Registers—The Snake Pit of Voice Pedagogy

PART 1: PROPRIOCEPTION, PERCEPTION, AND LARYNGEAL MECHANISMS

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TERMINOLOGICAL CONFUSION

According to Thurman et al., the first attempts to define vocal registers date back to the thirteenth century.[1] Since then, a large variety of register definitions and categorizations have been proposed (see, e.g., excellent historical overviews by Henrich, Stark).[2] A limited selection of noteworthy register classifications is provided in Table 1.[3]

A review by Mörner et al. found more than 100 different terms for registers used in scholarly writing.[4] Some thirty years ago, Sundberg commented on this situation, stating that, "Unfortunately, there is no generally accepted clear definition of the term register."[5] While recent decades saw some excellent scientific contributions, some of which are mentioned in this article, there

TABLE 1. Exemplary overview of proposed register classifications.

Author	Year	Count	Terms
Zacconi	1596	2	*voce di petto, voce di testa*
Garcia	1847	3	*voix pointrine, registre de fausset, registre de téte*
Behnke	1886	5	lower thick, upper thick, upper thin, upper thin, small
Van den Berg	1963	3 (+2)	chest, head or mid, falsetto (main registers) *Strohbass*, whistle (further registers)
Vennard	1967	3	chest, middle, head (females) Chest, head, falsetto (males)
Hollien	1974	3	pulse, modal, loft
Miller	2000	4	chest, middle, upper, flageolet (females) Chest, full head, falsetto (males)
Roubeau	2009	4	M0 (fry), M1 (chest), M2 (falsetto), M3 (whistle)*

* The terms in parentheses were added by the author in order to increase readability; see Table 5 in Roubeau for a complete list of synonyms.

remains some controversy concerning both (the lack of) unanimously accepted definitions and pedagogic application.

The variety of seemingly incongruent register definitions suggests that the subject matter might be more complex than sometimes assumed. In particular, some confusion may stem from the fact that various register definitions target different aspects of reality. Janwillem van den Berg, for instance, critically observed that the different register terms

> are a hodge-podge arising from such divergent sources as: secondary clues (resonances in the chest with the chest voice); misconceptions (non-existing resonances in the head with the head voice); acoustical illusions (with the falsetto); acoustical resemblance (the rattling sound of trodden straw with the Strohbass voice); and similarity of origin (eddies generated in a narrow opening and subsequent cavity resonance with the flute or whistle register).[6]

The notion that vocal registers might be assessed on several levels provides the conceptual framework for this study, which will discuss registers against the following backgrounds: 1) proprioception; 2) psychoacoustic perception; 3) laryngeal mechanisms; 4) vocal tract effects; and 5) individual didactic systems. The aim is to show that some apparent discrepancies between register definitions/classifications can be resolved by considering the different backgrounds against which they have been established. Such an acknowledgement of the increased complexity of the topic of registers (or, rather, the removal of unjustified oversimplification) may eventually lead to increased clarity and better understanding in both science and teaching.

To conclude these introductory remarks, a crucial disclaimer must be made. Unfortunately, all available vocal register terms come with certain connotations and interpretations; this is true even for the apparently neutral terminology of M0 to M3.[7] However, discussing registers and their classification unfortunately requires an *a priori* auxiliary terminology; thus, an arbitrary choice for preliminary register terms had to be made. During parts of this text, the terms (vocal) fry, chest, falsetto, and whistle register are used as proxies, because they seem—at least in the opinion of this author—to be the most widely utilized terms, without making a concession that these terms are appropriate or even "correct." Rather, it should become clear from this article that the terms themselves are not important, but rather the proper descriptions and definitions of underlying phenomena. Once the latter becomes clear, the terminology may even become irrelevant, as long as everyone who partakes in a discussion about registers has the same basic understanding.

1. PROPRIOCEPTION

Probably the first explicit mention of vocal registers was made by Zacconi at the end of the sixteenth century. In his *Prattica di musica,* he distinguished *voce di petto* (literally translated as "voice of the chest") from *voce di testa* ("voice of the head").[8] Since these register terms clearly target distinct regions of the body, they most likely have been established in close relation to the concepts of *appoggiarsi in petto* und *appoggiarsi in testa*. For instance, the *Enciclopedia Garzanti della musica* explicitly states that *appoggio* refers to both the torso and "the part of the facial cavity where the cervical resonances of the sound are perceived."[9] Surprisingly, this description very closely matches a current definition of resonant voice; "a voicing pattern involving oral vibratory sensations, particularly on the alveolar ridge and adjacent facial plates, in the context of what subjects perceive as 'easy' phonation."[10] This impressively demonstrates that proprioception is an important common denominator of various notions of voice pedagogy. However, it also hints at a certain degree of convolution of the involved concepts, that is, proprioceptively defined registers, *appoggio*, and resonant voice. This may potentially exacerbate respective discussions, particularly when (currently partially lacking) objective empirical evidence is substituted by subjective impressions of proprioceptive experience.

The central question is whether the historical proprioceptive register definition of "head" (relatively higher in pitch) vs. "chest" register (lower in pitch) is supported by empirical evidence provided by modern voice science, objectively documenting vibrations of the head or chest. In a highly significant review, Sundberg summarized the results of nine different studies, coming to the following conclusions.[11]

- Vibrations in the chest and head regions do indeed typically occur during singing. However, they do not significantly contribute to the radiated sound but may (only) serve as a feedback for the respective singers.

