Toward a More Informative Voice Range Profile: The Role of Laryngeal Vibratory Mechanisms on Vowels Dynamic Range

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Summary: Purpose. The impact that vowels have on the variation across voice range profiles (VRPs) is studied along with three factors: fundamental frequency, singer's gender, and laryngeal vibratory mechanism used to sing.

Materials and Methods. VRPs of 21 advanced singers were established by recording, in separate takes, vocal productions using laryngeal vibratory mechanisms M1 and M2 for /a/, /i/, and /o/. Recordings were focused on the range C3–C5, where most singers can sing in either M1 or M2. It allows to compare the singer's dynamics in M1 versus M2 while holding other variables constant.

Results. The vowel has an influence on the upper limit of singers' VRPs when they use M1 but not when they use M2, independently of the singer's gender and the fundamental frequency.

Discussion and Conclusion. The laryngeal vibratory mechanisms allow one to explain the nonconsensual results observed in the literature about the influence of vowels on the VRP. A simulation shows that the different influence of vowels on the VRP partially results from the different open quotient values that can be observed in M1 and in M2.

Key Words: Voice range profile–Laryngeal vibratory mechanism–Register–Vowel–Singing voice–Open quotient.

INTRODUCTION

One of the key elements of singers' vocal technique is the development of a wide dynamic range over their entire tessitura. The exercise that allows singers to work on this control is the *messa di voce*, which is singable on every vowel.

The manner in which one changes one's vocal intensity range with respect to changes in fundamental frequency may be measured by means of a voice range profile (VRP). This diagram has been used for several years to describe the capacity of trained voices[1–7] as well as pathological voices.[8–10] The vowel that is usually used in these measurements is /a/, but several authors argue that this vowel is not neutral and is thus an important parameter that must be taken into account when studying VRPs.[11,12] Nevertheless, the dependence that vowel choice has on a resultant VRP remains poorly understood, and the existent literature on the subject has only superficially (or parenthetically) addressed the problem. Table 1 presents a synthesis of the principal studies carried out on the subject, specifying the vowels used, the type of subjects, and their vocal training.

In the last column, we have reported the observed results for two "cardinal" vowels, /a/ and /i/, common to each study. These results indicate variations at the upper limit (in terms of vocal intensity) of the VRP.

The studies carried out exclusively on male voices[6,13] describe the upper limit of VRPs as being more intense on /a/ than on /i/. The same observation was attained for male subjects in other literatures.[14,16] The results are not as uniform for female voices. Gramming[15] and Gramming and Sundberg[16] note differences in the lower part of the female tessitura whereas Seidner et al[14] does not find any notable variation among different vowels.

The objective of this study is to propose an explanation for the observed disparities. In ascertaining the reason for these disparities, the first parameter to examine is the difference of fundamental frequency among the singers. To begin by establishing some generalities, it is known that women generally have higher voices than men. Also, as the pitch of the males voices rose, the /i/ vowel dynamic characteristics should begin to resemble those of the /a/ vowel. However, this was not observed by the authors. The question then arises: are the disparities between male and female observations the result of physiological differences, or are they the result of different vocal techniques? At this point, we argue that the use of the laryngeal vibratory mechanisms by lyric singers must be considered.

The concept of laryngeal vibratory mechanisms takes into account the physiological behavior of the vocal source independent of the transformations that occur in various subsequent resonators, conversely to the concept of register, which is linked to vocal quality and is thus more suitably classified in the domain of sound perception. Two laryngeal vibratory mechanisms are mainly used for singing, namely M1 and M2. In the mechanism M1, the vocal folds are thick and the muscles in this region contribute to the folds vibration. However, in the mechanism M2, the vocal folds are thin and stretched out, and the vocal muscles do not take part to the vibration of the folds. The reader will find a complete description of laryngeal vibratory mechanisms and the way to attest the use of a given mechanism in previous articles.[17,18] A singer's vocal training leads the singer to favor one or the other of these two mechanisms, although the singer still has access to part of the overlapping tessitura of these mechanisms. In classical singing, most male singers (basses, baritones, and tenors in most of their register) use the mechanism M1 in exclusivity, whereas very few women use it. Conversely, sopranos, mezzo-sopranos, and altos use the mechanism M2 mainly or exclusively.

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TABLE 1.
Summary of the Principal Studies Concerning the Relationships Between VRPs and Vowels

Publication	Vowels	Subjects	Comparison of Upper Limits (Only on /i/ and on /a/)
Wolf et al[13]	/a/, /ε/, /u/, and /i/	5 Baritones (singers)	SPL higher on /a/ than /i/
Stout[6]	/a/, /i/, and /u/	3 Men (singers)	SPL higher on /a/ than /i/
Seidner et al[14]	/a/, /i/, and /u/	90 Subjects (men and women, singers and nonsingers)	Men: maximum SPL on /a/, weaker on /i/ and /u/. Women: in general, SPL independent of vowel
Gramming,[15] and Gramming and Sundberg[16]	/a/, /i/, and /u/	22 Women (speech-therapy students)	Upper limit 10 dB higher for /a/ than /i/. This difference diminishes in the upper register
Gramming,[15] and Gramming and Sundberg[16]	/a/, /u/, /i/, and /e/	One man and one woman (vocal training unindicated)	Man: more intense upper limit on /a/ than on other vowels. Woman: same for the low range, more uniform in the upper range

Abbreviations: VRP, voice range profile; SPL, sound pressure level.

