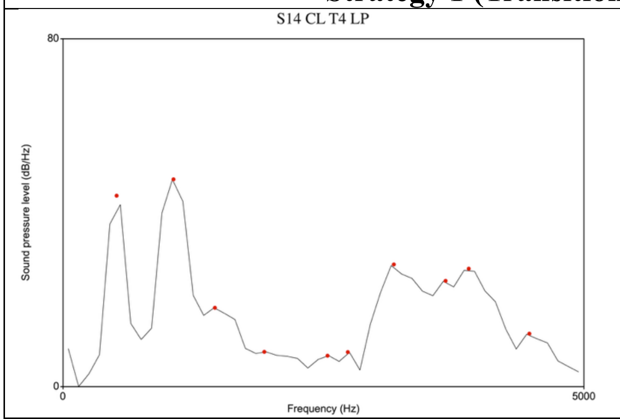
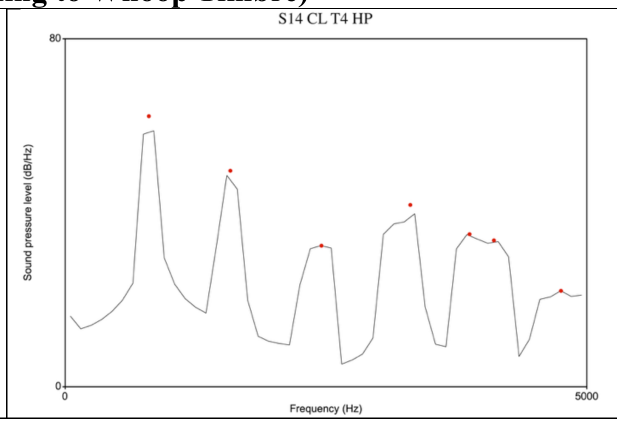
Strategy 2 or "Whoop Timbre Only," displays a positive H1-H2 value or fundamental frequency dominance on both pitches. Bozeman explains that switching to f_{R1} tracking $1f_o$ before $1f_o$ reaches F_1 for the vowel being performed can result in a loss of acoustic power that presents a challenge for vocal projection.[423] The low note for the WC task (C_5) has a fundamental frequency that is likely below F_1 for most /a/ vowels, so it seems that Strategy 2 would not be an optimal acoustic strategy for WC singing. However, switching from one acoustic strategy to another smoothly is a challenge as the many treatises, books and articles on the topic of training registration can attest. Since the study participants are university students, it is not inconceivable that they are still developing the technical skills required to optimize acoustic power across their range, so this author hypothesized that the "Whoop Timbre Only" strategy might be utilized for the WC Task by some participants.

Strategy 3 is called "Quasi-Mix to Belt" and Strategy 4 is called "Belt to Quasi-Mix." Several studies of MT belters note that some singers use an f_{R1} tracking $2f_o$ to create a

[422] Bozeman, *Practical Vocal Acoustics*, 51-57.

[423] Bozeman, *Practical Vocal Acoustics*, 51-57.

recognizable belt sound.[424] For Strategy 3 H1-H2 is negative for both pitches, but more negative for the higher pitch reflecting either a decrease in the SPL of the fundamental or an increase in SPL for the second harmonic. This might also be described as a mix-like registration transitioning to belt. Strategy 4 shows the opposite pattern: H1-H2 is more negative on the low pitch and less negative on the high pitch reflecting either an increase in SPL for $1f_o$ or a decrease in SPL for $2f_o$. This is the opposite of Strategy 3, so it likely represents belt transitioning to quasi-mix. Since the f_{R1}:$2f_o$ resonance tracking strategy is associated with belting by several authors, this author hypothesized that either Strategy 3 or 4 would be the most prevalent for the MT task.

<table>
<tr><td>Low Pitch</td><td>High Pitch</td></tr>
<tr><td colspan="2">Strategy 1 (Transitioning to Whoop Timbre)</td></tr>
<tr><td>
</td><td>
</td></tr>
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<table>
<tr><td colspan="2">Strategy 2 (Whoop Timbre Only)</td></tr>
</table>

[424] Miller, *Resonance in Singing*, 88; Lebowitz and Baken, "Correlates of the Belt Voice," 161-165; Flynn et al., "Acoustic Comparison of Lower and Higher Belt Ranges in Professional Broadway Actresses," 411-414; Howell *Hearing Singing*, 163-169.