- The strength of the vibrations occurring in the supraglottal regions is dependent on the sung vowel, notably influenced by jaw opening which has a causal influence on the center frequency of the lowest vocal tract resonance, and thus the first formant. In contrast, the strength of the vibrations of the subglottal region is independent of the sung vowel.
- The strength of the vibrations is greatly dependent on the sung pitch or, in physical terms, the fundamental frequency of vocal fold oscillation. In particular, only fundamental frequencies up to 300 Hz (D_4) can be perceived in the chest.[12] Surprisingly, that upper frequency limit of ca. 300 Hz coincides more or less precisely with the *zona di passaggio*, constituting the main register transition in classical singing. Along those lines Sundberg suggests that

> as the sensitivity to vibrations decreases above about 300 Hz and as phonatory vibrations decrease with rising frequency, phonatory vibrations cannot be perceived at high pitches. A bass singer should be able to sense vibrations of his sternum throughout his range. A tenor should be able to sense them for the lower and middle part of his range, the notes below the pitch G_4. An alto is not likely to sense vibration of the sternum except for her lowest notes. This may be the reason why the register used in the female voice for the lowest pitches is called the “chest” register.[13]

Whether facial/cranial vibrations are actually linked to different voice registers remains unclear, according to Sundberg’s review. A recently published pilot study by Kitamura and Othani, investigating three female singers with laser Doppler vibrometer scans, suggests that the amplitude of facial surface vibrations is dependent on fundamental frequency of the emitted voice. However, in that study’s methodology vocal registers have not been explicitly controlled. Therefore, it remains unclear whether the effect is caused by fundamental frequency or by the chosen vocal register.[14]

In summary, the available empirical evidence base seems to suggest that there is some systematic correlation (if not causal relation) between the fundamental frequency of voice production and vibrations in the head, neck, and chest, with the choice of sung vowel being notably relevant for the quality of vibrations in the head. While particularly the pitch dependency of vibrations and their perception may explain why Zacconi introduced the kinesthetically oriented concept of “head” vs. “chest” voice, this can not be taken as evidence or even proof that laryngeal registers (see Laryngeal Mechanisms below) are the cause for these vibrations; rather, these phenomena might simply be linked to fundamental frequency/pitch. Along those lines, a consensus report produced by the Collegium Medicorum Theatri maintains that “while the sensations felt by singers, of course, are valid sensations (indeed, even the non-singer can experience them), they have nothing to do with vocal registers!”[15] It would appear that a series of rigorous empirical experiments is needed to shed further light on the matter.

From a pedagogic point of view, it is remarkable that vibrations of the chest and the head only marginally contribute to the radiated sound.[16] It is thus safe to assume that they are actually more or less inaudible. Rather, these vibrations may serve as a proprioceptive feedback for singers and, indirectly, for their teachers. In this context it is important to realize that vibrations in the supraglottal region are greatly dependent on the sung vowel. This would suggest that proprioceptive feedback is relatively stable during vocalises with constant vowels, at least over a limited pitch range, but may greatly vary when singing lyrics made up of multiple, varying vowels. Furthermore, assuming that cervical vibrations are created by acoustic standing waves in the supraglottal vocal tract,[17] the respective proprioceptive sensations may not be comparable across singers, due to intra-individual anatomic differences. For these reasons, concepts of “voice placement,” like the one proposed by Lilli Lehmann,[18] should, in the opinion of this author, not be treated as absolute truth, because there might be limits to generalizing them. Rather, such concepts are useful in illustrating proprioceptive principles. They may be utilized individually. There potentially exists a “body map of voice placement” for each singer, which is dependent on personal anatomy and sung vowels and pitches. Such maps need to be developed carefully and individually in voice training. Once reliably established, they are likely most useful in situations where the singer does not have good acoustic feedback, as, for example, when singing in the midst of a loud orchestra.

2. PSYCHOACOUSTIC PERCEPTION

One way to describe vocal registers is to perceptually assess the sound of the voice, typically without considering the underlying physiological and physical production mechanisms. For instance, Titze reported that "The term register has been used to describe perceptually distinct regions of vocal quality that can be maintained over some ranges of pitch and loudness."[19] This definition exclusively targets the psychoacoustic domain (with pitch and loudness being the respective perceptual counterparts of the physical qualities fundamental frequency and sound level). In light of this definition it needs to be established to what extent listeners can actually distinguish between different registers. It appears that two register transitions have been investigated in more detail: between vocal fry (sometimes termed pulse register) and chest register; and between chest register and falsetto (please recall the initial disclaimer concerning vocal register terms).

Vocal Fry vs. Chest Register

Vocal fry was defined by Hollien as a physiologically normal kind of voice production having pitches—or, rather, fundamental frequencies—below those of the chest register.[20] Vocal fry is characterized by distinct glottal pulses, where each pulse is more or less completely attenuated before the next pulse commences. Owing to the relation $f_o = 1 / T$, the long oscillatory period T found in vocal fry is responsible for the low fundamental frequency f_o. The perception of vocal fry is closely linked to f_o,[21] with the upper threshold being at $f_o \approx 70$ Hz[22] or about $C^{\#}_2$. In other words, vocal sounds with a fundamental frequency of 70 Hertz or below are likely perceived as vocal fry.

Chest vs. Falsetto Register

When considering the perceptual differences between what is provisionally called chest and falsetto register in this text, one can—at least as regards older literature—again refer to an excellent review paper by Sundberg.[23] According to this review, several studies suggest that especially trained listeners can discriminate between the chest and falsetto registers relatively well,[24] particularly when these two voice qualities are presented as distinct antagonists. This has been at least partially corroborated by a more recent study in the context of quantitative voice analysis.[25] Both the spectral composition of the voice source (i.e., the amplitudes of the individual harmonics created by the laryngeal sound source) and the resonance structure may play a role in this respect.[26]

Upon closer inspection however, the situation is not trivial.

