Acoustic impact of the glottal chink on the production of fricatives: A numerical study

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The paper presents a numerical study about the acoustic impact of the glottal chink opening on the production of fricatives. Sustained fricatives are simulated by using classic lumped circuit element methods to compute the propagation of the acoustic wave along the vocal tract. A recent glottis model is connected to the wave solver to simulate a partial abduction of the vocal folds during their self-oscillating cycles. Area functions of fricatives at the three places of articulation of French (palato-alveolar, alveolar, and labiodental) have been extracted from static MRI acquisitions. Simulations highlight the existence of three distinct regimes, named $\mathcal{A}$, $\mathcal{B}$, and $\mathcal{C}$, depending on the chink opening. They are characterized by the frication noise level: $\mathcal{A}$ exhibits a low frication noise level, $\mathcal{B}$ is a mixed noise/voice signal, and $\mathcal{C}$ contains only frication noise. They have significant impacts on the first spectral moments. Boundaries of these regimes are defined in terms of minimal abduction of the vocal folds, and simulations show that they depend on articulatory and glottal configurations. Regime $\mathcal{B}$ is shown to be unstable: it requires very specific configurations in comparison with other regimes, and acoustic features are very sensitive in this regime.

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I. INTRODUCTION

Fricatives are a class of consonants that are produced by creating a supraglottal constriction in the vocal tract so that a turbulent airflow is generated, usually downstream of the constriction. This results in the production of the so-called frication noise, which is the main characteristic of the fricative consonants. Voiceless fricatives are produced by adjusting the glottal opening area such that it is significantly greater than the area of the supraglottal constriction[1]. In that case, the glottis is completely abducted, and the generated sound contains only frication noise. In voiced fricatives, the glottis is adjusted so that both a frication noise and a voiced signal are generated. The aeroacoustic conditions required to produce voiced fricatives are then very specific.

Studies about fricatives have focused on the spectral characteristics of the produced sound[2], the frication noise source[3], the geometry of the supraglottal constriction[4], and the vocal tract configuration downstream of the supraglottal constriction[5], especially the potential obstacles (teeth, lips, etc) encountered by the airflow[6]. These studies have contributed to a better understanding of the specific aeroacoustic conditions that are required to produce fricatives. It has been shown that the frication noise is generated when the airflow becomes turbulent, namely when the Reynolds number is sufficiently high[1]. High Reynolds numbers occur when the cross-sectional area of the supraglottal constriction is small and/or when the low-frequency component of the acoustic volume velocity through the constriction is large. The latter condition implies that the glottal opening area should be sufficiently large. For voiced fricatives, in addition to these conditions for the generation of frication noise, other aeroacoustic conditions at the vicinity of the glottis are required to produce the voicing: the vocal folds should not be completely abducted, and the transglottal pressure drop must be large enough to guarantee self-oscillations[7]. This implies subtle adjustments of the geometry of both the supraglottal constriction and the configuration at the glottis.

Most studies about the perceptual distinction between voiced and voiceless fricatives at a same place of articulation have focused on the duration of the voiced and the voiceless parts of the considered fricative[8–11]. Voicing of fricatives is then considered as binary. However, the amount of energy of the voicing component over that of the frication noise component is likely to vary continuously during the production of a fricative. Indeed, one may assume that the motions of the articulators and the abduction movements of the vocal folds, which are relatively slow in comparison with the oscillations of the vocal folds, gradually modify both the amplitude of the frication noise source and the amplitude of the voiced source during the production of the fricative. The acoustic impact of the vocal tract configuration on frication noise sources has been widely studied[5,6], but little attention has been paid to the acoustic impact of the configuration at the glottis. Recently, the existence of the glottal chink due to a partial abduction of the vocal folds[12] has been proposed to be an important feature in the production of voiced fricatives[13]. Since the glottal chink opening directly acts on the acoustic volume velocity, it also modifies the amplitude of the frication noise source. Thus, bad coordination between the glottal opening and the geometry of the constriction may result in an uncontrolled frication noise, and is likely to produce voiced fricatives that are perceived as voiceless because of a too large amount of frication noise.

The paper develops this idea: it uses the glottal chink model introduced in our recent papers[13,14] for a numerical study about the acoustic impact of the configuration at the glottis on the production of the voiced fricatives as a function of the geometry of the supraglottal constriction and the place of articulation. It focuses on the influence of the glottal chink opening on some acoustic features of the speech signal, such as the spectral centroid, the spectral spread, and the voicing quotient. The aim is to define the boundaries of the different regimes of production of fricatives in a phonatory-articulatory space spanned by the glottal chink opening, the position and the geometry of the supraglottal constriction. After presenting the acoustic model in Sec II, the paper details the configurations of the vocal tract used for the numerical simulations in Sec. III as well as the acoustic features that are investigated. Results of the simulations are presented in Sec. IV, which discusses the impact of the glottal chink opening on the first spectral moments of the simulated fricatives, and on the amount of the generated frication noise. Finally, the boundaries of the different regimes of fricative production and their impact on the phonetic strategies used by real speakers to contrast voiced and voiceless fricatives are discussed in Sec. V.