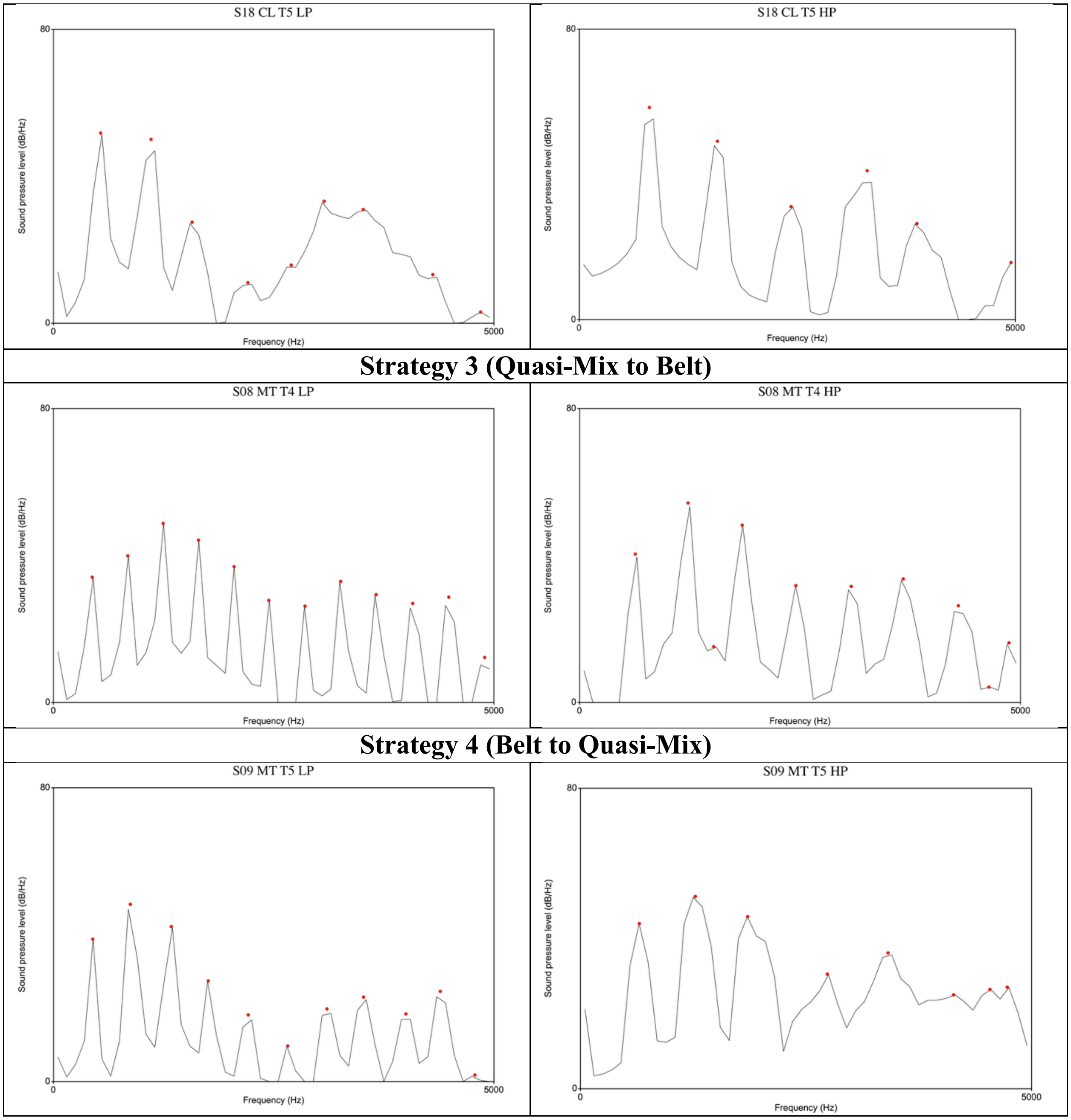

Figure 5.1 Acoustic strategies used by study participants.

5.2.1 WC Acoustic Findings

For the WC Task, 14 of the 19 participants who completed the task utilized Strategy 1 (Transitioning to Whoop Timbre,) 4 participants used Strategy 2 (Whoop Timbre Only,) and 1 participant used Strategy 4 (Belt to Quasi-Mix.) The breakdown by style primarily performed is displayed in Table 5.1.

Table 5.1 Summary of Western Classical Task Acoustic Strategies

Style Primarily Performed	**Strategy 1 (Transitioning to Whoop Timbre)**	**Strategy 2 (Whoop Timbre Only)**	**Strategy 4 (Belt to** Quasi-Mix**)**
WC	11	3	0
MT	3	1	1

The average of all participants also reflects the preference for the "Transitioning to Whoop" strategy (H1-H2$_{\text{low pitch}}$ = -1.90 dB; H1-H2$_{\text{high pitch}}$ = 11.00 dB; p-value < 0.05.) These results support results obtained by Lissemore who demonstrated a similar switch from a negative H1-H2 below 600 Hz (around D5-D#5) to a positive H1-H2 above that pitch in "techniqued" WC sopranos.[425] The large effect size (Cohen's d = 1.17) found in this study speaks to the magnitude of the acoustic benefit of this strategy that has been discussed by many authors.[426]

Th effect size was largest in participants who mostly perform MT vocal music (2.07 compared to 1.17 overall and 1.12 for WC participants.) It is also interesting to note that, though not a statistically significant trend, the participants who primarily perform MT displayed a more negative average H1-H2, or a more $2f_o$ dominant strategy, on the low pitch (-4.67 compared to -0.92 for the WC participants.) This may reflect a greater tolerance in MT styles for register transitions that LeBorgne and Rosenberg refer to as "abrupt, noticeable transitions with distinct vocal quality and timbre changes."[427]

5.2.2 MT Acoustic Findings

Of the participants who completed the MT task, 7 reported primarily performing MT vocal music and 8 reported primarily performing WC vocal music. Participants were allowed to

[425] Lissemore, *Articulatory Activity of the Tongue, Jaw, and Lips*, iv–vi.