To test our hypothesis, we will measure the relative impact of the three parameters—the fundamental frequency, the gender of the singer, and the laryngeal vibratory mechanism—on the maximum and minimum dynamics created using different vowels.

METHODS

In this section, we will describe our experimental protocol as well as the composition of the database used in the construction of VRPs. We will also survey the methods of analysis used on these VRPs. Lastly, we will present a detailed description of the means by which one may distinguish laryngeal vibratory mechanisms.

The zone of overlap

An important attribute of this study's experimental design is its reliance on the comparison, at a given frequency and for both genders, between the maximal vocal dynamic of several vowels across the two mechanisms M1 and M2. This comparison is feasible owing to the common tessitura that mechanisms M1 and M2 share. More precisely, the high-register sounds produced in mechanism M1 overlap with the low-register sounds of M2. The range of this overlap changes with respect to the singer in question, but it averages around one and a half octaves.[5] Figure 1 presents the VRPs of two singers, annotated according to the mechanism being used. For the countertenor, the zone of overlap of the two mechanisms extends from C3 to F4. For the mezzo-soprano, this zone ranges from E3 to C5. In these respective ranges, both singers were able to achieve a wide range of dynamic intensities using either mechanism, thereby allowing us to make the comparison between mechanisms M1 and M2 on a given vowel and between genders while holding frequency constant.

Given the aims of present study, we will thus focus only on the laryngeal vibratory mechanisms zone of overlap.

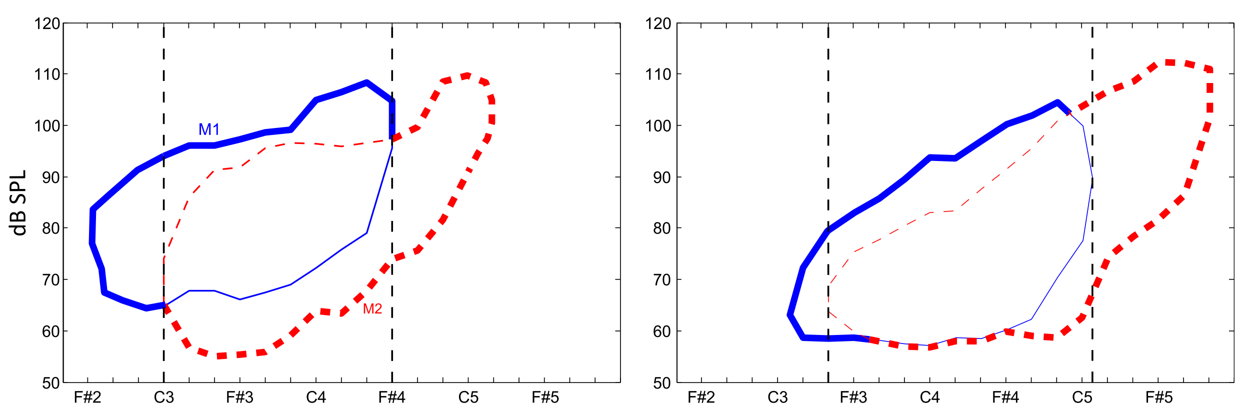

FIGURE 1. VRPs by laryngeal mechanism of a counter-tenor (*left*) and a mezzo-soprano (*right*). M1: connected line, M2: dotted line, vowel: /a/. The shared portion of both zones is drawn using thin lines, whereas the unshared portions of M1 and M2 are drawn with thick lines. VRP, voice range profile; SPL, sound pressure level.

Singers

Twenty-one singers participated in the study: 8 women (4 sopranos and 4 altos) and 13 men (2 basses, 5 baritones, 4 tenors, and 2 countertenors). All of the singers are practicing musicians. Eleven of them are trained amateurs, and the other 10 are professional. The average age of the singers was 36 years, ranging from 22 to 52 years.

Protocol

Three different vowels were chosen for the recording: /a/, /i/, and /o/ (close vowel). To have a good enough overview of what can happen depending on the vowel, we should have chosen the vowels corresponding to the corner of the vocalic triangle (/a/, /i/ and /u/). The /o/ was chosen over the /u/ to provide the singer with a vowel that varied less over the targeted tessitura. Each singer recorded six VRPs, representing each of the three vowels in both mechanisms M1 and M2.

To focus the study on the mechanisms zone of overlap, we restrained the range of the tessitura to the interval C3–C5 (131–523 Hz). As the recording of a VRP is a long and tiring task, this restriction allowed us to reduce the time of the recording session to around 1 hour. Each singer was asked to produce crescendos and decrescendos on every whole tone in this interval (13 in total, including both limits). Singers were furthermore asked to push vocal dynamic changes to their personal limits of loudness or softness, respectively. The organization of the recording session proceeded in four steps: the low and high ranges were tested separately for M1 and M2. In each step, we started with the /a/ vowel in the middle of the singers tessitura (C4 for most singers), then moving either down or up by whole tones toward the chosen limits (C3 or C5), and stopping if need be at the physiological limit of the singers laryngeal vibratory mechanism. On each note, we asked the singer to sing first a crescendo and then a decrescendo. This task was then repeated on /o/ and then on /i/ before moving onto the subsequent stages of the recording. The order of these four steps (low/high and M1/M2) were left to the singer to decide.