- It can be assumed that the ability for perceptual register identification is influenced to a certain degree by a conceptual and contextual bias of the listener.[27] Therefore, care should be taken when formulating the listener's instructions, because the use of explicit register terminology may have an effect on the perceptual rating.
- Voice registers theoretically can be distinguished via several acoustic (perceptual) features: fundamental frequency (pitch); spectral composition (timbre); and sound level (loudness).[28] Therefore, the perception of voice registers is a multidimensional phenomenon, relying on several sound attributes of the voice. This may explain why the perceptual discrimination of registers in the *zona di passaggio* (i.e., a region where the fundamental frequency/pitch of registers may overlap) is more challenging, due to ambivalent and thus potentially unusable f_o information.
- The perceptual discrimination of distinct register changes or even breaks—consider yodeling as an extreme case—is typically straightforward. In contrast, the task at hand is obviously more difficult when trained singers skillfully mask a laryngeal or resonatory register transition. That latter situation leads to the question of whether there are clearly defined and measurable minimal changes of (psycho-) acoustic parameters that reliably allow one to identify register transitions. In other words, is there a "just noticeable difference" (JND) that is required for two vocal sounds to be perceived as different registers?[29] If so, how would it be defined?

As indicated above, voice registers may be perceptually differentiated on three levels: pitch, loudness, and timbre. The JNDs for pitch and loudness have been rigorously researched,[30] and there are serious attempts to investigate and describe the JND of timbre.[31] However, establishing JNDs for the differentiation of vocal registers may be more challenging, due to potential perceptual interactions between the aforementioned parameters pitch, timbre, and loudness, and possibly also additional influences from the temporal dimension. (When does a gradual transition turn into a "register break"?) To the best knowledge of this author, this very complex topic is still under-researched, requiring further scientific investigation.

(Perceptually) Unifying the Registers

Particularly within the aesthetic context of classical singing, it is required to unifiy the registers in a way that no transition between them is audible. While this makes sense on a perceptual level, some authors go one step further and altogether deny the existence of registers. For instance, Lilli Lehmann stated in an essay, which still seems to have some influence in the German-speaking community of singing teachers, "When teaching a voice, registers should not exist nor should they be created"; "Do registers naturally exist? No."; and "As long as the term 'register' is retained, registers will not vanish" [translations by CTH].[32]

In the opinion of this author, even these relatively extreme postulates have some merit, but only when being assessed and interpreted exclusively on a psychoacoustic level. They might then serve as an aesthetically motivated definition of the perceptual end result of voice production. However, they hardly bear any noteworthy relevance to the physiological and physical reality of singing voice production.

The Purely Perceptual Approach in Voice Pedagogy

It should be evident that a voice pedagogue always should consider the final "product" of teaching, that is, the sound of the singer's voice, and how it is perceived within the chosen aesthetic context. In classical singing, for instance, abrupt timbral and pitch changes expose inexpertly executed register transitions (see remarks about blending the registers in Part 2 of this article), while such phenomena might actually be crucial features in other singing styles, such as CCM (contemporary commercial music) or some forms of world music. For these reasons, a teacher's assessment of the singing voice should always have a perceptual component.

However, a purely perceptual approach in voice pedagogy—neglecting the physiology and physics of voice production—does have a clear limitation: It treats the voice as a "black box," targeting only the system's output and disregarding its inner workings. Such a *modus operandi* reduces the pedagogue's available didactic strategies to only imitation learning through trial and error, likely introducing a certain degree of inefficiency when student and teacher are not of the same voice type or *Fach*, or in the presence of a fundamental functional voice production issue on the part of the student. In particular, if the physiological reasons and principles of physics (i.e., the inner workings of the "black box") for any (un)wanted vocal phenomenon are unknown, it may be difficult to find the most appropriate teaching strategies.

This may be especially true for the issue of vocal registers. As will be shown in the following sections of this article, register transitions can be predominantly of laryngeal nature, or they can be caused by vocal tract influences. Naturally, since both these potential causes are attributed to different subsystems of the voice apparatus, they would require fundamentally different pedagogic interventions, because different motor control aspects of voice production are targeted.

The perceptual ambivalence linked to register transitions is best illustrated with the example from Donald Gray Miller's book *Resonance in Singing*, shown in Figure 1.[33] The G major scale sung by a mezzo soprano on vowel [ɑ] has two audible transitions: one at $t \approx 3$ s (from B_3 to C_4) and the other at $t \approx 5.5$ s (from E_4 to $F^{\#}_4$). (It will be shown in the following sections that the transition at $t \approx 3$ s is laryngeal and the other at $t \approx 5.5$ s is resonatory in nature.) Repeated *ad hoc* listening tests performed by this author at various symposia with a larger audience revealed that, singing teachers and voice therapists about equally chose either transition when asked to "identify one register transition in the scale," with very few declared abstentions. The ambivalence of opinion found even among experts demonstrates the limitations of the purely perceptual approach.

3. LARYNGEAL MECHANISMS

In the first two sections of this article, vocal registers were discussed from the propriceptive and perceputal point of view. A fundamentally different approach was proposed in the mid nineteenth century by Manuel Garcia. He suggested that a vocal register is