[426] Bozeman, *Practical Vocal Acoustics*, 13-23; Howell, *Hearing Singing*, 160-163; Miller, *Resonance in Singing*, 70, 77; Titze, *Principles of Voice Production*, 180.

[427] LeBorgne and Rosenberg, *The Vocal Athlete*, 183.

self-select whether they wanted to complete the MT, the WC or both tasks regardless of whether they had formal training in the style. For the WC task, a smaller percent of the participants who performed the task primarily perform MT vocal music (26%) compared to the MT task where 53% of the participants who completed the task primarily perform WC vocal music. Also, MT students at CU Boulder are required to include at least one WC song in their jury repertoire, while WC singers are not required to included MT pieces in their juries. This means that the participants in this study who primarily perform MT have had some WC training in their applied lessons, while some of the WC singers may never have received MT training. This creates a quandary for interpreting the results of the MT task and is one of the reasons that data collection for this task is ongoing.

For the MT task, 9 of 15 participants used Strategy 1 (Transitioning to Whoop Timbre), 3 of 15 used Strategy 3 (Mix to Belt) and 3 of 15 used Strategy 4 (Belt to Quasi-Mix.) The breakdown by style primarily performed is displayed in Table 5.2.

Table 5.2 Summary Musical Theater Task Acoustic Strategies

Style Primarily Performed	**Strategy 1 (Transitioning to Whoop Timbre)**	**Strategy 3 (**Quasi-Mix **to Belt)**	**Strategy 4 (Belt to** Quasi-Mix**)**
WC	5	0	3
MT	4	3	0

The results for the combined participants support a significant increase in H1-H2 from an average of -8.31 dB for the low pitch to 1.92 dB for the high pitch (p-value < 0.05.) However, when one considers the results of just the participants who primarily perform MT, the increase in H1-H2 is not statistically significant ($H1\text{-}H2_{low\ pitch}$ = -7.46 dB; $H1\text{-}H2_{high\ pitch}$ = 3.59 dB; p-value > 0.05.) The effect size of changing pitch on H1-H2 is also lower for the MT participants (0.62) when compared to the WC participants (0.94,) and the standard deviation for the high pitch is larger for the MT participants (16.72 dB compared to 12.13 dB.) These differences suggest that the participants who primarily perform MT may approach this task, especially the production of the high note, with a wider variety of acoustic strategies than their WC counterparts.

Flynn et al. studied professional treble belters singing the notes C_5, $E^b{}_5$ and F_5 from songs in MT repertoire and did not observe a positive H1-H2 for any participants. They observed a variety of either $2f_o$ or $3f_o$ dominant strategies on the pitches they studied.[428] The MT task in the current study included a low pitch of $A^b{}_4$ ascending to a high pitch of $E^b{}_4$, so to align with the findings of Flynn et al., one would expect to see either Strategy 3 or Strategy 4 utilized by the participants. Instead, our study shows that some of the participants who primarily perform MT styles used Strategy 1 (Transitioning to Whoop Timbre). This could be a result of many factors including the age and training level of the participants (most of the MT singers in the study were undergraduate BMMT students,) and suggests that collecting samples from singers with more MT training is required to confirm or challenge the findings of this study. For the analysis of future data for the MT task, it will also be important to consider the comparative SPL of $3f_o$ along with $1f_o$ and $2f_o$.

Notably, WC singers performing the MT task universally avoided Strategy 3 (Quasi-Mix to Belt.) Strategy 3 is acoustically the most distinct from Strategy 1 (Transitioning to Whoop Timbre,) which research suggests is the WC ideal for the $A^b{}_4$ to $E^b{}_5$ transition. This pattern likely reflects the WC singers' training backgrounds: limited MT training combined with extensive WC training.

[428] Flynn et al., "Acoustic Comparison of Lower and Higher Belt Ranges," 412.

5.3 F0-Nasalance and Nasal DC Airflow Findings

5.3.1 Limitations to F0-Nasalance and Nasal DC Airflow Findings

As noted in section 4.2, the F0-nasalance results were likely affected by the previously undocumented fundamental frequency limitation of the Glottal Enterprises OroNasal 2-Chamber CV Mask. The nasal DC flow results are not likely to be affected by the limitation.[429] By considering the two sets of data together and examining the similarity in the trends and how they compare to previous studies, it is possible to make several interesting observations. However, future research with updated equipment will be required to confirm the conclusion for the F0-nasalance data. It is also important to note that while this data provides information about airflow through the nose which is controlled by the opening and closing of the VP, it does not provide direct data about VP behavior because the study did not use an accompanying nasoendoscopy to visualize the VP during the task.

5.3.2 Western Classical Task F0-Nasalance and Nasal DC Airflow Findings

For the WC task, F0-nasalance and nasal DC flow significantly decreased for all participants and participants who mostly perform WC vocal music (p-values < 0.05, see Tables 4.2 and 4.3 for numerical values.) Nasal DC flow also significantly decreased for participants who mostly perform MT (p-value < 0.05.) Change in pitch had a large effect size for all groups for both F0-nasalance and nasal DC flow. These results support the findings of previous studies that suggest VPO decreases as pitch increases.[430] Other studies show that increasing VPO,

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[429] "Roy Thompson, email message to Berton Coffin Lab personnel, March 20, 2026."