The recordings were made in a soundproofed room so that we could talk to the singer during the recording sessions. A Brüel & Kjaer microphone (Darmstdt, Germany) with an omnidirectional capsule was placed 30 cm away from the mouth of the singer. A dual-channel electroglottograph (EGG) was used to capture the EGG signal. The audio and the EGG signals were recorded at sample rate of 44100 Hz and a bit depth of 16 bits directly to a Mac OS X computer (Apple Company Store, Cupertino, CA) by means of a Metric Halo 2882 (Safety Harbor, FL) sound card.

Each singer had the possibility to warm up before the recording. The sound pressure level (SPL) was calibrated by means of a sustained tone at a constant dynamics produced at the beginning of each session, measured using a sonometer placed at the same location as the microphone.

Identification of laryngeal vibratory mechanisms

As the protocol of the study is based on the distinction between the two laryngeal vibratory mechanisms, it is important to identify these mechanisms from the recording phase onward. In many situations, a trained musician is able to identify laryngeal vibratory mechanisms by listening to their own voice. The singer, by feeling changes in their own physiology as well as by listening to their own voice, is also able to identify these mechanisms.[19] For most vocal productions, and in particular for strong vocal production, we were thus able to identify with certainty the laryngeal mechanism being used at the time of the recording by combining the experimenters and the singers observations.

For vocal production that was ambiguous to listening, the experimenter could determine the laryngeal vibratory mechanism used not only via the acoustic characteristics of the sound produced but also from a variety of indices registered at the level of the glottis and based on the EGG signal. These are the open quotient (Oq), the amplitude of the EGG and its waveform. Nevertheless, one must remember that the measurement of an isolated parameter (eg, the Oq) cannot in and of itself reveal the used laryngeal vibratory mechanism because the value of this parameter can change in function of the SPL, the fundamental frequency, the vowel used, and the singer.[20] Although the variations of the different parameters are gradual and coherent for a given singer in a single mechanism, they may be rather brusque while changing mechanisms on a sustained note, especially as the note becomes more intense. In the case of a protocol limited to sustained sounds (as in our case), one need to only detect these discontinuities to find the transitions between mechanisms and, as a result, to identify the mechanisms used during the stable parts of the sound.

The recording proceeded in the following manner. For each production, the used mechanism during the attack was validated by the experimenters and by the singer. When there was doubt with respect to the mechanism used, the singer was asked to begin his or her vocal production anew by starting in a comfortable vocal space, then ascending if the targeted production was to use M1 or descending if the said production were supposed to be in M2. Then, the experimenter assured that the singer was not changing his or her mechanism during the vocal production by verifying the absence of variation in the sound as well as in the waveform visualization of the EGG in the oscilloscope, and by trusting the expertise of the singer.

When there was doubt as to the mechanism being used, the experimenter asked the singer to redo a particular crescendo or decrescendo. For more details regarding the usage of the EGG to characterize laryngeal mechanisms, the reader may refer to Roubeau et al.[18]

Analysis procedure

The recording sessions of each singer were segmented using *Praat* (P. Boersma and D. Weenink, University of Amsterdam, The Netherlands) and then processed using *Matlab* (MathWorks, Natick, MA). The objective was to study only the steady-state portions of the recorded frequencies, omitting all samples where the singer failed to sing on the requested frequency using the requested laryngeal vibratory mechanism. Segmentation and labeling of these steady-state portions are based on the fundamental frequency, the SPL, the Oq (we used the DECOM method, or DEgg Correlation-based method for Open quotient Measurement[20,21]), the amplitude of the

EGG signals, and the spectrogram of the vocal production. Any data for which the laryngeal vibratory mechanism could not be confirmed were excluded from the corpus. For each note in the studied tessitura, and for each vowel in each mechanism, the maximum and the minimum SPL were established and the limits of the VRPs were indicated on the visualizations.

Convention

In the following, the terms “upper limit” and “lower limit” of the VRPs will exclusively refer to the maximum and minimum SPL of the vocal intensity (and not to the frequency range).

RESULTS

Figure 2 shows the average VRPs presented separately with respect to gender, laryngeal vibratory mechanism, and vowel. The average VRPs of men are presented in the left column and women are presented on the right. The two laryngeal vibratory mechanisms are vertically stacked to make for easier reading. On each of the four diagrams, we have indicated the upper and lower limits for the three vowels studied. As stated in the Methods section, these VRPs are incomplete insofar as they do not represent the totality of each singer’s tessitura. The men’s M1 VRP only describes the medium-high notes of their tessitura in this mechanism, whereas the measurements in M2 only correspond to the low end of vocal production for both men and women. However, this delimited range proved to be accurate given the physiological constraints of women in mechanism M1: only 30% of women were able to sing crescendos and decrescendos below C3 or above C5 using this mechanism. Thus, we are confident in claiming that the presented VRPs are representative of women’s tessitura for this laryngeal vibratory mechanism.

