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ORIGINAL ARTICLE

Mirroring the voice from Garcia to the present day: Some insights into singing voice registers

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Abstract

Starting from Garcia's definition, the historical evolution of the notion of vocal registers from then until now is considered. Even though much research has been carried out on vocal registers since then, the notion of registers is still confused in the singing voice community, and defined in many different ways. While some authors consider a vocal register as a totally laryngeal event, others define it in terms of overall voice quality similarities. This confusion is reflected in the multiplicity of labellings, and it lies in the difficulty of identifying and specifying the mechanisms distinguished by these terms. The concept of laryngeal mechanism is then introduced, on the basis of laryngeal transition phenomena detected by means of electroglottography. It helps to specify at least the laryngeal nature of a given singing voice register. On this basis, the main physiological, acoustic, and perceptual characteristics of the most common singing voice registers are surveyed.

Key words: *Laryngeal mechanism, singing voice, vocal register*

Introduction

Before the nineteenth century, knowledge about human phonation was limited to what could be perceived by auditory perception and proprioceptive sensations, or observed from outside during phonation and inside on cadavers. The singing voice registers are a known fact, related to perception of different voice qualities. In this context, the singing voice teacher Manuel Garcia II (1805–1906) shows not only an interest in the voice sound quality but also in the underlying vocal physiology mechanisms. On November 16th, 1840, he presented the results of his observations as a voice teacher and his experiments on the human voice to the French *Académie des Sciences* (1), prior to the publication of his famous singing voice method *Ecole de Garcia: Traité complet de l'art du chant* (2). In this paper, he claims that the human voice is composed of different registers: *poitrine* (chest), *fausset-tête* (falsetto-head), and *contre-basse* (counter bass). He defines the registers as follows: 'By the word register we mean 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'.¹ Therefore, Garcia pioneers the definition of vocal registers in relation to a given mechanical principle, independently of any timbre variation. In his definition of vocal registers, the concept of a mechanical principle prevails over the perceptual dimension. Basing his rationale on physiological observations of the larynx position, he demonstrated that the falsetto and head registers result from the same laryngeal mechanism, their difference being a timbre effect.²

Nowadays, we have experimental techniques to which Garcia did not have access at that time. How has the knowledge about singing voice registers evolved since Garcia's time? How are the vocal registers defined and identified? What are their physiological, acoustic and perceptual attributes? By reviewing the historical evolution of the notion of vocal register, this paper aims to provide a possible

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guide for a better understanding of this notion. A brief overview of the evolution of definition, numbers and labellings will be given. The different means of identifying a vocal register will be discussed, and the concept of laryngeal mechanism will be introduced, on the basis of laryngeal transition phenomena. Finally, the most common singing voice registers will be reviewed, and their physiological, acoustic and perceptual properties will be given.

Historical evolution of the notion of vocal register since Garcia

From Garcia to the present time, the notion of vocal registers has evolved in many ways. In particular, this evolution concerns the definition of a vocal register, the number of registers identified and their labelling.

From Garcia to the 1960s

As mentioned in the introduction, the singing teacher Manuel Garcia in 1847 is considering three main different registers, *chest*, *falsetto-head* and *contre-basse*, the other possible registers, such as *voix mixte*, sharing similar mechanical principle with these main ones (for a detailed discussion about Garcia's *falsetto-head* register, we refer the reader to (3)). The frequency ranges of these registers are shown in Figure 1. Interested in understanding the physiology of these registers, Garcia explores his own larynx and those of a few of his students by using a laryngoscope, a clever observation tool which would give rise to our present endoscopic camera. It

consists of a small mirror fixed to the end of a long handle and placed at the back of the throat (see Figure 2). When the throat is lighted in the proper way, the glottis may be observed from above. The laryngoscope was already available in the early nineteenth century—Babington used it in 1827 (4)—so Garcia did not invent it, but he was the first to use it successfully, being able not only to see the vocal folds at rest, but also in the act of singing. Garcia's observations were communicated to the Royal Society by Dr Sharpey on May 24th, 1855 (4,5).

In 1880, the physiologist and voice production teacher Emil Behnke and the throat surgeon Lennox Browne also made use of the laryngoscope to obtain *in vivo* images of the glottis. Behnke defines the vocal registers as follows: 'a register consists of a series of tones which are produced by the same mechanism. [...] There are, broadly speaking, three registers in the human voice, and the mechanisms are plainly visible, as follows: 1) During the lowest series of tones the vocal ligaments vibrate in their entire thickness. 2) During the next series of tones the vocal ligaments vibrate only with their thin inner edges. 3) During the highest series of tones a portion of the vocal chink is firmly closed, and only a small part of the vocal ligaments vibrates.' ((4), p. 86). In this definition, similarly to Garcia's, the concept of laryngeal mechanisms is underlying. On the basis of these physiological observations, he adopts Curwen's *thick*, *thin* and *small* labelling, and he describes three registers for the male voice (*lower thick*, *upper thick* and *upper thin*) and five registers for the female voice

