Experimental study of the frequency leap interval produced by the change of laryngeal vibratory mechanism during sustained notes

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ABSTRACT

The transitions between two different laryngeal vibratory mechanisms are often characterised by frequency jumps. The leap interval of these frequency jumps is studied for the transitions from M1 to M2 and conversely from M2 to M1. Its correlation with the starting fundamental frequency, the vocal intensity and the vowel is investigated.

Seven singers have produced sustained notes with laryngeal mechanisms transitions occurring during the production. The sound and the electroglottographic signals were recorded.

The leap intervals values depend on the subject. However global tendencies can be observed for most of them: the leap interval rises with the musical dynamics for the M1→M2 transition, and decreases with the frequency for some subjects. Concerning the M2→M1 transition, no tendency was observed. The frequency leap interval does not depend on the vowel; however the results show individual strategies.

The subglottal pressure at the beginning of the jump could play a role in the leap interval variation. Results show that the relation between the fundamental frequency and the subglottal pressure could be different in M1 and in M2.

1. INTRODUCTION

Classical singers use only their vocal apparatus in a ”stable” configuration. However it is now known that instabilities can occur during phonation. These instabilities can be frequency jumps, period doubling or tripling, or phases of ”chaos” (which can be produced at the physiological level by an irregular oscillation of the vocal folds). They are used in non-classical techniques (yodel, tahrir) [1], or specific singing styles like contemporary music [2].

These instabilities may result from different phenomena, especially acoustic [3] and biomechanic ones. This paper is about frequency jumps which are observed at the transition between the two main laryngeal vibration configurations of the vocal folds, which are commonly used in classical singing, contemporary commercial music as well as in traditional music: the laryngeal vibratory mechanisms M1 and M2.

These two mechanisms are already well-documented and correspond to modal and falsetto registers when these terms refer exclusively to the laryngeal oscillation of the vocal folds. The vocalis, which corresponds to the internal layer of the vocal folds [4], participates with the vibration in M1, whereas it does not in M2. As a result, the surface of contact is greater in M1 than in M2 for a given fundamental frequency and vocal intensity [5]. The subglottal pressure is usually greater in M1 than in M2, the open quotient takes different values, etc. For more details, see [5].

One particularity of the frequency jumps is their very short duration (from a few milliseconds to 120 ms, depending on the observations and experimental conditions [6,7]). It allows one to compare glottal elements that don't change much before and after the transition, such as regulation of subglottal pressure and articulatory adjustments.

Instabilities have been reproduced from excised canine [8] or human [9–11] larynx by changing continuously the longitudinal tension of the vocal folds. Biomechanical modeling (two, three mass model) [12, 13] has confirmed these observations, allowing authors to consider the laryngeal function as a non-linear dynamic system. A significant result is that a range of longitudinal tension can be observed both in M1 and in M2.

Studies with living subjects are based on different protocols: either yodel-like productions (with a change of note at the change of laryngeal mechanism) [9, 14, 15], or sustained notes or glissandos [6, 7]. All these studies show a great variability among subjects, and smaller frequency leap intervals for females than for males. However the relation between source or resonantial parameters with the leap intervals remain poorly documented.

This paper aims at studying the M1→M2 and M2→M1 transitions for different vocal intensities, starting fundamental frequencies and vowels. In order to study these transitions, a well adapted experimental protocol has to be chosen. Svec et al [9] noticed for the yodel-like productions that the frequency jumps are composed of two parts: a transient part and a smoother variation (gliding part). According to them, only the transient part corresponds to the biomechanical phenomenon of laryngeal mechanism transition. The authors of this present paper hypothesize that a protocol based on sustained notes will allow them to distinguish more easily these two parts, and then to study precisely the transient part of the frequency jumps. This hypothesis will be discussed in part 4.

2. METHOD

2.1 Protocol

The instruction given to the subjects is to produce changes of laryngeal mechanisms while producing a sustained note. This instruction is realistic because the laryngeal mechanisms M1 and M2 have a great overlapping area in terms of fundamental frequency and vocal intensity [16, 17]. Subjects had to switch from one laryngeal mechanism to the other in the following order: M1-M2-M1-M2-M1.