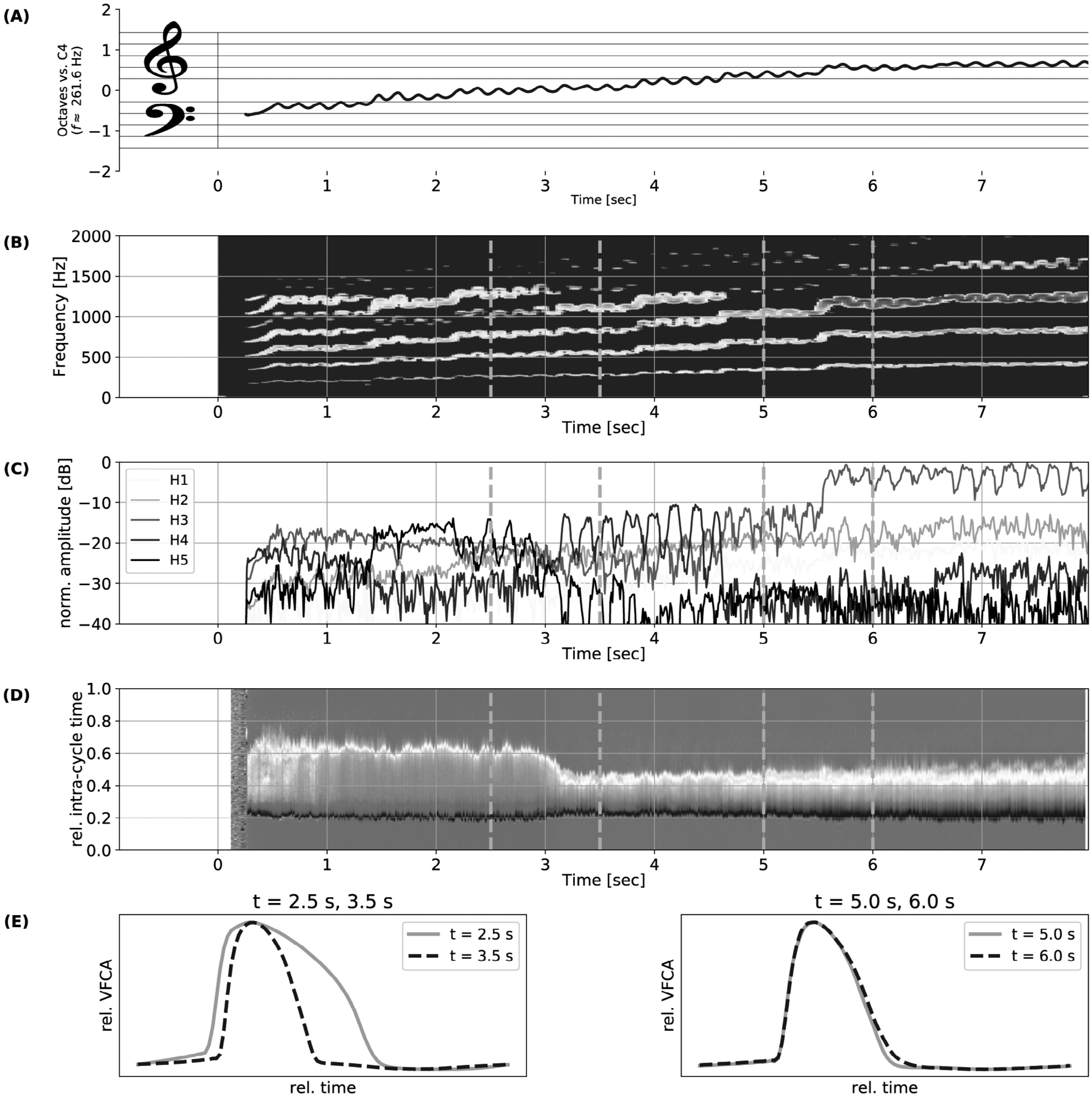

Figure 1. Example for a perceptually ambivalent register transition. (A) Fundamental frequency; (B) spectrogram of the acoustic signal; (C) relative amplitudes of harmonics 1 through 5; (D) dEGG *wavegram*; (E) Electroglottographic (EGG) waveforms. Left panel: shortly before (t = 2.5 s, solid line) and shortly after (t = 3.5 s, dashed line) the ***laryngeal*** register transition. Right panel: shortly before (t = 5 s, solid line) and shortly after (t = 6 s, dashed line) the ***resonatory*** transition. The dashed vertical lines in (B), (C), and (D) indicate the time offsets at which the EGG waveforms shown in (E) have been extracted. (Listen to this recording at 🔊 nats.org/JOSmedia.) (Example 5.7 from Miller, 2008,[33] with permission from the author.)

> a series of consecutive and homogeneous tones going from low to high, produced by the same mechanical principle, and whose nature differs essentially from another series of tones equally consecutive and homogeneous produced by another mechanical principle. All the tones belonging to the same register are consequently of the same nature, whatever may be the modifications of timbre or of the force to which one subjects them.[34]

Garcia's description of laryngeal registers, then a radically novel concept, is the centrally relevant concept even today. A comparable, but slightly different definition was proposed by Hollien: "A vocal register is a series or range of consecutive voice frequencies which can be *produced with nearly identical voice quality* [emphasis by CTH]."[35] While Garcia's definition considers only laryngeal phenomena of vocal fold vibration and sound production, Hollien's conceptualization (at least implicitly) also encompasses resonatory phenomena introduced by the vocal tract. Hollien further suggests that registers should be operationally defined on perceptual, acoustic, physiologic, and aerodynamic levels.

As far as the laryngeal voice production mechanism is concerned, often four "main" registers, or, rather, laryngeal mechanisms, are considered. A decision was made here provisionally to adhere to this classification, even if there is some disagreement among scholarly sources. (In this context please recall the initial disclaimer: The purpose of this text is not to propose a "correct" classification and terminology for voice registers, but rather to review the different ways of defining and discussing registers, in order to provide deeper information about the underlying principles.) These four laryngeal mechanisms are typically termed as: vocal fry (M0, pulse register); chest voice (M1, modal register); falsetto (M2, head voice?); and whistle register (M3).

In the following sections, these mechanisms are discussed, beginning with the less common vocal fry and whistle registers. Then, a distinction is made between the two central singing voice registers, chest and falsetto. Possibilities of blending these latter two registers are considered in part two of this study.

Vocal Fry (M0)

While vocal fry is basically unused in classical singing, it is relevant in some substyles of CCM, at least as a vocal effect. Perceptual aspects of vocal fry have been discussed above. While some of the physiological and physical aspects of vocal fry as a distinct register have been addressed previously in research, further complementary investigation may be necessary.

