The Human voice and its registers: the value of interdisciplinary collaboration.

As I was reflecting on my invitation to this congress where so many competent voice specialists are gathered, both singers and scientific researchers, I found myself in something of a quandary. I have to confess that I am not a singer and voice research is not my main field of investigation. The first title to come to mind was - "On the great advantage of being a non-singing female scientist who has met with exceptional collaborators in order to study the human voice." Nevertheless, as I have a specific and deep feeling for the human voice in all its variety throughout the world, I hope I will be able to contribute a little something to knowledge on the voice.

From music to acoustics: Emile Leipp and the "Laboratoire d'Acoustique Musicale".

It all began with a stroke of luck. I was a music teacher and by chance met in 1963, Emile Leipp, who had just created the laboratory at the Faculty of Sciences of Paris. I was immediately amazed by the new techniques of sound analysis, particularly the sonagraph. Being attracted by the scientific approach to musical problems, I decided to leave musicological studies aside for the new and exciting field of musical acoustics.

E. Leipp was an outstanding researcher. He was a musician, violin maker, with an inquiring mind for a wide range of topics. He was able to communicate his results with great passion to a wide public. The laboratory soon became a place where I could meet high level personalities coming from different environments. I would particularly like to mention Abraham Moles who introduced us to Information theory and to Gestalttheorie; Tran Van Khe, a Vietnamese ethnomusicologist with whom we discovered Asiatic music; Suzanne Borel-Maisonny the founder of French orthophonics, who posed us flood of questions and was in connection with many voice specialists.

I think that the greatest stroke of luck I had at that time, was being introduced into acoustics by Leipp. Compared with that of other researchers of this period, <u>Leipp's approach was original</u>. He used to say that, since musical sounds are produced for human ears, it is always necessary to link physical analysis with perceptive interpretation Ref [1].I This simple principle bears

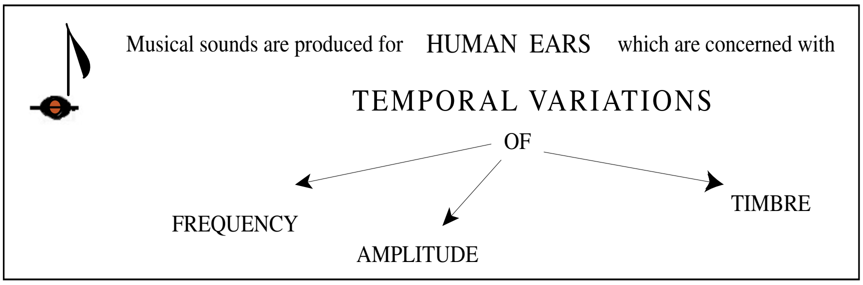


Fig.1 - Leipp's basic principle

many consequences. It means focusing upon temporal variations in the signal which carry the information to the ear, and upon setting up convenient experimental methods. For this purpose we used sonagraphic representation which displayed the temporal evolution of the spectrum, and showed us the life of the sounds : transients, vibrato, timbre fluctuations and fabulous speech patterns.

In the same way, study of an instrument included not only stable notes, but also the "champ de liberté" (lit. «field of freedom») of parameters. For each note, we asked the musician to produce all the possible changes in intensity, frequency and timbre. Hence my interest in the voice phonetogram. There was also a short instrumental test in use at the laboratory - the glissando. E. Leipp initiated it for violin testing, because it shows clearly the fixed spectral formants. Glissando also played an important role in my voice study.

The speech synthesis adventure: 1964-1974

On the basis of Gestalttheorie, Leipp had the intuition that speech intelligibility was related to the spectrographic forms which were visible on the sonagram. As the global temporal pattern of a word was characteristic, whatever the voice quality, we chose to work with the whispered voice which showed clearly the formant transients and the plosive noises. I analysed all the phoneme transitions (diphones) of three speakers, 2 males and myself, and a synthesiser was built to verify our hypothesis.

During this highly exciting period I depicted hundreds of transitions, first by hand and later with the help of a computer, and I set several psychoacoustical tests to improve on the elementary patterns. In the end we were able to produce automatic speech synthesis. The intelligibility was very good and the voice quality quite acceptable. In addition, we had the possibility of synthesising a male or female voice, simply by applying frequency anamorphosis to the patterns.

What I learned from this:

* Validation of the Gestalttheorie principles in the field of hearing.

* The opportunity to study both female and male voices confirmed us in the opinion that it is interesting to carry it out across genders.

* Good training of my analytic listening which came from long-term work with constant comparisons between spectral analysis and synthesis. Ref [2]

* As early as 1965, we were asked to analyse different pathological voices : oesophagian voice, bitonal voices, and palatal voices. With Mme Borel Maisonny we realised an X-ray film showing the participation of the different parts of the phonatory apparatus in some types of musical productions: Jew's harp playing, diphonic singing, Asian theatrical voice production (high falsetto). Ref [6]

The "glissando shock": 1967

In 1967 Leipp gave a GAM seminar where he developed an interesting functional analogy between two vibrating systems: the vocal cords and the lips of a brass player Ref [3]. The phonation theories, especially Husson's ideas, were under discussion and generally speaking, the way of varying the pitch of the vocal cords was not well known. At the end of the seminar, Leipp presented two analyses: a regular glissando sung by himself and another that I sang and which had a strange "break" in the middle.