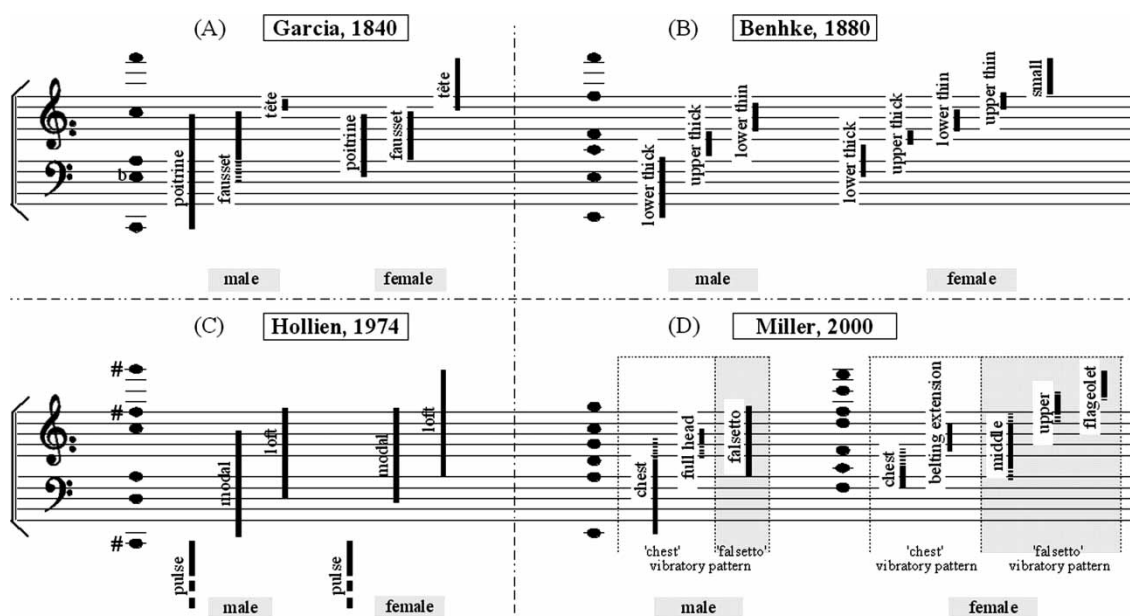


Figure 1. Frequency range of human voice and vocal registers, as defined by different authors: (A) Garcia (1), (B) Behnke (4), (C) Hollien (11), (D) Miller (17).

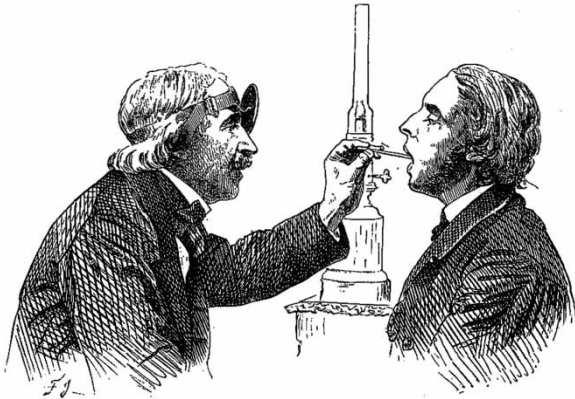


Figure 2. The laryngoscope. From (2).

(*lower thick, upper thick, lower thin, upper thin and small*). Their corresponding frequency ranges are shown in Figure 1. The transition between *thick* and *thin* registers is characterized by a break which occurs around F4 or F4# in both male and female voices, individual differences apart.

In the early twentieth century, whereas few singing teachers maintain that a 'natural' voice has only one single register (6,7), the general tendency is to accept the existence of at least two and at maximum five registers. The term 'register' is even sometimes replaced by 'mechanism', for example by Wilcox (6,7) who suggests the terms 'heavy mechanism' and 'light mechanism'.

The terms used to label the vocal registers are abundant and author dependent, and most of the time their usage is ambiguous. In 1963, a literature survey summary concerning the pitch range and labelling of voice registers (8) mentions that 'the only secure common denominator for defining a register is by means of its range on the musical scale.' Reasonable agreement is found on 'the average pitch of the boundaries between registers, i.e. the breaks or voice transitions.' It is also mentioned that these average boundaries do not vary much with the type of voice, and that the nature of the breaks is 'still a matter of controversy'.

The two most common registers are labelled as *chest* register and *head* or *falsetto* register. The distinction between *head* and *falsetto* is very much author dependent. In his time, Garcia placed the *falsetto* register between *chest* and *head* register, and it may thus correspond to a middle register, as suggested by Vennard (7). Yet, when the *head* register is recognized as a distinct register, it is very often placed between *chest* and *falsetto*. Otherwise, either it is put aside, or it replaces the *falsetto* register, in the case of female voice for instance. The two main registers overlap in a frequency region where a third register is sometimes mentioned, and

labelled as *medium, mid, middle*, or *mixed* register. It may correspond to the French *voix mixte* or the Italian *voce mista*. Two additional registers are mentioned at the extreme low and high ends of the frequency range: the *Stroh bass* register, and the *bell, flute* or *whistle* register.

From the 1960s to the 1980s

From the early 1960s to the 1980s, a good deal of research effort was dedicated to the understanding of the acoustic, mechanical, and physiological properties of these registers. Working on excised larynges, the physicist Janwillem Van den Berg 1963 explored the vibratory pattern of the vocal folds and the influence of the subglottal resonance. He came to the conclusion that the *mid* register may not be considered as a distinct register (9). The physician Minoru Hirano, together with two voice teachers William Vennard and John Ohala, investigated the role of intrinsic laryngeal muscles using electromyography (10). They found that the vocalis muscle is essential to register regulation, its activity being greater in *heavy* register. In particular, the vocalis muscular activity decreases during a register shift from *heavy* to *light* and increases from *light* to *heavy*. The lateral cricoarytenoid, interarytenoid and cricothyroid muscles also contribute to register regulation, but to a smaller extent.