Productions were asked for different notes and different levels. For each note, 3 or 4 levels were asked (depending on the subject). The notes were spaced by one tone. The task was first done for the vowel /a/, and then repeated for /i/ and for the close vowel /o/.

2.2 Subjects

Seven subjects were recruited for the experiment: 3 sopranos (S1, S3, S4), 1 mezzo-soprano (MS2), 1 tenor (T3), one baritone (Bar1) and one bass (B3). All the subjects were amateur or professional singers, so that they could be trained at smoothing the transition between the laryngeal mechanisms M1 and M2. All were untrained for the protocol. No one sang yodel-music or any similar vocal style.

The seven subjects had previsouly taken part in an experiment about Voice Range Profiles for the laryngeal mechanisms M1 and M2 separately and for the 3 vowels. [17]. Consequently the overlapping area of M1 and M2 was known by the experimentators for each subject.

2.3 Protocol

The sound signal was recorded with a 1/2” microphone (Brüel & Kjaer 4191), placed at 30cm from the singer’s mouth. This microphone was connected to a preamplifier Brüel & Kjaer 2669 then to an amplifier Brüel & Kjaer Nexus 2690. The EGG signal was measured with an electroglottograph EG-2-PC with two pairs of electrodes, which allowed us to take into account the vertical movements of the larynx. The sound and EGG signals were recorded with a Metric Halo Mobile 2882 soundcard connected to a Macintosh Power Mac G5. A digital oscilloscope has also been used to visualize the EGG signal during recording.

The sound level was calibrated on a stable vocal production, without vibrato and with a speech voice quality. At the beginning of each set, the sound pressure level was measured at the location of the microphone to compute the gain of the data acquisition chain.

The recording was carried out in a room that was large enough (15 m^2) for both the singer and the experimenter, which is more comfortable for singers and allows them to interact during the recording. It was a quiet room, isolated from the outside and with little reverberation (reverberation time at 60 dB: 0.3 s at 1kHz).

2.4 Data processing

2.4.1 *Fundamental frequency*

As the frequency jumps are especially fast (of the order of a few glottal cycles), the usual pitch determination algorithms, which are commonly based on an average frequency over a large window, do not allow to describe the dramatic pitch variation with enough precision. A solution could be to estimate the frequency cycle by cycle as the inverse of the fundamental period. However with this method, the frequency estimation is characterized by small instabilities just before and after the jumps which prevent one to estimate properly the frequency and therefore the leap interval. To solve this problem, the following procedure was used:

- the detection of the glottal closure instants (GCI) from the DEGG signal around the laryngeal mechanism transitions was manually validated;
- The fundamental frequency was computed as the inverse of the duration between two successive GCIs, and its curve was then passed through a 5 point median filter. Using a median filter allows one to cope with the instabilities rounding the jumps while keeping the leap interval.

2.4.2 *Jump labelling*

The starting time (t_{st}) and the ending time (t_{end}) of the frequency jumps were manually determined from the visualisation of several parameters: the radiated sound spectrogram, the fundamental frequency curve, the open quotient and the amplitude of the EGG signal. It allows to establish the onset frequency of the jump (f_{0st}), the ending frequency after the readjustment phase (f_{0end}), together with the frequency leap interval Δf_0. All these parameters are illustrated on figure 1. The sound pressure level before leap number k has been computed. It corresponds to the mean SPL between the end instant of the k-1$^{\text{th}}$ leap and the begin instant of the k$^{\text{th}}$ leap. The intensity after each leap is computed similarly. Therefore, for leap number k:

$$Idb_{bf}(k) = mean(Idb(t_{end}(k-1) : t_{st}(k)))$$

$$Idb_{af}(k) = mean(Idb(t_{end}(k) : t_{st}(k+1)))$$

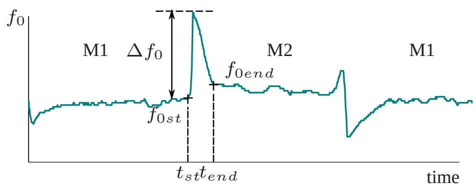

Figure 1. Adopted parameters to study the frequency jumps.