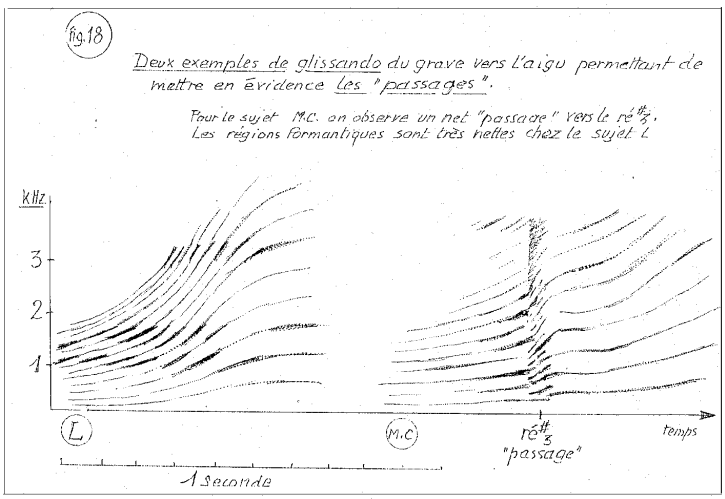


Fig.2 - Two vocal glissandi; left: male voice, right: female voice. (Ref [3])

During the discussion with singing teachers, no explanation of the break was given; I was just invited to take lessons in order to eliminate such a default. What I could not accept was the refusal to take into account an acoustical event. This shoked me, whilst at the same time arousing my curiosity.

Two years later we recorded professional singers singing glissandos on different vowels (Ref [5]). We studied the specific formant located in the frequency area corresponding to the ear's zone of maximum sensitivity, and I observed that my own glissandos always had a break but no formant. Undoubtedly I was not a singer!

I forthwith went back my doctoral research on flute-like instruments and took up harpsichord playing!

Bernard Roubeau and the E.G.G. : 1981-1993

- towards laryngeal and resonantial registers

In the 80's, interest for early music grew apace in France and some young singers began developing a counter tenor voice. Bernard Roubeau came to the laboratory to do research on "the use of falsetto in male voices" for his orthophonist's cursus. He worked with Bass, Baritone and Counter tenor who sang ascending and descending glissandos and sustained notes with register changes between chest and falsetto. The sound and the Electroglottographic signals were recorded simultaneously at the Hôpital de la Pitié Salpétrière. The mystery of the break began to melt away. The moment a singer changed register, the EGG curve suddenly changed, along with a frequency jump.

- We established the hypothesis that frequency discontinuity in the glissando - the break - corresponds to a change in the vibratory mechanism. We observed that the typical frequency pattern jump was reversed according to the direction of the transition.

- When no jump was heard, the EGG signal showed discontinuities in amplitude and in the global form. We didn't find gradual transition. On the sonagram analysis one could see perturbations such as intensity fall, spectral discontinuities, or irregularities in the vibrato graph.

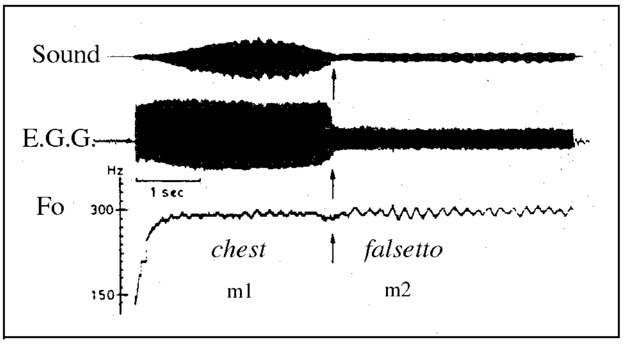


Fig.3 - Analysis of an isoparametric sound sung by a tenor (vowel O). The singer lowers the intensity to realize the transition between m1 and m2 without any discontinuity in the fundamental frequency. Even so we see a sudden radical change in the E.G.G. signal . Ref [4]

SOUND: # 01 *[23s.] - Mechanism change (from m1 to m2) on a sustained tone;* ***a)*** *counter tenor, E4, /i/, frequency break;* ***b)*** *tenor, E4, /o/, continuous frequency but intensity drop : cf figure 3.*

- From recordings, we selected some sound examples where the break may be heard. They come from well-known singers (Caruso, Callas), traditional styles of voice production (yodel, Japanese Edo style of singing) and also wolf songs (!)