In 1974, the speech scientist Harry Hollien reconsiders the definition, numbering and terminology of registers (11). He defines a vocal register 'as a series or range of consecutively phonated frequencies which can be produced with nearly identical *vocal* quality and that ordinarily there should be little or no overlap in fundamental frequency between adjacent registers. Furthermore, [he maintains] that a voice register is a totally laryngeal event and, before the existence of a particular register can be established, it must be operationally defined: 1) perceptually, 2) acoustically, 3) physiologically and 4) aerodynamically.' With regard to this definition based on a laryngeal entity, he considers three major registers, which have been experimentally validated, and to which he gives unfamiliar but also 'uncontaminated' labels: *pulse*, *modal* and *loft* registers. The pulse register includes *vocal fry*, *creak* and *stroh bass* registers; the modal register includes *chest*, *head*, *low*, *mid* and *high*; the *loft* register is the equivalent of the phoneticians' and speech pathologists' *falsetto* register. Their corresponding frequency ranges are shown in Figure 1. Hollien mentions a fourth register, the *flute*, *whistle* or *pipe*, which he puts aside because of a lack of empirical information and experimental exploration.

Hollien's significant paper has pointed out the confusion around the concept of vocal registers among the voice community, and it may have contributed to the emergence of an international discussion. In the late 1970s, spurred on by the Collegium Medicorum Theatri (CoMeT), an international organization composed of physicians, voice scientists, voice coaches and voice pathologists, a committee on vocal registers was formed in an attempt to clarify the notion of vocal registers and to find a consensual position among the international voice community. The committee agreed on five points, which are reported by Hollien (12):

1. Registers exist: voice registers exist in the speaking and singing voice, and they 'must be recognized as an entity'. Their perceived acoustic effects may be compensated for by appropriate training, if this 'is considered desirable'.
2. Singing/speaking registers: 'vocal registers in singing and voice registers in speaking (or in the untrained voice) are different and separate entities and must be treated as such'. However, they 'may overlap in function and probably have common physiological roots in the larynx'.
3. To 'remove' registers: two postulates are stated by the committee. On the one hand, 'eliminating or concealing register effects is desirable for the classical/western, concert/opera mode of singing'. On the other hand, 'register effects can be fundamental to certain types of singing'. It is also important to keep in mind that 'voice registers cannot be removed as they are physiologically given.'
4. The source of registers: First, the committee has 'accepted the notion that there probably are two sources for registers—the larynx and the vocal tract'. However, this point seems to have raised a great debate among the committee members. 'A substantial minority of the committee argued in favor of the source (of a voice register) being only laryngeal and that the other so-called register-like phenomena actually are some sort of quality/timbre events.'

This latter position is in line with Garcia's definition. Unfortunately, no mention of what defines and identifies a register in the human voice is given in the report. This may explain the controversy about the question of the source of registers. As a consequence, a great debate was also raised by the labelling question.

5. Labels: The committee has rejected the use of so called 'old terms', and in particular *chest* and *head* which are based upon singers' sensations. Two main proposals are made. The first suggestion is to number them: '#1: for the very

lowest of registers, probably used only in speaking (old terms: *pulse*, *vocal fry*, *creak*), #2: that (low) register, which is used for most speaking and singing (old terms: *modal*, *chest*, *normal*, *heavy*), #3: a high register used primarily in singing (old terms: *falsestto*, *light*, *head*), #4: a very high register usually found only in some women and children and not particularly relevant to singing (old terms: *flute*, *whistle*).⁹ An additional register is referred to as '#2A' and defined as 'that "register" which is described by many voice teachers as in the middle of the frequency range [...] (old terms: *head*, *mid*, *middle*, *upper*).⁹ The second suggestion is to favour 'new terms, generic terms, those that are clear and easy to understand', such as the pair of terms *heavy*, *light*, or *lower*, *upper*.

From the 1980s to the present time

Despite this great effort at clarification, the voice community remains divided on the question of vocal registers. The existence of at least two main laryngeal vibratory mechanisms has been experimentally validated. Among the speech community, an implicit agreement is found on three registers (*pulse* or *vocal fry*, *modal* or *chest*, and *falsestto* registers), in relation to specific laryngeal adjustments. In the singing voice community, the definition, numbers and labelling of registers are still a matter of debate, and they continue to vary among authors. Indeed, vocal registers have an acoustical and perceptual reality for singers, which cannot be ignored. On the one hand, a vocal register is defined by its laryngeal mechanical properties (13–15), following in this sense Garcia, Benhke and Hollien. As an example, Sakakibara (15) proposes the following definition: 'the vocal register is a set or range of serial sounds that are similar in perception and produced by similar vocal fold vibratory patterns.' On the other hand, a vocal register is defined by its characteristic voice quality, following in this sense Large ((16), cited in (17)). As an example, Titze mentions 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.'⁹((18), p. 253) These two approaches of the notion of vocal register are sometimes implicitly combined. In a recent thesis on registers in singing (17), the singer and voice teacher Donald Miller points out the distinction between registration defined 'as an exclusive feature of the voice source' and the 'integrated approach to registration, including adjustments of the vocal tract, as well as those of the source'. He chooses the latter approach, but defines the 'natural registers' as registers related mainly to

glottal source adjustments. These natural registers are designated ‘chest’ and ‘falsetto’, and the author refers to the ‘chest vibratory pattern’ and ‘falsetto vibratory pattern’ when emphasizing the voice source characteristics of a given register. According to this author, the female voice is divided into five registers: *chest* and *belting* registers, which both have the chest vibratory pattern, and *middle*, *upper* and *flageolet* registers, which all have the falsetto vibratory pattern. The male voice is divided into four registers: *chest*, *full head* and *mezza voce* registers, which all have the chest vibratory pattern, and *falsetto* register, which has the falsetto vibratory pattern. The corresponding frequency ranges are shown in Figure 1.