In these VRPs, we were able to observe a considerable zone of overlap for the two laryngeal vibratory mechanisms, ranging from one-and-a-half octave to two octaves. These results corroborate those observed by Roubeau et al.[5] The frequency range of the zone of overlap is larger than that of the modal (or chest) and falsetto registers observed by Colton and Hollien[22] and Schutte[23] (measured at one-sixth in both publications). We also observed that the upper and lower SPL limits of both mechanisms rose as frequency increased. This correlation between SPL and frequency is well known and has been reported in several previous studies.[7,10,24,25] What is worth noting in the present study is that the average slope of this correlation has a higher absolute value toward the upper limit of M2 (or rather the upper limit of M2 as circumscribed by the range studied in this article) than that of M1 (18 dB/octave as opposed to 12 dB/octave).

The most striking result to be gleaned from this study concerns the difference in dynamic production (or lack thereof) that arises with changes in vowel and laryngeal vibratory mechanisms. In mechanism M1, the upper limits of VRPs show a 10 dB difference in SPL between /a/ (stronger) and /i/ (weaker). The limit of /o/ and /a/ resemble each other in the low range (below D4), whereas /o/ is closer to /i/ in the high range (above E4). These tendencies were observed both for men and women. On the other hand, such a variation in SPL with respect to vowel neither exists at the upper limits of M2 for either gender nor does it exist at the lower limits of either mechanism. Because of the large variability between singers in general, it is important to evaluate the validity of these observed differences. The influence of vowel on the limits of VRPs in M1 and in M2 has been tested through an analysis of variance (ANOVA). More precisely, we tested the incidence of the vowel on the SPL, for each fundamental frequency,

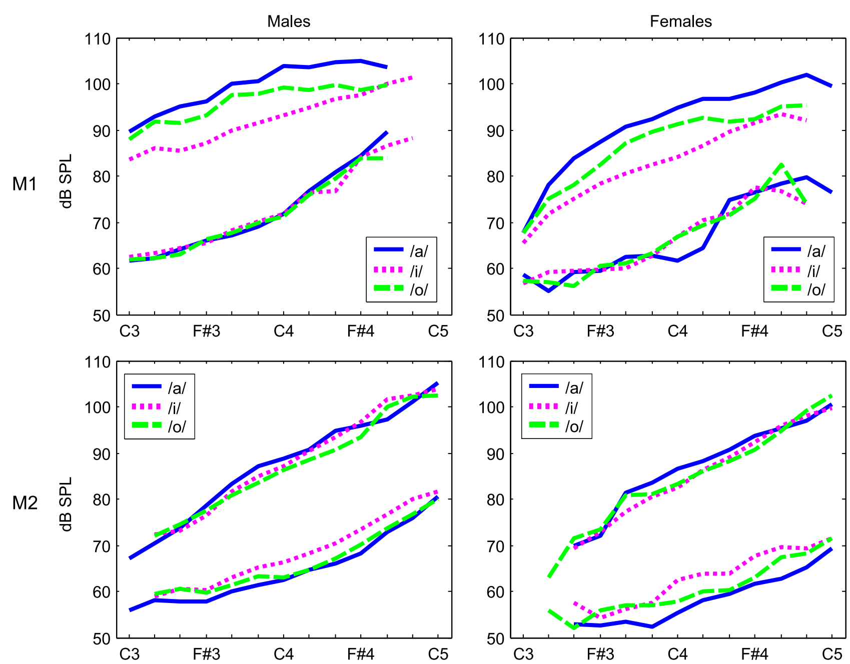

FIGURE 2. Average VRPs of men and women, on the three studied vowels, for laryngeal mechanisms M1 and M2. VRP, voice range profile; SPL, sound pressure level.

laryngeal vibratory mechanism, and gender separately. The details of the results (degree of freedom, F-statistic and P-value) are presented in Table 2. We see that vowels have a very significant influence ($P < 0.001$) on the maximum SPL for males as well as females from C3 to F4 as indicated above except on E4 (significant influence, $0.001 < P < 0.01$) on M1. On the contrary in M2, it has only a poor significativity level ($0.01 < P < 0.1$) on C4 for women and on E4 and G4 for men. For the other notes, the influence of vowels on the maximum level is not significant ($P > 0.1$).

For the lower VRP limit, the ANOVAs tests showed a nonsignificant influence ($P > 0.1$) of the vowels for each note, laryngeal vibratory mechanism, and gender.

Figures 3 and 4 present the average VRP limits of the three vowels and two mechanisms (as in Figure 2, but with a different layout) as well as the variability between subjects for each note in the studied range. Globally, the interquartile intervals are on the order of 5 dB at the upper limits of the VRP, independent of vowel, mechanism, and frequency of emission. However, there is a notable variability toward the lower limits, ranging from 4 to 15 dB and even attaining peaks that reach more than 25 dB (see /a/ in M1 around G4 for both men and women). In M1, the lower limits are slightly more variable around /a/ than around /i/ or /o/. In M2, the vowel seems to have no influence on the variability of the limits. Finally, the variability of the lower limits rises with the emitted frequency for both men and women (save men in M2).