[430] Austin, "Movement of the velum," 212-221; Fowler & Morris, "Comparison of Fundamental Frequency Nasalance," 739-746; Martell, "Task-Dependent Velopharyngeal Timing," 1-10; Troup et al., "On velum opening in singing," 35-39.

reflected in higher F0-nasalance and nasal DC flow, reduces the intensity of f_{R1}, widens its bandwidth, and attenuates the $1f_o$ energy peak.[431] Since the participants favored an acoustic strategy that relies on the strength of $1f_o$ on the high pitch, the attenuation of $1f_o$ via VPO would work against the acoustic power of the high pitch. A wider f_{R1} bandwidth with reduced intensity would also make it more difficult for a singer to tune f_{R1} to $1f_o$ for a large energy boost. Thus, the WC task results for F0-nasalance and nasal DC flow provide empirical support to previous findings on the acoustic effects of VPO.

It is interesting to note that the participants that primarily perform MT showed a significant decrease in nasal DC flow from the low to the high pitch, but that the decrease F0-nasalance was not statistically significant. Since the frequency limitation of the mask is predicted to artificially lower F0-nasalance values as $1f_o$ increases, this finding is unexpected and warrants further study with updated equipment.

5.3.3 Musical Theater Task F0-Nasalance and Nasal DC Flow Findings

For the musical theater task, there were no significant trends for F0-nasalance or nasal DC flow (all p-values < 0.05.) The effect size of changing pitch on both values was small for all groups (Cohen's d < 0.5,) except for the F0-nasalance value for participants who mostly perform WC which for which the effect size was medium (Cohen's d $= 0.54$.) These results suggest that for singers attempting a pitch transition from A^b_4 to E^b_5 in an MT style do not significantly alter the amount of air passing through the nose as was seen for the WC task. There a couple reasons why these results may be observed. It is possible that E^b_5 is not high enough to require singers to adopt a strong f_{R1}:$1f_o$ coupling. It is also likely, based on previous studies on the acoustic

[431] Titze, "Nasality in Vowels," 35; Sundberg et al., "Experimental Findings on the Nasal Tract Resonator in Singing," 127; Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing," 350-351.

strategies for belting which highlight a dominant $2f_o$ or $3f_o$ strategy, that a strong f_{R1}:$1f_o$ coupling would not create the sound expected from an MT singer.[432] Thus, the acoustic effects of VPO—lowering and widening of the first formant of the vowel being performed and an attenuated $1f_o$ energy peak—are not detrimental to the acoustic strategy used for belting.[433]

Two studies report that VPO may provide vocal fold stabilization during register transitions. Echternach et al. found that an increase in F0-nasalance around the primo passaggio (E_4) in non-treble singers resulted in an increase in vocal fold stability in their study participants.[434] Vampola et al. used a computer model to predict the effect of VPO on treble singers and found that an increase in VPO likely positions the f_{R1} for an /a/ vowel in a positive intertance frequency interval during the *secondo passaggio* (622-698 Hz.)[435] Both studies suggest that VPO may increase vocal fold stability in zones of register transition, so, if the acoustic effects of VPO do not hamper the acoustic strategy of the singer, VPO may help in stabilizing phonation during these transitions. This study did not assess vocal fold behavior, however, the F0-nasalance and nasal DC flow findings do suggest, that for the MT task, participants did not significantly decrease nasal airflow which potentially allows them to benefit from the vocal fold stabilizing effects of VPO.

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[432] Miller, *Resonance in Singing*, 90; Lebowitz and Baken, "Correlates of the Belt Voice," 161–65; Flynn et al., "Acoustic Comparison of Lower and Higher Belt Rangess," 413.

[433] Titze, "Nasality in Vowels," 35; Sundberg et al., "Experimental Findings on the Nasal Tract Resonator in Singing," 127; Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing," 350-351.

[434] Echternach et al., "The Effect of Nasalance on Vocal Fold Oscillation," 500.e13-500.e15.

[435] Vampola et al., "Finite Element Modeling of the Effects of Velopharyngeal Opening," 2160.

5.4 Two Musical Theater Task Case Studies

As discussed in section 5.1.2, some of the participants who selected to attempt the MT task had little to no MT training. Due to this limitation, five study personnel, all voice teachers who instruct both WC and MT students, used a five-point Likert scale to assess whether each MT task recording was representative of contemporary MT singing. Two subjects' recordings, S03 and S08, had the highest interrater agreement as examples of contemporary MT singing. Their H1-H2, nasal DC flow, and F0-nasalance results are displayed graphically in Figure 5.2.