Conclusion: what are the vocal registers?

In his time, Garcia was distinguishing vocal registers on the basis of a ‘mechanical principle’ which he related to a laryngeal event. Following Garcia’s path, other authors, such as Benhke, Hollien or Roubeau, have explored the concept of laryngeal-related vocal registers with the help of more and more sophisticated experimental techniques: laryngoscopy, cinematography, electromyography, electroglottography (EGG), etc. The understanding of laryngeal vibratory mechanisms has become more refined.

Yet, a vocal register classification based only on laryngeal phenomena does not take into account the great timbre variations which can be achieved in singing. This may explain that, even today, the notion of vocal registers in singing remains very often a matter of debate among the singing voice community. Whereas some authors define the registers exclusively on the basis of an underlying laryngeal mechanical principle, others prefer to define them on the basis of sound voice quality. In this context, to find a consensual position on the labelling of registers is inevitably problematic, but the core of this problem is less the terminology itself than the ‘failure to identify and specify the mechanisms distinguished by the terms’, as pointed out by Miller ((17), p. 32).

In the next section, we will see how the problem of identifying the mechanisms related to singing voice registers has been partly solved, at least at the laryngeal level.

Transition phenomena: how to identify a laryngeal mechanism

The reason for defining at least two registers in human phonation comes from the discontinuities or transition phenomena, which can occur voluntarily or involuntarily during the production of voiced

sounds. Different kinds of transition phenomena are listed in the literature, in particular periodicity, timbre, and laryngeal transitions. They will be briefly presented here. We will then focus on the laryngeal vibratory mechanisms, the consistency of which is evinced by laryngeal transition phenomena.

Detection of transition phenomena

A transition phenomenon may result from psychoacoustic properties of human perception. The ‘periodicity transition’ distinguished by Titze (18,19) is an example of such a transition. It refers to ‘changes in vocal quality that occur whenever glottal pulses are perceived as individual events rather than a continuous auditory stimulus’ (19). According to this author, it accounts for the distinction between *pulse* (or *vocal fry*) and *chest* registers. A given voice production is perceived as pulsed when its fundamental frequency F_0 is lower than a 70-Hz ‘crossover’ frequency, and perceived as non-pulsed above this frequency. In the case of a F_0/n subharmonic pattern, the crossover frequency is $n \times 70$ Hz. According to Titze, the reason for this perceptual fact lies in formant energy damping (related to the formant bandwidth) over the fundamental period: waveforms are perceived as pulse-like if the formant energy during one excitation is sufficiently damped out before the next excitation occurs. This author defines the *pulse-chest* registers boundaries on the basis of this periodicity transition.

Transition phenomena may also result from noticeable timbre variations (17,19,20), which may or may not be related to a laryngeal adjustment.

According to Titze (18,19), timbre transitions are characterized by an abrupt voice quality change, which is associated with a spectral energy change in the high-frequency part of the sound spectrum, i.e., a modification in the spectral slope. This spectral change may come from a variation in the glottal flow derivative discontinuity and the return phase, which can be more or less abrupt. From the acoustic point of view, it may result from an interference between a subglottal resonance and the vocal fold driving pressure.

According to Miller (17), either these transitions have a laryngeal source, or they result from resonance strategies, also called ‘formant tuning’. In this latter case, a vocal tract resonance is adjusted to match a given harmonic in frequency, reinforcing the energy in this harmonic frequency band. The tuning process may induce the presence of strong acoustic standing waves, which in return can affect the vocal fold vibratory movement, yet in a more subtle way than in the case of a laryngeal adjustment (17).

It is difficult to give strong evidence of these vocal tract adjustments, as the vocal tract resonances are difficult to measure reliably from the acoustic signal, especially when the harmonic spacing is broad. On the contrary, the laryngeal transition phenomena, which are related to a sudden adjustment of the glottal vibratory pattern, are more easily detectable. For instance, the pitch jump is the most common and obvious transition phenomenon which can occur during male and female phonation, in speech and singing (13,21–23). Avoided in the classical singing technique, it is used as an ornament or even a singing style in other vocal cultures, such as the Tyrolean or African yodel (20,24). Evidence has been given that this transition phenomenon is only related to a biomechanical laryngeal adjustment, as it can occur on excised larynges without the presence of vocal tract loading (25). As illustrated in Figure 3, a vocal fold is a heterogeneous layered structure (26), composed of the cover (mucosa, epithelium and superficial layer of lamina propria), the transition (intermediate and deep layers of lamina propria, also called vocal ligaments), and the body (vocalis muscle). The abruptness of the frequency jump is accounted for by a sudden variation of the vibrating mass in action, induced by a decoupling of the vibrating layers due to a modification in vocal fold tension (13). As this modification in tension may be gradual, these frequency jumps are considered to be manifestations of bifurcations in the vocal fold vibratory mechanism (23).