2.4.3 *Fundamental frequency and voice sound level: a numerical estimation of the dynamics*

Studying the correlation between a parameter and either the fundamental frequency or the sound level can be rather complicated because this two parameters are linked: the average sound level increases with the frequency [18–21]. In order to study the correlation between a particular intensity scale (independent of the fundamental frequency) and the leap interval, a new intensity scale, SPL_{cor}, is proposed. It is defined as follows:

$$SPL_{cor} = SPL - k_v.\log(f_0)$$

where k_v is the slope of the linear regression line linking $\log(f_0)$ and SPL computed on all the transitions of the same dynamics on a given vowel. It is estimated in mechanism M1 for each vowel separately, as the result of the average of the coefficient values computed for each dynamics produced by the singer. SPL_{cor} is a numeric scale expressed in dB, where the low values correspond to the pianissimi and high values to the fortissimi.

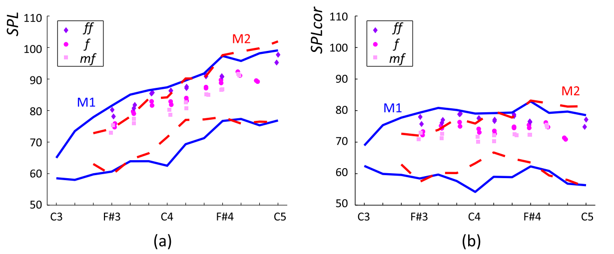

Figure 2. Voice Range Profiles (VRP) from MS2, for each mechanism, with indications of the starting positions of the jumps for the shift M1→M2. (a): Usual VRP (SPL vs f_0). (b): SPL_{cor} vs f_0. On this example, 78 dB (SPL_{cor}) correspond to a fortissimo, whatever the fundamental frequency. Vowel: /i/.

3. RESULTS

3.1 Qualitative observation of transitions M1→M2 and M2→M1 using the EGG signal

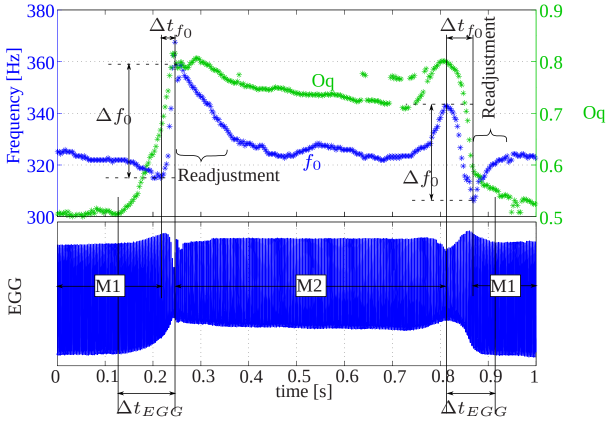

Figure 3. Example of laryngeal mechanisms transitions, produced by B3. Tone: E4, vowel /i/.

Figure 3 shows an example of M1→M2 and M2→M1 transitions, with the instruction to stay on the given note (here an E4, 330 Hz). The frequency leap that is noticeable after 0.2s characterizes the M1→M2 transition. It goes along with a decrease of the EGG signal and an increase of the open quotient. At 0.81s, the downward frequency leap characterizes the M2→M1 transition.

As the protocol requires that the subject keep constant the fundamental frequency as much as possible, he/she has to readjust it after the transition. It is what is done by the subject between 0.24s and 0.35s for the M1→M2 transition and between 0.86s and 0.92s for the M2→M1 transition. Moreover, before the jump that characterizes the M1→M2 transition, the fundamental frequency decreases slightly, and increases before the M2→M1 transition.

Besides, for the M1→M2 transition, one can observe that the open quotient variation is much slower and more continuous than the frequency jump. For the given example, the open phase duration increases as soon as 0.12s while the frequency jump starts around 10ms later. Similarly, the variation of the EGG signal amplitude starts before the frequency jump.

Then, two phenomena are superimposed: the fast frequency jump, and the slower variations of the EGG signal amplitude and of the open quotient.