Past research centered on speech rather than singing has suggested that vocal fry might be a distinct vocal register, differing from the pitch-wise superjacent chest (modal) register in several ways. In contrast to chest (modal) register, no correlation between the fundamental frequency (f_o) and vocal fold length was found in vocal fry (overall, vocal fold length was lower in vocal fry), suggesting a different mechanism for f_o control as compared to chest/modal register.[36] Furthermore, no correlation between f_o and the thickness of the vocal folds and/or ventricular folds could be documented, and the ventricular space was smaller than in chest (modal) register, indicating ventricular fold impingement.[37] Vocal fry was shown to have lower airflow, lower cricothyroid and interarytenoid muscle activity, and increased thyroarytenoid activity in comparison to modal register.[38] Comparisons of subglottal pressure in vocal fry vs. chest (modal) voice resulted in ambivalent data.[39] One type of vocal fry was found to be constituted by subharmonic vocal fold oscillation,[40] where each complete vibratory period consisted of two or three amplitude-modulated vibrations of the vocal folds.[41]

Whistle Register (M3)

A certain degree of disagreement about the physical nature of the whistle register exists, particularly in older literature. Some authors suggested an aerodynamic whistle mechanism where the sound is created by vibrations of air in the absence of vocal fold vibration, or where vocal fold vibration at least would not causally contribute to sound generation.[42] An alternative hypothesis suggests that the whistle register is produced in analogy to the "default" mode of voice production via passive self-sustaining vocal fold vibration,[43] as described by the myoelastic-aerodynamic theory of voice production.[44] In that case, laryngeal dynamics are hypothesized to be characterized either by a shortened glottis ("damping") to produce a "flageolet" tone,[45] or by vibration along the full length of the vocal folds.[46]

That latter hypothesis is corroborated by empirical data from laryngeal high speed videoendoscopy. In a single-subject pilot study, Echternach et al. documented full glottal closure along the entire antero-posterior glottal width in a professional classical singer phonating C_6 to G_6 (1047 Hz to 1568 Hz). This suggests that—at least in classical singing—there is little reason to believe that the whistle register is fundamentally different from the falsetto register as far as fundamental laryngeal mechanics are concerned. Rather, the main difference probably may be found in resonatory adjustments.[47]

A different concept termed "glottal whistle" or M4 was proposed by Edgerton in the context of the "extra-normal voice."[48] This glottal whistle, produced with both ingressive and egressive phonation, was speculated to be "the result of a vortex produced at the upper edges of the vocal folds."[49] Fundamental frequencies of the glottal whistle were found in the range of 1000 Hz to as much as 6503 Hz, or pitch $G^{\#}_8$.[50]

Chest (M1) and Falsetto Registers (M2)

The distinction between chest and falsetto registers at the laryngeal level is not as trivial as it may seem at first glance. Here, an attempt is made to describe the relevant physical and physiological underpinnings in more depth than what is typically found in texts aimed at an audience of singing teachers. For that reason, a few concepts and insights from voice research conducted in the past five decades are reviewed first. Please note that in order to keep the focus on providing intuition—rather than detail—about the underlying principles, this is in some instants done in a somewhat simplified/idealized way that may not withstand the most rigorous scientific scrutiny. Nevertheless, despite the author's best attempt to provide a clear and accessible account of the relevant material without sacrificing too much fundamental information, the following sections may be a challenging read. For a summary of the following sections, please refer to Figure 2 and Table 1.

VIBRATORY MODES AND MUCOSAL WAVES

Early computational modeling[51] has shown that the laryngeal sound generator needs two oscillatory degrees of freedom in order to lapse into and remain in self-sustaining oscillation.[52] One degree of freedom is constituted by a *translational* vibratory component of the vocal folds. This most fundamental vibratory component allows for movement of the vocal folds along the medio-lateral dimension, thus opening and closing the glottis and gating the airflow. Interestingly, if the system would be modeled with only this one degree of freedom, the vocal folds would likely just be blown apart by the tracheal air stream and then stay medialized/separated. Therefore, a second degree of freedom is required, which can be constituted in either of two ways (note that in reality, the following two phenomena are likely both contributing to vocal fold vibration at various degrees, depending on laryngeal and vocal tract configuration, subglottal pressure, and individual vocal fold morphology).

1. In the presence of a coupled supraglottal vocal tract, the delayed response of the supraglottal air column, caused by the mass (inertia) of the air molecules, sets up an asymmetric aerodynamic driving force that allows the intraglottal air pressure to become negative at the end of the open phase, thus facilitating vocal fold closure.[53] This may result in nonlinear interactions between vocal tract and voice source.[54] Major influence factors to this phenomenon are the coupling strength between source and vocal tract and the resonance structure of the vocal tract (see section "Nonlinear source-filter interaction effects" in Part 2 of this article for details).
2. The second degree of freedom can also be provided by a *rotational* vibratory component, constituted by out of phase movement of the inferior and superior vocal fold margins.[55] This creates a time varying glottal profile (convergent in the closing phase, divergent in the opening phase), also facilitating an asymmetric driving force in analogy to what has been indicated above. In the larynx, this phenomenon typically manifests itself through a so called mucosal wave at various levels of magnitude. In the presence of such a mucosal wave, vocal fold vibration is characterized by a vertical phase delay:[56] the inferior vocal fold edge leads the vibration, with the superior edge trailing behind. The magnitude of the phase delay is dependent on the vertical speed of the mucosal wave and typically ranges from 60 to 90 degrees, i.e., 1/6 to 1/4 of the vibratory cycle.[57]

As a very simplified first approximation, the vocal folds can be modeled as two parallel vibrating masses or