A noticeable frequency jump often goes with a jump in the open quotient (21,27), which can be detected on electroglottographic signals. This jump occurs, for instance, during the production of a glissando, as illustrated in Figure 4. The open

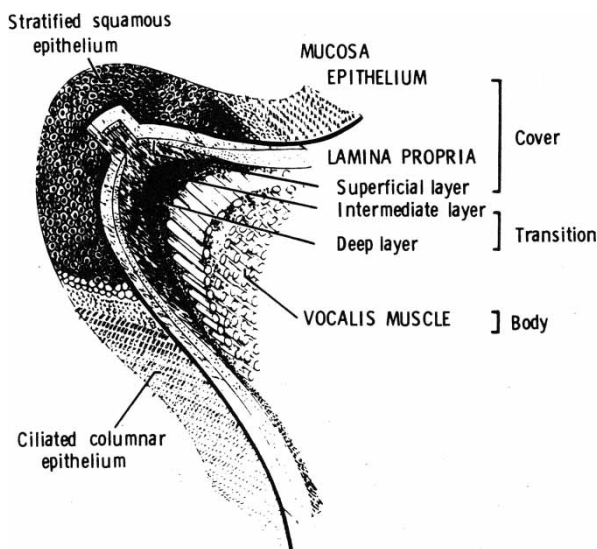


Figure 3. The vocal-fold layered structure. From (26).

quotient jump is one characteristic of a laryngeal transition. As illustrated in Figure 4, it may occur even in the case when the singer manages to smooth the transition, thus avoiding the frequency jump (27).

Laryngeal transition phenomena can be characterized by a noticeable change in the vocal fold contact area, which can easily be detected using electroglottography by an abrupt EGG amplitude variation (22,28). On the basis of these transition phenomena detected by electroglottography, the concept of laryngeal mechanism has been defined (13,22,29). This concept, which is of great help in clarifying the notion of vocal registers in terms of laryngeal configuration and glottal vibratory properties, will now be summarized.

The laryngeal mechanisms

The variation in EGG amplitude which goes with a noticeable register break (28,30) can similarly be observed during a register transition without any noticeable break (22,29). Therefore, a register transition associated with a laryngeal adjustment can easily be identified by an amplitude change in the EGG signal, as illustrated in Figure 4. Even when the singer is skilled enough to smooth the transition, so that no break or timbre change can be noticed, the vocal register transition can be detected on the EGG signal.

On the basis of these laryngeal-transition phenomena, the notion of laryngeal mechanism has been defined (13,22,29). The choice has been made to number them, following in this way one of the 1983 CoMeT labelling positions (12). During the production of a glissando from the lowest to the highest possible pitches, three laryngeal transitions can be detected, as shown in Figure 5. These transitions delimit four frequency regions, in which the voice is produced by the use of a precise laryngeal vibratory mechanism (laryngeal mechanism M0 to M3).

A laryngeal mechanism can be considered as a substitute for a vocal register which would totally be defined as a laryngeal entity. The corresponding register counterparts of the laryngeal mechanisms are given in Table I.

The laryngeal mechanisms correspond to different vocal fold configurations which will now be described. A schematic representation of the two main ones, M1 and M2, is plotted in Figure 6.

In laryngeal mechanism M0, the vocal folds are very short and thick, all the layers being slackened and pliant (11,26). Vocalis, cricothyroid, and interarytenoid muscular activities are minimal, as compared to other laryngeal mechanisms (26,31). The closed phase is usually very long. The lowest

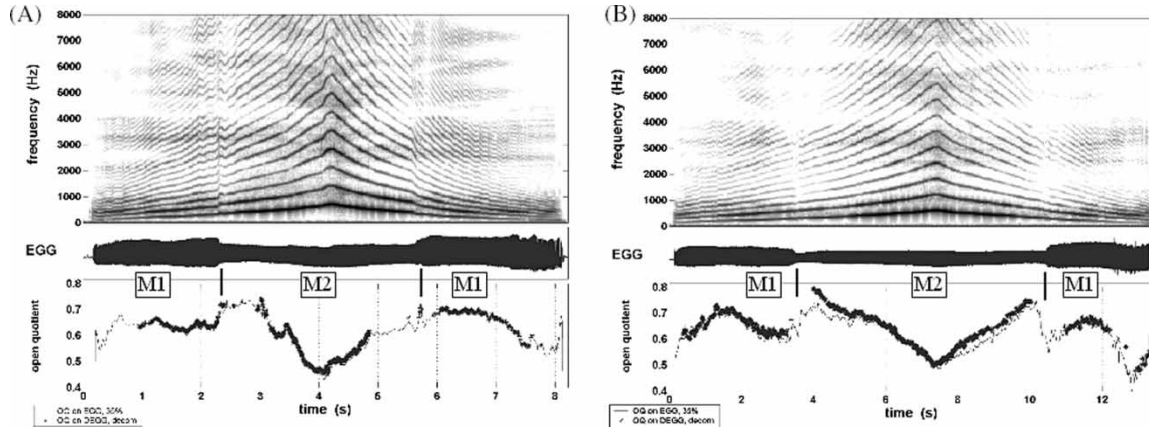


Figure 4. Illustration of vocal registers transition phenomena on a glissando sung by a counter tenor (A) with a pitch jump and a noticeable timbre change, (B) without any noticeable break. The top panel shows the time-frequency analysis, the middle panel the EGG signal, and the bottom panel the EGG measured open quotient. Two methods have been used to measure open quotient: on the EGG signal, using a 35% threshold method, and on the DEGG signal, using the DECOM method (55). The determination of the underlying laryngeal mechanism (M1 or M2) is based on the EGG detected laryngeal transitions.

frequencies are usually produced in this laryngeal mechanism.

In laryngeal mechanism M1, the vocal folds are thick and they vibrate over their whole length with a vertical phase difference (7). Vibrating mass and amplitude are important. The vocal fold body is stiffer than the cover and transition (26). Vocalis muscular activity is dominant over cricothyroid (26,31). Both activities increase with pitch. Closed phase is often longer than open phase, which is reflected in the open or closed quotient values (27). This laryngeal mechanism is used by both males and females in the low to mid part of their frequency range. The corresponding average voice range profiles for males and females are shown in Figure 7.