3.2 Study of the leap interval

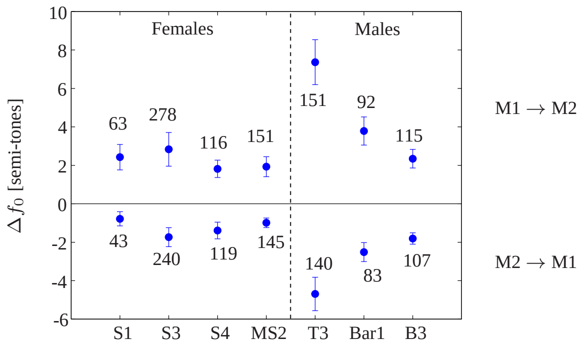

Figure 4. Frequency leap intervals (mean and standard deviation values), in semi-tones, for the 7 subjects, and for the 3 vowels. The positive values correspond to the M1→M2 transitions and the negative ones to the M2→M1 transitions. The indicated numbers correspond to the number of jumps.

Figure 4 shows the mean frequency leap intervals measured on the whole database. Some remarks can be made: while T3 shows a mean value of more than 7 semitones for the M1 to M2 transitions, S4 only shows a 2 semitone mean value. So there is an important variability between the different subjects with respect to the frequency leap interval.

The leap interval is greater for males than for females, for the M1→M2 direction as well as for the M2→M1 one (in absolute value). These observations (inter-subject variability and male-female differences) are in accordance with the results of Svec et al. [9] and Miller et al. [15] obtained respectively on two males and one female, and five males and six females (but, in both cases, with a very different recording protocol). They also support the results of Roubeau et al. [7] obtained this time with a similar protocol of sustained notes.

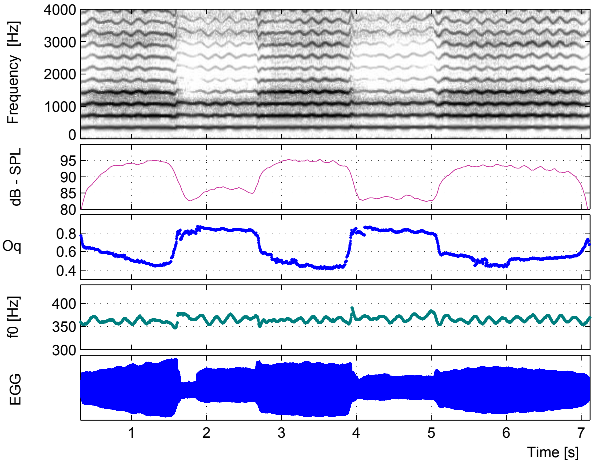

Figure 5. An example of the required production. The alternance of laryngeal vibratory mechanisms is characterized by the variation in terms of EGG amplitude and open quotient values. But the leap intervals are small. Vowel: /a/, tone: F#4.

Figure 5 shows an example of a voice production with alternating laryngeal mechanisms that shows very small frequency jumps, or sometimes even no jump at all. The open quotient changes (between around 0.5 and 0.8) and the EGG signal amplitude changes are related to the alternating laryngeal mechanisms imposed by the protocol. However, the corresponding frequency leap intervals are very small (between one and two semitones), or cannot even be seen as it is the case for the last M2→M1 transition (around 5s) where the frequency control loss (1.3 semitones) is close to the vibrato amplitude (0.74 semitones).

Finally, for each singer, **the M2→M1 leap intervals are smaller than the M1→M2 ones**. This asymetry has been scarcely described in the literature because the usual protocols cannot show it clearly [9, 15]. Roubeau et al. [22] pointed to this before in a protocol similar to ours using sustained notes. When the singer do not try to readjust the fundamental frequency after the transition, his/her production is of a "yodel" type, moving from a given frequency in M1 to another one in M2. This type of production cannot highlight the asymmetry of the leap intervals along with the direction of the transition.