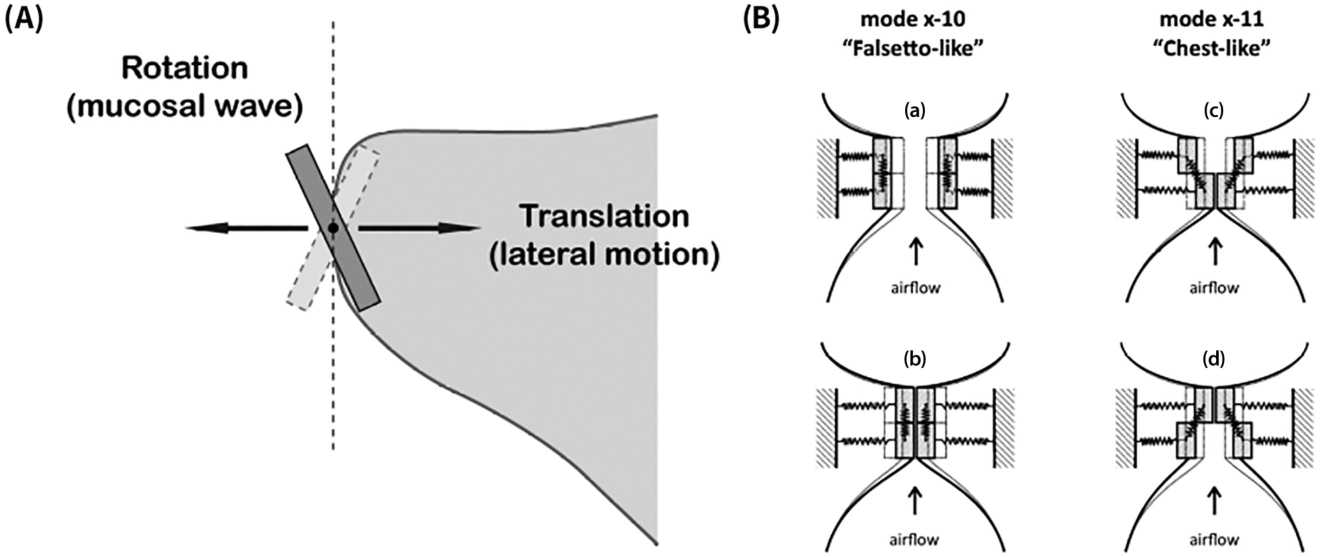

Figure 2. Simplified schematic illustration of vocal fold vibratory modes, with vocal folds modeled as thin plates capable of *translational* (i.e., away from the glottal mid-line and toward the glottal mid-line) and *rotational* (i.e., turning) motion. (A) Symbolic illustration of vibratory components in the right vocal fold: translational (signifying medio-lateral vocal fold motion, enabling glottal opening and closure) and rotational (representing vibratory phase delay along the inferior-superior dimension, i.e., the vertical aspect of mucosal waves).* (B) Simplified schematic illustration of two characteristic eigenmodes of vocal fold vibration: x-10 (a, b—representing the translational vibratory component) and x-11 (c, d—representing the rotational vibratory component). The vocal folds are shown at two opposite phases of the vibratory cycle.**

*** Taken from B. Story, "An overview of the physiology, physics and modeling of the sound source for vowels," *Acoustical Science & Technology* 23, no. 4 (July 2002); used with permission.**

**** Taken from J. G. Svec, "On vibration properties of human vocal folds: Voice registers, bifurcations, resonance characteristics, development and application of videokymography" (Doctoral dissertation, University of Groningen, the Netherlands, 2000); used with permission.**

two vibrating plates (Figure 2). When considering the possibilities of motion of these idealized masses or plates, the two mechanical vibratory components described earlier come into play: the *translational* vibratory component—fundamental to vocal fold vibration—is always present as soon as the vocal folds oscillate, facilitating glottal opening and closure. Disregarding the aforementioned option of a coupled supraglottal vocal tract for now (this concept is discussed in more detail in Part 2), the second feature is the *rotational* vibratory component, introduced by the vertical phase delay of vocal fold motion in the presence of a mucosal wave.

These two vibratory components (translational and rotational) are schematically illustrated in Figure 2A. When considering the vocal folds as a mechanical dynamic system consisting of two simple strings, these vibratory components would constitute so called vibratory modes or eigenmodes.[58] In particular, the translational vibratory component is the equivalent of the so-called x-10 (or x-n0) mode, and the rotational vibratory component is likened to the x-11 (or x-n1) mode. More such modes exist, and vocal fold vibration can be explained as a superposition of a certain number of eigenmodes at various amplitudes. In periodic (i.e., regular) vocal fold vibration, the observed vibratory patterns of the vocal folds are made up almost exclusively of low-order modes such as x-n0 and x-n1,[59] while higher order modes have a stronger influence in irregular vocal fold vibration, as found in screams in some singing styles, or in pathologic voice production.

ANATOMY AND PHYSIOLOGIC CONTROL

The anatomic boundary conditions for the distinction between chest and falsetto registers are constituted by the layered structure of the vocal folds, described by the body-cover theory.[60] While the cover consists of epithelium and the superficial (outer) and intermediate (middle) layer of the *lamina propria*, the body is made up of the deep layer of the *lamina propria* and the thyroarytenoid muscle (TA; note that this muscle is often described as having two portions, i.e., the more lateral *m. thyrovocalis* and the more medial *m. thyromuscularis*).[61]

The choice of chest vs. falsetto register is mainly controlled by contraction/relaxation of the TA. In chest, the TA is typically more active/contracted than in falsetto, leading to a thickening, shortening, and medial bulging—and thus at least partial adduction—of the membraneous portion of the vocal folds. For this reason, this maneuver can also be called membranous medialization.[62]

The contraction of the TA typically leads to an increased tension of the vocal fold body, which, all other things being equal, facilitates a relaxation of the vocal fold cover. Particularly at lower degrees of activity in the cricothyroid muscle (CT), considered to be an antagonist to the TA,[63] this results in different degrees of stiffness in the vocal fold body and the cover, therefore allowing a certain degree of vibratory independence of these two portions of the vocal folds.[64] In such a case, the vocal fold cover typically assumes an x-11 (or x-n1) vibratory mode, introducing a phase delay between the inferior and the superior vocal fold edge during vocal fold vibration, thus exhibiting a mucosal wave. The resulting vibratory characteristics are typically an identifying hallmark of chest (or modal) register, sometimes also termed mechanism M1. (In this context it is worth noticing that individual vocal fold morphology can play a huge role. Some persons may as a baseline have a more "chest-like" voice than others, simply because their vocal fold mucosa is thicker, more pliable, and thus more prone to exhibiting tranlational or x-11 vibratory modes.)