In laryngeal mechanism M2, the vibrating mass and amplitude are reduced (7), as compared to mechanism M1, and there is no vertical phase difference in the glottal vibratory movement. All the vocal fold layers are stretched, and the collagenous fibres in the vocal ligament are the stiffest of all the layers (26). Cricothyroid muscular activity is dominant over vocalis. The open phase is always longer than the closed phase, lasting at least 50% of the fundamental period (27). This laryngeal mechanism is used by both males and females in the mid to high part of their frequency range. The corresponding average voice range profiles for males and females are shown in Figure 7.

The laryngeal mechanism M3 is far from being understood. *Whistle*, *flute* or *flageolet* registers may be produced in mechanism M3, and only few studies have been dedicated to these registers. In this mechanism, the vocal folds are thin and very tensed. The vibratory amplitude is much reduced as compared to mechanism M2, and there even may be no contact in some cases. It has been suggested that the vocal fold vibration may be induced by periodic vortex shedding interacting with the resonator (32).

The laryngeal mechanisms are not related exclusively to speech or singing, but they are a physiological entity in human phonation (22). They are also common to male and female, who share similar laryngeal mechanism boundaries (see Figure 7). A characteristic of the human voice is that the frequency regions of the main mechanisms M1 and M2 can overlap over a precise frequency range (33), as shown in Figure 7: E3 (165 Hz) to F#4 (370 Hz) for male voices, and G3 (196 Hz) to G4 (392 Hz) for female voices. At those pitches, a speaker or singer can choose to phonate using either mechanism M1

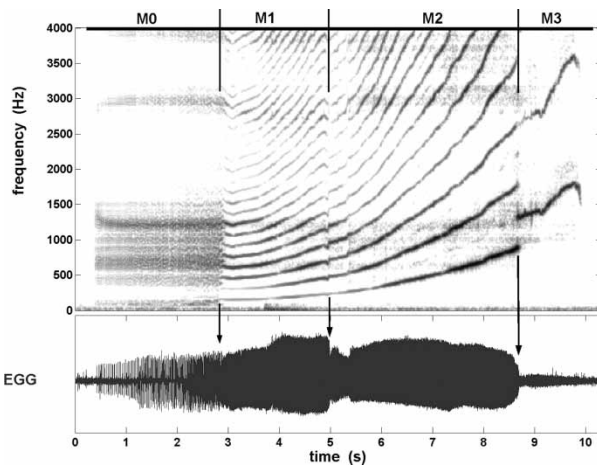


Figure 5. Illustration of the four laryngeal vibratory mechanisms on the production of a glissando. The top panel shows the time frequency analysis, and the bottom one the EGG signal.

Table I. Counterparts of the laryngeal mechanisms found in the literature, in the case when a vocal register is defined as a laryngeal entity. A question mark underlines a possible uncertainty in the equivalence.

Authors	Laryngeal mechanism M0	Laryngeal mechanism M1	Laryngeal mechanism M2	Laryngeal mechanism M3
Garcia, 1847 (1)	contre-basse?	poitrine	fausset-tête	
Behnke, 1880 (4)		thick	thin	small?
Wilcox, 1935; Vennard, 1967 (7)		heavy mechanism	light mechanism	
Hollien, 1974 (11)	pulse	modal	loft	
Miller D, 2000 (17)		chest vibratory pattern	false vibratory pattern	

or M2, and this choice may be voluntary or involuntary. In singing, it may be related to the singer's desire to produce a specific voice quality. Indeed, voice quality is dependent on the glottal flow properties. Because the laryngeal mechanisms correspond to different vocal fold vibratory mechanisms, they imply large differences in the glottal flow pulse shape. Their use results in the production of a specific voice quality in relation to the laryngeal configuration. However, skilled singers, and in particular classically trained singers, manage to modify this typical voice quality, in particular in adjusting their vocal tract in the proper way. This is for example the case of *voix mixte* (*mixed voice*) register, as will be seen in the next section.

Insights into the physiological, acoustic, and perceptual characteristics of singing voice registers

In this section, a survey of the most common singing voice registers mentioned in the literature is given. In each case, their main physiological, acoustic, and perceptual characteristics are briefly described. The choice has been made to take the underlying laryngeal mechanism in which they are produced as a common denominator for categorizing these registers. The special case of the *middle* or *voix mixte* register is discussed at the end of the section.

Registers produced in laryngeal mechanism M0: pulse, vocal fry or strobass

Pulse, vocal fry or *strobass* are equivalent labels (11). They designate the register which occurs in the lowest part of the human frequency range. This register is produced in laryngeal mechanism M0. The vocal folds are very short, thick and slack. A recent survey of the acoustic, aerodynamic, physiological, and perceptual characteristics of this register in speech can be found in (34). From a physiological point of view, the thyroarytenoid muscles tend to shorten, subsequently thickening the anterior-posterior dimension of the vocal folds, and allowing the anterior part of the vocal ligaments to vibrate (11). The glottal vibratory pattern is characterized by short pulses, which can be periodic and single, periodic and multiple (double, triple), or aperiodic (single and multiple) (34–36). The pulses are followed by a long closed interval (36,37), which implies small values of open quotient. The frequency range goes from a few Hz to about 80 Hz with a mean of 50 Hz, and is similar for males and females (34,38). This register is more commonly found in speech than in singing. However, few exceptions can be found in certain vocal cultures around the world (e.g., Russian and Papua New Guinea folk music, rhythm and blues singing style, (15)).