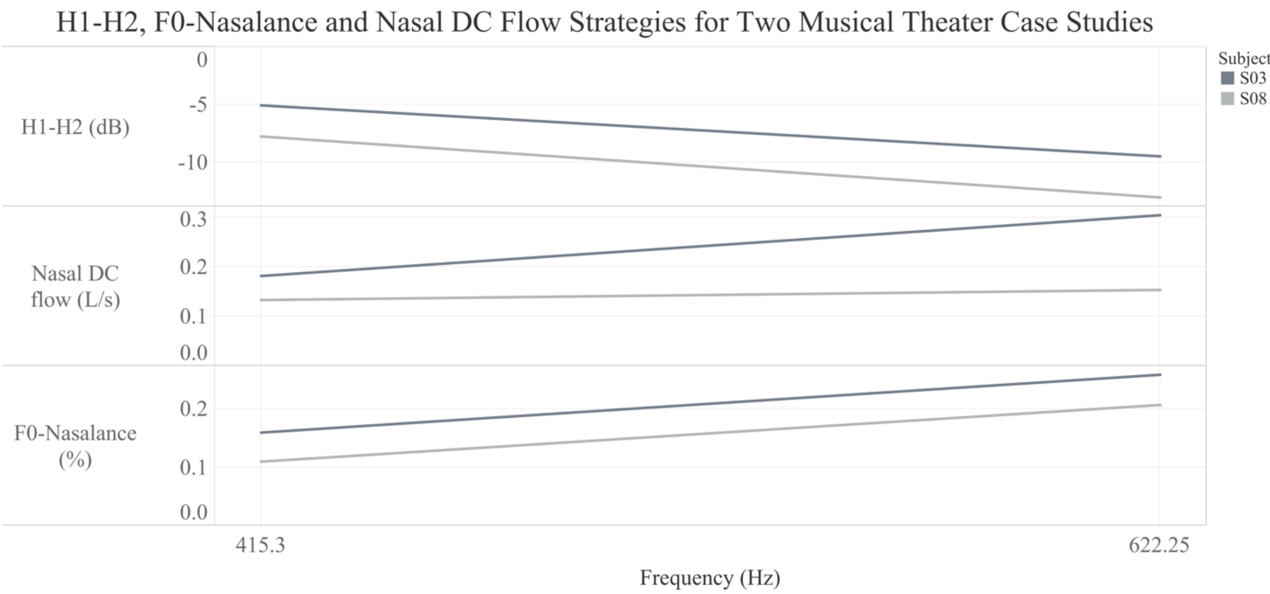

Figure 5.2 The line graph shows the data trends for S03 and S08 for H1-H2, nasal DC flow and F0-nasalance.

Both S03 and S08 utilized acoustic Strategy 3 (Quasi-Mix to Belt) and increased both nasal DC flow and F0-nasalance from the low to the high pitch. Since these participants were rated as the most representative of contemporary MT sound from within the participants who attempted the MT task, the strategies they used provide a comparative model for future data. If future data collected from MT treble singers with more experience and training corresponds to this model, then an argument can be made for VPO assisting MT singers with the performance of their highest belted notes.

5.5 Conclusions

This study yielded findings in three domains: acoustic strategy, F0-nasalance, and nasal DC flow. In the WC task, participants used a statistically significant acoustic strategy in which $2f_o$ exceeded $1f_o$ for the low pitch (C_5), with the relationship reversing at the high pitch (G_5). This pattern aligns with the experimental findings of Lissemore and with acoustic models predicting that treble singers will use an f_{R1} tracking $1f_o$ strategy above the *secondo passaggio* ($\approx F_5$).[436] In contrast, the MT task produced a greater variety of acoustic strategies, including the WC task pattern and two $2f_o$ dominant strategies.

The F0-nasalance and nasal DC flow decreased significantly from the low to the high pitch for the WC task, whereas the MT task showed no significant trend. This pattern is consistent with prior studies showing that VPO lowers the energy peak of $1f_o$ while also lowering the intensity of f_{R1} and widening its bandwidth.[437] Under these circumstances, VPO would be acoustically disadvantageous for the WC task, which relies on f_{R1} tracking $1f_o$ above the *secondo passaggio* to boost the energy level of $1f_o$ in the sound radiated from the mouth. By contrast, for the MT task, when singers used a $2f_o$ dominant strategy, the acoustic impact of VPO would likely be less detrimental. If VPO provides the vocal fold stabilizing effects suggested in prior studies, its use could therefore be advantageous for MT singers.[438]

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[436] Lissemore, *Articulatory Activity of the Tongue, Jaw, and Lips*, iv–vi; Bozeman, *Practical Vocal Acoustics*, 13-23; Howell, *Hearing Singing*, 160-163; Miller, *Resonance in Singing*, 70, 77; Titze, *Principles of Voice Production*, 180.

[437] Titze, "Nasality in Vowels," 35; Sundberg et al., "Experimental Findings on the Nasal Tract Resonator in Singing," 127; Gill et al., "Spectrum Effects of a Velopharyngeal Opening in Singing," 350-351.

[438] Echternach et al., "The Effect of Nasalance on Vocal Fold Oscillation Patterns," 500.e13-500.e15; Vampola et al., "Finite Element Modeling of the Effects of Velopharyngeal Opening," 2160.

Two participants for the MT task, rated by study personnel as most representative of contemporary MT style, serve as illustrative case studies for future data collection. Both singers used a $2f_o$ dominant strategy at both pitches, with stronger $2f_o$ dominance on the high pitch, accompanied by increases in F0-nasalance and nasal DC flow.