In conclusion, the influence of the vowel on the upper limit of VRPs is not the same for M1 as it is for M2. This holds true both for men and women and is independent of fundamental frequency. Among the three hypotheses that we tested, it appears that neither the physiological differences between men and women nor the differences in tessitura are responsible for the differences in vocal dynamics among vowels. It is rather because of the changes in laryngeal vibratory mechanisms that these differences arise.

DISCUSSION

Can the results be applied to a full VRP?

The VRPs used in our experiment are not representative of the subjects' entire ranges, as one of the *a priori* of our experiment was to compare the vocal dynamic of singers at the same frequency across two laryngeal vibratory mechanisms. One may nonetheless ask if these results extend to the higher part of M2 and the lower region of M1. It would be legitimate to assume that, below C3, the subjects cited in Table 1 were only men singing with mechanism M1. Given this relatively benign assumption, we see that the obtained results correspond to the phenomena observed around C3 in the study properly. By the same logic, the subjects in the studies cited in Table 1 (both the singers and even more so the nonsingers) can only use M2 to attain notes above C5.

However, above C5, another phenomenon appears: as the fundamental frequency increases, the vowels are less distinguishable in terms of formant frequency and vowel precision. The fact that vowels begin to resemble each other in the high register can only reinforce the perceived absence of difference in vocal dynamics. Therefore, the results of our observations on the partial VRPs may be reasonably generalized to the full range of VRPs measuring M1 and M2, even if in the uppermost extremes of the tessitura, the distinction one makes among different vowels begins to loose acoustical and perceptual meaning.

Comparison to the results from the literature

In light of this study, the results from the literature cited in Table 1 take on a new and not-at-all contradictory meaning: if it is neither the difference between the singers' gender nor the difference between tessitura but rather the difference between laryngeal vibratory mechanisms that explains the differences in dynamics among the vowels, then the results of Wolf et al,[13] Stout,[6] and Seidner et al[14] make perfect sense if one makes the reasonable assumption that the men sang using M1 and the women using M2. By the same logic, the different results that one sees in Gramming[15] and Gramming and Sundberg[16] indicate that women (speech therapy students who were not necessarily trained singers) used M1 in their lower register, whereas using M2 up high during the VRP recording sessions. It would have been interesting if, in each of these cases, the authors had noted the register or laryngeal vibratory mechanism used by the subjects for each note produced. However, even this rather stringent requirement would not be sufficient to describe the totality of a singers capacities with respect to a given laryngeal vibratory mechanism, as a single VRP cannot show differences in laryngeal vibratory mechanisms in the zone of overlap.

Toward a more informative VRP

The protocol that we elected to use, whereby each subject is recorded separately for each laryngeal vibratory mechanism, presents numerous advantages. In the present study, this approach proved to be useful in explaining difference in dynamic across different vowels. Other differences between VRPs for the two mechanisms exist as well, such as the difference of the slope at the upper limit of the common zone. Knowing this would allow one to explain the variability seen in this region when trying to describe the results of a VRP. Finally, to stand by the claim that a VRP is a meaningful tool for describing with precision a singer's vocal capacities, it seems rather natural to distinguish these laryngeal vibratory mechanisms at the outset and to describe a singers capacities with special attention to treating both methods separately. Applied to classical singing, this type of protocol has already allowed researchers to characterize *voix mixte* in terms of laryngeal vibratory mechanisms.[26,27] The only inconvenience associated with this method is one of time; such an experimental protocol takes the time of a given experiment and effectively multiplies it by two, which in turn may lead to vocal fatigue that plays into obtained results.

Acoustical discussion of the results

From an acoustical point of view, the SPL is linked to the strongest harmonics. For the voice, these are either one of the two first harmonics or those that are close to the formant

TABLE 2.
Results of the Statistical Analyses (ANOVA) With Respect to the Influence of the Vowel Toward the Limits of the VRPs