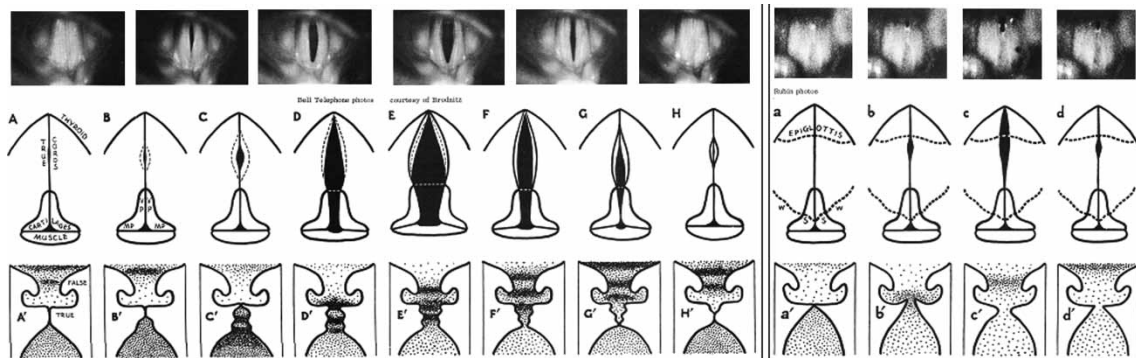


Figure 6. Schematic representation of the vocal folds vibratory movements in laryngeal mechanism M1 and M2. From (7).

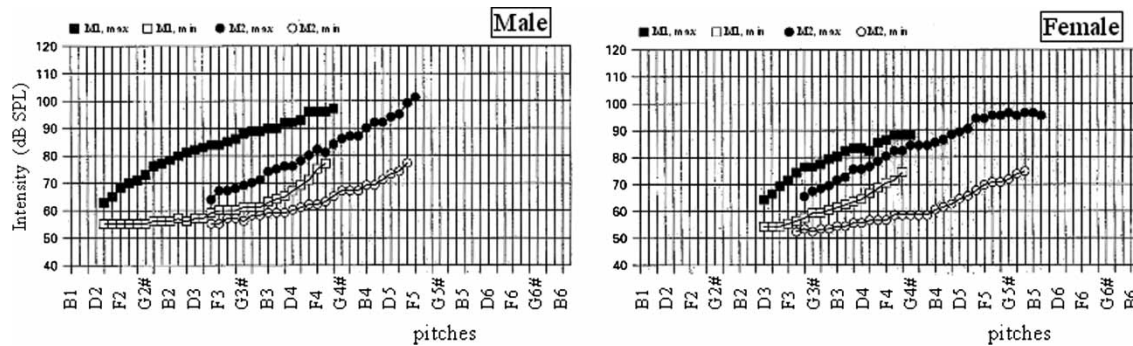


Figure 7. Average voice range profile (vocal intensity versus fundamental frequency) of male and female singers in mechanisms M1 and M2. Adapted from (33).

Registers produced in laryngeal mechanism M1: modal, chest, male head, belting

The low to mid frequency part of the voice can be divided into a single register (in this case *modal* or *chest* register), or into two or more different registers (*chest*, *male head*, *belting*, *voix mixte*, *voce finta*,...). The *modal*, *chest*, *male head*, *belting*, and *voce finta* registers are produced in laryngeal mechanism M1 (11,13,39,40). The *voix mixte* register will be described later and can be produced either in M1 or in M2 (41). The vocal folds are thick, with great vibrating mass and large vibratory amplitude. The inverse-filtered glottal-flow pulse is asymmetrical, the closing phase being shorter than the opening. The open quotient values range from 0.3 to 0.8, depending on vocal intensity (27).

The distinction between *chest* and *male head* registers is defined by Miller (42) in terms of vocal tract adjustment: ‘the *chest* register comprises the lower portion of the range, extending to the highest pitch where the first formant matches the second harmonic; the *head* register comprises that portion of the range where F1 falls below H2.’ The *head* register is used in the upper range and spans a musical interval of a fourth or fifth (39), located in the vicinity of D4b to A4b for a tenor and B3b to F4 for a baritone (42). Suitable for soft singing, the *head* voice is recognized by Vennard as an ‘intermediate adjustment, (...), easily confused with falsetto but continuous with full voice’ ((7), paragraph 935). From a laryngeal muscular point of view, *head* register is characterized by higher cricothyroid activity and lower vocalis activity than *chest* (26). Yet, it is clearly produced in laryngeal mechanism M1. As pointed out by Large (39), it is ‘a different laryngeal mechanism from falsetto’, with complete vocal fold approximation, greater energy in the higher partials and lower air flow rate than *falsetto*.

Belting is very often considered as a technique of loud singing commonly found in non-classical singing, with a voice quality similar to a yell (40,43–45). However, a few authors consider it nowadays as a vocal register on its own (17), and thus it seems that it is worth mentioning here. It could be produced by males and females, but only female voices have been studied up to now. Considered as an extension of *chest* register into the upper part, its frequency range goes from E4–G4 (about 330 Hz) to D5 (540 Hz) (40). Belting sounds are produced with high subglottal pressure, long closed phase of duration greater than half of the fundamental period, high SPL, and great harmonic richness (40,43,46). A tuning of the first formant with the second harmonic has been observed on open vowels (40,43).

Registers produced in laryngeal mechanism M2: falsetto, loft, female head, upper

The *falsetto*, *loft*, and *female head* are equivalent labels for registers which occur in the mid to high frequency part of the voice. The *falsetto* register can be used to designate altogether a female-like voice quality produced by males, in particular counter tenors, a soft and breathy fake voice quality produced by untrained male singers in the high range, and the female mid to high register, or *female head* register.