These results were presented at the GAM seminar and we were surprised by the hostility or the misunderstanding of the greater part of those present. In fact, the discussion was distorted because of register terminology. The same problem occurred at the Stockholm SMAC Conference in 1983. (Ref [7])

We decided to make a clear distinction between **laryngeal mechanisms** and **singer registers** which designate complex adjustments related to both larynx and resonance cavities. It appeared necessary to us to give up the usual terms and adopt a single designation system for the laryngeal mechanisms, whatever the singer's sex or singing technique. Simple numbers were chosen: **m0** (fry), **m1** (chest, modal, heavy mechanism), **m2** (falsetto, female head, loft, light mechanism), **m3** (flageolet, whistle, sifflet).

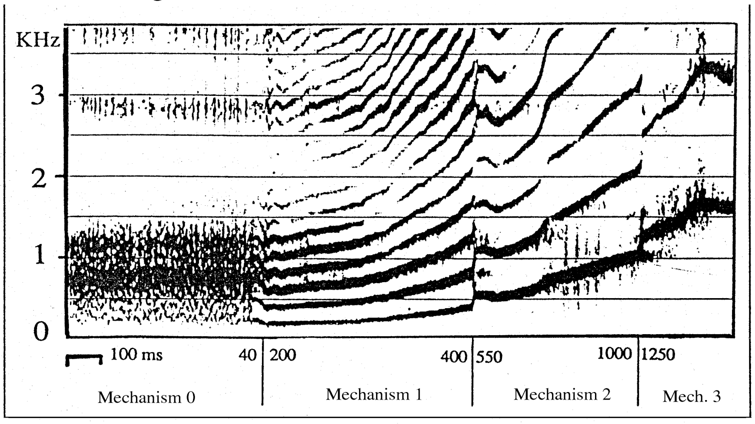


Fig.4 - Glissando over the whole voice range showing frequency discontinuity at each laryngeal mechanism transition; female.

SOUND: # 02 *[9s.] - Ascending glissando through the 4 laryngeal mechanisms, /a/; woman.*

The research was continued and the protocol extended to singers and non-singers of both sexes and to children, all being asked to produce sounds within the four basic mechanisms. In 1984 we had the luck to receive Richard Miller who kindly accepted to produce register changes with EGG recording. We also began developing a voice range profile - phonetogram - for each laryngeal mechanism

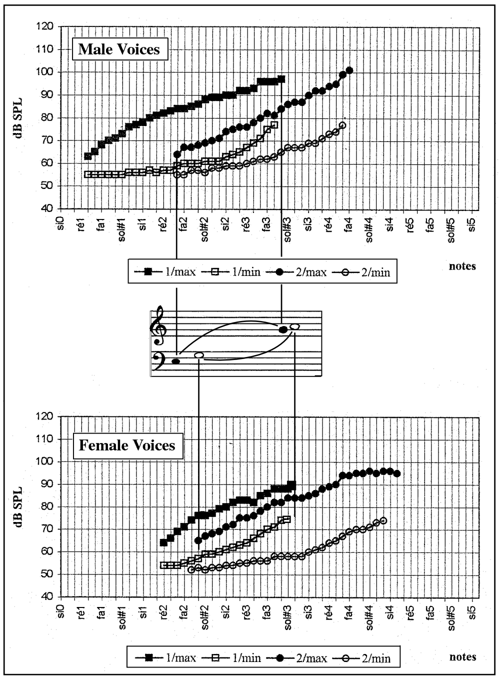


Fig.5 - Average voice range profile taken from 42 subjects. The diagram brings out the range overlap between m1 and m2. Roubeau and al , Ref [19].

At the request of the musical composer J.C. Eloy to give sonagram analysis of about fifty vocal samples taken from different musical traditions, I discovered vocal techniques which use in an artistic way, the acoustical events related to the transition between the two main mechanisms.

The reading of litterature, old treatises as well as scientific studies, once more showed conflicting opinions on the subject of registers.

The outcome of this was:

* Reliable knowledge on the laryngeal mechanism employed by a singer is necessary in order to carry valuable studies on registers.

* The four basic laryngeal mechanisms are common to all humans: children, male and female. Their range, their expressive possibilities through intensity and timbre vary with age, sex and greatly depend on the way they are used.

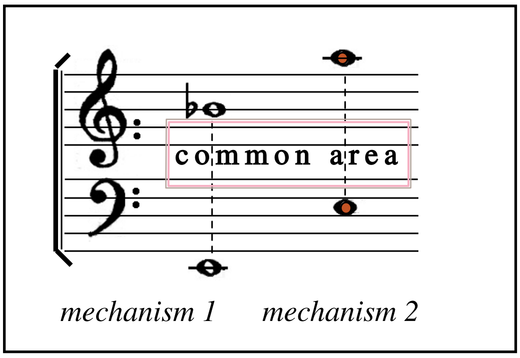


Fig.6 - Within the common area, the singer may use either m1 or m2.

* The frequency area where the main mechanisms m1 and m2 overlap is of primordial importance. It lies in the middle of the musical range, approximately between F3 and G4.

In this part of the tessitura, the singers develop an extreme variety of singing techniques, according to the stylistic rules of their cultures. Considering frequency and timbre changes from one mechanism to the other, one may distinguish 3 main categories (Ref [9]).

- Study of the transition between the two main mechanisms.