II. ACOUSTIC MODEL

The simulation framework to compute the acoustic propagation inside the vocal tract is derived from the *transmission line circuit analog* (TLCA) approach[15]. It considers plane waves propagating along a spatially sampled vocal tract, modeled as a set of connected acoustic tubes, or *tubelets*. Unlike the other widely used approach, the *reflection type line analog* (RTLA) model[16,17], it easily deals with time-varying lengths of the vocal tract, and also with uneven spatial sampling of the vocal tract. For further information, the reader may find a detailed review of existing techniques for speech synthesis in Ref.[18]. The framework that is used in this paper considers recent improvements of TLCA-based techniques[14,19], such as the possibility to connect self-oscillating models of the vocal folds with a glottal chink.

A. Acoustic propagation

Considering a general case, the vocal tract is seen as a waveguide network, where each waveguide models a side cavity (the oral tract, the nasal tract, the piriform fossae, etc). TLCA-based techniques have shown[15,19] that the wave propagation inside such networks is driven by a set of linear equations. In a matrix form, it writes

$$\mathbf{f} = \mathbf{Z}\mathbf{u}, \tag{1}$$

where $\mathbf{f} \in \mathbb{R}^{(N+1)}$ is a vector containing pressure forces, $\mathbf{Z} \in \mathbb{R}^{(N+1)\times(N+1)}$ is a tridiagonal matrix containing impedance and loss terms associated to each tubelet, and $\mathbf{u} \in \mathbb{R}^{N+1}$ is the vector containing the volume velocities inside each tubelet.

When dealing with self-oscillating models of the vocal folds, a quadratic term accounting for the pressure drop inside the glottal constriction, due to the Bernoulli resistance, should be added to the first line of the system[14]:

$$\mathbf{f} = \mathbf{Z}\mathbf{u}_Z + \mathbf{Q}\mathbf{u}_Q, \tag{2}$$

where $\mathbf{Q}$ is a square matrix the same size as $\mathbf{Z}$ having only one non-zero element, that is $Q_{(1,1)} = R_b$, and $\mathbf{u}_Q \in \mathbb{R}^{(N+1)} = [U_1^2, U_2^2, \ldots, U_N^2]^T$ is the vector containing the square power of the volume velocities. The term R_b is the Bernoulli resistance[14].

The domain of validity of the plane waves assumption depends on the radius of the maximal cross-sectional area of the vocal tract. Indeed, the cut-off frequency under which the assumption is considered as valid is defined by Eriksson[20] as

$$f_c = \frac{0.5861 c_s}{2 r_{max}}, \tag{3}$$

where c_s is the sound celerity and r_{max} is the radius of the largest vocal tract section. In this study, f_c differs according to the considered place of articulation, and is around 10 kHz for the palato-alveolar fricatives, 8 kHz for the alveolar and around 7 kHz for the labio-dental fricatives.

B. Frication noise generation model

The frication noise is generated by a turbulent air flow that appears downstream of the supraglottal constriction[1]. Interactions with obstacles, such as the teeth, the lips, and the walls of the vocal tract, usually occur and impact the acoustic nature of the turbulent noise source. The aeroacoustic mechanisms that are involved in the production of the frication noise are not totally comprehended yet. Consequently, their complicated nature makes them challenging to integrate into simplified acoustic models. Indeed, small variations of geometric or biomechanic parameters, such as the jet angle, the nature of the obstacle, or wall discontinuities downstream of the supraglottal constriction, may significantly modify the spectral characteristics of the produced turbulent noise[3,6]. Simplified models for frication noise sources commonly consider them as acoustic poles, dipoles, or quadripoles, depending on the cause of the turbulence[3,21].

In this paper, the frication noise source is modeled as an acoustic dipole that is activated when the Reynolds number is above a certain critical value, arbitrarily chosen at $Re_c = 1700$, referring to the previous study by Sondhi and Schroeter[22]. The noise source is a bandpass filtered Gaussian white noise[23]. Considering the i^{th} section of the spatially sampled vocal tract, the amplitude of the noise source $P_{n_i}(t)$ at section i and instant t is

$$P_{n_i}(t) = \max\left\{0, \xi w_c(t)\left(Re^2(t) - Re_c^2\right)\frac{U_{DC}^3(t)}{a_{i-1}^{3/2}(t)}\right\}, \tag{4}$$

where ξ is an arbitrarily adjustable real constant used to control the noise level, and $w_c(t)$ is a colored noise function, U_{DC} is the air flow volume velocity inside the vocal tract, and a_{i-1} is the area of the upstream tubelet. $Re = \frac{2\rho}{\mu}\frac{U_{DC}}{\pi\sqrt{a_c}}$ is the Reynolds number of the air flow inside the vocal tract, where a_c is the cross-section area of the supraglottal constriction, μ and ρ are the shear viscosity and the mass density of the air, respectively.