All these registers are produced in laryngeal mechanism M2. The vocal folds are thin and the vibrating mass and vibratory amplitude are reduced. The inverse filtered glottal flow pulse is more symmetrical, close to a sinusoidal shape. The open quotient values are high, ranging from 0.5 to 0.95 depending on the fundamental frequency (27). Their main acoustic characteristic is the predominance of the first harmonic, in relation to high values of the open quotient (47).

In the female case, the mid to high frequency part of the voice may be divided into two or more

registers, for instance *lower middle*, *upper middle*, and *upper* (48). The boundary between *middle* and *upper* registers is located around D5 to F5 (17). According to Miller (17), the main differences between these registers lie in the resonance strategies adopted by the singer. When the fundamental frequency is getting high enough to be close to the first formant, there is a tendency to tune the first formant to the first harmonic, and to maintain this tuning for higher pitches (49–51). The F1-H1 tuning on open vowels would be the determinative feature of the *upper* register (17).

Registers produced in laryngeal mechanism M3: bell, flute, whistle, flageolet

The *bell*, *flute*, *whistle*, or *flageolet* are equivalent labels for a register which occurs in the highest part of the human frequency range (52). It is produced in laryngeal mechanism M3. However, the phonatory mechanism has not been explored much. There may be several types of realization (15). Only a few studies have paid attention to this register, which is not much used in speech and classical singing, except in the high soprano range (48). It can be found in non-classical singing styles, such as jazz or contemporary music. The fundamental frequency typically ranges from B5 to F6, i.e., from about 1000 to 1400 Hz (17). The first harmonic is dominant, and the number of overtones is reduced (52,53). According to Miller, this register is used when the fundamental frequency is too high to remain close to the first formant. The corresponding sound quality is ‘small and thin’, but nevertheless ‘brilliant’, comparable to ‘a chime or a sharply-ringing distant bell’ (48).

What about the registers in the middle of the frequency range: mid, middle, mixed voice, voix mixte?

A special case are the registers found in the middle of the human frequency range, and often labelled as *mid*, *middle*, *mixed voice*, or *voix mixte*. The term *head* can also be found (18), and the female *middle* register can sometimes be considered to be similar to male *full head* register (17). Yet, the correspondence between these terms cannot be stated with certainty.

Singers make use of these registers to smooth the transition between the lower and upper part of their frequency range, in the frequency region where the frequency ranges of laryngeal mechanisms M1 and M2 overlap. For a long time, it has been queried whether this register would be a mixture of two registers. Recently, it has been demonstrated that, at least from the laryngeal point of view, singers use a precise laryngeal mechanism, which is either M1 or

M2 (41). Male singers very easily use the laryngeal mechanism M1 to produce sounds in *voix mixte*, whereas female singers very easily use the laryngeal mechanism M2. However, examples have also been studied of a soprano singing in *voix mixte* register using laryngeal mechanism M1, or a counter tenor singing in *voix mixte* register using laryngeal mechanism M2 (41).

The resonance properties of these registers still need to be explored, so as to understand how a singer manages to mimic the voice quality of a given register while using an inappropriate laryngeal mechanism.

Conclusion

Since Garcia, knowledge about singing voice registers has evolved, thanks to the development of new experimental techniques. Yet, the controversy about vocal registers, which already existed in Garcia’s time, is still present nowadays, and reflected in the multiplicity of labels for registers. It seems to have its roots in the definition of a register and its defining characteristics. If a vocal register is defined as a series of consecutive tones produced by the same laryngeal mechanism, the human voice can be characterized by four different voice registers, i.e., laryngeal registers such as Hollien’s *pulse*, *modal*, *loft* registers, and the *whistle* register. If a vocal register is defined as series of consecutive tones produced with similar voice quality, other registers exist in the human singing voice, such as *head*, *belting*, *middle*, *upper*, *voix mixte*,... One major issue is then to define a vocal register precisely before labelling it. Another major issue is to be precise about the means which are required to identify a given vocal register. The identification of vocal registers can benefit from the detection of transition phenomena. In this way, the concept of laryngeal mechanism, which is based on the detection of laryngeal transition phenomena by means of electroglottography, is of great help in clarifying the laryngeal nature of a given voice production. At least, the singing voice registers can now be described in terms of the laryngeal mechanism by which they are produced. Further research is needed to understand the singers’ resonance strategies and acoustic adaptations which are required to produce a specific voice quality or to successfully manage blending of singing voice registers. Furthermore, major voice quality differences are avoided in the Western lyric culture, whereas they may be a prime goal in other vocal cultures, such as jazz, blues and rock. Knowledge of singing voice registers would gain from a better understanding of these non-classical phonation types.

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Notes

1. English translation of ((1), p. 4) ((54) as mentioned by ((17), p. 30)): 'Par le mot registre, nous entendons une série de sons consécutifs et homogènes allant du grave à l'aigu, produits par le développement du même principe mécanique, et dont la nature diffère essentiellement d'une autre série de sons également consécutifs et homogènes, produits par un autre principe mécanique. Tous les sons appartenant à un même registre sont, par conséquent, de la même nature, quelles que soient d'ailleurs les modifications de timbre ou de force qu'on leur fasse subir.'
2. 'La séparation [entre registres de fausset et de tête] n'est pas le résultat d'un mécanisme différent du larynx, mais un effet de timbre (...) ' ((1), p. 18) — 'The division [between falsetto and head registers] does not result from a different mechanism of the larynx, but from a timbre effect (...) '.

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