The F0-nasalance and nasal DC flow measurements were influenced by a previously undocumented limitation of the Glottal Enterprises OroNasal 2-Chamber CV Mask which produced artificially high oral DC flow rates and may have had a small effect on the nasal DC flow rates as well. The Berton Coffin Voice Lab is working with Glottal Enterprises to develop a new DualView software algorithm capable of capturing oral and nasal DC flows accurately above 400 Hz. This will greatly assist in continuing research on VPO in treble singers. Future data collection will also aim to obtain sufficiently robust EGG signals to enable comparison of F0-nasalance, nasal DC flow and open quotient.

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Appendix 1: IRB Approvals

Office of Research Integrity
UNIVERSITY OF COLORADO **BOULDER**
INSTITUTIONAL REVIEW BOARD

Institutional Review Board
563 UCB
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Phone: 303.735.3702
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APPROVAL

03-Feb-2026

Dear Alice Del Simone,

On 03-Feb-2026 the IRB reviewed the following protocol:

Type of Submission:	Continuing Review/Check In
Review Category:	Administrative
Risk Level:	Minimal
Title:	The Vocal Pedagogy Implications of Facial Measurements on the Use of Voce Aperta or Voce Chiusa Techniques with Students of Western Classical Singing
Investigator:	Del Simone, Alice
Protocol #:	21-0588
Funding:	Non-Federal
Documents Reviewed:	HRP-212 Continuing Review v8c;

The IRB approved the protocol from **03-Feb-2026** to **02-Feb-2027** inclusive.

Before **3-Jan-2027**, you are to submit a Check-in Form to request continuing approval or closure. This protocol will expire if continuing review approval is not granted before **02-Feb-2027**.

You are required to use the IRB Approved versions of study documents to conduct your research. The IRB Approved documents can be found here: Approved Documents

In conducting this protocol you must follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,
Ethan Piacenti
IRB Student Assistant
Institutional Review Board

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within the University of Colorado Boulder's IRB records.

Office of Research Integrity
UNIVERSITY OF COLORADO **BOULDER**
INSTITUTIONAL REVIEW BOARD

Institutional Review Board
563 UCB
Boulder, CO 80309
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APPROVAL

06-Nov-2024

Dear Nicholas Perna,

On 06-Nov-2024 the IRB reviewed the following protocol:

Type of Submission:	Initial Application
Review Category:	Exempt - Category 2, 3 -
Risk Level:	Minimal
Title:	Velopharyngeal Opening Variability In Collegiate Treble Singers: A Pilot Study
Investigator:	Perna, Nicholas
Protocol #:	24-0656
Funding:	None
Documents Approved:	24-0656 Consent Form Apprv 11.6.24.docx; 24-0656 Advertisting Apprv 11.6.24.docx; 24-0656 Protocol Apprv 11.6.24.docx; 24-0656 Survey Apprv 11.6.24.docx; HRP-211: FORM - Initial Application v18;

The IRB confirmed the Exemption of this protocol on **06-Nov-2024**.

You are required to use the IRB Approved versions of study documents to conduct your research. The IRB Approved documents can be found here: Approved Documents

In conducting this protocol you must follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,
Catherine Pedrotti
Research Services Coordinator
Institutional Review Board

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within the University of Colorado Boulder's IRB records.

Appendix 2: Participant Survey

VPO Protocol

Survey for VPO Protocol

When you submit this form, it will not automatically collect your details like name and email address unless you provide it yourself.

* Required

1. What is your name? *

Enter your answer

2. What is your voice type? *

Enter your answer

3. What type of singing do you perform most often? *

- ◯ Classical/Opera
- ◯ Musical Theater
- ◯ CCM (Pop, Rock, R&B, etc.)
- ◯ Other

4. What other types of singing do you perform? *

Enter your answer

5. Number of years of singing instruction *

- ◯ <1
- ◯ 1-3
- ◯ 4-6
- ◯ >6

Appendix 3: Detailed Experimental Procedure

Procedure 1: Get Everything Ready

- Turn on lights and plug in the power strips, plug **EGG** in to charge, check that the wall power is plugged in too
- Turn on the **lab computer** and sign in
- Connect **MS110** to **lab computer** by plugging in wall power, turning on the switch on the back to EXT Power and turning on **USB power supply to connect to computer**
    - Ensure that the **T.C. on toggle** is switched down to the 7pm position (this is because the switch is backwards – we do need the TC on to have the pass filter running)
    - Adjust the **offset gain knobs** so that they flash red and then back them off a little from that setting
- Connect **EGG** (left channel/channel 1) and **Earthworks** (right channel/channel 2) to **Claret 4Pre**
    - Turn phantom power OFF before connecting Earthworks
        - After microphone is plugged in, turn on phantom power
- Open 13 or 7 pre-named **Audacity** windows on **Alice's Computer**
    - S1_Mic_CAL
    - If they are only doing Musical Theater:
        - S1_MT_T1 (Dual View, EGG)
        - S1_MT_T2 (Dual View, EGG)
        - S1_MT_T3 (Dual View, EGG)
        - S1_MT_T4 (Mic, EGG)
        - S1_MT_T5 (Mic, EGG)
        - S1_MT_T6 (Mic, EGG)
    - If they are only doing Classical:
        - S1_CL_T1 (Dual View, EGG)
        - S1_CL_T2 (Dual View, EGG)
        - S1_CL_T3 (Dual View, EGG)
        - S1_CL_T4 (Mic, EGG)
        - S1_CL_T5 (Mic, EGG)
        - S1_CL_T6 (Mic, EGG)
    - If both, open 12 windows

Procedure 2: Check M110 Calibration

NEVER pull the **syringe** to fill it with air when a **transducer** is inserted

During this procedure, the non-computer research personnel should take notes about every time that the computer personnel clicks **Record** in the **DualView software** and what the recording is. That way when we go to name the DualView files on the lab computer, we know what they are. This is important because every time you press Record, a new file is created in the Windows DualView folder.