In the first category the singer achieves perfect continuity in frequency and homogeneity of timbre through both mechanisms m1 and m2 (classical alto voices, counter tenor).

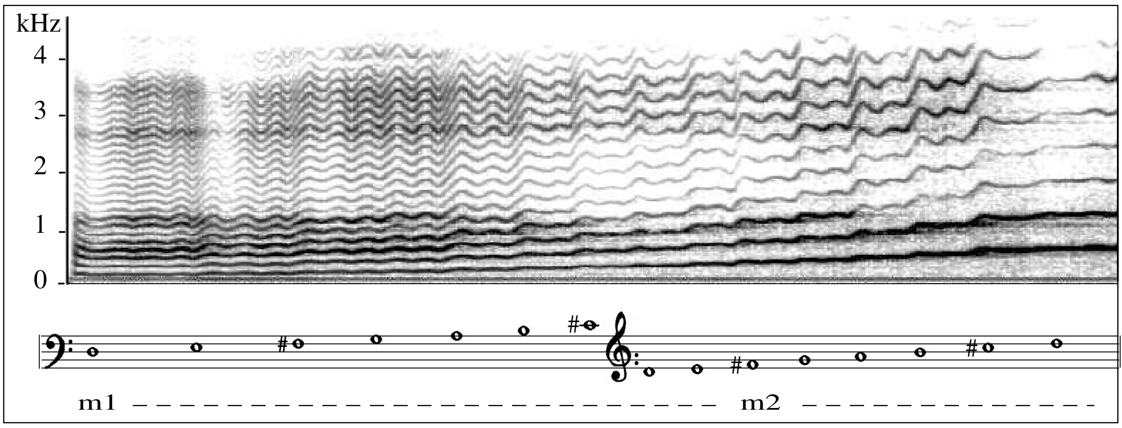


Fig.7 - Ascending scale sung by a counter tenor. The singers achieves a perfect continuity in frequency

SOUND: # 03 *[14s.] - Timbre homogeneity through m1 and m2, counter tenor; ascending and descending scale, D3-E5, /a/.*

Sometimes the singer uses break as an expressive effect like Caruso,

SOUND: # 04 *[29s.] - Expressive frequency break found in classical style; D4 - Bb4; Caruso, "Les pêcheurs de perles", Bizet.*

or D. Devries.

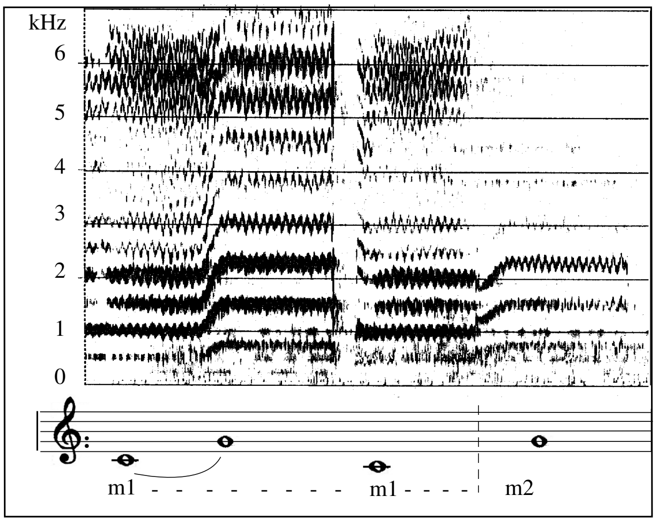


Fig.8 - Example of an «expressive break» between m1 and m2: D. Devries - Donizetti, «La dame blanche».

SOUND: # 05 *[40 s.] - Using the common frequency area of m1 and m2 in an artistic way. Pay heed to the octave C4 – C5 without break, and the three fifths C4-G4, without and with mechanism change; D. Devries, "La dame blanche".*

Fine examples are also found in Japonese traditional music;

SOUND: # 06 *[14s.] - Mechanism change on a sustained note (E4); "The music of Japan", VI, No-Play, Biwa and Chanting (Bärenreiter Musicaphon).*

In the second category, the singer looks for maximum contrast between the two mechanisms, with large melodic breaks and opposition of timber supported by alternation of open and closed vowels (Yodel).