The computation of U_{DC} follows the method proposed by Maeda[23]. Note that to generate a frication noise with high amplitude, the vocal tract should exhibit a narrow supraglottal constriction area, and U_{DC} should be large (open glottis).

The frication noise source function $w_c(t)$ is computed from a Gaussian white noise function $w_g(t)$, shaped by a filter $g(t)$ in order to simulate a colored noise, hence $w_c(t) = w_g(t) * g(t)$. Following previous studies[21,24], $g(t)$ is a low-pass filter with a cut-off frequency $f_c = 0.15\sqrt{\pi}\frac{U_{DC}}{a_c^{3/2}}$. The gain ξ has been empirically chosen. It has been tuned so that, when vowel-fricative-vowel (VFV) pseudowords are simulated, the relative level of energy of the fricative in comparison with the surrounding vowels is similar to that observed in natural speech signals. As expected, the amplitude ξ varies according to the place of articulation, and is higher for sibilant fricatives than for non-sibilant fricatives ($\xi = 4.3\times10^{-7}$ for the palato-alveolar fricatives /ʒ,ʃ/, $\xi = 0.78\times10^{-7}$ for the alveolar fricatives /z,s/, and $\xi = 0.61\times10^{-7}$ for the labiodental fricatives /v,f/).

C. Glottis model with a glottal chink

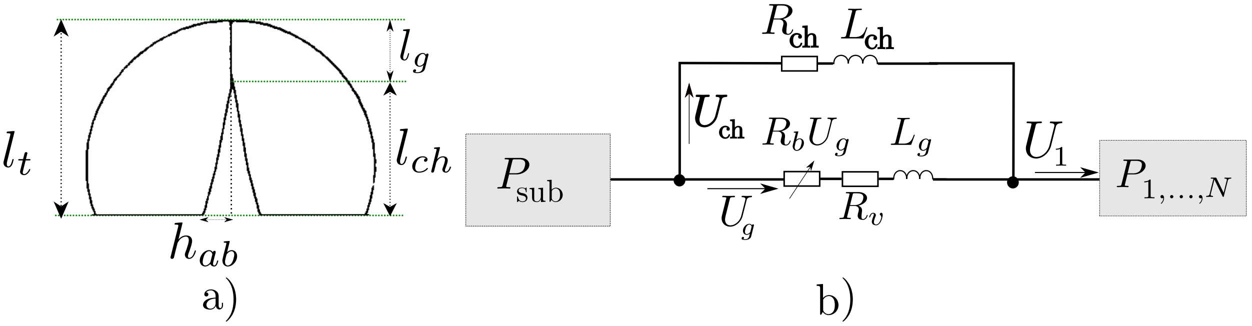


Figure 1. a) View of the partial closure model of the glottis, after Cranen and Schroeter[12]. In this model, the partial closure is due to a partial abduction of the vocal folds. l_g is the length of the vibrating part of the vocal fold, l_{ch} is the length of the glottal chink and $l_t = l_g + l_{ch}$ is the total length of the vocal folds. the abduction of the vocal folds is assumed to be constant and is denoted by h_{ab}. b) Electric-circuit analogy of the partially closed glottis. U_{ch}, R_{ch}, and L_{ch} are the volume velocity through the glottal chink, the energy loss, and the air inertance inside the glottal chink, respectively.

The model used to simulate the glottis is similar to the glottal chink model introduced in recent extensions of the Single-Matrix Formulation paradigm[14] and used to simulate voiced fricatives[13]. It considers two distinct portions of the glottis, represented in Fig. 1:

an oscillating part that is computed using a classic two-mass model of the vocal folds[25], and a partially abducted part, the so-called *glottal chink*, that allows an incomplete closure along the length of the vocal folds during the oscillation cycles. The two-mass model of the vocal folds considers recent improvements to take into account smooth contours, a mobile separation point[25], the viscous losses and the unsteady flow effects[26,27]. A surveys of existing self-oscillating models for the vocal folds may be found in Ref.[28].

The glottal chink has been shown to have significant acoustic impact on speech production, whether on the spectral tilt[12], or on self-oscillating movements of the vocal folds[29]. Except for a preliminary study[13], its acoustic impact on the fricative production has been given little interest. However, its role during voiced fricative production has been implicitly shown from electroglottography (EGG) measurements on real speakers[30]: during voiced fricatives, the amplitude of EGG signals is smaller than during the production of the adjacent vowels in vowel-fricative-vowel (VFV) context. Besides, external lighting and sensing photo-glottography (ePGG) measurements[31] (*cf.* Fig. 2) show a glottal opening waveform which is the superimposition of two components, a low frequency component that reaches the maximum around the middle of the fricative segment, and a higher frequency component that corresponds to the oscillations of the vocal folds. The ePGG signal displayed in Fig. 2 is an example of time evolution of the glottal opening chosen among a set of VFV pseudowords recorded for several speakers. The coexistence of these two components confirms the idea of a partial abduction of the glottis, which results in a glottal configuration similar to our model shown in Fig. 1. In this model, the partial closure of the glottis is due to a partial abduction of the vocal folds and the chink is linked to the membranous part of the glottis.

We have shown that the glottal chink may be connected to the Single-Matrix Formulation as an acoustic waveguide connected in parallel to the oscillating part of the glottis[14]. One may refer to previous papers[15,19] for details about the numerical computation, and to our previous paper[14] for details about the integration of the glottal leakage side branch.

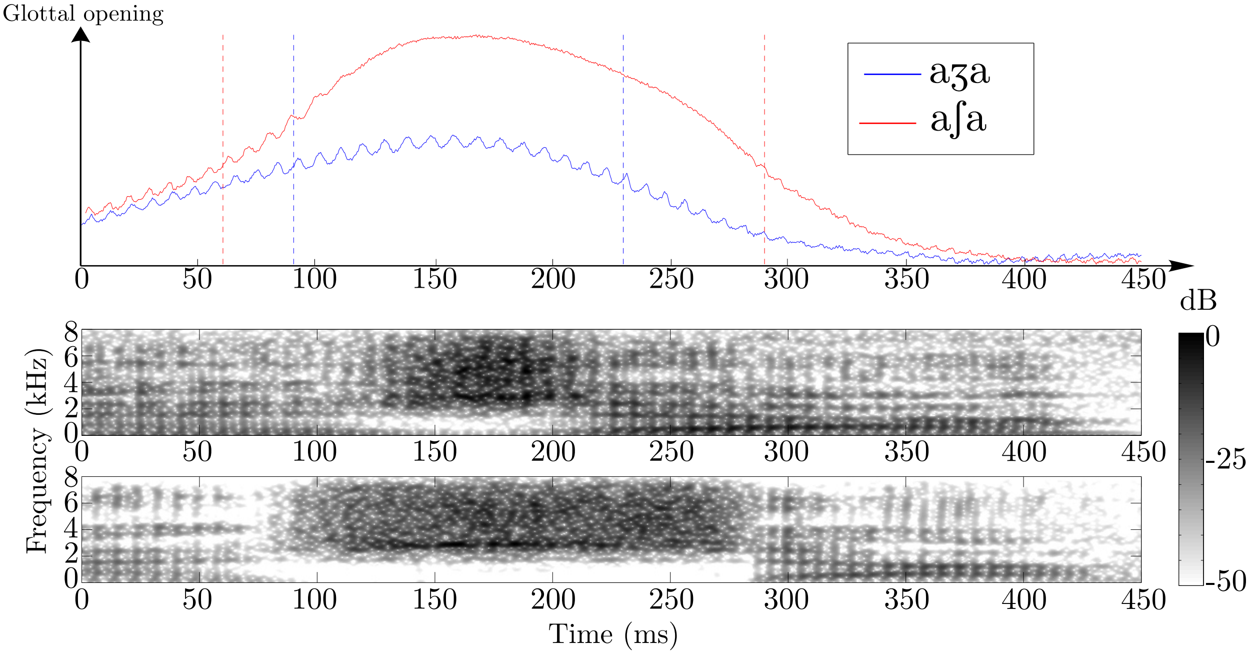


Figure 2. Top: example of external lighting and sensing photo-glottography (ePGG) curve of a VFV sequence. Here is the minimal pair /aʒa/-/aʃa/. The glottal opening axis has no value because the conversion between voltage and the opening area cannot be done with the device. The glottal opening area is in a linear scale. The phonetic segmentation is represented by vertical dashed lines. Middle: wide band spectrogram of the acoustic signal of the utterance /aʒa/. Bottom: wide band spectrogram of the acoustic signal of the utterance /aʃa/.

III. DATA AND METHODS FOR THE NUMERICAL STUDY

A. Data

1. Extracting the area function

Area functions are extracted from MRI acquisitions of sustained fricatives at the three places of articulation of French fricatives: palato-alveolars (/ʃ,ʒ/), alveolars (/s,z/), and labiodentals (/f,v/). Each shape has been acquired 7 times: for each place of articulation, the subject was asked to articulate the fricative as if he had to pronounce different vowels afterward, namely /i,ɛ,a,o,u,y,ø/. The subject is a volunteer with informed consent and approval of the local ethics committee. It is a male native French speaker who was 33 years old at the time of the acquisitions.

Then, the contours of the vocal tract have been extracted by hand on the midsagittal slice to compute the midline. This line, which should be perpendicular to the propagation of a plane wave in the vocal tract, is used to decompose it into tubelets. The method used to compute the midline is based on dynamic programming to select the best path of segments connecting the larynx to the lips[32]. The criterion to be minimized takes into account the cosine of the angle between the midline and the current segment to add in the path, and the distance between the middle points of the current and previous segments. The overall criterion C to be minimized is given by:

$$C = \sum_{i=1}^{N} \alpha cos^2(\overrightarrow{m(s_{i-1})m(s_i)}, \overrightarrow{s(i)}) + \parallel m(s_{i-1})m(s_i) \parallel, \tag{5}$$

where α is a weight, s the segments, $m(s)$ the midpoint of segment s and N the number of segments used to connect the first segment, i.e. the glottis, to the last one, i.e. the lip output.

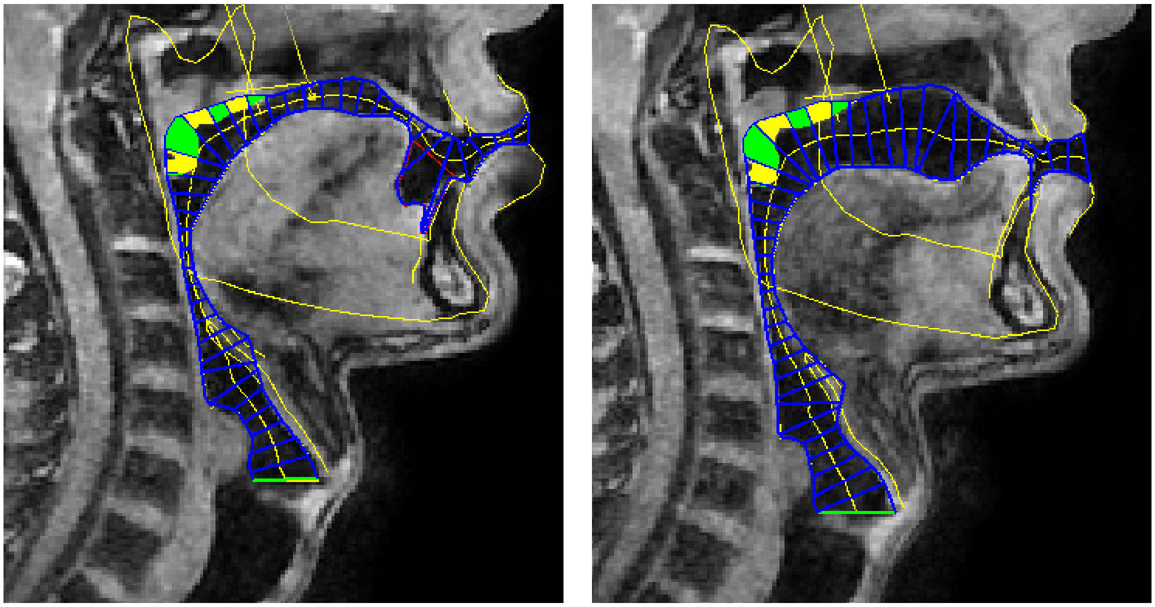
The determination of the midline is applied either on the whole vocal tract when there is no occlusion, which is the case with the vocal tract shapes of fricatives exploited in the paper, or on all the open sections delimited by the vocal tract extremities or occlusions.

The last step consists in dividing the vocal tract into tubelets perpendicularly to the midline. Attention is paid to the fact that two consecutive tubelets cannot cross in high curvature regions of the vocal tract. Recovering the third dimension from the 2D information, namely the midsagittal distance and the length of each tubelet, in order to estimate the area function has given rise to a number of works[33–35]. However, the improvement with respect to methods derived from that proposed by Heinz and Stevens[36] is not very marked. We thus accepted the α β parameters proposed by Soquet *et al.*[34].

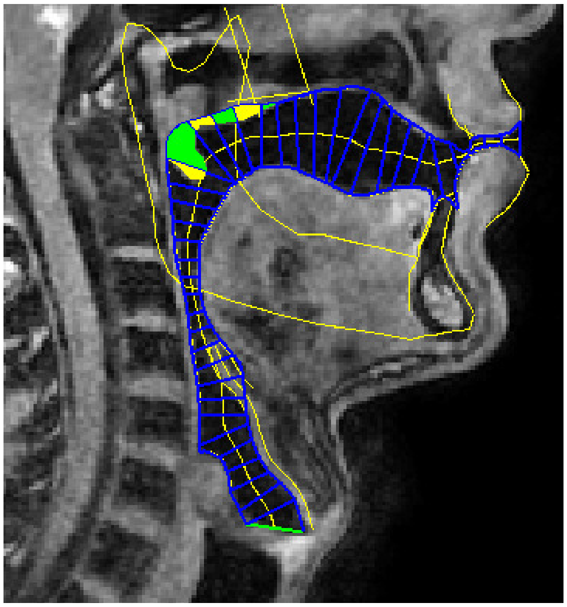
Fig. 3 shows an example of the midsagittal slice, as well as the corresponding tubelet decomposition of the vocal tract, for the three different fricatives in different contexts. Note that for palato-alveolar fricatives /ʃ/, the sublingual cavity is not considered as a side cavity, but as a extension of the main oral tract.

2. Trachea

The incomplete closure of the glottis during the oscillation cycle of the vocal folds leads to a constant coupling between the vocal tract and the trachea. It is therefore important



(a)/ʃ/ in /u/ context (b)/s/ in /a/ context



(c)/f/ in /i/ context

Figure 3. Decomposition of the vocal tract into elementary tube. View of the midsagittal slice of three fricatives, a) palato-alveolar /ʃ/, b) alveolar /s/, and c) labiodental /f/.

to account for this coupling by connecting a subglottal waveguide upstream of the glottis. Such connection with the single-matrix formulation has been previously proposed by Ho *et al.*[37], but it uses a very complex geometry of the subglottal system, modeled as a tree-like structure that accounts for all the branching patterns of the bronchial airways. Achieving such a fine degree of modeling is not in the scope of the paper, since it is hard to get such information for real speakers. Consequently, the subglottal system is modeled here as a single waveguide connected to a pressure source located at the input. The area function that is used is borrowed from a previous study by Story[17].

3. Glottal parameters

The input parameters used for the glottis model are the same than the one used in our previous paper[14]. Values of the mass and stiffness of the vocal folds model have been chosen so that the fundamental frequency of the simulated voiced signal is approximately 150 Hz. This corresponds roughly to the resonance frequency of the lumped mass-spring system.

B. Simulated configurations

The numerical study investigates the acoustic impact of various phonatory and articulatory configurations on the simulated signals, namely the subglottal pressure, the position, and the geometry of the supraglottal constriction, each of them as a function of the glottal chink opening. It consists in simulating voice signals with static vocal tract area functions. For each simulated configuration, the chink opening varies from 0 to 100% of the glottal length with an increment step of 2%, which results, for each of the configurations, in 51 simulated signals with various chink openings. In this paper, the length of the glottal chink is expressed as the proportion of the chink length in regards with the total length of the vocal folds, hence the fact that it is expressed in percent ($l_{ch}(\%) = 100\frac{l_{ch}(m)}{l_t(m)}$). Each simulated signal is 200 ms long, with a simulation frequency of 60 kHz. The purpose of setting a simulation frequency to 60 kHz, which is far above the frequency domain of interest, is to avoid frequency warping[15].

1. Subglottal pressure

In this paper, the subglottal pressure refers to the constant value assigned to the pressure source connected to the trachea input. In the simulations presented in Sec. IV A, it varies from 500 to 2000 Pa, with an increment step of 100 Pa. These values correspond to values of subglottal pressure encountered in normal voice[38], and in loud voice or singing[39]. In Sec. IV B, it is set to the nominal value of 1000 Pa.

2. Supraglottal constriction

The acoustic impact of the geometry of the supraglottal constriction is studied by modifying the cross-sectional area of the constriction, denoted by a_c, of the area functions extracted from MR images. In the simulations presented in Sec. IV B, a_c is set to different values ranging from 0.1 cm^2 to 0.5 cm^2. In the simulations presented in Sec. IV A, a_c is taken as the minimal cross-section area extracted from MR images.

C. Investigated features

1. Regimes of fricatives: voicing quotient and minimal lengths of the glottal chink

In a previous study[13], it has been shown that, for a given articulatory condition corresponding to a fricative, the simulated speech signal could exhibit three distinct regimes according to the glottal chink opening: i) an almost purely voiced signal when the chink is almost entirely closed (little frication noise is generated, similar to an approximant consonant), ii) a mixed voiced/noisy signal when the level of both voiced component and the frication noise share a similar order of magnitude, and iii) a purely noisy signal, similar to the voiceless fricative, when the voiced component is negligible in comparison with the frication noise. These three regimes, respectively denoted $\mathcal{A}$, $\mathcal{B}$, and $\mathcal{C}$ in the rest of the paper, are studied as a function of the glottal chink opening. This is done by using a voicing index, named the *voicing quotient*[40]. The voicing quotient (denoted VQ in this paper) is defined as the proportion, expressed in percent, of the energy of the periodic component in the speech signal, hence

$$VQ(\%) = 100 \times \frac{||s_p||_2^2}{||s_p + s_n||_2^2}, \tag{6}$$

where s_p is the periodic (or voiced) component of the signal, and s_n is the frication noise signal. Both periodic and aperiodic components of the simulated signals are computed thanks to a specifically designed periodic/aperiodic decomposition technique of the speech signal, that has been proven to be robust in the case of colored noise such as in voiced fricatives[40]. A value of 100 % indicates a speech signal containing only periodic components, and a value of 0 % indicates a speech signal containing only noisy components. Note that the voicing quotient is directly related to the Harmonics-To-Noise ratio (HNR) that quantifies the harmonicity of the signal, but the definition of the voicing quotient is more adapted to our study, since it directly quantifies the amount of voicing in fricatives.

For a given area function, varying the glottal chink opening leads to a decreasing voicing quotient as the chink opens up. A typical curve, shown in Fig. 4, highlights the presence of these regimes. In $\mathcal{A}$, the voicing quotient is constantly high, around 90%, since just a little frication noise is generated so that the voiced components dominate in the simulated speech signal. In $\mathcal{B}$, frication noise is generated along with voiced source due to the oscillating part of the vocal folds. The amount of frication noise that is generated is very sensitive to the value of the chink opening, hence large variations of the voicing quotient. Then, in $\mathcal{C}$, the voicing quotient vanishes. In this regime, the noise source is predominant over the voiced source, leading to a voiceless fricative. This can be seen in the spectrum in Fig. 4, where the harmonics at $f = nF_0$, with $F_0 = 150$ Hz, are visible in the low frequency domain, and vanish in regime $\mathcal{C}$.

From the variation of VQ as a function of the chink opening, it is possible to define two quantities, called the minimal lengths, denoted l_1 and l_2, and corresponding to the boundaries between regime $\mathcal{A}$ and $\mathcal{B}$, and between $\mathcal{B}$ and $\mathcal{C}$, respectively. They are computed as the two values $l_{ch} = \{l_1, l_2\}$ so that it leads to the best linear fitting in the three regions of the function $VQ = f(l_{ch})$, as shown in Fig. 4.

2. Spectral characteristics

The studied spectral characteristics investigated in this paper are the first two spectral moments, namely the spectral centroid, and the spectral spread.

The spectral centroid is a measure of the balance between the low and high frequency contributions in a spectral distribution, it writes

$$S_1 = \frac{\sum_{n=1}^{N} f_n A_n}{\sum_{n=1}^{N} A_n}, \tag{7}$$

where f_n, with $n = 1, 2, \ldots, N$ indicates the frequency bins of the N-order FFT, and A_n are

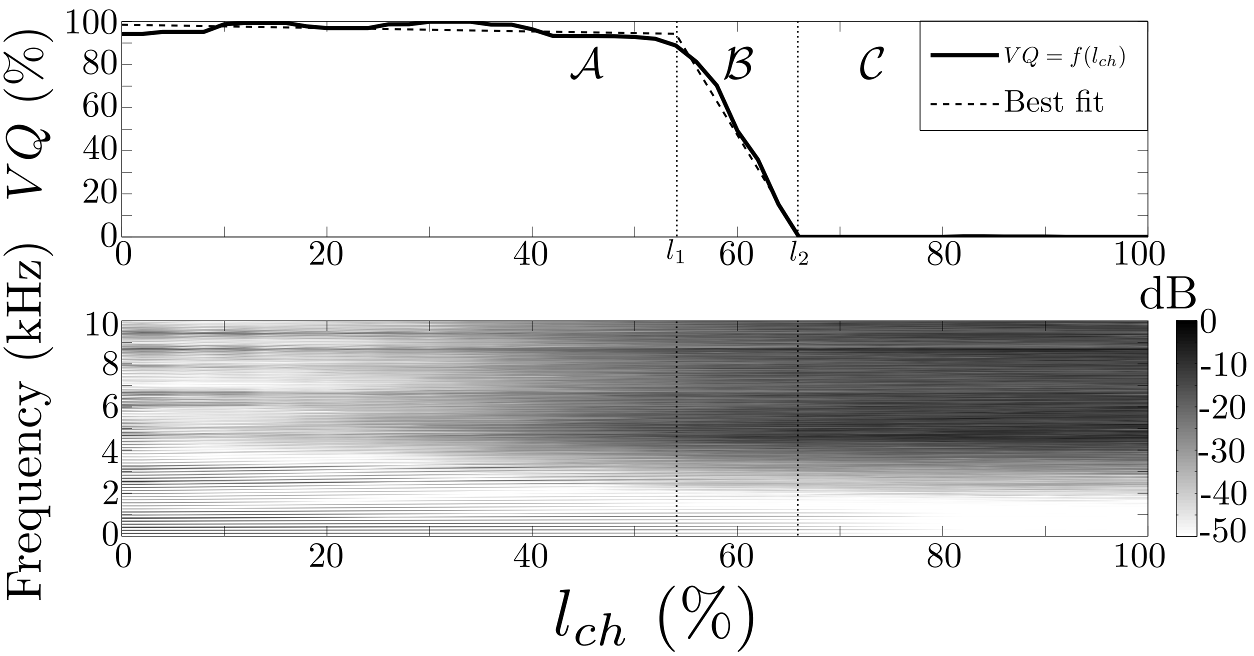


Figure 4. Top: example of curves representing the voicing quotient VQ as a function of the chink opening l_{ch}. The area function is the alveolar fricative in the /i/ context. The subglottal pressure value is $P_{sub} = 1000$ Pa, and $a_c = 0.15$ cm^2. The optimized linear fitting used to estimate the minimal lengths l_1 and l_2 is represented by the dashed line. Bottom: Spectrogram representing the evolution of the simulated signal spectrum as a function of the chink opening.

the corresponding magnitude.