In contrast, relaxation of the TA and contraction of the CT typically are associated with a greatly reduced or even absent mucosal wave, thus considerably decreasing the rotational vibratory component (and thus more or less eliminating the x-11 or x-n1 mode, or at least limiting it to the epithelium instead of the entire vocal fold cover).[65] Such a vibratory pattern would then quintessentially constitute the falsetto register, sometimes also termed mechanism M2.

Both these scenarios (TA and CT at absolute antagonistic levels of engagement) describe stereotypical cases. In reality, the activity of the TA vs. CT, particularly in trained singers, can also be varied gradually, likely leading to intermediate scenarios with various contribution of the rotational vibratory component. The singer's huge potential to diverge from the aforementioned stereotypical scenarios gives rise to two possible—and not mutually exclusive—interpretations: There may be a great potential for producing what might be considered "mixed voice" at the laryngeal level; contrasting modeling and textbook examples, identification of vocal registers at the laryngeal level is in reality much less trivial than hoped for. Finally, vocal tract interactions (discussed in Part 2) may have an influence that is not to be neglected.

A highly simplified summary of the relation between vibratory components, eigenmodes, and the resulting registers (most certainly not covering the entire complexity of phenomena seen in reality) is provided in Table 2.

INFLUENCE OF VOCAL FOLD ADDUCTION

A somewhat surprising alternative physiological explanation for the chest (modal) vs. falsetto dichotomy is given by Titze, suggesting a "spectral slope transition" (see below for acoustic effects) that "can occur as a result of either an *adductory* change or a *loudness* change" (text emphasis by CTH).[66] Apart from the unmentioned implicit contribution of the adductors (i.e., the lateral cricoarytenoid [LCA] and the interarytenoid [IA] muscles), Titze suggests that the bottom of the vocal fold may be more adducted in modal (chest) register than in falsetto via contraction of the TA. This conceptualization is in line with later empirical findings in both humans and dogs, showing that cartilaginous adduction (through the LCA and IA muscles) and membranous medialization (via the TA) can be controlled independently.[67] That independence of motor control facilitates the production of a wide variety of different sound qualities at the laryngeal level.

ACOUSTIC MANIFESTATION OF THE CHEST AND FALSETTO REGISTERS

In chest register, both the membranous adduction (via the vertical bulging of the vocal fold) and the vertical vibratory phase delay between the inferior and superior vocal fold margins prolong the *closed phase*, or the time interval of a glottal cycle during which the glottis is closed (either fully, or—in the case of breathy voice

TABLE 2. Simplified summary of the relation between vocal fold vibratory components, vibratory eigenmodes, observable oscillatory phenomena, and resulting vocal registers.

vibratory component:	**translational**	**rotational**
eigenmode:	x-10	x-11
vibration mechanics:	medio-lateral vocal fold vibration (glottal opening and closing)	phase-inverted vibration of inferior and superior vocal fold margins; constitutes inferior-superior aspect of mucosal wave
stereotypical cause:	always present during vocal fold vibration	TA contraction, CT relaxation; anatomical predisposition (thick mucosa)
resulting vocal register:	either **falsetto** register (in the case of a reduced rotational component) or **chest** register (in the presence of a rotational component)	needed for **chest** register

production—partially, typically in the more anterior part). The relative duration of the closed phase, often expressed through the closed quotient (i.e., the duration of the closed phase divided by the respective glottal cycle's period) typically corresponds with the strength of noteworthy harmonics (i.e., overtones) found in the voice source.[68] Within limits, reached in "pressed phonation," a longer closed phase results in stronger overtones and thus a more "carrying" voice.

A simplified explanation for this phenomenon—for instance, disregarding nonlinear vocal tract influences—is provided as follows: During each vibratory cycle, the glottis is open for a certain duration. During this open phase, higher-frequency voice source harmonics (overtones) are dampened out in the trachea. Therefore, a shorter open phase, and thus a longer closed phase, typically results in a "brighter" voice sound with stronger overtones.[69] Furthermore, as a first approximation, the acoustic pressure (i.e., the sound) created in the larynx is proportional to the rate of change of air flow, with the main acoustic event typically occurring during air flow deceleration at the end of the open phase. A quicker deceleration of the glottal air flow leads to more abrupt pressure changes (described in the concept of the *maximum flow declination rate* [MFDR]) in the larynx,[70] producing increased acoustic output.[71] Because chest register typically has a longer closed phase than falsetto register, it is, as a rule of thumb, characterized by stronger overtones. Note that in this context, the degree of (cartilaginous) adduction has an impact on the closed phase duration, introducing a further layer of complexity into the concept of sound quality control at the laryngeal level.