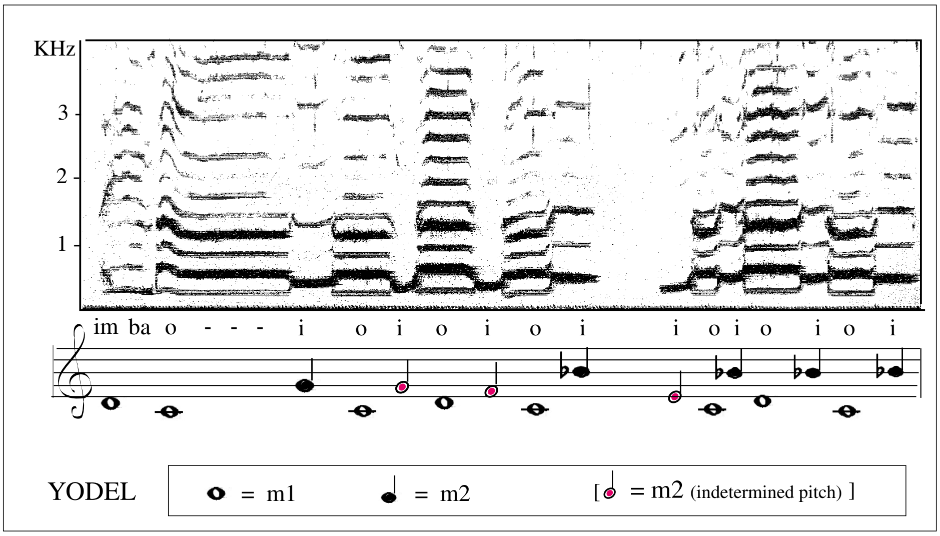


Fig.9 - In the yodel song, the opposition between the two mechanisms is emphasised by the use of two different vowels : / o / for m1 and / i / for m2.

SOUND: # 07 *[20s.] - African song, yodel; "Musiques Africaines". Musique de tous les temps, N° 44/45 (Mett PEP 6890/6891) Pygmées Babenzélé de République Centrafricaine.*

The third category brings together various singing styles which transform the frequency jump into complex melodic ornaments. For example, the Iranian Tahrir consists in a melodic line sung in m1 with short, rapid incursions into m2. As the musical interval of the jump is almost a fourth, a parallel melodic line is heard above the first one. (Fig.10 -)

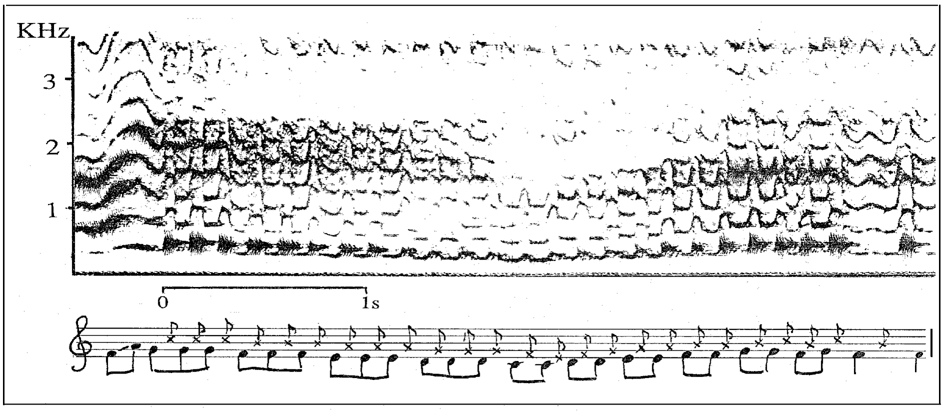


Fig.10 - Iranian singer. The frequency jump is transformed into a melodic ornament.

SOUND : # 08 *[14s.] - Iranian song in the "tahrir" style, Zabihi; Iran II, Collection Unesco (Bärenreiter Musicaphon BM L 2005)*

Questions:

- Questions arose about the high mechanism m3 (the whistle), which is found in female and in male voices. Is this mechanism a new vibratory pattern? Or does the break occur around 800 Hz result from a coupling with supraglottal resonances? And what about the mixed voice? Is it really possible to produce a mixing mechanism intermediate between chest and falsetto?

Invited to give a number of talks for singers, phonatricists and acousticians (Ref [8], Ref [10]), we adopted a radical and perhaps shocking point of view. But it seemed to us necessary to clearly speak of the phenomena observed by objective explorations, and to establish the notion of distinct laryngeal mechanisms, for further progress at the higher level of resonantial registers. Dr M.A. Faure invited us to present a general report at the French Phoniatric Society and opinions progressively began to change.

We had in mind the necessity of communicating these ideas to a wide public. We began writing a small bulletin on "The notion of vocal registers" with sound examples, intended to non-specialised readers. This ambitious project, requiring much time, was abruptly interrupted in 1993 with Bernard Roubeau defending his thesis (Ref [14]) and my taking charge the laboratory.

At the same time, I had also developed some research on pitch perception of vocal sounds.

Vibrato and trill perception; Ch d'Alessandro & G. Richard: 1987-1994

I have been always interested in pitch perception of musical sounds. Around 1976, I analysed multiphonic flute sounds at IRCAM where powerful sound synthesis devices were available. Vocal sounds presented more difficult problems. When closely examining a scale sung by a soprano, C. Herzog, I suddenly realise that I could hear "notes" which I was not able to pick out on the analysis. The comparison with a similar scale played on a piano was striking.

In 1986, it became possible to do synthesis on a desktop computer and C. d'Alessandro, who had worked on a formantic based synthesis method (FOF) joined the laboratory, together with G. Richard (Ref [11]). We carried out several studies on the transition between legato vibrated notes, and then on pitch perception of very short vibrated notes, such as "notes piquées" (Ref [13]).