3.3 Vocal intensity and fundamental frequency

3.3.1 Direction M1→M2

Table 1 shows the partial correlation coefficients for the frequency leap intervals Δf_0 and the starting frequency f_{0st} or the vocal intensity before the jump SPL_{bf}, for the data which were obtained for the M1→M2 transition. Results show that the partial correlation coefficients between Δf_0 and f_{0st} are mostly negative, and the ones between Δf_0 and SPL_{bf} are mostly positive. It means that **the frequency leap interval increases with the vocal dynamics and decreases with the starting fundamental frequency**. Besides, **strong correlations were mostly observed for male subjects**.

	/a/		/o/		/i/	
singer	f_{0st}	SPL_{bf}	f_{0st}	SPL_{bf}	f_{0st}	SPL_{bf}
S1	-0.37	0.46	-0.65	-0.09	-0.14	-0.11
S3	0.51	-0.16	-0.16	0.10	-0.02	0.09
S4	-0.46	**0.82**	-0.31	0.47	-0.53	0.65
MS2	-0.30	0.62	-0.60	0.67	-0.47	0.42
T3	**-0.79**	**0.78**	**-0.81**	**0.85**	**-0.89**	**0.82**
Bar1	-0.43	**0.78**	-0.53	**0.75**	**-0.78**	**0.89**
B3	**-0.85**	**0.86**	-0.30	0.47	**-0.92**	**0.92**

Table 1. Partial correlation coefficients for Δf_0 (in semitones) and f_{0st} or SPL_{bf}, for the M1→M2 transitions. Results are presented separately for the 3 vowels and the 7 singers.

3.3.2 Direction M2→M1

	/a/		/o/		/i/	
singer	f_{0st}	SPL_{bf}	f_{0st}	SPL_{bf}	f_{0st}	SPL_{bf}
S1	-0.43	0.04	-0.22	-0.28	0.32	-0.31
S3	-0.43	0.05	-0.18	0.16	-0.10	0.01
S4	-0.04	-0.21	0.10	-0.25	0.00	-0.02
MS2	-0.00	-0.48	0.22	-0.22	0.11	-0.19
T3	0.00	-0.20	-0.15	-0.19	0.31	-0.54
Bar1	-0.18	0.06	0.10	-0.37	0.32	-0.43
B3	0.31	-0.36	-0.02	0.05	0.55	-0.52

Table 2. Partial correlation coefficients for Δf_0 (in semitones) and f_{0st} or SPL_{bf}, for the M2→M1 transitions. Results are presented separately for the 3 vowels and the 7 singers.

Table 2 shows the partial correlation coefficients for the leap intervals measured at **M2→M1 transitions**. Since leap intervals are negative in this case, one must take the opposite of the correlation coefficients to obtain a description of the correlations between Δf_0 (absolute value) and f_{0st} or SPL_{bf}.

The most important factor is the **absence of clear tendency** contrary to what happens in the M1→M2 transitions: no strong correlation was obtained and only few coefficients greater than 0.5 (absolute value) were found (no one for females and 3 for males). **The M2→M1 transition is not the reverse phenomenon of the M1→M2 one**.

3.4 The influence of vowels on the leap intervals

Figure 6 presents the leap interval for the transition M1→M2, for the 3 different vowels and for different levels of SPL_{cor}. For the 7 subjects, the evolution of the Δf_0 values with SPL_{cor} is very similar for the 3 vowels. Consequently, one can say that **the influence of the vowel on the frequency leap interval is at most a second order effect**, whereas the influence of the dynamics corresponds rather to a first order effect.

Results also show that **the influence of the vowel depends on the singer**. Indeed for T3, the frequency leap interval is smaller for /i/ than for /o/ (especially for high levels). For S3, the leap intervals are also smaller on /i/ than on /a/ and /o/, but on the contrary, S4 obtained her larger leap intervals on the vowel /i/.