1. In Documents>DualView: delete any old or unidentified files so that your first recording will automatically become DualView 1.
2. Launch **DualView** software
3. For the **transducers**:
    - A = Oral
    - B = Nasal
4. Sanitize the **DualView Mask**
    - Use a **MagiCare wipe** (alcohol wipe)
    - DO NOT TOUCH THE MESH
    - Wipe the inside surfaces that the participant's face will touch
5. Put the **transducers** into the **DualView mask**
    - **Transducer A** (Oral) goes into the bottom, oral portion of the mask
    - **Transducer B** (Nasal) goes into the top, nasal portion of the handle
6. Check gain levels in **DualView software**
    - Instruct participant to hold the mask parallel to the floor and away from their mouth
    - In **DualView software**, click File → **Record New Airflow Signal**
    - Click **Set Zero Mask** in the pop-up window
    - Instruct participant to bring mask to their face to create a tight seal
    - Have the participant try the WC or MT task 1 time
    - During the practice task, watch the signal bar in the pop-up window to see if they reach red
        - If the bar reaches red in a certain channel, adjust the offset gain down on the MS110 for that channel
    - Do 2 more trys to make sure that no peaking occurs and so the participant gets used to doing the pitch glide into the mask
    - ***If this is not the first subject of the day and there are no changes made to the offset gain or anything else in DualView or on the MS110 box, then you do not have to do a new calibration – just copy the calibration files from the previous subject of the day
7. Insert **syringe** into calibration devise
8. ENSURE that the **transducer** is NOT inserted
9. Pull out the **syringe** to fill it with 140 mL of air at the side ring
    - Not the lowest middle point
10. Insert **transducer A** (Oral)
11. In **DualView** software, click **Calibrate → Record Airflow Calibration Signal ChA**
12. In the dialog box that pops up
    - Click **Set Zero Mask** and wait for that to complete
    - Computer person clicks **Record** while syringe person depresses the syringe over 1.5 - 2 seconds.
    - Close the dialog box

13. In the main window left click the left side of the calibration data and right click the right side of the calibration data, be sure to have captured the entire signal, having just a bit of space before and after the calibration is OK.
14. Click **Calibrate → Calibrate Airflow Ch A**
    - Input a mask calibration factor of 4.0
    - Before the very first participant, save this file as S1_CAL_A
        - We need one calibration file per day that we know is correct for our data entry into the PRAAT script
    - If it is not the very first participant, and the pop-up box shows 1.4 L +/- 0.05 L (1.35-1.45 L is acceptable) error, then you don't need to accept the calibration, the transducer has held calibration, and you can move on
15. Remove **transducer A** (Oral)
16. Pull out the **syringe** to fill it with 140 mL of air at the side ring
17. Insert **transducer B** (Nasal)
18. In **DualView** software, click **Calibrate → Record Airflow Calibration Signal ChB**
19. In the dialog box that pops up
    - Click **Set Zero Mask** and wait for that to complete
    - Computer person clicks **Record** while syringe person depresses the syringe over 1.5 - 2 seconds.
    - Close the dialog box
20. In the main window left click the left side of the calibration data and right click the right side of the calibration data. be sure to have captured the entire signal, having just a bit of space before and after the calibration is OK.
21. Click **Calibrate → Calibrate Airflow ChB**
    - Input a mask calibration factor of 4.0
    - Before the very first participant, save this file as S1_CAL_B
        - We need one calibration file that we know is correct for our data entry into the PRAAT script
    - If it is not the very first participant, and the pop-up box shows 1.4 L +/- 0.05 L (1.35-1.45 L is acceptable) error, then you don't need to accept the calibration, the transducer has held calibration, and you can move on

Procedure 3: Collect Data

- Sign Consent Document
- Complete Survey
- Put on gloves!
- Confirm EGG waveform in **VoceVista Video Pro (VVVP)** on **Alice's Computer**
    - Turn off the **DualView** at the **USB power strip** attached to the lab computer and unplug the DualView from the USB power strip
    - Unplug **EGG** if you were charging it
    - Turn the **EGG** on by turning the knob in the upper left-hand corner left or right

        - Check that the light is green. If it is red, turn the knob the other direction and check for green. If both are red, then you need to charge the EGG and unplug it before taking data.
    - Have participant attach **EGG neck strap** to their neck, with the electrodes on either side of their larynx, near laryngeal prominence (thyroid cartilage)
        - Check the **EGG** front panel right side meter to see if the EGG needs to be repositioned higher or lower – generally, don't panic if this is not perfect.
    - Open a **VVVP window** and check that the waveform looks normal and consistent without flat tops
        - If it is not normal, turn EGG output switch to high
        - If still not normal, use contact gel
        - If still not normal, you won't get EGG signal, which is not the best but not the end of the world, not everybody gets good EGG signal
- Connect **Claret 4Pre** to **Alice's computer** via USB using the dongle
- Reconnect the **DualView** to the lab computer **USB power strip** and turn on
- Ask participant if they like blue or green
    - If they answer **blue**, proceed with DualView, if **green**, proceed with Earthworks

Audio & EGG Data Collection (**Alice's computer** only)
If this is the first procedure, complete steps 1-7. If this is the second procedure, bring the microphone stand in and make sure the positioning is set up as described in step 2di. Non-computer personnel should observe the participant to ensure that they remain at the proper distance from the microphone.