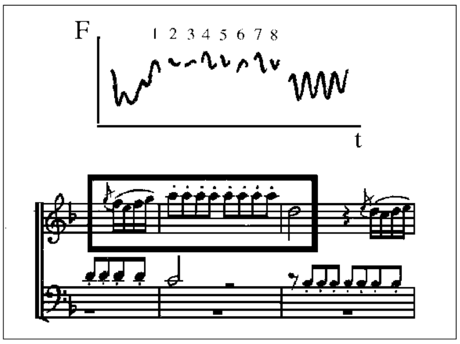
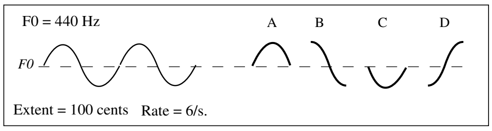


Fig.11 - Short vibrated notes may present various oscillating shapes. Left, the figure shows the fundamental frequency patterns of a short sequence extracted from Mozart's Magic Flute; Aria of the Queen of the Night. Figures refer to the eight quavers. Below, the frequency shapes used in the perception test.



SOUND: # 09 *[17s.] - Short vibrated "Notes piquées"; sequence extracted from the aria of the Queen of the Night, Mozart; B. Hoch. (figure 11, left)*

SOUND: # 10 *[11s] - Four examples of short vibrated notes, successively A, B, C, D. Figure 11, right. FOF synthesis.*

SOUND: # 11 *[14s.] - Pitch adjustment test for the perception of short vibrated notes. 5 pairs. The first tone, (frequency form A), is associated with 5 different frequencies : 431, 439, 454, 446, 449. The last pair was chosen by the subjects themselves.*

Afterwards, for 2 years my interest focussed the vocal trill (Ref [12]).

The outcome of this:

* Pitch perception of vocal vibrated notes is a rather difficult question, far more complex than those pertaining to other musical sounds.

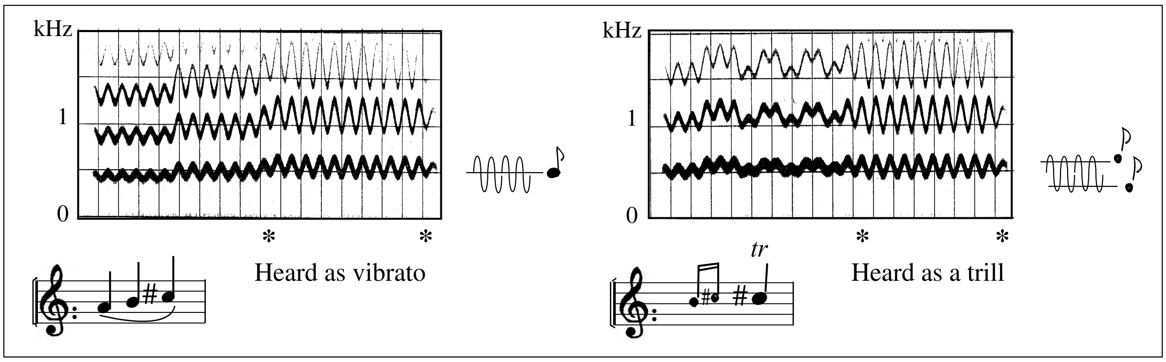


Fig.12 - A given modulated sound may be heard as a a vibrated note or as a trill on two notes. Ref [12]

SOUND: # 12 *[22s.] - According to the context, whether a scale or a trill preparation, the same vocal event will be perceived differently.*

* Vocal sounds hold a special status in our mind.

The fact that the same sound - a given vibrated sung note - here C# - may be heard either as one note - a vibrato - or as two notes - a trill - according to the musical context, shows that pitch interpretation of vocal sounds is not only a psychophysiological problem but rather a cognitive one. It is well known that a spectral vocal sound synthesised with a fixed fundamental is not recognised as vocal sound.

The glottal open quotient, the "cover" and the mixed voice. (Nathalie Henrich, Bertrand Chuberre). 1997-2002

In 1997 two young persons came into contact with me. They were Nathalie Henrich, a physicist specialising in musical acoustics, and Bertrand Chuberre, both physician and singer, a student at the Music Conservatory of Paris.

N. Henrich's doctoral thesis (Ref [17]), which I supervised in collaboration with C. d'Alessandro, is devoted to the study of glottal wave parameters in relation to voice quality. For full information on her work, you may see the poster she presents at this conference. For the moment, I only wish to quote one important result: viz. the possibility of measuring the glottal open quotient using a reliable method.

From her exhaustive work, in which she systematically analysed 18 singers following a comprehensive protocol including similar sounds produced in the two main laryngeal mechanisms, 2 important results came out for my purpose:

1 - Glottal open quotient, Oq, is a good indicator of mechanism changes. For a given singer and for a given vocal intensity, the Oq value is higher in mechanism 2 than in mechanism 1.

2 – Within mechanism 1, the Oq value is inversely correlated to the voice intensity: the higher the intensity, the lower the Oq value.

