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The Interplay between Glottis and Vocal Tract during the Male Passaggio

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Key Words

Singing register · Male voice · Register transition · Passaggio · Formant tuning

Abstract

The transition between 'chest' and 'head' register is essential for male opera singers in order to reach the higher pitches. The 'passaggio', which is a scale passage where this transition takes place, but also a maneuver of register equalization, is typically difficult to learn. Studies on parameters for a definition of this transition are restricted to a small number of singers so far. Audio, electroglottographic, and equivalent subglottic pressure signals of 11 male opera singers were recorded while singing scales on open back vowels and passing the register transition. A spectrum analysis of the audio signal revealed that the second harmonic (H_2) dominates in 'chest', resonated by the first formant (F_1), together with the fourth harmonic (H_4), supported by the second formant (F_2). During the passaggio, H_2 level decreases because it loses the resonance of F_1, while the third harmonic (H_3) gains the resonance of F_2. At this point the H_4 level drops because that harmonic is no longer supported by F_2. The transition from 'chest' to 'head' register is marked by characteristic changes in the amplitude patterns of the partials H_2, H_3, and H_4, and the frequency progressions of the first two formants, defining an objective distinction between the two registers.

K.N. and P.S. contributed equally to this work.

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Introduction

In the Western classical music tradition, negotiating the proper transition between 'chest' and 'head' register, the lower and upper parts of the male full singing voice (as distinguished from falsetto), is essential to reach the higher pitches [1]. The 'passaggio', a maneuver for this transition, is one of the main challenges for singers and singing teachers [2]. Individual approaches prevail in teaching and learning the passaggio execution, usually of an intuitive nature. They are generally successful for most professional singers, but for a sizeable fraction who struggle with the proper execution of this register transition, knowledge about the physical essentials would be desirable. The aim of the present study is to make a contribution, based on objective parameters, to the definition of these essentials.

Historically, since Garcia [3] the registers in the singing voice have been considered a series of succeeding sounds of equal quality produced by the same mechanical principle, which differs basically from another series of sounds produced by another mechanical principle. Later this conception of registers was refined by the addition of perceptual aspects: a series of consecutive similar vocal tones are distinguishable by the musically trained ear from an adjoining series [4]. Indeed, registers may be distinguished by perception of listeners only, or by the production mode, or both, and often in the self-perception of the singer. Titze [5] proposed two types of register transitions, namely periodicity transitions and timbre transitions. The periodicity transition is a perceptional one as in the vocal fry, where a listener perceives the deepest male voice as a separate register, although there is no change in the phonation mode. In contrast, timbre transitions differ in the sound production mode.

The existence of two natural registers, 'chest' (the term used in a wider sense than above; synonym: full voice, 'voce piena') and 'falsetto', was already described by Tosi [6]. It was the merit of Garcia [3] to attribute a different laryngeal adjustment to both registers. But singers claimed that there are more than the two main registers and demanded the recognition of additional register subdivisions. However, ambiguities in terminology, distinction, and enumeration of the single registers by singers and voice researchers produced confusion [1, 7]. In classical singing, audible register transitions are not easily accepted by the audience, possibly because in a far-field communication mode the maintenance of voice identity is desired [8]. In order to achieve the skills of register equalization and to reach the highest notes of the voice range by appropriate register transitions, it might therefore be of importance for singers to be informed about the acoustical details of registers and their transitions.

Conventional register definitions rely largely on singers' self-reports, and perceptual studies presumed that expert listeners concurred with such reports [9, 10]. However, singers themselves are frequently unable to localize their point of transition and to distinguish clearly between registers. The problem of subjective register distinction is aggravated by the fact that listeners [11], including even experienced singing teachers, cannot always distinguish between different registers with certainty, especially if sung with a register equalization [12]. There has thus been and still is a need for objective criteria for the distinction of vocal registers [11, 13].

In the early last century the sound homogeneity of a register was already recognized as depending on definite acoustic features. It was assumed that these features are caused by particular mechanisms of tone production as vocal fold vibration, glottal shape, and airflow, and that neighbouring registers may overlap to a certain degree

[4]. Thus, over a long period the origin of registers was attributed predominantly to the larynx. An 'integrated theory' on registers which arrived in the nineteen-seventies and based on spectrum analysis and acoustic phonetics [14] took into consideration that not only laryngeal adjustments, but additional resonance adjustments determined the register transitions [1]. In particular, the recognition that formants (vocal tract resonances) [15] make a significant contribution to the acoustical power of a tone, if one of the harmonics falls close to its center frequency [16–22], brought about a change in this understanding of registers. The tuning of vocal tract formants on harmonics by vowel modification, called 'formant tuning' [19], enhances the resonance qualities of a voice. Vocal tract resonances are highly adjustable by articulatory changes. Even within a given vowel category the first and second formant (F_1 and F_2) frequencies can vary as much as 50–100%. Therefore, formant tuning is obviously the most appropriate way to manage register transition and equalization [5]. The bandwidth of the vocal tract formants normally ranges between 40 and 100 Hz. A bandwidth reduction increases the selectivity of the vocal tract and makes enhanced harmonics prominent, in the extreme case of overtone singing even audible as discrete tones [22]. Mainly the work of Sundberg [18, 19], Titze [5, 23], Miller [1], and Schutte and Miller [24] led to our contemporary understanding of registers as reflecting an adjustment process of either the glottis (between voice piena and falsetto) or the vocal tract to the demands of changing fundamental frequency F_0.

The term passaggio designates the transition between chest register and full head register, carried out over a series of pitches within the upper part of the male frequency range. It refers to the transition itself, but even more often to the pitches just below where the transition is prepared (zona di passaggio). The term also denotes a strategy for register equalization to manage this transition without obvious discontinuities [2].

So far there exists no generally accepted definition of the transition from 'chest' to 'head' register which is based on objective determinants. An initial study of Miller and Schutte [2] refers mainly to the phonation of just 2 singers, a bass-baritone and a tenor, and to historical recordings of opera singers. The authors proposed a register definition based on spectrographic, electroglottographic, and supraglottal and subglottal pressure measurements. As the salient feature of the highest portion of the 'chest' register they detected a strong resonance generated by the tuning of the first vocal tract formant (F_1) on the second harmonic (H_2). The upper limit of chest should be around 600–750 Hz on the open vowels. When F_0 rises in the 'chest' register in an ascending scale, F_1 follows the rising H_2, which mostly leads to a shortening of the pharynx tube and a slight elevation of the larynx. Characteristic for the 'chest'-to-'head' transition is that at a critical pitch F_1 cannot follow the rising H_2 any longer and falls below it, so that a new resonance mode is established by adjusting the second formant (F_2) to the third harmonic (H_3), at least for back vowels.

The alternative for performing this transition is either to break into falsetto or to stay in the 'chest' register and let F_1 follow H_2 further as the pitch ascends. The latter maneuver leads to an 'open' sound as in shouting or 'belting', a raising of the larynx and shortening of the pharynx tube, which elevates F_1. Following R. Miller [25], D. Miller and Schutte [2] call this kind of circumvention of the passaggio a 'register violation', because this strenuous phonation mode reaches its upper limit after a few more semitones where F_1 cannot be linked to H_2 any longer, without a chance to reach the highest tones of the male full voice.

The purpose of the present study was to (1) detect typical changes of the acoustical parameters which characterize the male passaggio, based on a sample of singers of each of the major male voice categories, and (2) thus provide generalizable knowledge for a definition of the chest-to-head register transition on the basis of objective parameters.

Methods

Subjects

Recordings were taken from 11 male professional singers (4 tenors, 4 baritones, 3 basses, age range 28–55 years, median 46 years) of the Frankfurt Opera House chorus. All singers were able to perform the passaggio according to both their own judgment and that of the examiners. All participants gave written consent to the study.