LARYNGEAL EVIDENCE OF A REGISTER TRANSITION

Any laryngeal sound production phenomenon in speech and singing can be assessed on two levels: on a purely output-related level (thus treating the voice as a "black box"), only considering the radiated sound as documented by the acoustic signal; or also considering the laryngeal dynamics of the voice production phenomenon. A practical, noninvasive method for the latter approach is constituted by electroglottgraphy (EGG). The EGG signal is a physiological correlate of vocal fold contact during phonation, measuring the relative vocal fold contact area (VFCA). Within reason, it can provide in many cases an approximate indication about the relative duration of vocal fold contact per glottal cycle, thus serving as an inexact "proxy" for glottal closure.[72]

In section 2 of this article, the example presented in Figure 1 was briefly discussed on perceptual grounds, indicating that it contained two candidates for registration events: one at $t \approx 3$ s and the other at $t \approx 5.5$ s. It was claimed that the first transition at $t \approx 3$ s was a laryngeal register transition. This assumption is based on the EGG data presented in Figure 1D and E. The dEGG wavegram shown in Figure 1D provides an intuitive visualization of the development of relative duration of vocal fold contact per glottal cycle.[73] In a dEGG wavegram, overall time is mapped onto the x-axis, going from left to right. The relative distance between the dark horizontal line (representing the contacting event within each glottal cycle) and the light horizontal line (representing the de-contacting event) documents the temporal development of the relative duration of vocal fold contact per cycle. Around $t \approx 3$ s there is a clearly observable and relatively abrupt reduction of that relative contact duration, as is typically seen when changing from chest to falsetto register. Because the EGG signal in many cases is an imprecise proxy of glottal closure, it can thus be hypothesized that at $t \approx 3$ s a reduction of the closed phase also occurred. That presumed reduction of the closed phase was likely brought about by relaxation of the TA (reducing the vertical bulging of the vocal fold and thus reducing membranous medialization of the vocal folds) and shortening of the glottal closure duration by reducing the vertical phase delay between the inferior and superior vocal fold margins (via decrement of the rotational vibratory component, i.e., the x-11 mode—recall the previous discussion).

An alternative portrayal of that laryngeal register transition is provided in the left panel of Figure 1E. The two EGG waveforms, representing one glottal cycle (normalized in time) immediately before and after the register transition clearly document the reduction of the relative duration of vocal fold contact that is characteristic for a chest-falsetto transition. In contrast, the laryngeal evidence for the event occurring at $t \approx 5$ s (right panel of Figure 1E) reveals a stable vibratory regimen, thus suggesting that that transition at $t \approx 5$ s is most likely not of laryngeal nature, but is rather caused by resonance effects (see section 3 for a discussion).

FALSETTO VS. HEAD VOICE REGISTER

Particularly in the German speaking community, some authors seem to make a clear distinction between the terms "falsetto" and "head" register. For instance, Seidner and Wendler suggest that the term falsetto should be exclusively used in the context of male voice, while in females the register above the *primo passaggio* should be termed "head voice" (*Kopfstimme*).[74]

However, when considering vocal registers at the laryngeal level via vibratory mechanisms, in the opinion of this author there is no reason to assume that the register above the chest is functionally any different in females and males, regardless of whether it is called falsetto, head, M2, or "thin." Both females and males have comparable laryngeal anatomy and morphology, and they have access to the same laryngeal configurations through activity in the same intrinsic laryngeal muscles.[75]

It is speculated here that different vocal tract settings and resonatory strategies in various singing styles may have an influence on whether that register is perceived as "supported" or not, and this might then perhaps have an influence on the chosen terminology. Furthermore, the confusion of falsetto register and head voice may perhaps come from the somewhat surprising notion that in temporary classical singing, males likely extend the chest register beyond the *zona di passaggio* (D_4), mainly applying resonatory adaptations, while females probably seek a laryngeal register transition, switching from chest to falsetto. Rigorous empirical research targeting both voice production, perception, and potentially also proprioception is required to shed more light on this matter.

PEDAGOGIC RELEVANCE

It has been shown here that, broadly speaking, vocal sounds produced in chest register typically have stronger overtones than those produced in falsetto register, resulting in a "brighter" and thus more "carrying" voice. This may give rise to the somewhat inconsiderate assumption that it might be advantageous to always sing in chest register, rather than falsetto register. On physiological grounds, that notion might be supported by maximizing the closed phase (recall the discussion above, highlighting the general relation between closed phase and occurrence of overtones), through extreme TA dominance (relative to CT activity) and/or maximizing vocal fold adduction. In the opinion of this author, however, such an extreme strategy would be certainly unfavorable, to say the least, for the following reasons:

1. Most probably, each voice has its own closed quotient limit, likely influenced by individual laryngeal anatomy and morphology. Such a limit should be determined and approached carefully in vocal training. Surpassing this limit, typically through excessive vocal fold adduction and helped by TA dominance, will result in "pressed voice," giving rise to an unwanted reduction of the overall amplitude of the voice source spectrum and a reduction of the MFDR and flow pulse amplitude.[76] Furthermore,

such a phonation scenario even bears the potential risk of inducing vocal injury via increased vocal fold collision force.[77]

2. TA contraction has a more or less complex influence on fundamental frequency.[78] Higher frequency ranges can only be reached with a relaxed TA, facilitating falsetto register. In such a glottal configuration, the better part of the longitudinal tension is borne by the vocal fold cover, which is more suited for high frequency oscillation, due to its biomechanical properties.[79] Failure to relax the TA may thus considerably limit the achievable vocal range. (In plain terms, in falsetto register, higher pitches can typically be reached, as compared to chest register.)
3. An excessive TA dominance likely impedes the ability to blend or mix the chest and falsetto registers (Part 2), potentially introducing audible register breaks into the voice range. While such features may be part of some singing style aesthetics, they are certainly undesirable in classical singing. (In this context, one may argue that some singing styles actually would never make use of falsetto register. However, even in such cases a certain degree of freedom in TA contraction [and vocal fold adduction] may be required, allowing the singer to adeptly vary the created vocal timbre through voice source control on the laryngeal level.)

The discussion presented here suggests that, greatly simplified, the singer's choice of register is a compromise, influenced by the following considerations: chest register produces stronger overtones; falsetto register produces higher pitches. Likely, the choice is not a (binary) dichotomy, but has to be made along a continuum. This is where mixing or blending the registers comes into play, a notion that will be discussed in Part two.

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