Statistical Analyses	C3	D3	E3	F3	G3	Bb3	C4	D4	E4	F4	G4	Bb4	C5
Men													
M1													
Upper limit													
DF	38	38	38	38	38	38	38	38	35	28			
F	13.1	23.2	37.4	26.4	29.3	32.8	40.9	26.8	8.2	9.8			
P	0***	0***	0***	0***	0***	0***	0***	0***	0.001**	0.001***			
Lower limit													
DF	38	38	38	38	38	38	38	38	35	28			
F	0.07	0.15	0.16	0.06	0.05	0.05	0.02	0.03	0.42	0.01			
P	0.928 (NS)	0.858 (NS)	0.849 (NS)	0.946 (NS)	0.952 (NS)	0.955 (NS)	0.984 (NS)	0.975 (NS)	0.662 (NS)	0.99 (NS)			
M2													
Upper limit													
DF		28	37	37	38	38	38	38	38	38	38	38	36
F		0.29	0.28	0.63	0.99	1.8	0.9	1.94	4.92	2.04	4.53	0.66	1.27
P		0.752 (NS)	0.761 (NS)	0.538 (NS)	0.381 (NS)	0.181 (NS)	0.417 (NS)	0.159 (NS)	0.013*	0.145 (NS)	0.018*	0.524 (NS)	0.295 (NS)
Lower limit													
DF		28	37	37	38	38	38	38	38	38	38	38	36
F		0.21	0.74	1.08	0.81	1.04	1.7	2.05	1.66	2	1.22	1.41	0.11
P		0.813 (NS)	0.485 (NS)	0.351 (NS)	0.452 (NS)	0.364 (NS)	0.197 (NS)	0.144 (NS)	0.204 (NS)	0.15 (NS)	0.307 (NS)	0.258 (NS)	0.895 (NS)
Women													
M1													
Upper limit													
DF	38	38	38	38	38	38	38	38	35	28	16	8	5
F	13.1	23.2	37.4	26.4	29.3	32.8	40.9	26.8	8.2	9.8	2	0.4	0
P	0***	0***	0***	0***	0***	0***	0***	0***	0.001**	0.001***	0.167 (NS)	0.665 (NS)	0.953 (NS)
Lower limit													
DF	11	16	21	23	23	23	23	23	23	23	15	9	5
F	0.28	0.79	1.24	0.08	0.25	0.02	1.24	1.47	0.46	0.18	0.39	0.17	0.09
P	0.76 (NS)	0.473 (NS)	0.312 (NS)	0.925 (NS)	0.78 (NS)	0.983 (NS)	0.311 (NS)	0.253 (NS)	0.636 (NS)	0.835 (NS)	0.683 (NS)	0.846 (NS)	0.919 (NS)
M2													
Upper limit													
DF			11	16	17	19	22	23	23	23	23	23	23
F			0.13	0.13	2.63	0.58	4.11	1.06	0.87	1.45	0.35	0.81	2.32
P			0.882 (NS)	0.883 (NS)	0.105 (NS)	0.569 (NS)	0.032*	0.365 (NS)	0.433 (NS)	0.257 (NS)	0.71 (NS)	0.457 (NS)	0.123 (NS)
Lower limit													
DF			11	16	17	19	22	23	23	23	23	23	23
F			1.4	0.26	0.51	1.72	1.9	1.33	0.85	1.04	1.41	0.46	0.13
P			0.295 (NS)	0.777 (NS)	0.614 (NS)	0.21 (NS)	0.176 (NS)	0.286 (NS)	0.441 (NS)	0.369 (NS)	0.266 (NS)	0.637 (NS)	0.877 (NS)

Notes: The results are presented separately for men and for women, stratified along M1 and M2.
Notes: Adopted thresholds of statistical significance—$P < 0.001$: very significant (***), $0.001 < P < 0.01$: significant (**), $0.01 < P < 0.1$: of little significance (*), $P > 0.1$: not significant.
Abbreviations: DF, degrees of freedom; *F*, F statistic; *P*, *P* value; NS, not significant.

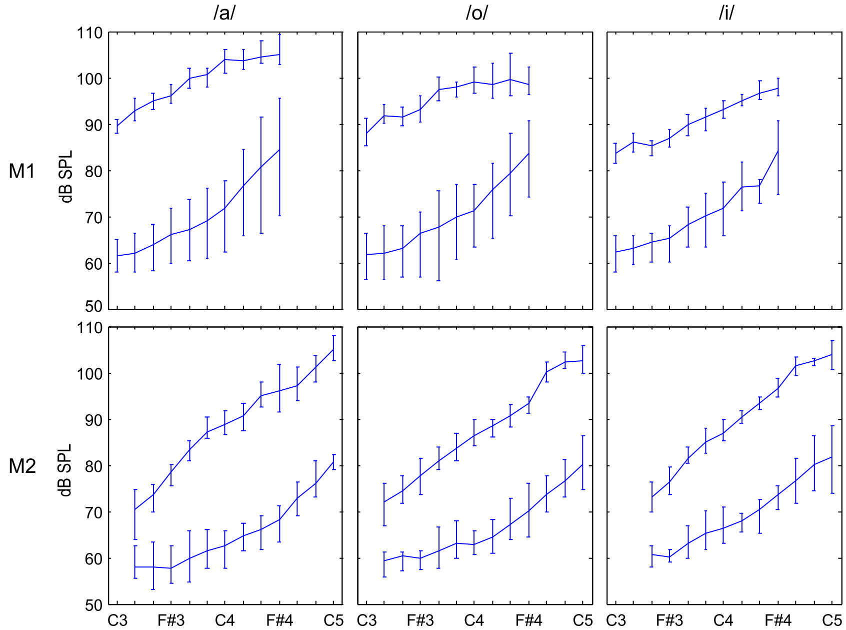

FIGURE 3. Subjects: men. Average VRPs and interquartile intervals for the two mechanisms and three vowels. VRP, voice range profile; SPL, sound pressure level.

frequencies, especially to the first formant (F1). Two factors linked to F1 can thus explain variations in SPL:

1. When F1 increases, the level of energy situated in high frequencies increases, thus causing the SPL to increase as well.[28]
2. When F1 is close to a harmonics, the energy of this harmonics increases (this is called the format-tuning phenomenon), which implies as well a rise in SPL.[16,28,29]

On the /a/ vowel, the F1 is higher than on /i/ and /o/—one can thus expect to measure higher SPL levels on /a/ than the other studied vowels. This is consistent with the results we found for M1, whereas this reasoning does not help to explain the results found for M2.