Procedure

The participants sang scales on the open vowels [a:] and [ɔ:] passing the region of the register transition from 'chest' to 'head' registers. The same scales for each subject were recorded 3–5 times. A total of 43 register transitions was accumulated. The singers were instructed neither to make the register transition more prominent than usual, nor to direct additional effort to register equalization. Register transition was judged subjectively by 2 of the authors and by the singers. Whenever possible – that is, when the singer was able and willing to perform this passage while remaining in 'chest' production – the same scales sung without register transition served as control conditions. Because for a trained operatic singer it is difficult to manage this open, 'white' phonation of the register violation, which contains a certain risk of voice injury, some of the participants declined to perform it.

Audio and electroglottographic (EGG) signals were recorded. An additional trial to record an equivalent of subglottal pressure signals with an external microphone at the outer neck [26] did not deliver reliable data because the high sound pressure of singing resulted in audio signals superimposed on the subglottal pressure readings. Audio signals were recorded with a Lavalier electret condenser microphone (Vivanco, EM 116®) placed 30 cm away from the mouth. EGG signals were registered simultaneously with an electroglottograph (Laryngograph®). All data were recorded using a four-channel sound card.

Data Analysis

The audio signals were processed and analyzed with the software Cool Edit Pro® (Syntrillium). A fast Fourier transformation real-time spectrum analysis was carried out with the Frequency Analyser Blackmann-Harris, FFT-Size 1024 using time windows of 200 ms for averaging the frequency distribution. Some of the images were made with the program VoceVista 2.8.7.® [27]. Closed quotient, which is the proportion of the closed time of the glottis within a glottal cycle, and total cycle length were calculated with the software Glottal Segmentation of Voice and Speech® [28]. The program estimates the time in which the glottis is closed as the duration of that part of the glottal cycle which lies above a horizontal line, adopted as a zero-line, crossing the turning point of the steep flank of the EGG signal (designated as the moment of fast glottal closure). In this study a mean closed quotient of 200 cycles per recorded tone step was averaged.

Results

In all singers the register transition from 'chest' to 'head' is marked by the same characteristic spectral patterns governing the vocal tract formants F_1 and F_2, and the harmonics H_2, H_3, and H_4. The pitch range in which these patterns occur is determined by the voice category. Near the upper boundary of the 'chest' register, a char-

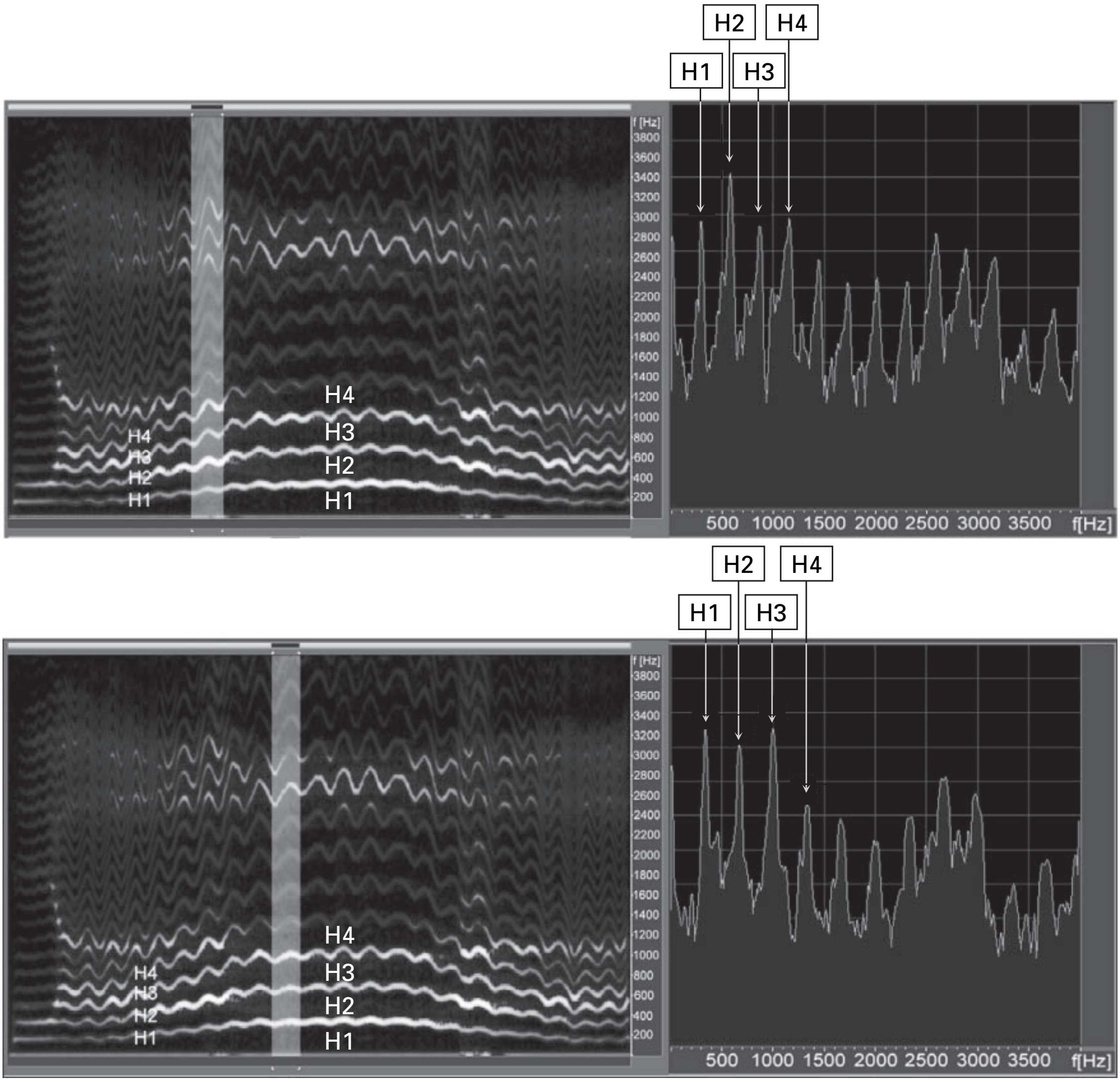


Fig. 1. Sonagrams (left) and spectra corresponding to the light vertical stripes in the sonagrams (right) of a passaggio within a scale from F3 to F4 sung by a baritone on [a:]. The light stripes in the sonagrams and the corresponding amplitude spectra highlight the spectral intensity of the harmonics H_1 to H_4 in a passage just before (top row of the figure) and after (bottom row) the register transition. In the top spectrum on D4 both H_2 and H_4 are strong. In the bottom spectrum showing F4, H_3 is strong whereas H_2 and H_4 have fallen in level.

acteristic feature for the back vowels is a tuning of F_1 on H_2 and of F_2 on H_4. Thus, H_2 and H_4 are the dominant partials in this range of the chest register. The singers' intuitive adjustments to maintain an optimal resonance are reflected in a tendency of the F_1 and F_2 frequencies to increase with rising pitch in order to keep being tuned on H_2 and H_4. F_1 follows the rising pitch only up to a critical point where a register