1. In **Audacity** go to Audio Set Up → Recording Devise → Select Claret 4Pre, Stereo
2. Instruct participant where to stand in accordance with the taped lines on the floor
    a. Participant should be singing perpendicular to the microphone
    b. Let them know they need to stand in the same place for all the tasks
    c. Ideal placement is mouth 15 cm from microphone
    d. Give the participant a ruler for their own reference to check prior to each sample
        i. They can check by putting the **15 cm ruler** on their chin and measuring 15 cm to the microphone
3. Describe the **task**
    a. MT: ask what their highest comfy natural/speech belt pitch is.
        i. Options: Ab4 – Eb5, A4-E5 or Bb4-F5, we'd accept G4-D5, but only if they say they can't do Eb5.
        ii. Task is to slide from low pitch to high pitch (NOT back down again) like it is a climactic phrase in a MT song (I. E. belting)
    b. WC: slide from C5 – G5
4. Check gain levels in **Audacity**
    a. Open File S1_Mic_CAL (or S2 etc)

    b. Record participant testing the task 3 times, start with MT if doing both
    c. As they record watch:
        i. the **Claret 4Pre** for red lights on either channel – this means gain needs to be turned down
        ii. **Audacity** for flat tops – this means gain needs to be turned down
            1. We want signals that are about between +/- 0.5
    d. After the gain is set, record 7 seconds of signal with **REED Sound Level Calibrator** at 94dB
        i. This is ONLY for the left channel and will provide a calibration for the entire subject for SPL
        ii. Each subject needs their own mic calibration
5. Record the 3 or 6 **tasks**
    a. Switch windows each time to the appropriately labeled window

MS110 & EGG Data Collection (**Alice's computer** and **lab computer**)

If this is the first procedure, repeat steps 1-7 of the **Audio & EGG Data Collection, you are doing this because you still need to collect EGG data with the DualView**

If this is the second procedure, remove the microphone stand. If you want to disconnect and store the Earthworks, remember to turn off the phantom power (48v) to do so. During this procedure, the non-computer research personnel should take notes about every time that the computer personnel clicks **Record** in **DualView software** and what the recording is. That way when we go to name the DualView files on the lab computer, we know what they are. This is important because every time you press Record, a new file is created in the Windows DualView folder.
The non-computer personnel should also observe the participant to ensure that the mask remains parallel to the ground.

1. Record the 3 or 6 **tasks**
    a. MT first if doing both tasks
    b. Check that the transducers are still cleanly connected to mask and handle.
    c. Open the appropriate window in **Audacity** and click Record
    d. In **DualView software**, click File → **Record New Airflow Signal**
        i. Click **Set Zero Mask** in the pop-up window
        ii. Instruct participant to bring mask to their face to create a tight seal
    e. Click **Record** and have the participant complete the task
    f. Close **DualView software** window
    g. Stop **Audacity** recording
    h. Repeat twice more

Procedure 4: After the participant leaves

- Go back into each **Audacity** project and trim the unwanted parts of the files
- Separate the channels (Split stereo to mono)

- Export Audio of each channel separately, which might require you copy/paste of one channel into a new project.
- Save each channel:
    - S1_MT_T1_EGG
    - S1_MT_T1_Audio
    - Save to One Drive folders
    - For S1_Mic_CAL take 5 seconds of steady state signal from the middle of the calibrator sound
- Go into the **DualView folder** on the **lab computer**
    - Name the files
    - S1_MT_T4_DV
        - Save in OneDrive folders

Shut down the computer and manually turn everything off.
Disconnect transducers from mask and leave them cleanly placed on the table.
Clean mask.
Unplug everything and leave the lab as you found it.

Appendix 4: Expert Listener Survey

Expert Listener Analysis

1. Is this recording representative of contemporary musical theater singing?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

2. Is this recording representative of contemporary musical theater singing?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

3. Is this recording representative of contemporary musical theater singing?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

4. Is this recording representative of contemporary musical theater singing?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

5. Is this recording representative of contemporary musical theater singing?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

6. Is this recording representative of contemporary musical theater singing?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

7. Is this recording representative of contemporary musical theater singing?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

8. Is this recording representative of contemporary musical theater singing?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

9. Is this recording representative of contemporary musical theater singing?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

10. Is this recording representative of contemporary musical theater singing?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

11. Is this recording representative of contemporary musical theater singing?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

12. Is this recording representative of contemporary musical theater singing?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

13. Is this recording representative of contemporary musical theater singing?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

14. Is this recording representative of contemporary musical theater singing?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree

15. Is this recording representative of contemporary musical theater singing?

Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree