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Lip hyper-articulation in loud voice: effect on resonance-harmonic proximity

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ABSTRACT

Men and women speakers were recorded while producing sustained vowels at comfortable and loud levels. Following comfortable speech, loud levels were produced in three different conditions: first without specific instruction (UL); then, maintaining the same pitch as the comfortable level (PL); finally, keeping both pitch and lip articulation constant (PAL). The Sound Pressure Level (SPL), the fundamental frequency (f_0), the first two vocal tract resonances (R1 and R2), the lip geometry, and the larynx height were measured. For women, a closer proximity of R1 to its nearest harmonic, nf_0 was observed in UL. However, no such increased proximity was found in PL, when speakers could, and did, hyper-articulate. No increased proximity was also observed in PAL, when lip articulation was constrained. No significant increase in R1: nf_0 proximity was observed in men in any of the three loud conditions. Finally, R2 was not observed significantly closer to a voice harmonic in loud speech, for neither men nor women.

Keywords: Loud voice, Lip hyper-articulation, Resonance tuning, Vocal tract resonances

I. INTRODUCTION

Loud or shouted speech involves significant modifications of speech production at aerodynamic, glottal and articulatory levels: First, speakers increase subglottal pressure, which not only has direct consequences on the level of the output sound (Isshiki, 1964; Plant and Younger, 2000), but also contributes, along with other accompanying or compensatory glottal modifications (Holmberg et al., 1988; Sundberg, 1987), to an increase in the voice's fundamental frequency f_0 (Gramming et al., 1988; Plant and Younger, 2000; Titze, 1989), and a voice spectrum with a flattened spectral tilt (Raitio et al., 2013; Rostolland, 1982a; Sundberg and Nordenberg, 2006).

Concomitant modifications of the vocal tract articulation are also observed with increased vocal effort. In particular, vowels in loud speech are articulated with an increased mouth aperture and a higher vertical position of the larynx (Garnier et al., 2018; Geumann, 2001; Schulman, 1989), both associated with an increase of the frequency of the first vocal tract resonance (R1) and of the formant (F1) it produces (Bond and Moore, 1990; Lienard and Di Benedetto, 1999; Rostolland, 1982b; Traunmüller and Eriksson, 2000). Variation of the second formant frequency (F2) is less consistent and depends on languages and vowel categories. The simultaneous changes in f_0 and in the resonances may alter the relative distribution of resonances and harmonics. The present study tests the hypothesis that lip hyper-articulation and raised fundamental frequency of loud speech, commonly observed in any speaker, contribute to an increased proximity between vocal tract resonances and voice harmonics, which may facilitate the production of loud sounds.

This hypothesis originates from the previous observation of comparable lip hyper-articulation in singers when they vocalize in their high range and/or at loud intensity. This hyper-articulation was consistent with formant tuning, or resonance tuning: a systematic proximity of vocal tract resonances (usually R1, sometimes R2) to voice harmonics (often f_0 , sometimes higher harmonics nf_0). For example, R1: f_0 tuning has been observed in a professional woman singer (Sundberg, 1975), but has been subsequently observed in trained and untrained singers (Joliveau et al., 2004; Garnier et al., 2010; Henrich et al., 2011). R1: nf_0 tuning for $n > 1$ has been reported in both men and women singers of different musical styles (Bourne et al., 2016; Bourne and Garnier, 2012; Henrich et al., 2007, 2011; Sundberg et al., 2011). Resonance tuning has also been suggested in the case of some stage actors (Raphael and Scherer, 1987). Such a closer proximity between vocal tract resonances and voice harmonics is expected to enable the production of loud phonation with less effort. First, the proximity would boost the amplitude of the tuned harmonic and its associated formant, and therefore contribute to the increased overall intensity (Titze and Sundberg, 1992; Vurma, 2020). Second, it could optimize the energy exchange between the glottal source and the vocal tract filter and stabilize vocal fold vibration (Titze, 2001, 2004, 2008). The supra-glottal acoustic load at the frequency of a voice harmonic nf_0 is inertive (or mass-like with acoustic pressure leading acoustic flow) when that harmonic lies close but below the nearest vocal tract resonance R_i , whereas the load is compliant (spring-like, with pressure lagging flow) when it is close to but above nf_0 . It is thus interesting to ask whether any enhanced resonance-harmonic proximity could also be observed in speech production at loud intensity, and by speakers without any specific vocal training.

Variations of voice intensity, frequency and articulation are inter-related. However, since all three variables can be consciously controlled, this allows, to some extent, the possibility of

measuring some of the relations with one or more variables held constant. Therefore, three different experimental conditions for the production of loud speech were studied. In the first condition, changes in lip articulation and resonance-harmonic proximity were measured when participants went from a comfortable to a loud voice in “natural” or unconstrained phonation (condition UL for Unconstrained Loud). The second required participants to keep the pitch constant when vocal intensity was increased (condition PL for constrained Pitch-constrained Loud); this should enable us to examine how articulatory modifications of loud speech might, on their own, contribute to any increase in resonance-harmonic proximity. For the third condition, vocal intensity was increased with both pitch and lip articulation constrained (PAL – Pitch & lip Articulation-constrained Loud); in the case of an increased resonance proximity in the previous conditions UL and PL, this last condition PAL should enable us to verify that this proximity is controlled by variations in lip articulation: if this is the case, no increase in resonance-harmonic proximity is expected in that condition, when lip articulation is constrained.

II. MATERIALS AND METHODS

A. Participants

In a study approved by the Human Ethics Committee of UNSW Sydney, eight native speakers of Australian English, 4 men (M1, M2, M3, M4) and 4 women (W1, W2, W3, W4), aged 22 to 65 years old, participated in the study without payment. None of them reported any hearing or voice disorders. None reported any academic knowledge about voice production, about hyper-articulation or formant tuning phenomena. They were only informed that they would undertake an experiment in speech production.

B. Experimental protocol

The corpus consisted of six Australian vowels: [æ], [ɛ], [u], [ʊ], [ɔ] and [ɜ], described to the participants as the vowels in the words /had/, /head/, /hoot/, /hood/, /horde/ and /heard/ respectively (No further description or context for the vowels was given.) [æ] and [ʊ] were chosen as extremes of the vowel system. The third extreme vowel [i] was not selected here, because R1 for that vowel is less easy to measure accurately with vocal tract spectrometry (Epps et al., 1997). The vowels [ɛ], [u], and [ɔ] were selected as intermediate vowels between [æ], [i] and [ʊ] in the (F2, F1) plane. The vowel [ɜ] was considered as a central vowel in the Australian English vowel system. Each vowel was first sustained for five seconds at a comfortable level (Comf) and then, in the same breath, for five more seconds at loud level (as if addressing a person situated 20 m ahead). An audio beep indicated to the participants when to start increasing vocal effort and when to stop phonation (see Fig. 1).

Three conditions were recorded:

- In a first session (UL, for Unconstrained Loud voice), participants were told to increase vocal intensity after the beep.
- In a second session (PL, for Pitch-constrained Loud voice), participants were asked to keep a constant pitch when increasing vocal SPL. Such a task was not easy for most of the speakers, who did not have any particular vocal expertise, so that the experimenter gave them some examples and the participants were asked to practice for five minutes approximately before

being able to record the task.

- In a third session (PAL, for Pitch and lip Articulation-constrained Loud voice), participants were instructed to increase vocal SPL while keeping both pitch and lip articulation constant. Again, a brief practice session was necessary before recording that condition.

Each vowel was produced five times in every session, at both comfortable and loud level, before moving on to the next session. The order of the three conditions was the same for all the participants so they were unaware of the constraint(s) to be imposed in the next condition. To prevent the development of vocal fatigue (the whole protocol lasted for about 45 minutes, including about 25 minutes of phonation), participants were instructed to take regular breaks and were provided with water throughout the recording session to keep their mouths and throats hydrated.

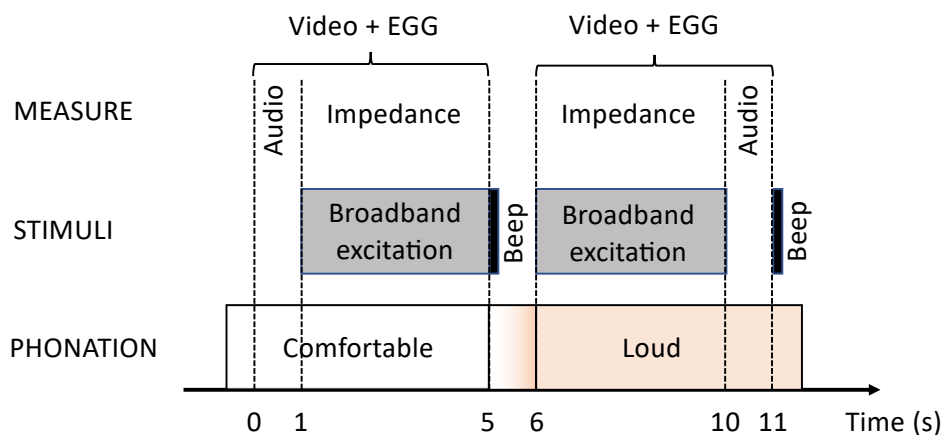


Figure 1. Illustration of the protocol: Participants produced sustained vowels for about 11 seconds with an increase in vocal SPL after five seconds, in a same breath. Audio beeps (black bars) indicated to the participants when to start loud voice and when to stop phonation. The vocal tract was excited with a calibrated broadband sound signal during four seconds of comfortable and loud phonation in order to measure the vocal tract impedance spectrum. Voice SPL and spectrum were characterized from the audio signal, during the remaining second of ‘clean’ phonation at comfortable and loud levels. The laryngeal behavior and lip articulation were characterized over the whole 5 s interval of comfortable or loud phonation, based on electroglottographic measurements and video images

C. Measurements

Five signals were simultaneously recorded:

- The audio signal was recorded with two 1/4-inch pressure microphones (Bruël and Kjær 4944-A, Nærum, Denmark), one located at the participant's lips, the second placed 30 cm in front of him/her. Both signals were then amplified (Bruël and Kjær Nexus 2690), and digitized at 16 bits and a rate of 44.1 kHz using a FireWire audio interface (MOTU 828, Cambridge, Mass.). The lip microphone was attached alongside a slightly flexible tube, 8 mm inner diameter, that was connected to a loudspeaker via an impedance matching horn. This acoustic source was used to excite the vocal tract with a synthesized broadband signal for the last four seconds of phonation at comfortable level and the first four seconds of phonation at loud level (see Fig. 1). The broadband signal was synthesized as the sum of sine waves over the range of 200–3000 Hz spaced at 10.8 Hz ($= 44.1 \text{ kHz}/2^{12}$) with amplitudes adjusted to improve the signal to noise ratio and relative phases adjusted to improve dynamic range (Joliveau et al., 2004; Smith, 1995). During the 4 seconds when the acoustic source was used, the microphone recorded the response of the vocal tract to that excitation in order to measure the vocal tract impedance and to detect from it the frequency of vocal tract resonances (see (Epps et al., 1997) and (Garnier et

al., 2010) for details on vocal tract impedance spectrometry). A stand was adjusted for height so that the microphone and the flexible tube to which it was attached rested gently against the participant's lower lip during measurements.

The microphone situated 30 cm away from the lips was also attached to a stand adjusted to the height of the participant's mouth. Its signal was used to measure vocal sound pressure level (SPL) and spectrum descriptors during the 'clean' second of phonation, when there was no broadband excitation (see Fig. 1).

- The electroglottographic (EGG) signal and the larynx tracking (LT) signal were recorded with an electroglottograph EG2 (Glottal Enterprises, Syracuse NY), using medical conductive gel to improve electrical contact between the skin and the electrodes. Two pairs of electrodes were placed, one on each side of the thyroid cartilage at the height of the cartilage while the participants were phonating in their comfortable middle range. No automatic gain control was used. The high-pass filter was set to a 10 Hz cutoff frequency. Both signals were then digitized at 16 bits and a rate of 44.1 kHz using the same audio interface as for the audio signal. Since the LT signal presents slow variations, below the cutoff frequency of the audio interface, it was acquired by modulating the amplitude of a 10 kHz carrier wave.

- Front images of the speaker's lips were recorded at a rate of 25 images/s, using a standard video camera mounted on a stand and placed at a 30 cm distance from the speaker's face and at the same height. The camera's audio signal, compared by cross-correlation with the main audio signal of the microphone at 30 cm, enabled post-synchronization of the articulatory measurements with other audio and EGG data.

C.1. Sound Pressure Level

The mean SPL was measured precisely from the clean second of comfortable and loud phonation (no broadband excitation, see Fig. 1), using the internal calibration signal of $1 V_{RMS}$ at 1 kHz delivered by the conditioning amplifier and knowing its V/Pa transduction coefficient. It is expressed in dB(Z) with respect to $20 \mu\text{Pa}$, with (Z) meaning that no weighting was applied to account for the frequency sensitivity of the human ear.

C.2. Fundamental frequency

The mean fundamental frequency f_0 was extracted from the EGG signal over the whole 5 s time interval of comfortable and loud phonation (see Fig. 1), using MATLAB scripts. The EGG signal was first high-pass filtered above 60 Hz and low-pass filtered below 1 kHz. Then, the fundamental frequency was estimated from the derivative of the EGG signal (DEGG), by detecting glottal closing times (Henrich et al., 2004). Its variations were measured in equal-tempered semitones.

C.3. Vocal tract resonances

The mean frequency of each of the first two vocal tract resonances (R1 and R2) was measured over a 4 s time interval for both comfortable and loud modes of phonation, while the vocal tract was excited with a broadband signal (see Fig. 1). R1 and R2 were detected visually from local maxima of the measured pressure ratio $\gamma = p_{//}/p_r$, where $p_{//}$ is the pressure spectrum measured with an open mouth (whilst phonating) and p_r is the spectrum measured at the lips with the mouth closed (performed during an earlier calibration measurement for each participant, see (Garnier et al., 2010)).

C.4. Lip geometry

Mean lip spreading (LS – horizontal dimension), aperture (LA – vertical dimension) and inter-lip area (ILA) were measured over the same 5 s time interval of the vowel as for glottal measurements (see Fig. 1), using a semi-automatic detection method of the inner edge of the

external lip aperture. The distance to the camera remained constant, because the participants kept the microphone and the broadband source on their lower lip. The pixels to millimeters conversion was calibrated prior to the recordings, using a 1 cm × 1 cm grid.

C.5. Larynx height

The mean variation in Larynx Height (ΔLH) was measured from the demodulated LT signal and converted into millimeters, using a calibration method suggested by Pabst and Sundberg (1992).

D. Data analysis

Several statistical analyses were conducted using the R software (Team, 2013). The conventional notation was adopted to report statistical results: * for $p < 0.05$, ** for $p < 0.01$, *** for $p < 0.001$, and ns (not significant) for $p > 0.05$.

For each of the voice descriptors, the variation from comfortable to loud phonation was considered and an analysis of variance (ANOVA) was conducted from these ‘Delta’ variables, in order to examine whether the variations of these descriptors were significantly non-null, and whether they depend on the VOWEL (six levels: [æ], [ɛ], [u], [ʊ], [ɔ] and [ɜ]) and the SESSION (three levels: UL – unconstrained loud voice, PL – loud voice with constrained pitch, PAL – loud voice with constrained pitch and lip articulation). A group analysis was conducted, based on a mixed model of the data (using the R package lme), considering again two fixed effects (factors VOWEL and SESSION) but also a random effect (factor SPEAKER, on the intercept). The simplest model that best explains the variance of a Delta variable was searched, using a descending approach (function step in R), based on likelihood ratio tests (LRT) and the minimization of the Bayesian Information Criterion (BIC). Hypotheses about the model’s normality and homoscedasticity were validated by looking at the residuals graphs. After examining the effects of the interaction terms remaining in the simplified model, specific contrasts were tested using the multcmp package in R and applying Bonferroni adjustments for multiple comparisons.

For each vowel and gender, the proportion of cases when R1 or R2 were found closer than $\pm 35\text{Hz}$ to a voice harmonic was also calculated. An analysis of variance was then conducted in order to examine whether this proportion varies significantly with GENDER and the PHONATION MODE (4 levels: Comfortable voice (Comf), Loud voice of UL, PL and PAL), based on a generalized linear model of the data (using the R package glm). This proportion of cases in our data was also compared to a chance level of observing such resonance-harmonic proximity, calculated from Monte-Carlo simulations for R1 and R2 and both genders.

III. RESULTS

A. Performance of the task

The five graphs of Fig. 2 show the extent to which the speakers complied with the experimental instructions.

As requested, all the participants were able to increase significantly their vocal SPL after the first audio beep of the protocol, for all the vowels and the 3 sessions (UL, PL and PAL).

However, that increase strongly depended on the Session: the increase was much greater when unconstrained (UL) (on average $+16.1 \pm 0.6$ dB, $p < 0.001$) when vocal SPL was increased ‘naturally’ compared with PL when that increase was constrained in pitch only (on average $+8.3 \pm 0.6$ dB, $p < 0.0001$) or PAL with both pitch and lip articulation constrained (on average $+8.7 \pm 0.6$ dB, $p < 0.0001$).

No participant showed a significant variation in f_0 from comfortable to loud phonation in the second and third session, for which pitch was supposed to be maintained. The average variation of f_0 was of -0.002 ± 0.30 semitones in PL ($p = 1$, NS) and 0.11 ± 0.30 semitone in PAL ($p > 0.9$ NS). In contrast, f_0 increased significantly by $+8.2 \pm 0.3$ semitones on average in UL ($p < 0.001$). For men, the average values of f_0 increased from 115 to 197 Hz, 128 to 129 Hz and 128 to 130 Hz for UL, PL and PAL constrained respectively. For women, the corresponding changes were 236 to 362 Hz, 258 to 257 Hz and 263 to 261 Hz.

All the participants were able to maintain their lip articulation whilst increasing vocal SPL in the third session: lip aperture (LA) increased by only $+0.4 \pm 0.2$ mm on average in PAL ($p > 0.09$, NS) and spreading (LS) by $+0.3 \pm 0.5$ mm ($p > 0.7$, NS), whereas it varied significantly in UL (on average $\Delta LA = +5.5 \pm 0.2$ mm ($p < 0.001$) and $\Delta LS = +6.3 \pm 0.5$ mm ($p < 0.001$)) and PL (on average $\Delta LA = +2.6 \pm 0.2$ mm ($p < 0.001$) and $\Delta LS = +3.4 \pm 0.5$ mm ($p < 0.001$)). It is interesting to note that, although the requested constraint in PL was only applied to pitch, participants nevertheless showed a reduced increase of mouth aperture and spreading: roughly half as much when pitch was constrained as when no constraint was requested.

Participants were not instructed to control the vertical displacements of the larynx. However, none of the participants showed a significant variation in larynx height with the increase of vocal SPL in PAL (on average -0.2 ± 0.4 mm, $p > 0.9$, NS). In contrast, all the participants showed a significant rise of their larynx in UL (on average $+1.6 \pm 0.4$ mm, $p < 0.001$). In PL, half of them showed a significant rise whereas the other half did not, so that no significant variation was observed on average over the whole group (-0.1 ± 0.4 mm, $p > 0.9$ NS).

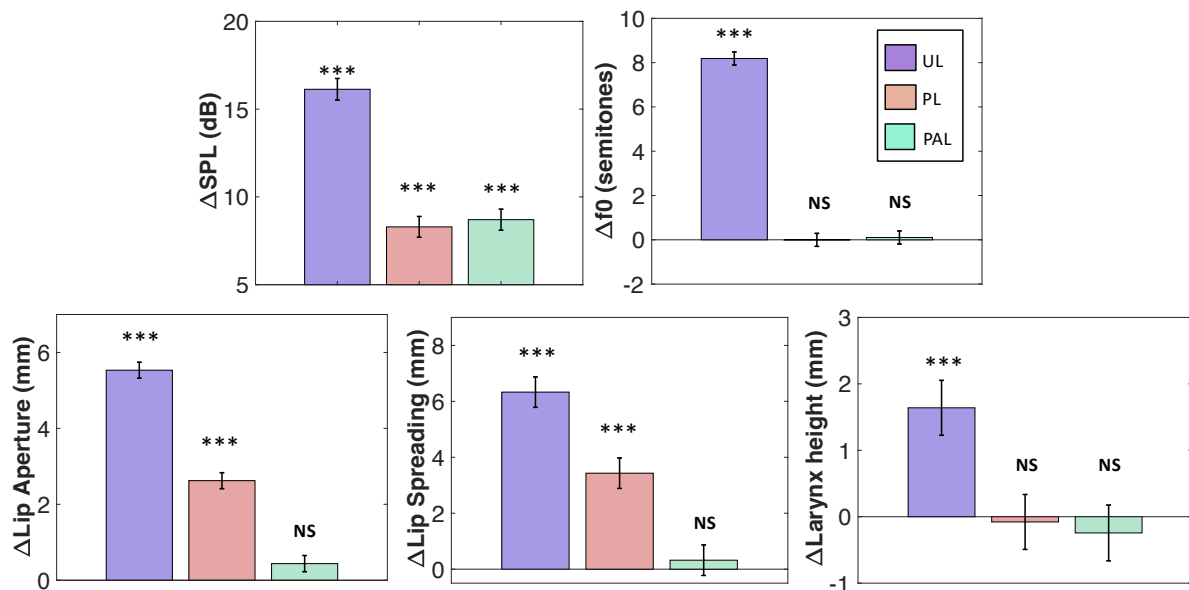


Figure 2. Average change of voice SPL (Sound Pressure Level), fundamental frequency (f_0), lip aperture (vertical dimension) and spreading (horizontal dimension), and larynx height with the increase of vocal intensity in the three sessions (UL, PL and PAL).

B. Proximity between the first vocal tract resonances (R1, R2) and voice harmonics

The acoustic consequences of R1 and R2 variations on the reorganization of the whole vowel system are shown in Fig 3. To sum-up, the variations of R1 and R2 in ‘naturally’ loud voice (UL) were in agreement with the variations of F1 and F2 reported in previous studies of loud and shouted speech (Bond and Moore, 1990; Garnier et al., 2018; Lienard and Di Benedetto, 1999; Rostolland, 1982b). They mainly consisted in a shift of the vowel system towards higher frequencies of the first resonance R1 and a tendency towards a slight reduction of the vowel system along the back-front dimension, due to the greater increase in R2 on back rounded vowels.

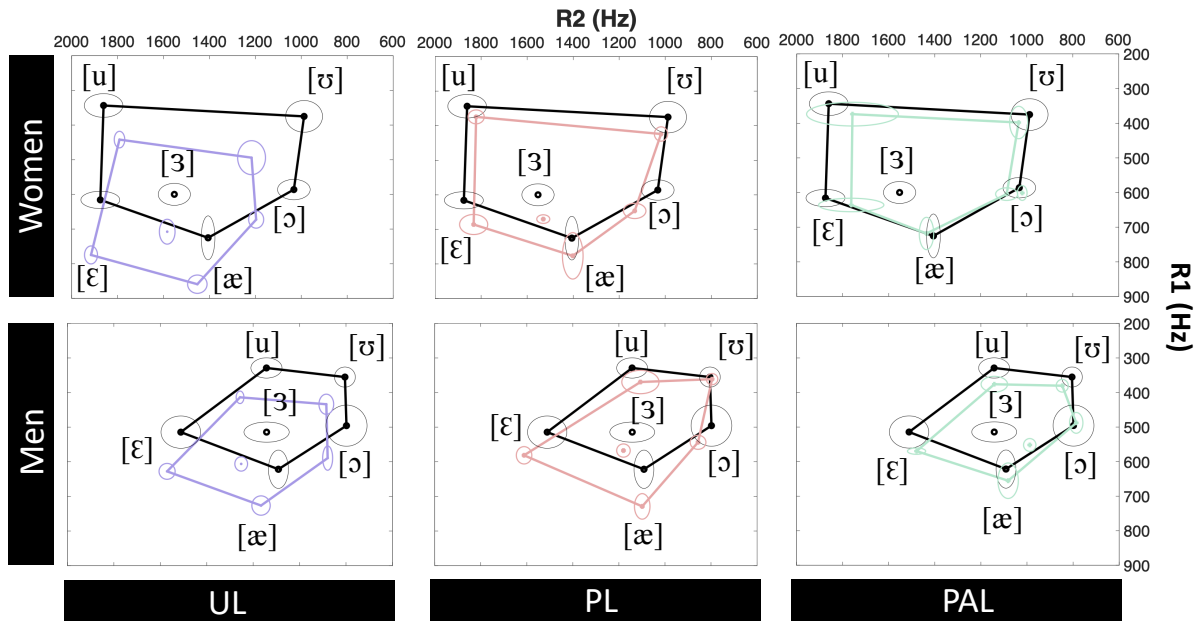


Figure 3. Average frequency of the first two vocal tract resonances (R1, R2) showing the effect of increasing vocal effort from comfortable speech (black) to loud speech (light colour), in the three sessions (UL, PL and PAL), for all the 6 vowels and both genders. The ellipses represent the average intra-speaker variability within each vowel category.

B.1. First resonance (R1)

If lip hyper-articulation in loud speech had the effect of ‘tuning’ the first resonance frequency R1 close to a voice harmonic, the distribution of R1 frequencies would show unusually many cases where $R_i \sim n f_0$ in UL and PL, when participants could adjust their lip articulation, compared with Comf, and when also compared with PAL, for which the participants maintained lip articulation constant.

As expected, all the participants showed a significant increase of the first resonance frequency R1, when increasing vocal SPL in UL ($+22.8 \pm 2.4\%$ on average, $p < 0.001$) (see Fig. 3). There was no significant difference between men and women ($\Delta = -4.6 \pm 5.2\%$, $p = 0.41$). This percentage increase did not depend significantly on the vowel (LRT: $df=5$, LRatio= 12.95, $p=0.23$). A significant increase of R1 was also observed in PL ($+9.3 \pm 2.4\%$, $p < 0.001$) and PAL ($+9.1 \pm 2.4\%$, $p < 0.001$) when pitch was maintained constant, although it was considerably reduced compared with UL. A surprising result was that the increase in R1 was still significant in PAL, and comparable with that observed in PL, even though measured lip articulation was maintained in that PAL session and larynx height did not vary significantly (see Fig. 2).

For women

Figure 4 shows, for women, the distribution of the frequency difference $R1 - nf_0$, where R1 is the frequency of the first vocal tract resonance R1 and nf_0 , the closest harmonic. The shaded area corresponds to a resonance bandwidth of ~ 70 Hz (Hanna et al., 2016), where a voice harmonic is expected to benefit substantially from a boosting effect of the resonance. If the vocal tract resonances systematically fell close to voice harmonics (which we call resonance proximity), one would observe a single-peak distribution with a mode situated in this shaded central area.

For women, distributions of the frequency difference $R1 - nf_0$ in comfortable speech do not demonstrate a monomodal shape with a high central peak (see Fig. 4), meaning that R1 is not systematically close to a voice harmonic. Figure 4 instead shows that, in comfortable speech and the context of this experiment, the R1 for women do not often lie within the bandwidth of the $R1 = nf_0$ lines. During unconstrained loud voice (UL), however, a centered and single peak distribution of the $R1 - nf_0$ frequency difference is observed for the mid-open vowels [ɛ], [ɜ] and [ɔ]. Figure 5 shows in more detail that these cases of resonance proximity involve R1 and the second voice harmonic ($2f_0$), which occurs for some speakers and some vowels. For mid-open vowels, the centered and single peak distributions, evident for UL, are no longer apparent in PL and PAL, meaning that no significant resonance proximity is observed in these constrained modes of loud phonation. The situation is different for the close vowels [u] and [ʊ], where the increase in $(f_0, R1)$ only slightly increases the average proximity to the first and second harmonics in UL. For the open vowel [æ], the increase in $(f_0, R1)$ shifts the average away from the higher harmonics in UL.

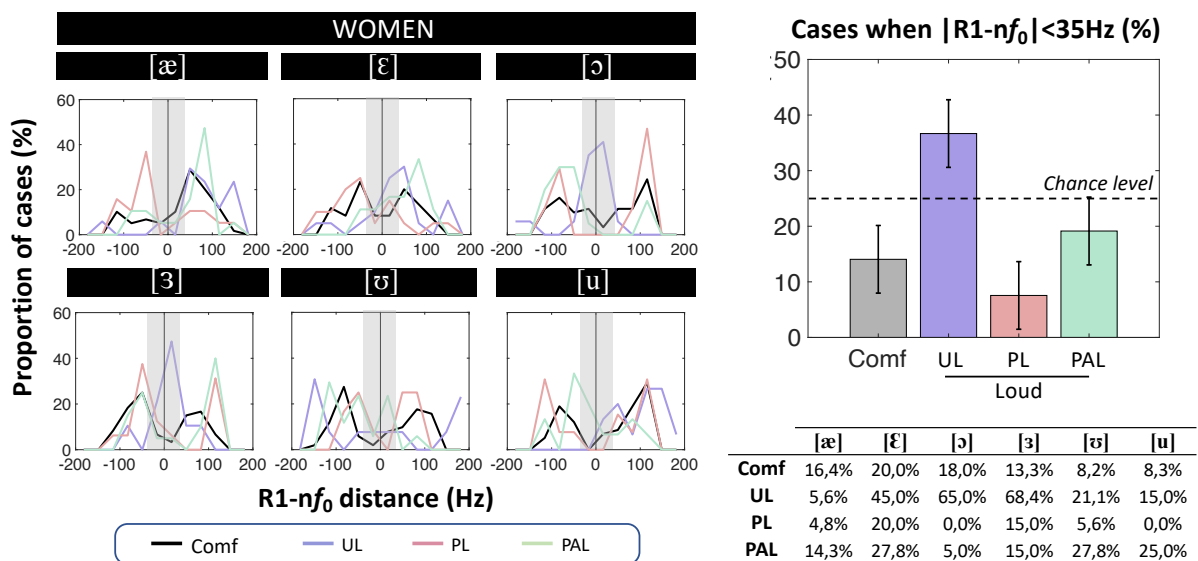


Figure 4. On the left: The distribution of frequency differences observed between the frequency of the first vocal tract resonance (R1) and the closest voice harmonic (nf_0), for women pronouncing each vowel and mode of phonation (Comfortable voice and loud phonations (UL, PL, PAL)). On the right: Percentage of cases for which R1 frequencies are closer than 35 Hz to a voice harmonic, on average, and for each vowel produced by women at comfortable and loud levels. The dashed line represents the level of chance for observing such a resonance-harmonic proximity.

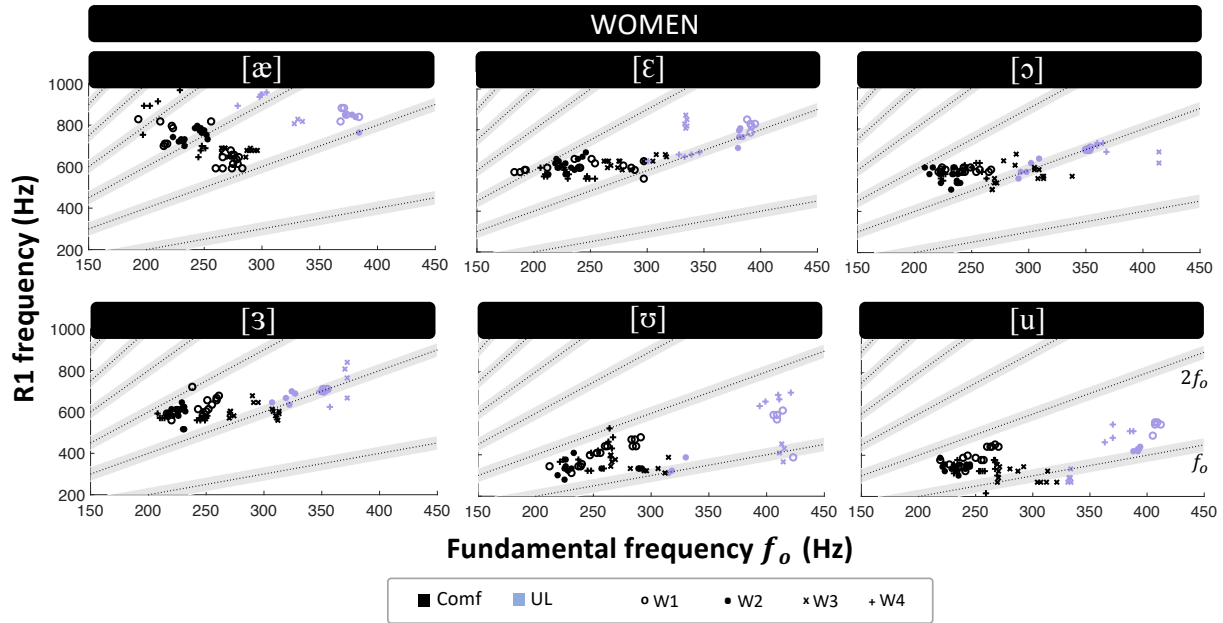


Figure 5. The relationship between values of $(f_0, R1)$ measured simultaneously for the six vowels produced by the four women of this study (W1, W2, W3, W4), in comfortable voice (black) and ‘natural’ loud voice UL (light blue). The dashed lines represent the voice harmonics nf_0 . Shaded grey areas indicate a 70 Hz interval centered around these voice harmonics, corresponding to the typical bandwidth of vocal tract resonances (Hanna et al., 2016).

These qualitative observations are corroborated by further analysis of the proportion of cases for which $|R1 - nf_0| < 35\text{Hz}$, and its variation with vowel and phonation mode (see Fig. 4). On average over the different vowels, R1 was found close to a voice harmonic significantly more frequently in the ‘natural’ loud voice (UL), compared with comfortable speech ($\Delta_{UL-Comf} = 22.6 \pm 8.6\%$, $p=0.041$), and with a proportion of cases in UL above chance level (25%). No significant variation in the proportion of cases was observed in the two other constrained modes of loud voice ($\Delta_{PL-Comf} = -6.5 \pm 8.6\%$, $p=0.79$; $\Delta_{PAL-Comf} = 5.1 \pm 8.6\%$, $p=0.88$), with a proportion of cases that was not greater than chance level.

For men

$|R1 - nf_0|$ separations for men were globally smaller than for women, because their lower f_0 gave a reduced separation between voice harmonics. No monomodal, centered distributions of the separations $R1 - nf_0$ were observed in men for any vowel produced at comfortable level (see Fig. 6). Further, no significantly increased resonance proximity was observed in ‘natural’ loud voice (UL) or in constrained loud phonation (PL and PAL). The proportion of cases observed was also never greater than chance level (47%). Figure 7 shows with more detail how R1 frequencies varied from Comf to UL without ‘following’ any particular voice harmonic.

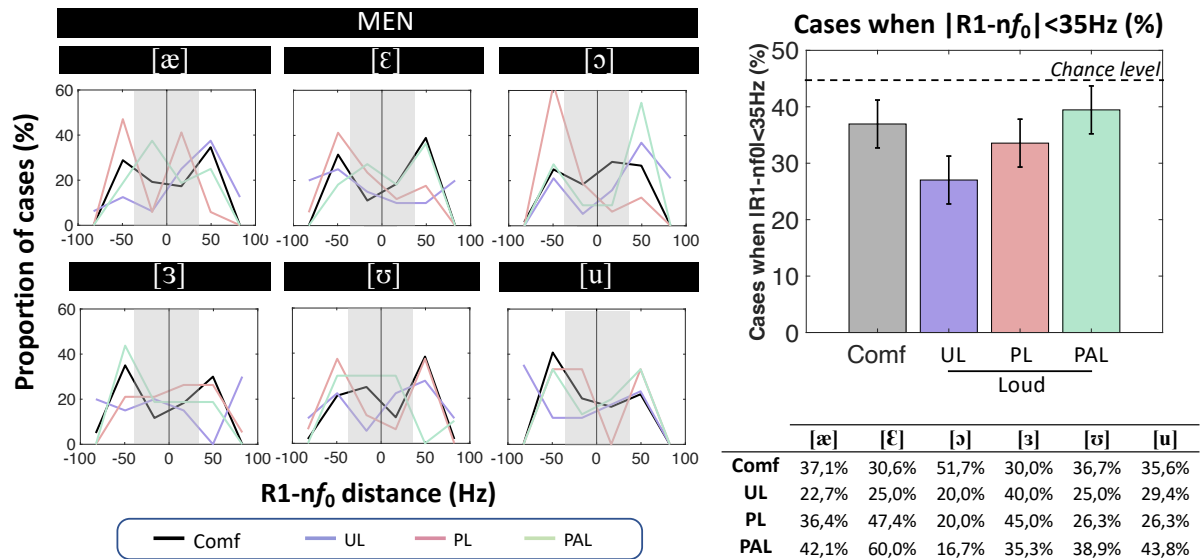


Figure 6. On the left: Average distributions in men, for each vowel and mode of phonation (Comfortable voice and loud phonation (UL, PL, PAL)), of the frequency differences observed between the frequency of the first vocal tract resonance (R1) and the closest voice harmonic (nf_0). On the right: Percentage of cases for which R1 frequencies are closer than 35 Hz to a voice harmonic, on average, and for each vowel produced by men at comfortable and loud levels. The dashed line represents the level of chance for observing such a resonance-harmonic proximity.

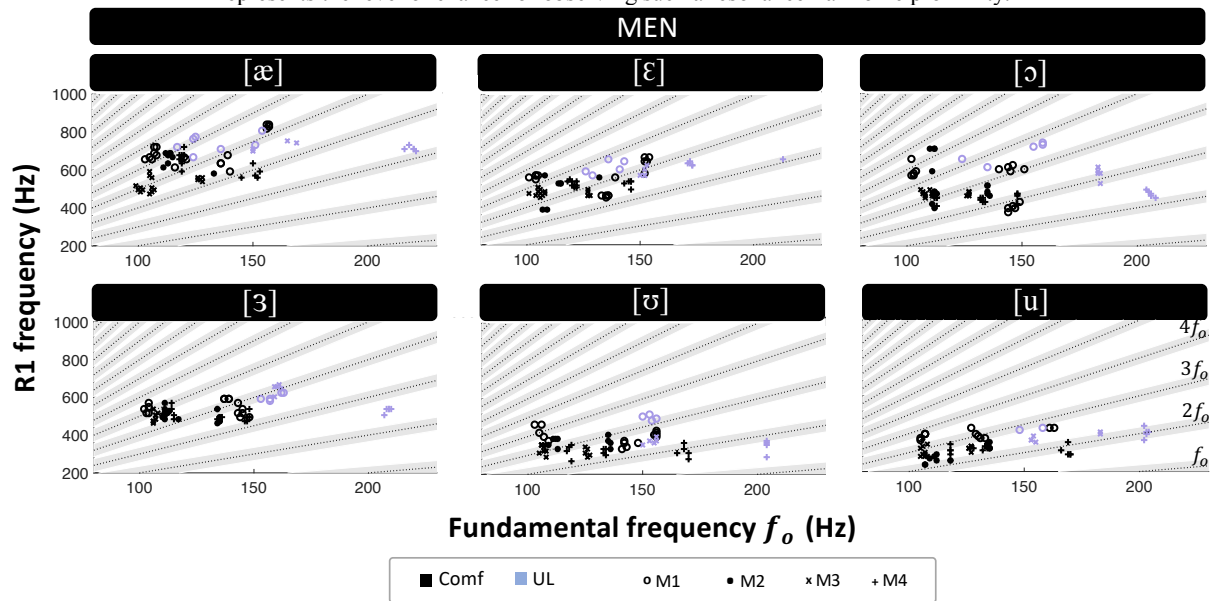


Figure 7. The relationship between values of (f_0 , R1) measured simultaneously for the six vowels produced by the four men of this study (M1, M2, M3, M4), in comfortable voice (black) and ‘natural’ loud voice UL (light blue). The dashed lines represent the voice harmonics nf_0 . Shaded grey areas indicate a 70 Hz interval centered around these voice harmonics, corresponding to the typical bandwidth of vocal tract resonances (Hanna et al., 2016).

Further statistical analysis confirmed that on average over all the vowels, R1 for men was not found close to a voice harmonic significantly more frequently in any of the loud modes of phonation, compared with comfortable speech ($\Delta_{UL-Comf} = -9.9 \pm 6.0\%$, $p=0.26$; $\Delta_{PL-Comf} = -3.4 \pm 6.0\%$, $p=0.90$; $\Delta_{PAL-Comf} = 2.5 \pm 6.0\%$, $p=0.95$) (see Fig. 6).

B.2. Second resonance (R2)

For women

For women, distributions of the frequency difference $R2 - nf_0$ in comfortable speech did not demonstrate a monomodal shape with a high central peak (see Fig. 8), meaning that R2 frequencies are not systematically tuned close to a voice harmonic. Figure 9 indeed shows that, for women, harmonics in comfortable speech do not often lie within a typical resonance bandwidth of the $R2 = nf_0$ lines. During unconstrained loud voice (UL), however, a centered and single peak distribution of the $R2 - nf_0$ frequency difference is observed for the vowels [ɜ] and [u]. Figure 9 shows in more details that these cases of resonance proximity corresponded to a proximity of R2 to the 4th, 5th and 6th harmonics, depending on the speaker and the vowel. Finally, Fig. 8 does not show centered and single peak distributions of the $R2 - nf_0$ frequency difference in PL and PAL, meaning that no significant resonance proximity was observed any longer in these constrained modes of loud phonation.

These qualitative observations are corroborated by further analysis of the proportion of cases when $|R2 - nf_0| < 35$ Hz, and its variation with vowel and phonation mode (see Fig. 8). This proportion did not vary significantly with the vowel ($df=5$, LRatio= 1.11, $p=0.40$). The statistical analysis showed that for R2, no significant variation in proportion of proximity cases was observed for women in loud voice (UL), compared with comfortable speech, regardless of the session ($\Delta UL - Comf = +4.4 \pm 5.8\%$, $p=0.78$; $\Delta PL - Comf = -10.0 \pm 5.8\%$, $p=0.23$; $\Delta PAL - Comf = -2.6 \pm 5.8\%$, $p=0.94$), and that this proportion of cases was never greater than chance level (24%), anyway.

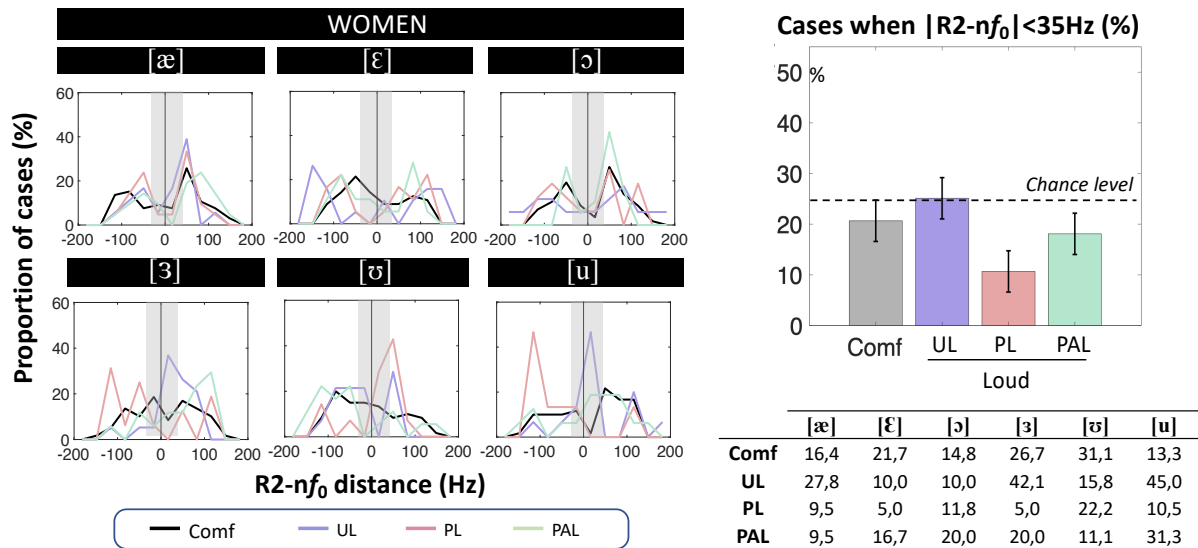


Figure 8. On the left: Average distributions in women, for each vowel and mode of phonation (Comfortable voice and loud phonation (UL, PL, PAL)), of the difference observed between the frequency of the second vocal tract resonance (R2) and the closest voice harmonic (nf_0). On the right: Percentage of measurements for which R2 frequencies are closer than 35 Hz to a voice harmonic, on average, and for each vowel produced by women at comfortable and loud levels. The dashed line represents the level of chance for observing such a resonance-harmonic proximity.

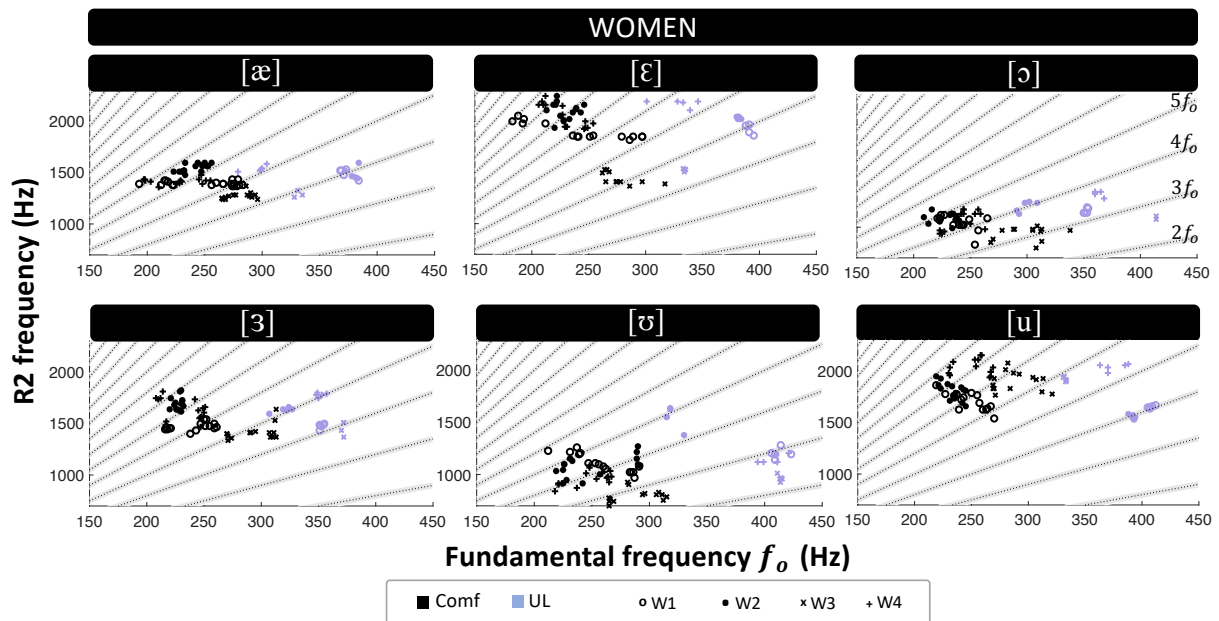


Figure 9. The relationship between values of $(f_0, R2)$ measured simultaneously for the six vowels produced by the four women of this study (W1, W2, W3, W4), in comfortable voice (black) and ‘natural’ loud voice UL (light blue). The dashed lines represent the voice harmonics nf_0 . Shaded grey areas indicate a 70 Hz interval around these voice harmonics, corresponding to the typical bandwidth of vocal tract resonances (Hanna et al., 2016).

For men

For men, smaller $|R2 - nf_0|$ distances were globally observed than for women, resulting directly from their lower f_0 , and the consequently reduced distance between voice harmonics. No monomodal, centered and peaked distribution of the distances $R2 - nf_0$ are observed in men for any vowel produced at comfortable level (see Fig. 10). No significantly increased resonance proximity is observed in ‘natural’ loud voice (UL) or in constrained loud phonation (PL and PAL), and the proportion of cases observed was never greater than chance level (46%). Figure 11 shows with more detail how R2 frequencies vary from Comf to UL without ‘following’ any particular voice harmonic.

Statistical analysis confirmed that for men, R2 was not observed significantly more frequently closer to a voice harmonic in any of the loud modes of phonation, compared with comfortable speech ($\Delta UL - Comf = +13.0 \pm 7.2\%$, $p=0.20$; $\Delta PL - Comf = -11.2 \pm 7.2\%$, $p=0.30$; $\Delta PAL - Comf = -14.0 \pm 7.2\%$, $p=0.16$) (see Fig. 10).

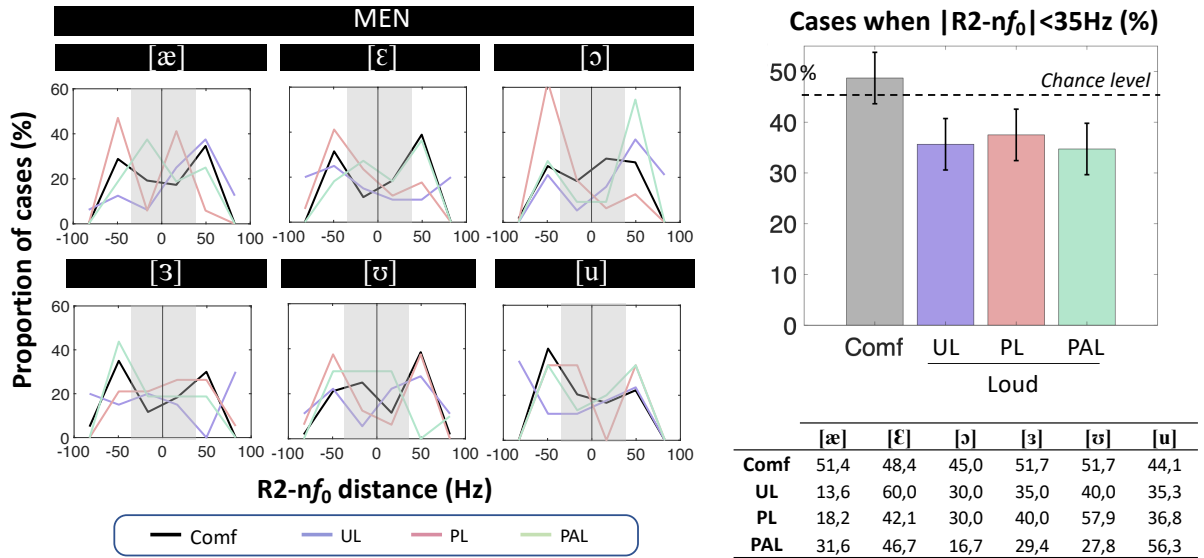


Figure 10. On the left: Average distributions in men, for each vowel and mode of phonation (Comfortable voice and loud phonation (UL, PL, PAL)), of the difference observed between the frequency of the second vocal tract resonance (R2) and the closest voice harmonic (nf_0). On the right: Percentage of cases for which R2 frequencies are closer than 35 Hz to a voice harmonic, on average, and for each vowel produced by men at comfortable and loud levels. The dashed line represents the level of chance for observing such a resonance-harmonic proximity.

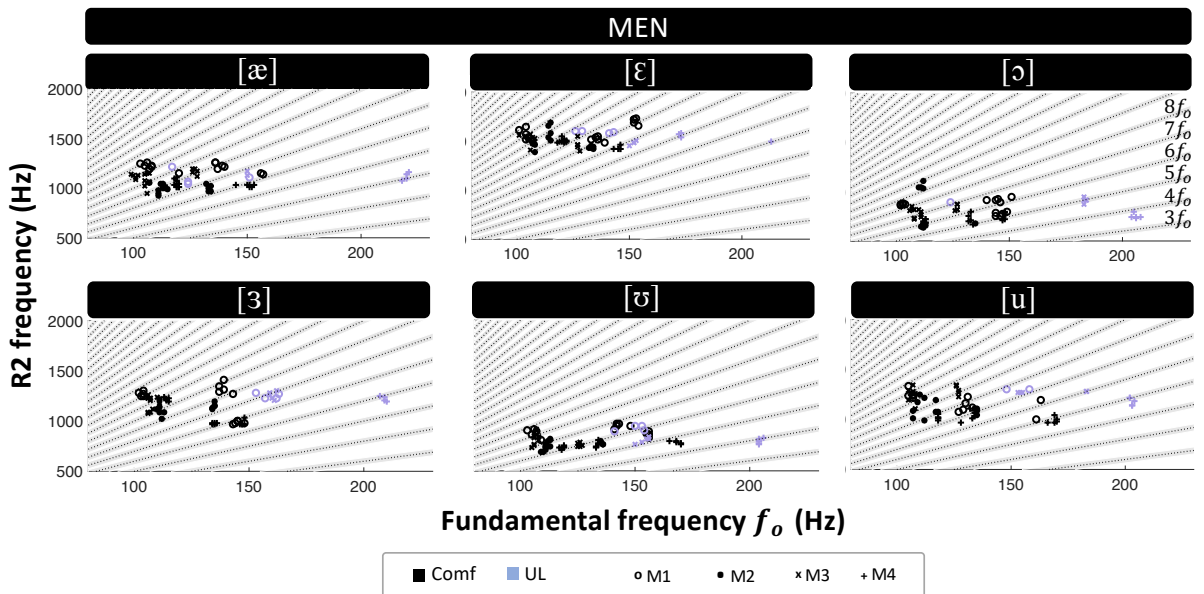


Figure 11. The relationship between values of ($f_0, R2$) measured simultaneously for the six vowels produced by the four men of this study (M1, M2, M3, M4), in comfortable voice (black) and ‘natural’ loud voice UL (light blue). The dashed lines represent the voice harmonics nf_0 . Shaded grey areas indicate a 70 Hz interval around these voice harmonics, corresponding to the typical bandwidth of vocal tract resonances (Hanna et al., 2016).

IV. DISCUSSION AND CONCLUSION

When and to what extent are lip hyper-articulation and f_0 increase in loud voice associated with increased proximity between a vocal tract resonance and a voice harmonic?

The results of this present study showed, for women only, and less than 40% of the time, a significantly more frequent R1: nf_0 proximity in the unconstrained loud voice (UL) than in either the comfortable voice or in the PAL condition, where speakers increased vocal effort

with constrained pitch and lip articulation. However, women did not show a significant increase in $R1:nf_0$ proximity in PL, where loud voice was constrained in pitch but where participants could still adjust their lip articulation. No significant improvement of the $R1:nf_0$ proximity was observed in the loud voice of men, regardless of how vocal intensity was increased (“naturally” (UL), with constrained pitch (PL) or with constrained pitch and lip articulation (PAL)). Resonance tuning or resonance proximity would be of limited advantage to men in the low part of their f_0 range, where the harmonic spacing f_0 is not much smaller than the bandwidth of a vocal tract resonance, so harmonics are more often boosted by a resonance even without adjustment. However, men still showed a significant increase in lip opening in loud voice, accompanied by a significant rise of R1, as did women.

Proximity between the second vocal tract resonance (R2) and voice harmonics was also examined. For R2, there was no significant adjustment of the resonance close to a voice harmonic when unconstrained loud voice was compared with comfortable voice, for either men or women.

Altogether, these different results suggest that, at least for men, and probably also for women, increasing the resonance-harmonic proximity may not be the main motivation of lip hyper-articulation in loud speech.

This study measured only sustained spoken vowels, so these observations should not be extrapolated to loud speech produced in more normal contexts. Because precise measurements of the resonances require several seconds of phonation, studying resonance-harmonic proximity in conversational speech and ecological situations remain a technical challenge.

A question remains about the observed increase of R1 in the loud voice of PAL, while the lips (and apparently the larynx position – see Fig. 2) were nevertheless maintained as in comfortable speech. This suggests additional contributions to R1 variations from non-visible articulatory modifications, such as oro-nasal coupling or dilation of the pharyngeal cavity, in particular (Xue et al., 2018). Part of this rise could also be due to an increase in average glottal opening (Barney and Stefano, 2007; Swerdlin et al., 2010). Further exploration of tongue, velum and pharyngeal articulation in loud speech would be needed to better understand these variations of R1.

Another question raised by this work concerns the inter-speaker variability of such ‘resonance tuning’ behaviors in loud voice, and its consequence on voice efficiency and laryngeal effort. Indeed, if lip hyper-articulation facilitates the vocal fold vibration in loud phonation – through improved resonance-harmonic proximity (Titze, 2008), this could result in improved glottal behavior and voice quality when speakers increase vocal intensity with flexible lip articulation, whereas constrained lip articulation might be associated instead with pressed or strained phonation. The results of this study, obtained from 8 participants, already show some inter-individual and gender differences in variations of lip aperture, resonance frequencies and resonance-harmonic proximity with increased vocal intensity. Exploring further this inter-individual variability, not only in healthy individuals, but also in dysphonic patients, may bring some useful information for the prevention and rehabilitation of vocal fatigue and muscle tension dysphonia (Morrison and Rammage, 1993; Roy et al., 2009).

Finally, alternative explanations for the interest or motivations of lip hyper-articulation in loud speech might be envisaged, especially for men for whom no significant improvement of the resonance-harmonic proximity was observed. A first hypothesis is that lip hyper-articulation, and the resulting variation of formants, may enable them to compensate for the concomitant rise of f_0 with increased vocal effort, by preserving some relative tonal distances between

formant frequencies and f_0 , which are considered as perceptual cues to vowel identification and distinction (Hoemeke and Diehl, 1994; Traunmüller, 1981). Not supporting this hypothesis, however, is the fact that lip hyper-articulation, and consequent increase of R1, was still observed here in the PL condition of our experiment, when pitch was constrained and when no compensation for a pitch rise was therefore needed. Another hypothesis is that lip hyper-articulation in loud speech may contribute to improve sound directivity, and thus to increase voice intensity as measured in front of the speaker. These different hypotheses deserve to be tested further by dedicated experiments.

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FIGURE CAPTIONS

Figure 1. Illustration of the protocol: Participants produced sustained vowels for about 11 seconds with an increase in vocal SPL after five seconds, in a same breath. Audio beeps (black bars) indicated to the participants when to start loud voice and when to stop phonation. The vocal tract was excited with a calibrated broadband sound signal during four seconds of comfortable and loud phonation in order to measure the vocal tract impedance spectrum. Voice SPL and spectrum were characterized from the audio signal, during the remaining second of ‘clean’ phonation at comfortable and loud levels. The laryngeal behavior and lip articulation were characterized over the whole 5 s interval of comfortable or loud phonation, based on electroglottographic measurements and video images.

Figure 2. Average change of voice SPL (Sound Pressure Level), fundamental frequency (f_0), lip aperture (vertical dimension) and spreading (horizontal dimension), and larynx height with the increase of vocal intensity in the three sessions (UL, PL and PAL).

Figure 3. Average frequency of the first two vocal tract resonances (R1, R2) showing the effect of increasing vocal effort from comfortable speech (black) to loud speech (light colour), in the three sessions (UL, PL and PAL), for all the 6 vowels and both genders. The ellipses represent the average intra-speaker variability within each vowel category.

Figure 4. On the left: The distribution of frequency differences observed between the frequency of the first vocal tract resonance (R1) and the closest voice harmonic (nf_0), for women pronouncing each vowel and mode of phonation (Comfortable voice and loud phonations (UL, PL, PAL)). On the right: Percentage of cases for which R1 frequencies are closer than 35 Hz to a voice harmonic, on average, and for each vowel produced by women at comfortable and loud levels. The dashed line represents the level of chance for observing such a resonance-harmonic proximity.

Figure 5. The relationship between values of ($f_0, R1$) measured simultaneously for the six vowels produced by the four women of this study (W1, W2, W3, W4), in comfortable voice (black) and ‘natural’ loud voice UL (light blue). The dashed lines represent the voice harmonics nf_0 . Shaded grey areas indicate a 70 Hz interval centered around these voice harmonics, corresponding to the typical bandwidth of vocal tract resonances (Hanna et al., 2016).

Figure 6. On the left: Average distributions in men, for each vowel and mode of phonation (Comfortable voice and loud phonation (UL, PL, PAL)), of the frequency differences observed between the frequency of the first vocal tract resonance (R1) and the closest voice harmonic (nf_0). On the right: Percentage of cases for which R1 frequencies are closer than 35 Hz to a voice harmonic, on average, and for each vowel produced by men at comfortable and loud levels. The dashed line represents the level of chance for observing such a resonance-harmonic proximity.

Figure 7. The relationship between values of ($f_0, R1$) measured simultaneously for the six

vowels produced by the four men of this study (M1, M2, M3, M4), in comfortable voice (black) and ‘natural’ loud voice UL (light blue). The dashed lines represent the voice harmonics nf_0 . Shaded grey areas indicate a 70 Hz interval centered around these voice harmonics, corresponding to the typical bandwidth of vocal tract resonances (Hanna et al., 2016).

Figure 8. On the left: Average distributions in women, for each vowel and mode of phonation (Comfortable voice and loud phonation (UL, PL, PAL)), of the difference observed between the frequency of the second vocal tract resonance (R2) and the closest voice harmonic (nf_0). On the right: Percentage of measurements for which R2 frequencies are closer than 35 Hz to a voice harmonic, on average, and for each vowel produced by women at comfortable and loud levels. The dashed line represents the level of chance for observing such a resonance-harmonic proximity.

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Figure 10. On the left: Average distributions in men, for each vowel and mode of phonation (Comfortable voice and loud phonation (UL, PL, PAL)), of the difference observed between the frequency of the second vocal tract resonance (R2) and the closest voice harmonic (nf_0). On the right: Percentage of cases for which R2 frequencies are closer than 35 Hz to a voice harmonic, on average, and for each vowel produced by men at comfortable and loud levels. The dashed line represents the level of chance for observing such a resonance-harmonic proximity.

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