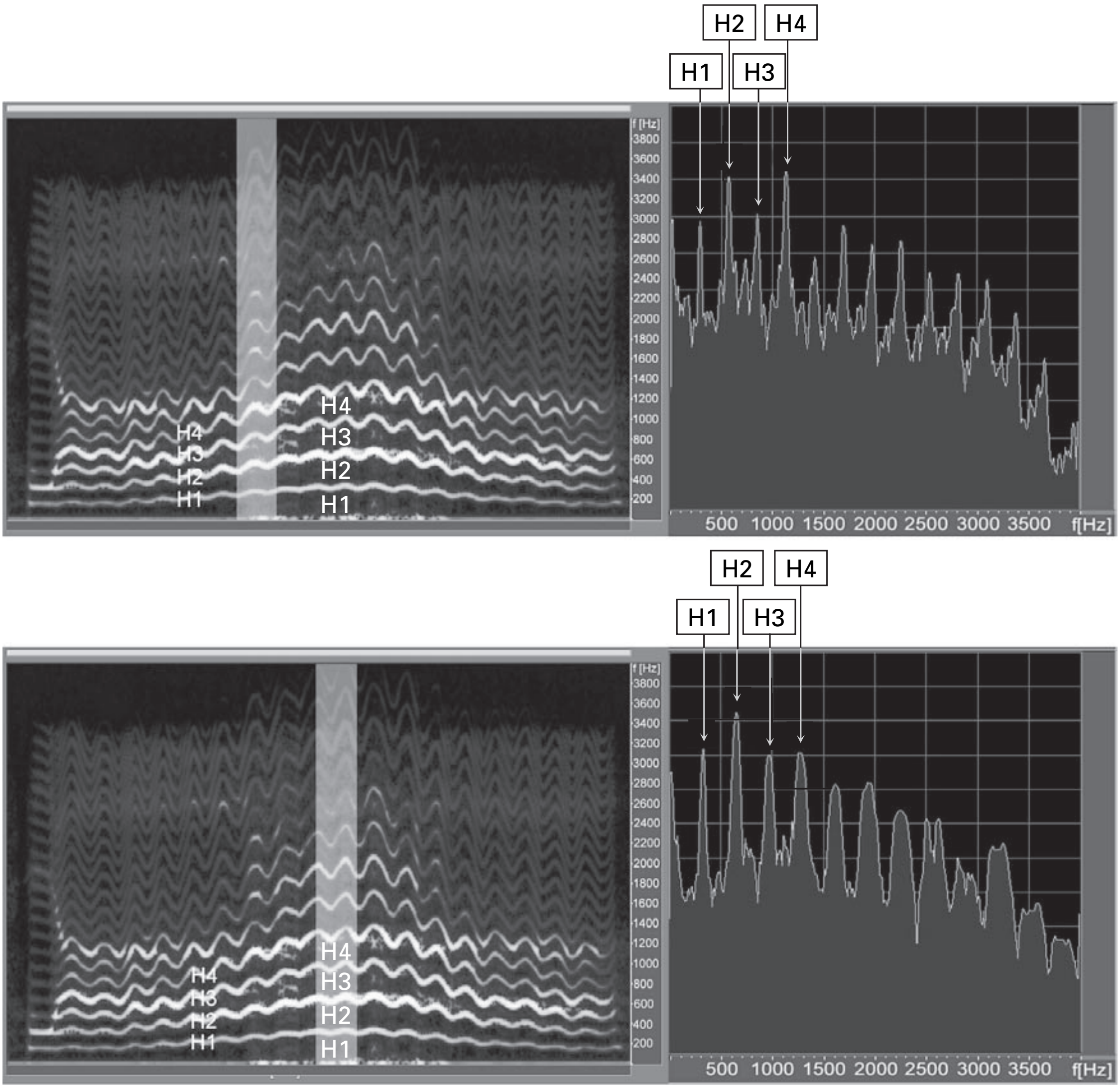


Fig. 2. Sonagrams (left) and amplitude spectra corresponding to the light vertical stripes in the sonagrams (right) of the same scale as shown in figure 1 but sung *without* register transition. In the top row H_2 and H_4 are strong again. On higher pitches (bottom row), H_2 remains the strongest harmonic.

transition becomes increasingly obligatory in the tradition of western operatic singing, because otherwise the highest tones in voce piena cannot be attained. During the transition F_1 drops in frequency, resulting in a decrease of H_2 amplitude, which is no longer resonated by F_1. Furthermore, H_4 has a high spectral energy in 'chest' for back vowels because of the proximity of F_2. During the register transition, the

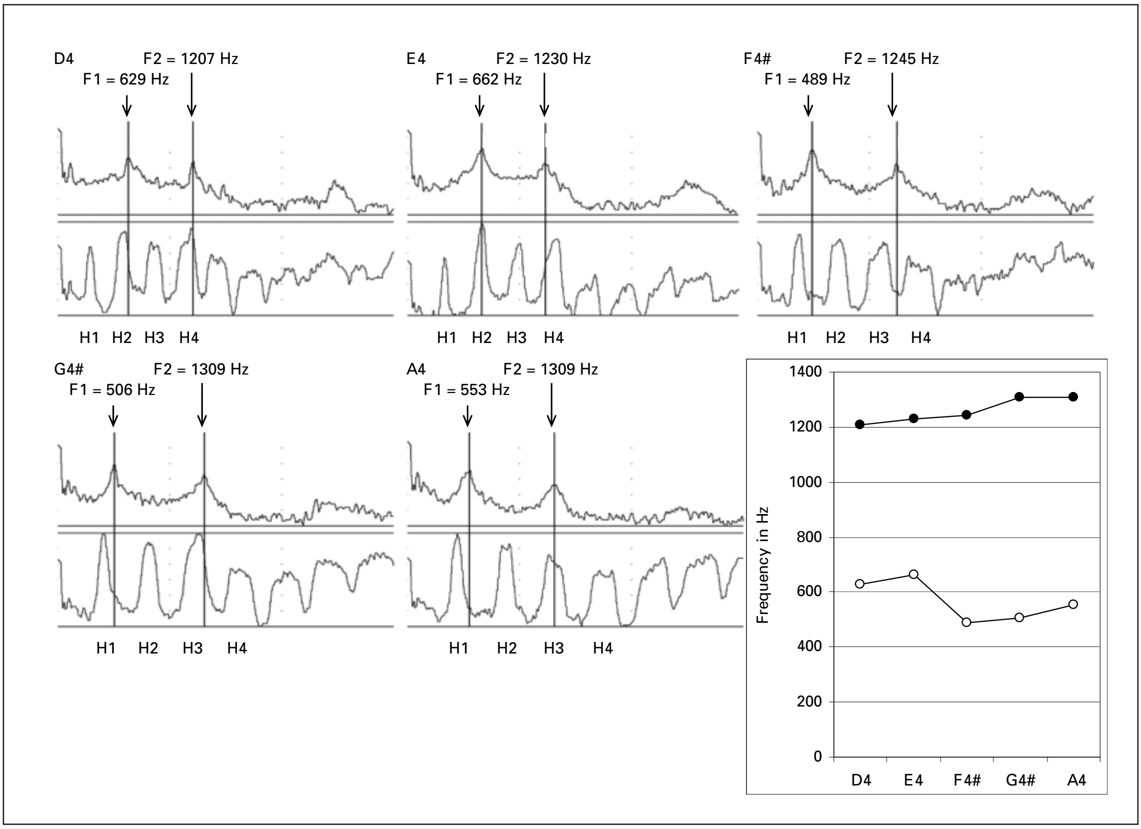


Fig. 3. Passaggio of a baritone sung on [a:] showing the scale D4–E4–F4-sharp–G4-sharp–A4. Upper curves: vocal tract formants of each tone sung with ingressive phonation. Lower curves: spectrum of the same passage sung in normal phonation mode. The harmonics are clearly recognizable. The changes of formant tuning to the harmonics are indicated by vertical lines (see text). Inserted diagram: Frequency courses of F_1 and F_2.

tuning of F_2 shifts from H_4 to H_3, leading to a characteristic reduction of the level of H_4, together with an increase in that of H_3. This pattern is not seen in the case of a register violation, where F_1 and F_2 keep following H_2 and H_4. The details of these changes are described below and illustrated in figures 1–9.

The sonagrams on the left side of figure 1 show the changes in the distribution of spectral energy during passaggio of a baritone. The light stripe in the upper sonagram of this figure shows the spectral energy of the first four harmonics in a passage just before the register transition. H_2 and H_4 have a higher spectral power than H_1 and H_3, presumably because they are supported by F_1 and F_2, a pattern which characterizes the upper part of the chest register in all recordings. The same pattern is visible in the spectrum on the right side, which shows a snapshot on D4 within the time window marked by the light stripe in the sonagram. In the bottom sonagram of figure 1 the light stripe highlights a passage immediately after the register transition. This time

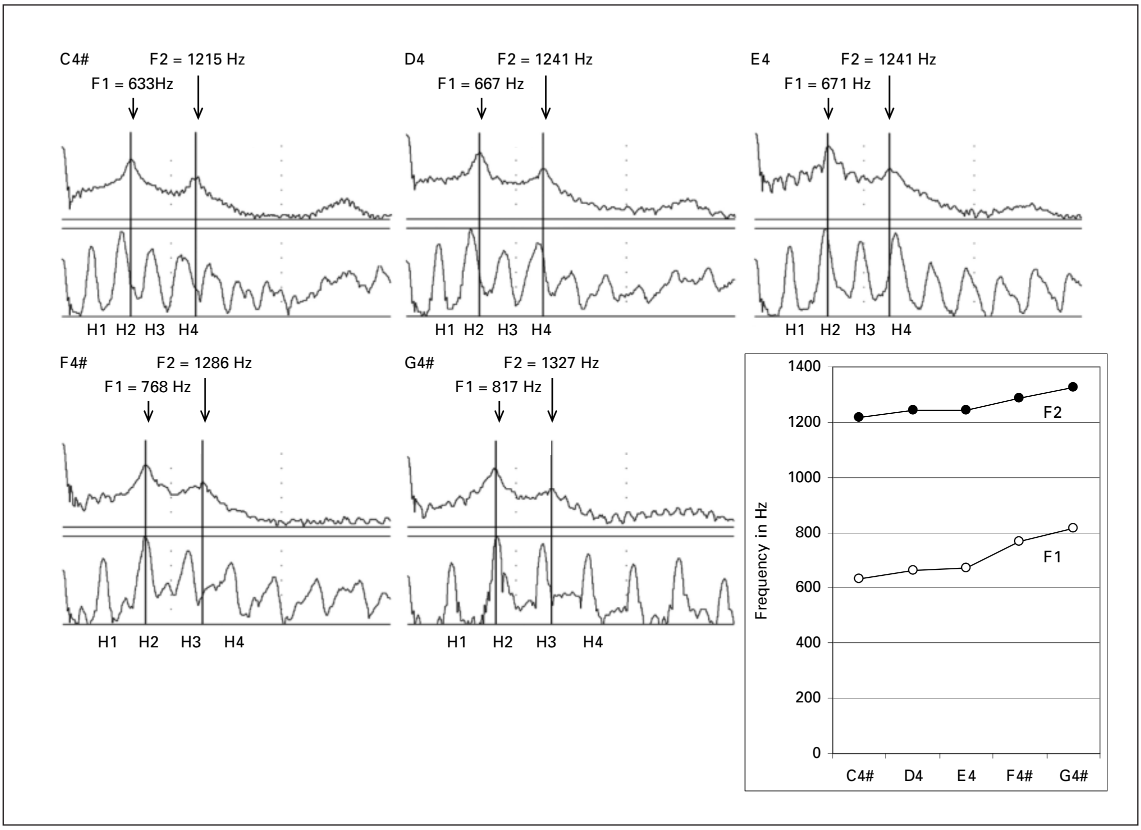


Fig. 4. A scale similar to that in figure 3 but sung *without* register transition.

window, as well as the corresponding spectrum, now on F4, shows a sudden loss of spectral energy of H_2 and H_4 during the register transition. Simultaneously, H_3 has risen and now exceeds H_2 and H_4 in amplitude, presumably because H_3 is supported by F_2. These patterns characterize the 'head' register in all the examples.

Figure 2 shows the same passage, but sung without register transition (register violation). Such a persistence in 'chest' production reveals an unchanged pattern with strong H_4 and H_2, supported by the still rising F_1 and F_2. In the top part of figure 2, H_2 and H_4 have again the highest levels, evidently supported by F_1 and F_2. However, at higher pitches (bottom part of fig. 2) H_2 remains the strongest harmonic because it continues to be supported by F_1.

The spectra of figure 3 depict the passaggio processes at each scale step from D4 to A4 sung by a baritone. The upper curves show the vocal tract formants as revealed by ingressive phonation, which allows a quite accurate visualization of the vocal tract formants F_1 and F_2, providing the ingressive phonation is made with the same articulation as that of the sung note [16]. The lower curves show the spectrum of the same passage in singing phonation. Here the harmonics are clearly recognizable. The

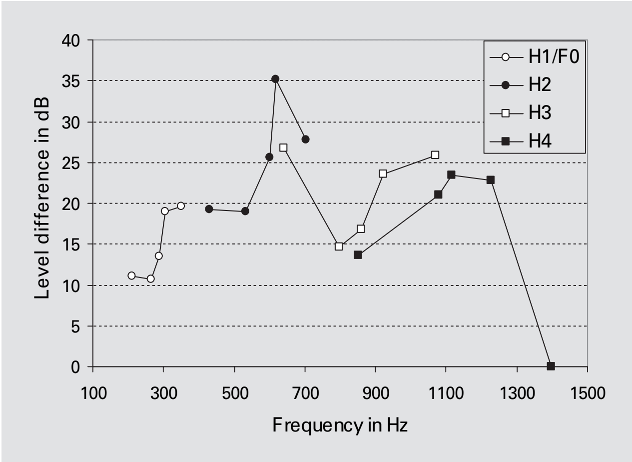


Fig. 5. Typical frequency course of the harmonics H_1 to H_4 during a passaggio within a diatonic scale from B3-flat to F4 sung on [a:] by a tenor. For each of the four harmonics the successive data points correspond to the successive tone steps.

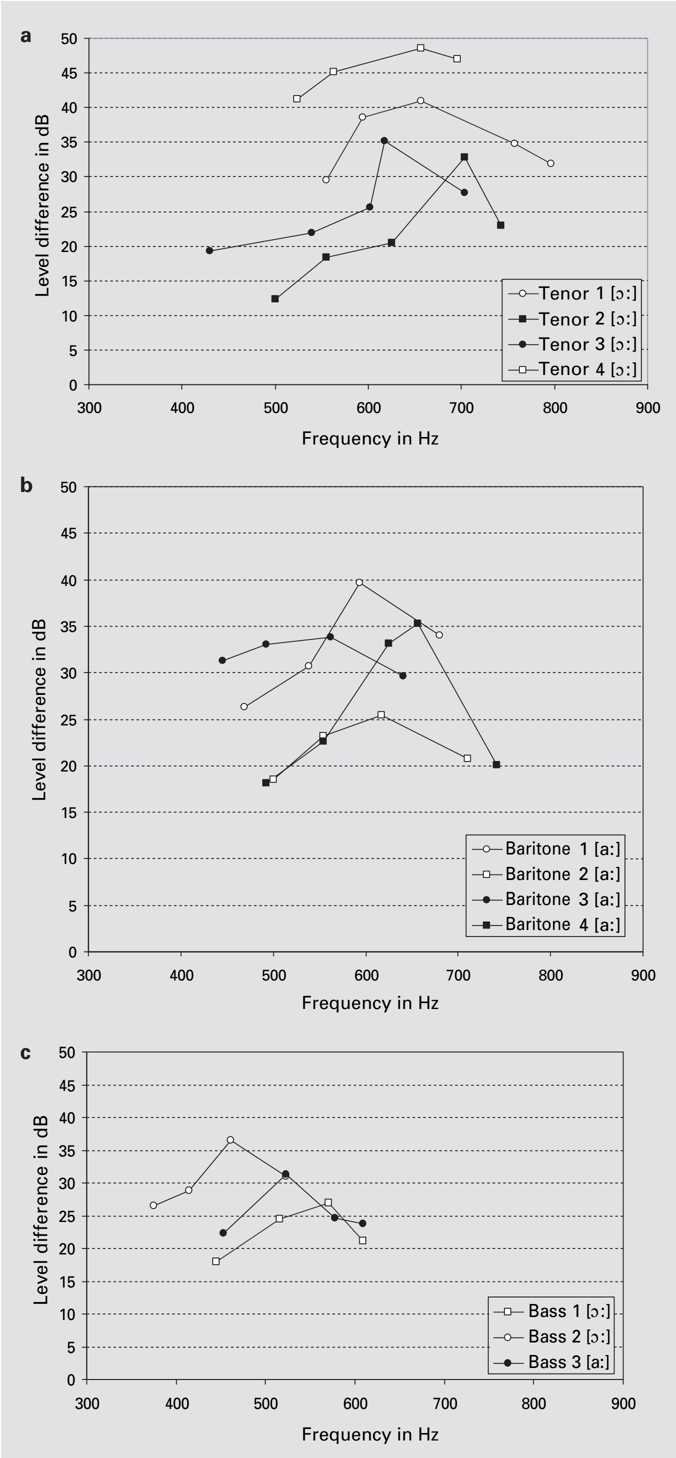
vertical lines between the upper and the lower curves indicate which formant of the ingressive phonation is tuned to which harmonic in singing phonation. At the beginning of the passage, at D4, F_1 is tuned to H_2 and F_2 to H_4. In the following tone steps F_1 and F_2 rise with rising pitch. Thereby F_1 remains tuned on H_2. Between E4 and F4-sharp, however, F_1 stops rising, falls in frequency, and is no longer tuned to H_2, concurrent with an amplitude decrease of H_2. Furthermore, from E4 upwards, F_2 cannot be tuned to the rising H_4 any longer. Instead it resonates H_3 from G4-sharp on, causing an amplitude loss of H_4 and an increase of H_3. The tuning of F_2 to H_3 is the point where the register transition is completed.

The inserted diagram on the right side of figure 3 depicts the frequency course of F_1 and F_2. Whereas F_2 rises continuously, F_1 does not rise beyond E4, but drops and starts rising again with increasing pitch.

Figure 4 shows the same scale as the one in figure 3, but sung without register transition. Because here F_1 rises continuously with pitch, it remains tuned to H_2, as is characteristic for chest. F_2 gradually moves away from H_4 and toward H_3. The inserted diagram shows that F_1 and F_2 both rise continuously, but F_2 less than F_1.

Figure 5 shows a typical progression of the harmonics H_1 to H_4 during a passaggio of a tenor. For each harmonic the successive data points correspond to the successive scale steps.

Fig. 6. H_2 courses of each male voice category. Passaggio by 4 tenors on [ɔ:] within a diatonic scale between B3-flat and G4 (**a**), 4 baritones on [a:] within a scale from A3 to F4-sharp (**b**), and 3 basses on [a:] or [ɔ:] within a scale from G3-flat to E4-flat (**c**).


a
Level difference in dB
Frequency in Hz
Tenor 1 [ɔ:]
Tenor 2 [ɔ:]
Tenor 3 [ɔ:]
Tenor 4 [ɔ:]
b
Level difference in dB
Frequency in Hz
Baritone 1 [a:]
Baritone 2 [a:]
Baritone 3 [a:]
Baritone 4 [a:]
c
Level difference in dB
Frequency in Hz
Bass 1 [ɔ:]
Bass 2 [ɔ:]
Bass 3 [a:]

6

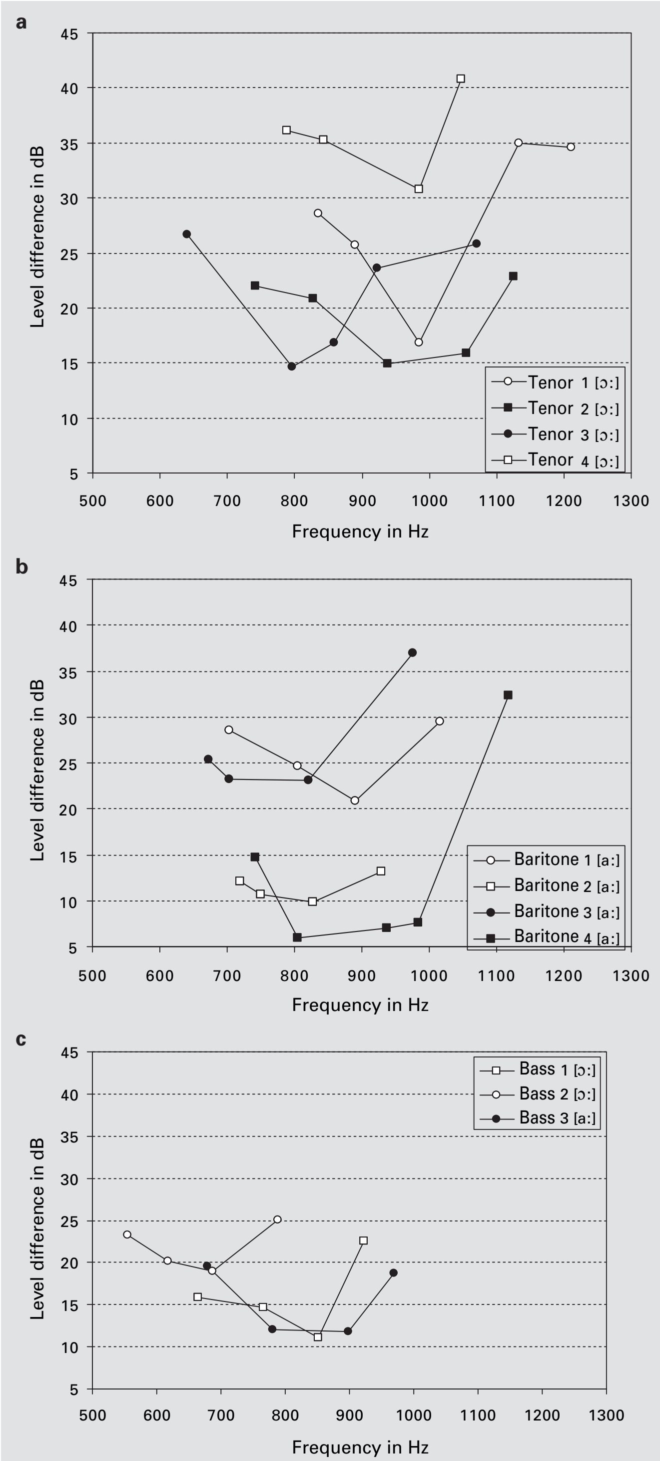
Figures 6–8 depict typical progressions of H_2, H_3, and H_4 for each singer of each voice category for one selected phonation. The figures suggest that the passaggio is always characterized by the same features, independent of voice category, vowel ([a:] or [o:]), and subject: H_2 levels rise during the first two or three scale steps up to a peak, in figure 6 between about 610 and 710 Hz (tenors), 560 and 660 Hz (baritones), 460 and 570 Hz (basses), and drop thereafter. The drop occurs at the point where F_1 no longer follows and resonates the rising H_2. The acoustical parameters of the main resonance changes for each voice category and each partial, averaged across the singers and for all phonations, are shown in table 1. Thus, table 1 presents more general information than the figures. The H_2 maxima range in table 1 lies for tenors between D4-sharp and F4-sharp, for baritones between C4-sharp and E4, and for basses between B3-flat and C4-sharp.