We must thus look toward the analysis of acoustic differences between M1 and M2, differences that are principally found at the source of vocal production. It is well known that the Oq is usually larger in M2 than in M1 for a given frequency and SPL and that this difference is particularly pronounced for strong intensities.[20] Additionally, the Oq is correlated to the energy difference between the first two harmonics of the glottal flow waveform.[30,31] The result is that, in most cases, the first harmonics is dominant in M2, whereas the second is dominant in M1.[32] One hypothesis is that the difference in the Oq between M1 and M2 does, in fact, modify the amplitude of the first two harmonics to an extent that it compensates for any changes in F1.

Source-filter simulation of differences between M1 and M2

To test this hypothesis, the following simulation has been conducted. It looks to recreate this difference in Oq to test if this parameter can explain the differences in vowel importance at the upper limit of M1 and M2 in the VRPs.

In linear source-filter theory, we can write:

$$S_{M1}(f) = Ug_1(f).V_1(f).L_1(f)$$

$$S_{M2}(f) = Ug_2(f).V_2(f).L_2(f)$$

where, in the laryngeal vibratory mechanism M_i ($i = 1$ or 2), S_{Mi} corresponds to the spectrum of the emitted vocal signal, Ug_i to the spectrum of the source signal, V_i to the spectrum of the vocal tract, and L_i to the effect that the lips have on the sound. If one begins from the hypothesis that the filters as well as the lip radiation are the same in M1 and M2—that is to say if $V_1(f) = V_2(f) = V(f)$ and $L_1(f) = L_2(f) = L(f)$, one obtains:

$$S_{M2}(f) = \frac{Ug_2(f)}{Ug_1(f)}.Ug_1(f).V(f).L(f) = \frac{Ug_2(f)}{Ug_1(f)}.S_{M1}(f)$$

thus by knowing Ug_1 and Ug_2, one can reconstruct the signal of M2 beginning from that of M1.

As our goal is to test the effect of differing Oqs in M1 and M2 on the SPL, we have measured the Oq from the EGG signal on the outer limits of the VRPs for M1 and M2 along each of the three vowels, for each note that each singer sung. We then used the measured values of the Oq and the fundamental frequency to simulate, in each case, the spectra of Ug_1 and Ug_2 by using an LF model.[33] Besides the variables of the Oq and the fundamental frequency, the other parameters were fixed arbitrarily ($\alpha_m = 0.65$, E = 1, TL = 3 dB, see[32] for more information). Then, the synthetic filter whose frequency response corresponds to Ug_2/Ug_1 was applied to S_{M1} to obtain the simulated signal $S_{M2,sim}$, or in other words, signal S_{M1} with a modified Oq.

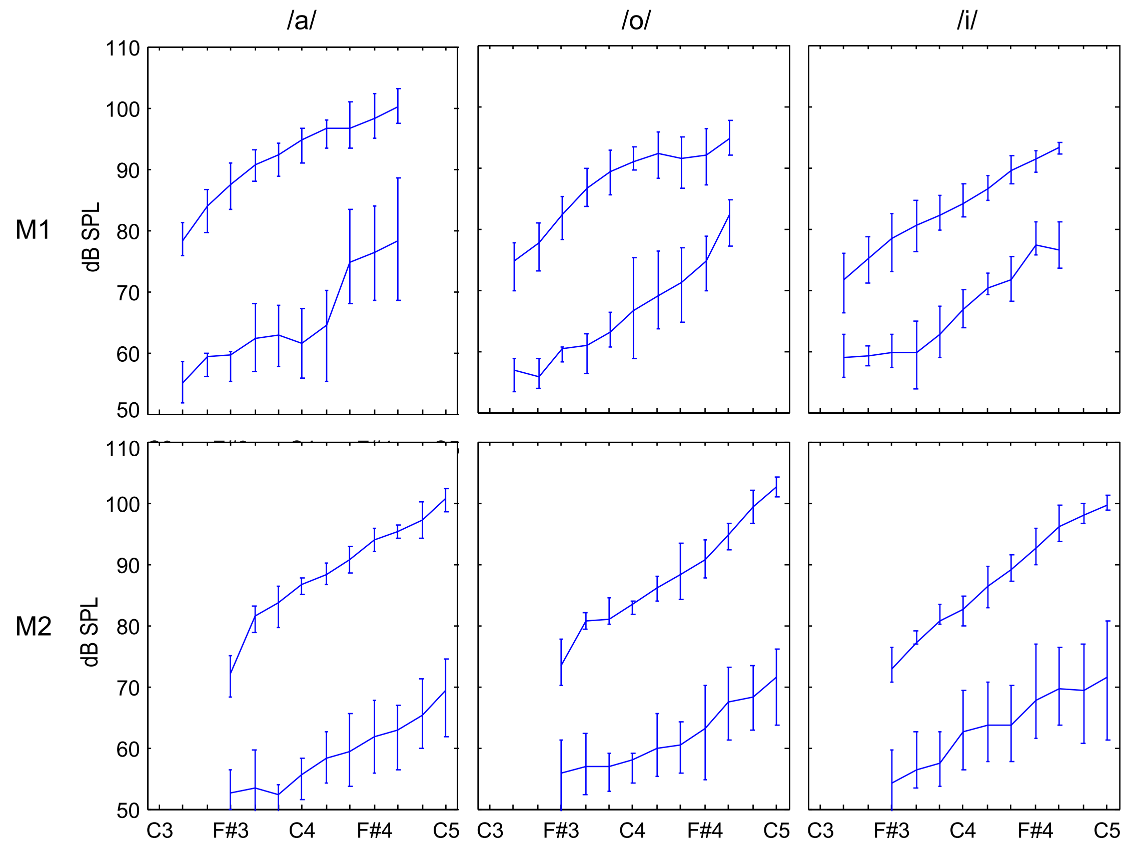

FIGURE 4. Subjects: women. Average VRPs and interquartile intervals for the two mechanisms and three vowels. VRP, voice range profile; SPL, sound pressure level.

We then calculated the level of each obtained$S_{M2,sim}$. Figure 5 presents, for M1, M2, and the result of the simulation, the average SPL differences measured for each note between vowels /a/ and /i/. As described in the Results section, these values are close to 10 dB for M1 and 0 dB for M2 for both men and women. The curve one obtains via simulating the Oq difference is drawn with a dotted line. One can see that the open-quotient modification diminishes the difference in SPL a great deal, although this difference is not completely suppressed.

We can thus conclude that, from this model, the difference in Oq between M1 and M2 partially explains the differing influences that vowels have on the upper limits of the M1 and M2 VRPs.

Nonlinear source-filter interactions?

Other factors may also contribute to this discrepancy: either there exists another parameter at the source that varies with respect to the laryngeal vibratory mechanism used and that influences SPL, or the linear source-filter model is insufficient and one must look for nonlinear effects in the coupling of source and filter to explain the observed phenomena. Titze[34] showed that an inertive load of the vocal tract on the vocal folds would enhance their vibration. This situation is found when

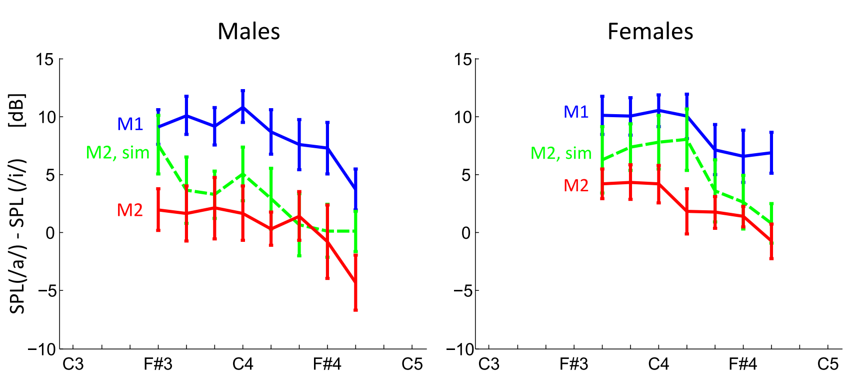

FIGURE 5. Differences in the upper limits of VRPs measured on /a/ and /i/ (SPL [/a/] − SPL [/i/]), for M1 and for M2 (*connected lines*), and the simulated difference (M2, sim) by modifying the open quotient using the data from M1 (*dotted lines*). VRP, voice range profile; SPL, sound pressure level.

a harmonic is located slightly below a formant, thereby reinforcing the vocal level (more than according to the linear source-filter model). This reinforcement would be especially strong when the first harmonic is close to the first formant frequency, which is observed for the vowel /i/ on most of our frequency range. A stronger reinforcement in M2 (owing to a lower vibratory mass) than in M1 could participate to reduce the difference between the maximum levels on /i/ and /a/. But this hypothesis needs further investigations to be validated.

CONCLUSION

VRPs were established for 21 singers on three different vowels (/a/, /i/, and /o/), separately for each laryngeal vibratory mechanism, over a common frequency zone ranging from C3 to C5. The experimental protocol allowed us to interpret the diversity of the data reported throughout the literature based on the following two results:

- The vowel has a strong influence on the upper limit of VRPs in mechanism M1. For example, the vowel /a/ allows one to attain SPL levels that are 10 dB higher than those of /i/.
- With respect to mechanism M2, the maximal level is the same for the three vowels studied.

As we have shown by a simulation using a source-filter model, the difference between this and the above stems from a spectral difference induced by very different Oq values in M1 and M2, in particular around the upper limits of VRPs, linked with the difference in frequency between the first formants of the studied vowels. Remarkably, this result is identical for men and women and is independent of the singers' tessitura.

The originality of our study stems from the manner in which it looks at VRPs through a prism of laryngeal vibratory mechanisms, separating the aspects linked to glottal vibrations from those that are linked to sonic resonators and lip radiation. The existence of a surprisingly large zone of overlap for all singers poses the problem of these mechanisms distinction, which in this study was something that we took into account when recording the singers.

This distinction seems important to us when studying classical singing insofar as singers work to homogenize the timbre of their voice over its entire range in spite of the fact that they sometimes use two distinct mechanisms to attain this effect. For these singers, the notion of register and that of laryngeal vibratory mechanism are not equivalent.

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