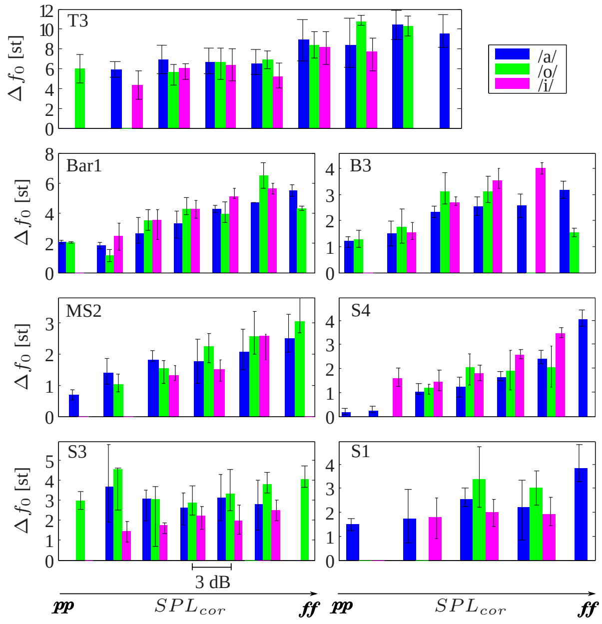

Figure 6. Variations of the frequency leap interval according to SPL_{cor}, for M1→M2 transitions, for the different vowels and for the 7 subjects. Each group of bars is spaced by 3 dB (SPL_{cor}).

3.5 Explored phonetographic area

Figure 7 shows the Voice Range Profile (VRP) of S3, T3 and B3 for the vowels /a/ and /i/. In these representations, the starting and ending positions of the frequency jumps for the M1→M2 transitions are added. It shows that the starting positions cover quite largely the overlapping area for S3 and T3 (G#3 - C5 for S3, E3 - G4 for T3). However the jumps for B3 cover only the high frequency range of the overlapping area (Bb3 - G#4). It confirms the ability of singers to produce laryngeal mechanisms transitions on a large frequency range (larger than one octave for S3 and T3), even if these subjects are non-expert for these vocal productions.

Figure 7 shows also interesting aspects regarding the vocal intensities: T3 covered a large level range in M1, but the ending levels in M2 are all located at a smaller level range. B3 essentially explored his fortissimo productions in M1 as well as in M2. These observations may provide a partial explanation of the inter-subject variability.

4. DISCUSSION AND CONCLUSION

The electroglottographic study shows that the uncontrolled frequency jumps are going along with a fundamental frequency readjustment produced by the singer to return to the targeted value. This readjustment is very similar to the slow frequency variation observed by Svec et al [9] on a yodel-like protocol. The difference between these two protocols relies upon the direction of frequency variation. In the sustained notes protocol, the frequency variation of the readjustment is in the opposite direction of the frequency variation of the transient part, while in the yodel-like protocol the direction of the frequency variation is the same for

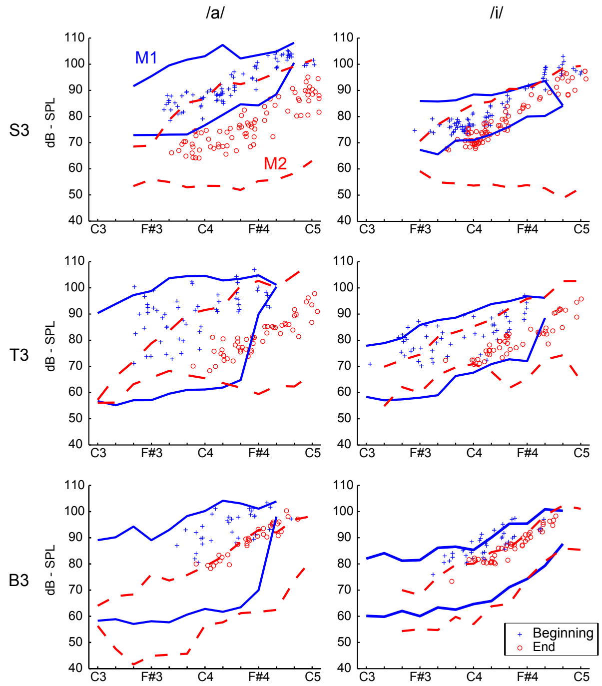

Figure 7. Starting (f_{0st}, SPL_{bf}) and ending (f_{0end}, SPL_{aft}) positions of the frequency jumps for the M1→M2 transitions, 3 singers, and the vowels /a/ and /i/.

both, which makes it difficult to identify the two phases. The sustained notes protocol is therefore more efficient to isolate the transient part which corresponds to the phenomenon of voice instability. However, it is possibly more difficult to produce for the subjects.