Simultaneously with the sudden decrease of H_2 energy the H_3 levels increase rapidly out of a valley into which they had dropped during the first or the first two tone steps of the passage. This drop might occur because H_3 dissociated from the F_1 region and fell into an 'unsupported hole' between F_1 and F_2. The increase of H_3 starts in figure 7 between 790 and 990 Hz (tenors), 700 and 900 Hz (baritones), and 680 and 900 Hz (basses). The subsequent rise of spectral energy, which is caused by the tuning of F_2 to H_3, mostly occurs at the same pitch where H_2 loses its energy (5

Table 1. Acoustical parameters of the main changes in H_2, H_3, and H_4 courses during the register transition: H_2 and H_4 maxima before drop, H_3 maxima of rise

Acoustical parameters	Partials	Tenors	Baritones	Basses
Frequency range of maxima, in Hz	H_2	617–757	562–656	453–570
	H_3	1,039–1,234	945–1,117	789–1,015
	H_4	1,039–1,312	992–1,117	812–1,039
Pitch range of maxima	H_2	D4#–F4#	C4#–E4	Bb3–C4#
	H_3	F4–G4	E4–F4#	C4–E4
	H_4	C4–D4	B3–C4#	A3–C4
Mean of maxima, in Hz	H_2	672	608	523
	H_3	1,118	1,030	900
	H_4	1,136	1,048	913
Mean maximum tone	H_2	E4	D4	C4
	H_3	F4#	E4	D4
	H_4	D4	C4	Bb4

Fig. 7. H_3 courses of each male voice category. Passaggio by 4 tenors on [ɔ:] within a diatonic scale between B3-flat and G4 (**a**), 4 baritones on [a:] within a scale from A3 to F4-sharp (**b**), and 3 basses on [a:] or [ɔ:] within a scale from G3-flat to E4-flat (**c**).


a
Level difference in dB
Frequency in Hz
Tenor 1 [ɔ:]
Tenor 2 [ɔ:]
Tenor 3 [ɔ:]
Tenor 4 [ɔ:]
b
Baritone 1 [a:]
Baritone 2 [a:]
Baritone 3 [a:]
Baritone 4 [a:]
c
Bass 1 [ɔ:]
Bass 2 [ɔ:]
Bass 3 [a:]
45
40
35
30
25
20
15
10
5
500
600
700
800
900
1000
1100
1200
1300

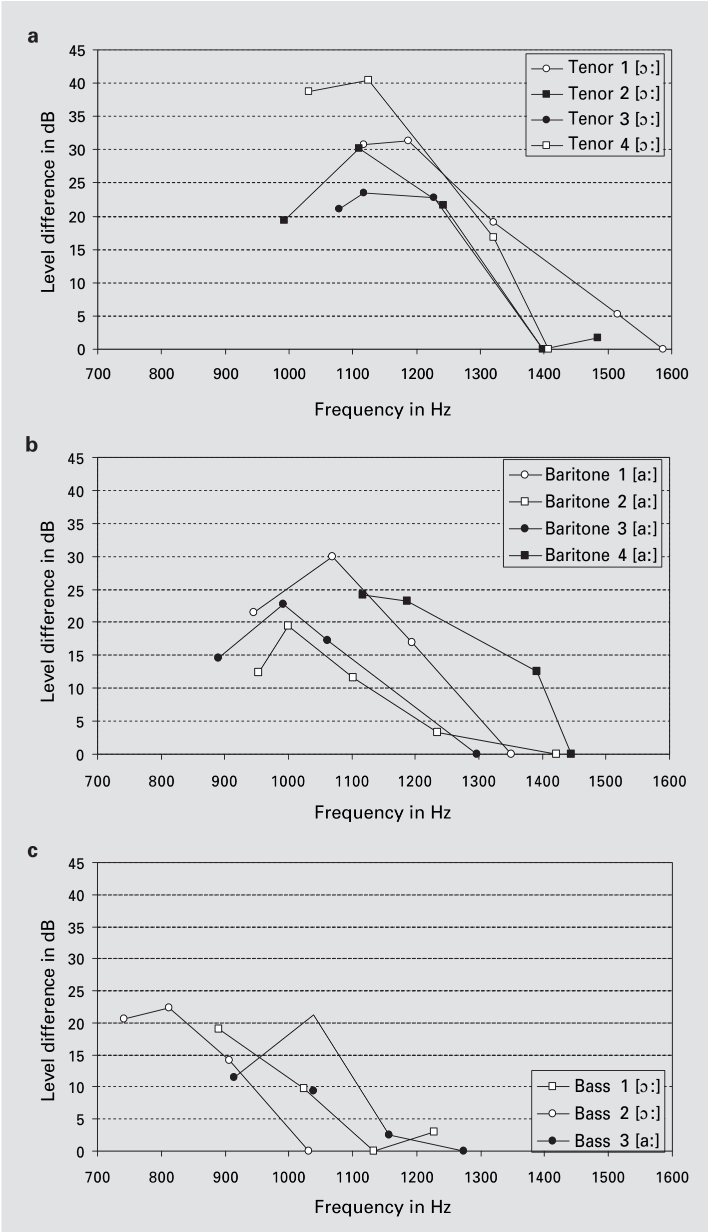


Fig. 8. H_4 courses of each male voice category. Passaggio by 4 tenors on [ɔ:] within a diatonic scale between B3-flat and G4 (**a**), 4 baritones on [a:] within a scale from A3 to F4-sharp (**b**), and 3 basses on [a:] or [ɔ:] within a scale from G3-flat to E4-flat (**c**).

out of 11 cases). The rise starts one to two tone steps before or one step after the H_2 drop. The most prominent rise can be observed frequently during the H_2 dropping step. For all samples (table 1) the maximum of H_3 is reached for tenors between F4 and G4, for baritones between E4 and F4-sharp, and for basses between C4 and E4.

H_4 has its maximum energy when H_3 is in the valley noted above. From that peak on, which is situated at the beginning of the passage or after the first tone step, H_4 drops continuously. The peak in figure 8 lies between about 1,100 and 1,190 Hz (tenors), 990 and 1,120 Hz (baritones), and 810 and 1,040 (basses). Across all samples (table 1), it lies for tenors between C4 and D4, for baritones between B3 and C4-sharp, and for basses between A3 and C4.

The change from the H_4 peak to the H_3 peak (shift of F_2 from H_4 to H_3) takes 1–3 diatonic scale steps (mean 1.8 steps) covering on average 2.75 semitones (range 1–5) for tenors, 2–3 scale steps (mean 2.5 steps) covering on average 4.5 semitones (range 3–6) for baritones, and 2–3 scale steps (mean 2.3 steps) covering on average 4 semitones (range 3–5) for basses. The distance between the onset of the H_2 drop and the H_3 peak is 1 scale step covering on average 0.5 semitones (range: 0.5–1 semitone) for tenors, 1 scale step covering on average 1.8 semitones (range: 1–2) for baritones, and 1–2 scale steps (mean 1.3 steps) covering on average 2 semitones (range: 1–3) for basses. The whole passaggio (F_1 leaves H_2, and F_2 shifts from H_4 to H_3) thus requires for baritones and basses more steps than for tenors, where it can be done in only one step, and covers a markedly larger tone range.

The intra-individual comparisons between the progressions of the harmonics of several phonations (fig. 9) document a good reproducibility of the curves across several recordings and vowels. Even if the intra-individual differences are relatively large (fig. 9c), the shapes of the curves do not differ markedly from each other.

Twenty-four of the closed quotient curves yielded an interpretable analysis. In contrast to the progressions of the harmonics, those of the closed quotients (fig. 10) do not show a similar pattern regularity. There are increases (fig. 10a), or decreases (fig. 10b), or a mix of both increases and decreases (fig. 10c) across several recordings and vowels of the same subjects. During the register transition the closed quotients more frequently increased (16 recordings) than decreased (5 recordings), or remained at the same level (3 recordings). With respect to subjects, 5 singers (3 tenors, 2 basses) performed the passaggio with predominantly increasing closed quotients, 2 with predominantly decreasing ones (1 baritone, 1 bass), and 2 with no preference for increase or decrease (1 tenor, 1 baritone). The mean closed quotients were 47% one tone before the register transition and 50% one tone thereafter; i.e., there was a tendency for an increase. The degree of change differed individually. One tenor increased his closed quotient in all four recordings by 14–17 percentage points; for the others it varied within a range of –3 to 7%.

Discussion

This study showed what seems to be a general feature of register transition between 'chest' and 'head' for open back vowels: F_2 starts to resonate H_3 when F_1 cannot follow the rising H_2 anymore. When singing through passaggio a professional singer anticipates and avoids a register violation by allowing F_1 to fall below H_2 be-

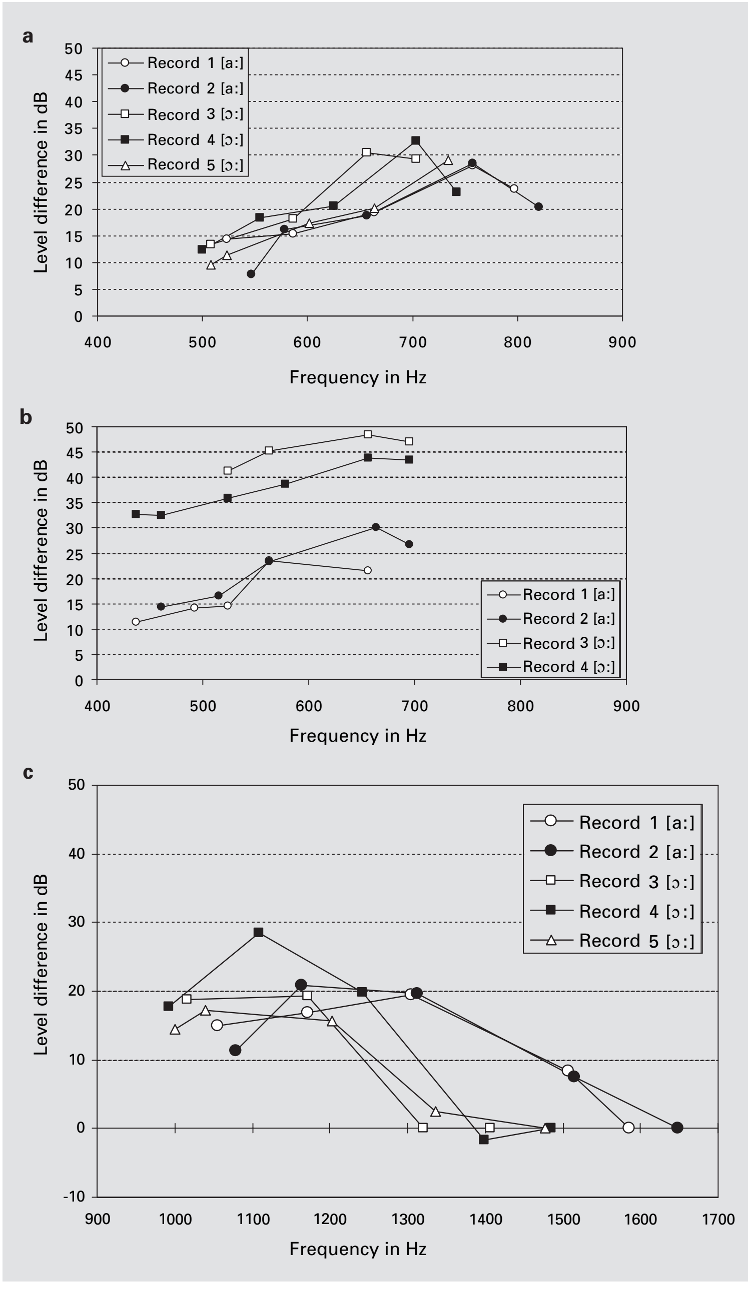


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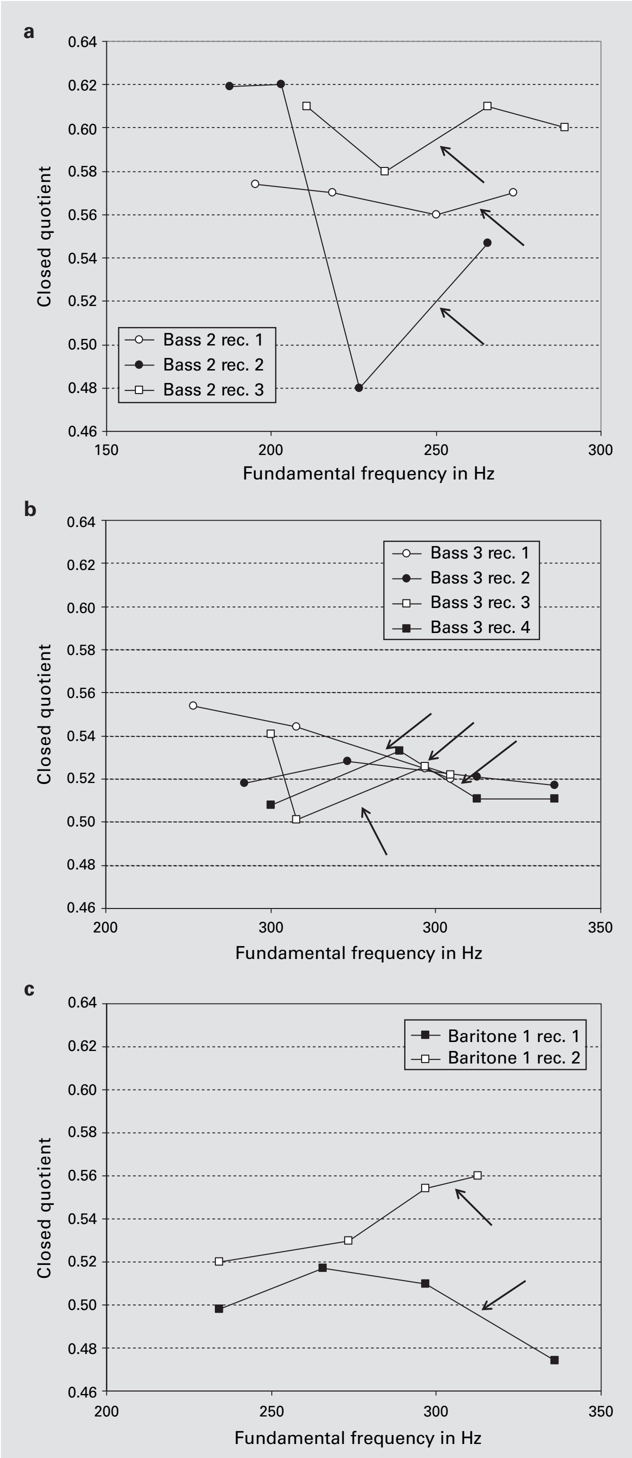
Fig. 9. Intra-individual comparisons between the frequency courses of the harmonics of several phonations, with minimum (**a**), medium (**b**), and maximum intra-individual differences (**c**).
Fig. 10. Intra-individual comparisons of the closed quotient courses. Arrows indicate the register transitions. Repeated intra-individual recordings of several phonations and vowels show an increase (**a**), a predominant decrease (**b**), and an increase in one phonation and a decrease in another one (**c**).


a
Closed quotient
Fundamental frequency in Hz
Bass 2 rec. 1
Bass 2 rec. 2
Bass 2 rec. 3
b
Closed quotient
Fundamental frequency in Hz
Bass 3 rec. 1
Bass 3 rec. 2
Bass 3 rec. 3
Bass 3 rec. 4
c
Closed quotient
Fundamental frequency in Hz
Baritone 1 rec. 1
Baritone 1 rec. 2

10

fore both become locked together by an elevated larynx [2]. Thus our data confirm those of Miller and Schutte [2]. Additionally, it could be shown that for open back vowels F_2 is tuned to H_4 in the high range of 'chest' register, and the level of H_4 decreases markedly when the F_2 tuning changes from H_4 to H_3 ('head').

Our findings also concur with those of other voice researchers. For example, Hertegård et al. [29] reported a lowered F_1 during this register transition. Sundberg and Askenfeld [30] identified higher formant frequencies and reduced H_1 levels due to larynx elevation, which meets our findings in the case of the register violation (fig. 2, 4).

The described changes characterized the register transition even if it was not audible or if the singers were not certain whether they had performed the transition. Such an uncertainty frequently occurred when the sung passage exceeded the 'zona di passaggio' by only one or two notes, or when the registers were 'equalized'. Hence the self-estimation of a singer does not reveal highly reliable information as to whether and between which tones a transition has been made. Also the judgment by musically trained persons is the less reliable, the more the transition is hidden behind a well-performed passaggio. Large [12] even detected reduced differences in spectral envelope when register equalization had been made. In the study presented here, the consistent results for each partial H_2 to H_4 in each recorded register transition, obtained with spectrum analysis, reveal the most reliable and robust information about whether and where the passaggio has been made.

Some singers need intermediate steps to manage the F_2 tuning, others do not. During these intermediate tones F_1 has already left H_2, and F_2 is not yet adjusted to H_3 (fig. 3). As did Miller and Schutte [2], we detected nearly equal levels of the first three or four harmonics, together with amorphous audio signals, indicating that during these passing steps F_1 and F_2 fall relatively ineffectively between the harmonics and reveal poor resonance. Miller and Schutte [2] suggested that these intermediate steps might be more necessary in deeper voice categories than in tenors. Our data confirm this suggestion by showing that tenors need fewer steps (one to three) than basses and baritones (two to three) to complete the passaggio, as well as managing the transition without intermediate steps. Whether semitone or full tone steps are used for the passaggio seems to be less important, but in most cases a certain number of single adjustment processes covering a certain pitch range are needed to manage this resonance change.

We searched for typical features of the passaggio also in the time domain with the program Glottal Segmentation of Voice and Speech®. This program stacks the subsequent glottal cycles cascade-like on top of each other, and the partial waves are positioned strictly with respect to their temporal order. The cascade patterns sometimes indicated the register transition by a lapse in the temporal partial wave structure of the audio signals, as well as by flattened or irregular curves for one or more glottal cycles. However, these patterns could be found reliably only during pronounced register transitions with the described intermediate steps indicating a short-term loss of vocal tract resonances. A one-step passaggio or a well-done register equalization did not reveal patterns which identified a passaggio with certainty. Because of this lack of reliability, we did not follow this track any further.

No gross spectral differences were detected between the passaggios produced with [o:] and [a:]. Therefore the data of both vowels were pooled. The reason for using these two vowels was that singers anyhow often have difficulties to maintain the same vowel because of the vowel modification during register transition. Even trained phoneticians may have difficulties in determining proper vowel differences [12]. Both are open back vowels with a deep or medium position of the back portion of the tongue, and their F_1 and F_2 ranges cover neighbouring or overlapping frequency regions [31]. It therefore comes as no surprise that both vowels show the same features during the register transition. The described patterns, however, can be generalized only for these particular back vowels. Further research should also include other vowels, because there are indications that for front vowels F_2 is tuned to H_4 [2].

Among several options described by Miller and Schutte [2] to manage the passaggio, only the technique of 'covering' is mentioned here because it is used most frequently by classical singers. Covering employs a lowering of F_1 (fig. 3) while extending the length of the pharynx and supralarynx by lowering the larynx [32], and a lowering of F_2, for instance by protruding the lips and reducing the mouth opening [2]. To prevent a register violation these processes have to happen early enough in an ascending scale. Thereby the vowel [a:] is modified toward [o:].

Titze [5] suggested that singing registers might result from subglottal resonances which interfere with the vocal fold driving pressure, and may have a constructive or destructive influence on the vibrational amplitude of the vocal folds, depending on the fundamental frequency. He postulated a region of maximal constructive influence between D3 and D4 causing a richer timbre of the phonation. For higher frequencies the vibrational amplitude of the vocal folds should decrease quickly, causing the glottal abduction quotient to increase and the register to shift to a poorer timbre. Therefore, notes of about 400–800 Hz (G4 to G5) should be less suitable for 'chest' production. For notes higher than D4 the inhibitory influence of the subglottal resonances on the vocal fold vibration becomes increasingly effective. Accordingly, the register shifts should be based on subglottal formant influence, and they should be abrupt quality changes which result from either loss or gain of high-frequency sound energy at the source. Titze [5] proposed that the register equalization could go along either with an increased adductory control or an increased lung pressure. A higher degree of adduction should offset the reduced vocal fold amplitude during the transition toward an inhibitory influence of the subglottal pressure on the amplitude of vocal fold vibration. Alternatively, an increased lung pressure should increase the amplitude of vocal fold vibration, thereby reducing the abduction quotient and enriching the timbre. Even if the formant tuning is the most appropriate way of register equalization, our findings of frequently increased closed quotients during the passaggio indicate that an increased adductory control [5] may also contribute to the maintenance of resonance in 'head'.

The observed inconsistent patterns of the closed quotients confirm that the glottal source in general remains the same in 'head' as in 'chest'. A general rule for the course of the closed quotients during the passaggio is not apparent from our data. The remarkable inter-individual differences rather indicate that the glottal adjustment to the new resonances might be due to individually employed techniques. However, in the majority of our measurements the closed quotient increased during the passaggio. The closed quotients increased during the register transition in 16 recordings and remained the same or decreased in three and five recordings, respectively. Three of the 4 tenors tended to increase the closed quotients. The tenor with the strongest increase rose his mean closed quotient from 32% in chest to 47% in head. No statements can be made about the progress of the closed quotients beyond the register transition. In a recent source-filter model, Titze [33] estimated the dependence of vocal fold vibration on the vocal tract, the latter assisting the vibration under certain circumstances. Thus, a retrograde effect on the glottis has to be expected, which may also play a role in register equalization.

The recordings of subglottal pressure equivalents at the outer neck [26] did not yield reliable results due to the higher sound pressure level during singing, compared with speaking. It is known, however, that subglottal pressure increases with pitch because stiffer vocal folds at higher pitches require a higher driving pressure [34].

We neglected the frequency modulations of F_0 and the partials with respect to the formant frequencies resulting from the vibrato cycles. Vibrato leads to a varying distance of the partials to vocal tract formants. Schutte and Miller [35] have shown that the vibrato at high tenor tones does not disturb the resonance but facilitates the vocal tract tuning on an optimal resonance, even if the excursion of the harmonics of interest exceeds the bandwidth of the formants. Simplified, the tuning effort seems to be directed in the presence of vibrato on either F_1 or F_2 and intermittently activates the singer's formant and the selected lower formant [35]. Even if a harmonic sweeps F_2 completely, the relation of F_1 bandwidth and frequency modulation range of the vibrating H_2 ensures its coverage by F_1 [36].

Conclusion

This study confirmed with a larger sample of singers and for the three basic male voice categories the existence of definite spectral features, for open back vowels, that characterize 'chest' and 'head' registers and the transition between them. In 'chest' both H_2 and H_4 dominate because they are resonated by F_1 and F_2. During the passaggio the spectral energy of H_2 is reduced because it loses the resonance of F_1, whereas now F_2 is tuned to H_3. Simultaneously, H_4 decreases its amplitude because it is not supported by F_2 any longer. These patterns provide objective parameters for the definition of the two registers. The changing patterns of the closed quotients indicate that the 'chest' source remains essentially the same in the transition. They also suggest that variable glottal adduction might be employed to manage the register transition. This transition, however, is mainly caused by supraglottal resonance adjustments rather than by laryngeal ones as the fundamental ascends and the interference of subglottal resonances with the vocal fold vibration changes.

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