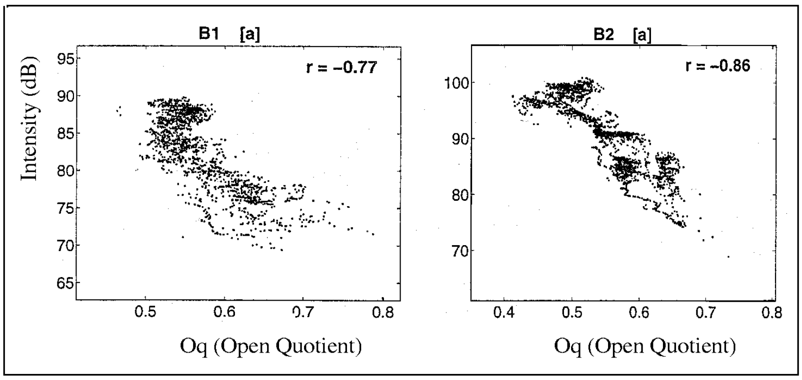


Fig.13 - Relation between Oq and the vocal intensity, within m1. Measurements done with 2 baritones, B1 and B2; frequency: G3; vowel [a] - Ref [17].

As an experienced singer: B. Chuberre wished to carry his research on some specific vocal adjustments relevant to vocal pedagogy, both from the acoustical and physiological points of view. In his thesis (Ref [16]), B. Chuberre studied two resonantial registers, "cover" and mixed voice, with different young professional singers: baritones, countertenor, and sopranos.

The concept of mixed voice may vary within different singing schools. Discussion on that point is developped in a paper being written. I would like to end this presentation with some results on the French «voix mixte».

The recording protocol comprises sustained notes sung with 5 different vowels. For each pitch, B. Chuberre asked the singers to produce both laryngeal mechanisms m1 and m2, and then mX (mixed voice). Each note is followed by a vocal fry (m0) production, according D. Miller's fruitful protocol. For the mixed voice, a crescendo was always required to confirm the mechanism in use.

The figure shows the results for two singers, a soprano and a baritone. We present only the measurements of the intensity and the Open quotient, for two vowels /i/ and /o/.

SOUND: # 13 *[28s.] - Soprano; Eb4 /o/; here follow successively, laryngeal mechanism 1, laryngeal mechanism 2 and mixed voice. Announcement in French : «poitrine, tête, mixte». Figure 14.*

The soprano (left) said she was using m2 for her mixed voice. The Oq value is effectively the same for m2 and mX. The intensities of the three notes are quite similar. But on comparing what one hears with the spectral analysis (not shown here), mX is quite similar to the note sung in m1.

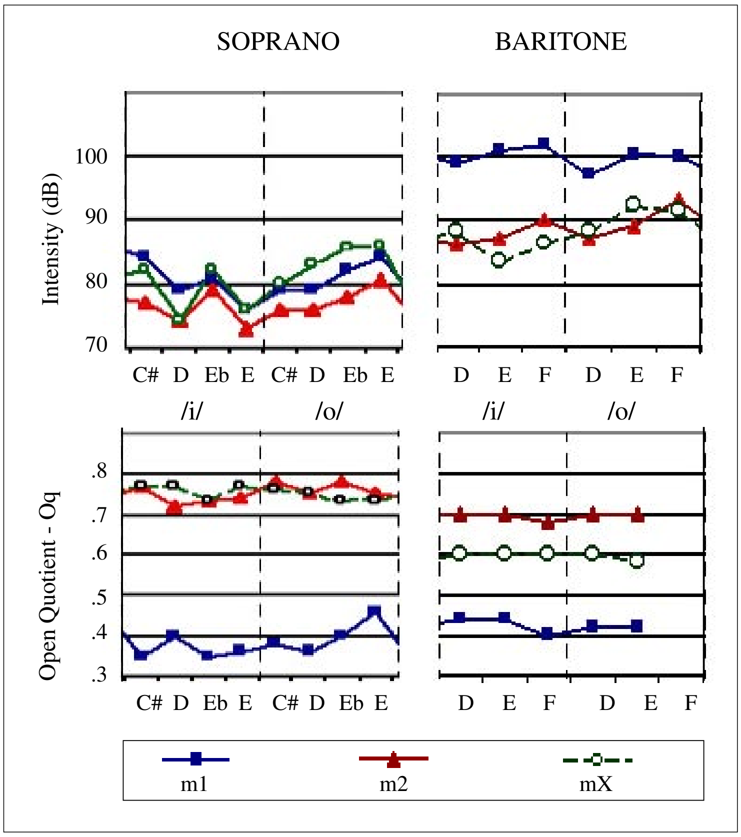


Fig.14 - Two singers, a soprano (left) and a baritone (right) sang in three different «registers» : mechanism 1 (m1), mechanism 2 (m2) and «mixed voice» (mX). Comparison of the intensity (top) and the Open Quotient (bottom) for two vowels /i/ and /o/ and for different notes (octave 4). After Ref [16].

SOUND: # 14 *[17s.] - Baritone; E4 /o/; successively m1, m2, mixed; crescendo into mixed voice. Figure 14*

The baritone (right) said that he was using m1 for his mixed voice. According to what one hears andwhat appears on the spectral analysis (not shown here), the mX sound is quite similar to m2 . But we notice that **the mX Oq value is intermediate between those of m1 and m2 which may seem problematic. But we do know that, within m1, the lowering of intensity**

produces an increase of Oq value.

We think that such a change in the EGG for mixed voice sounds may have induced some researchers to write that mixed voice is an intermediate mechanism between m1 and m2.

My last slide is the analysis of an example sung by R. Miller in 1984 who compared head and mixed voices on a sustained note

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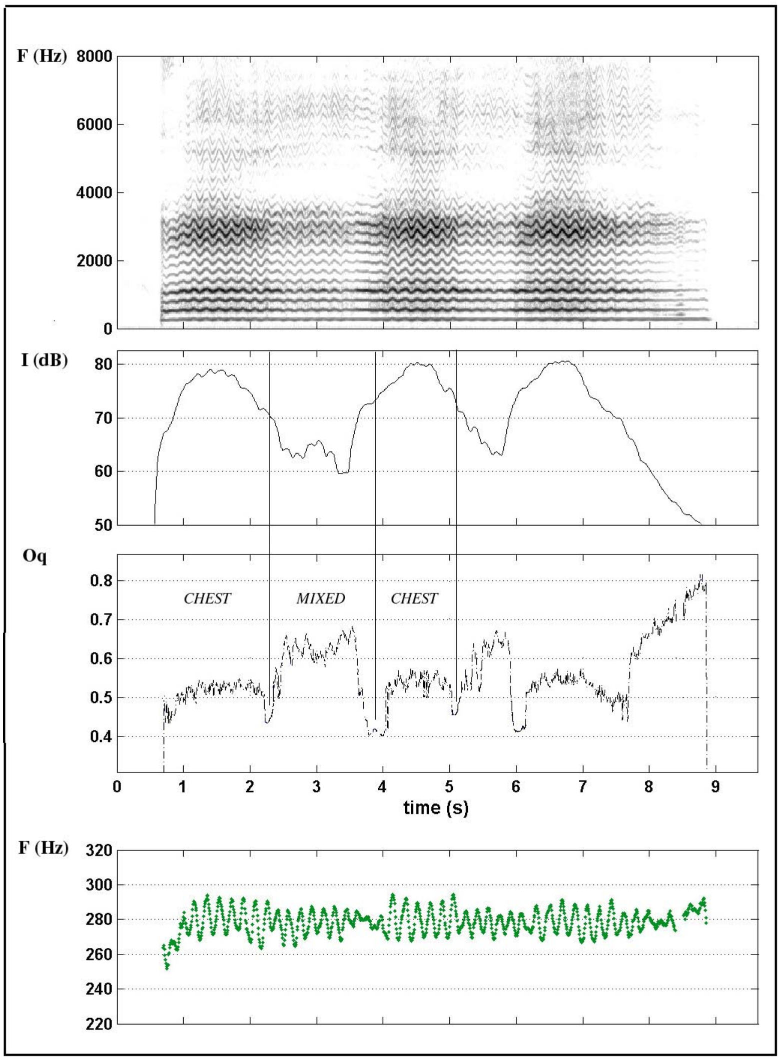

Fig.15 - Alternation of chest voice and mixed voice on the same sustained note D4, sung by R. Miller. Change of Oq values correspond to the variations of the voice intensity. These two productions are in mechanism 1 (chest voice).

SOUND: #15 *[12s.] - Tenor; D4 /a/; changes from chest to mixed voice; Figure 15.*

We clearly understand now the variations of Oq with the change of intensity in the chest voi-ce. I suppose that Richard Miller would agree with us that he was really using mechanism1 when producing mixed sounds.

The outcome of this:

* According to the vocal technique the French mixed voice may be found either on the first or on the second laryngeal mechanism. As the laryngeal adjustments needed to produce the desired sound quality of "mixed timbre" change with the mechanism, it is necessary to clearly identify them, and to carry out two distinct studies.

Study of the mixed voice is ongoing.

Many questions remain unanswered, particularly the following:

Questions

- Is it possible to find an objective parameter related to the vocal fold adduction force? Independently of Oq variations, the singers are able to adjust the spectral content of the sound (see the soprano). On the DEGG signal, B. Chuberre noticed that the amplitude of the negative peak at glottal closure was well correlated with spectrum changes. May we consider this parameter as a valuable clue?

- We have a lot of data on the first mechanism (chest) but the second one needs further study. Almost all the exploration to date has been made with male singers who do not use this mechanism.

- The same remark applies to the third mechanism, the whistle voice. In addition it is very difficult to analyse m3 EGG signals because of the weakness of the vibratory amplitudes. As this mechanism is widely used by sopranos, as B. Chuberre showed in his work, it would be interesting to pursue the study of higher tones.

Acknowledgement - The author thanks John Wright for his patient assistance in improving english writing of the original version.

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