One can link the observed results to the physiology and the acoustics of voice production. The vocal fold oscillation frequency is regulated mainly by three parameters: the vibrating mass, the longitudinal tension and the vibrating length. For the vocal folds to oscillate, an air flow must be provided which is adapted to the laryngeal system. The subglottal pressure and the glottal flow result from the equilibrium of the laryngeal resistance (which depends amongst others on the parameters that regulate the fundamental frequency) and from the forces that generate the air flow (resulting from the breathing muscles).

At the muscular level, the vibrating mass is mainly determined by the thyroarytenoid (TA) muscle, while the tension and the length of the vocal folds are due to the equilibrium between the thyroarytenoid and the cricothyroid (CT) muscle. The laryngeal resistance depends more on the TA and other muscles as the inter-arytenoids and the lateral cricotyroids [23].

The main difference between M1 and M2 mechanisms is the involvement of the TA muscle in the vocal fold oscillation itself. During the M1→M2 transition, the decoupling of the different layers which constitute the vocal folds triggers a dramatic decrease of the vibrating mass, which in turn is probably responsible for a large part of the frequency jump. Inter-subject differences may then be linked to vocal fold morphological and internal constitution differences. The fact that on average women have a smaller and a lighter vocal muscle than men could in particular explain why their frequency jumps are smaller.

In their works, Tokuda and Horacek et al [10–13] show that it is possible to reproduce laryngeal mechanism transitions by continuously varying the longitudinal tension, or more precisely the CT activity. For experimental reasons, these experiments are carried out at a constant flow rate. Large et al. [24] experiments show that the M1→M2 transition is marked by a dramatic variation of the flow (the flow being larger in M2 than in M1). Besides, Miller et al. [15] set up a protocol that requires the subject to produce their transitions at a constant subglottal pressure. These observations allow us to put forward the hypothesis that **during the transition, the CT activity and the subglottal pressure are not varying much**. In the presented protocol, those two parameters can be subject to little or no variation during the transitions, but can be modified during the fundamental frequency readjustment phase. **The leap interval could provide us an indication of the pitch difference between the vocal productions emitted in M1 and in M2 with the same subglottal pressure and CT activity**.

The leap interval is smaller in the M2→M1 transition than in the M1→M2 one. An explanation could be that the subglottal pressure is lower in M2 than in M1 [25] so that the subglottal pressure measured at the jump is lower in the M2→M1 direction than in the M1→M2 one for given initial fundamental frequency and sound level.

In mechanism M1, the vocal sound level is linked to the subglottal pressure [26, 27]. Besides, the results show that the frequency leap interval increases with the dynamics in the M1→M2 direction. These two observations lead to the flollowing hypothesis: **for a given CT activity, the greater the pressure, the larger the frequency difference between the two mechanisms**. Therefore, **the role played by the subglottal pressure in the fundamental frequency control could be different in M1 and in M2**.

In the M2→M1 direction, the frequency leap interval is not correlated with the dynamics. This result clearly shows that when considering only such parameters as the fundamental frequency and the sound level, **the M2→M1 transition does not correspond to the inverse phenomenon of the M1→M2 transition**. As reported by Svec et al [9], the M2→M1 transition is produced at a lower tension than the M1→M2 one because of the hysteresis which is characteristic of the phenomenon. Aerodynamic and biomechanic supplementary data are needed to interpret the obtained results.

The results show that despite the rapidity of the fundamental frequency jump, some glottal parameters like the EGG amplitude or the open quotient (which takes different values in M1 and M2), vary much slower than the fundamental frequency. Roubeau et al [6] already made a similar observation about the EGG while stressing the fact that the duration of variation does not depend on the transition direction nor on the vocal training. As a matter of fact, in the M1→M2 direction, the results show that the contact surface decreases but that the open phase duration begins to increase before the beginning of the jump. These observations suggest that a preparation of the mechanism transition takes place before the loss of control itself. Further investigation is needed to describe in more detail the observed phenomenon.

Acknowledgments

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