The spectral spread is a measure of the square root of the variance of the spectral distribution. A small spectral spread indicates a spectrum that concentrates its energy in a small frequency range, located in the vicinity of its centroid. It writes

$$S_2 = \sqrt{\frac{\sum_{n=1}^{N} A_n (f_n - S_1)^2}{\sum_{n=1}^{N} A_n}}. \tag{8}$$

Both S_1 and S_2 are expressed in Hz and are computed in the frequency domain ranging from 50 Hz to 10 kHz.

IV. ACOUSTIC FEATURES

A. Effect of the subglottal pressure

1. *Voicing quotient*

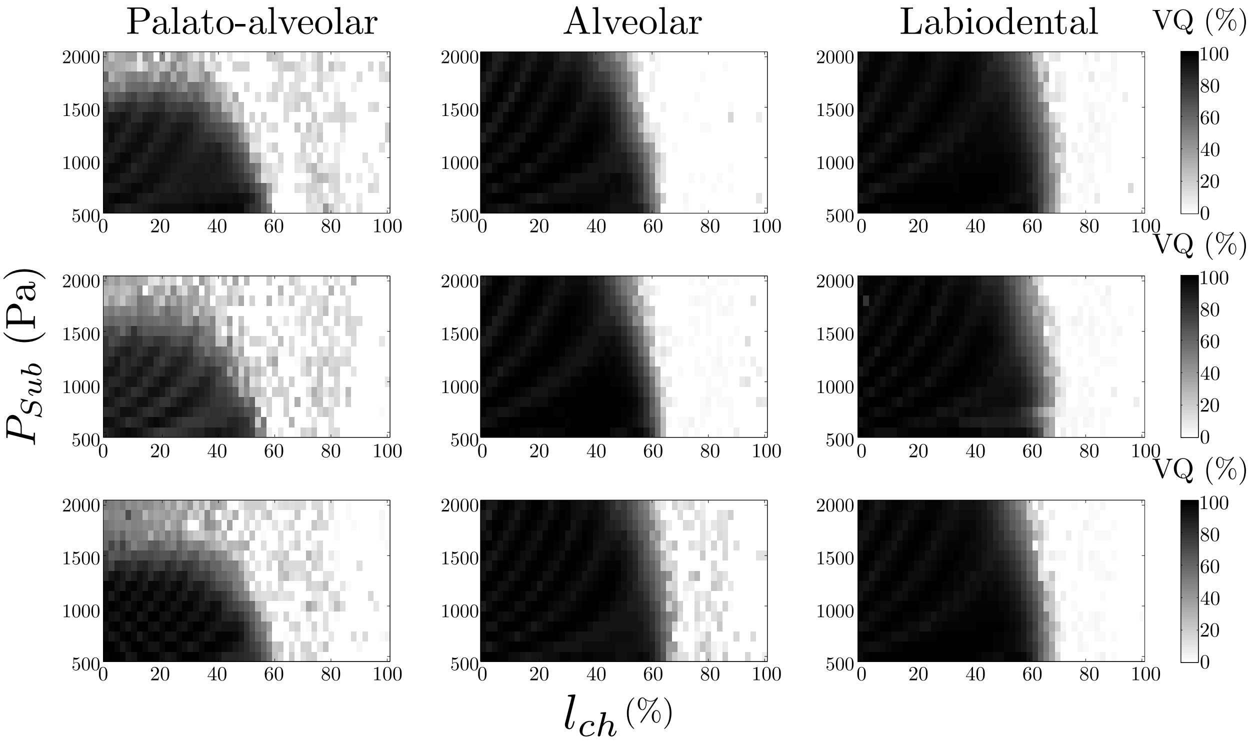


Figure 5. Voicing quotient of simulated voice signals as a function of the subglottal pressure P_{Sub} and the glottal chink opening l_{ch}. Each column of figures corresponds to a place of articulation. From left to right: palato-alveolar fricatives /ʃ,ʒ/, alveolar fricatives /s,z/, and labiodental fricatives /f,v/. Each row of figures corresponds to a vowel context, /i,a,u/, from top to bottom.

Fig. 5 shows the voicing quotient as a function of the glottal chink opening and the subglottal pressure. For the sake of clarity, it does not show results of all of the 21 configurations (7 contexts for each of the 3 places of articulation), but only those corresponding to the context of cardinal vowels, namely /i,a,u/. The same simplification applies in the rest of the paper. The general behavior of the voicing quotient as a function of the glottal chink opening is similar to the typical curve displayed in Fig. 4: the voicing quotient is constantly high for small chink opening, then it suddenly plunges at a certain point, called l_1, and vanishes at the second critical point, called l_2. Minimal chink openings tend to be smaller when the subglottal pressure rises. Indeed, when the subglottal pressure increases, this raises the Reynolds number due to an higher DC component of the airflow volume velocity inside the vocal tract. Consequently, the Reynolds critical number Re_c above which the frication noise is generated is reached at smaller chink openings. In a $l_{ch} - P_{Sub}$ plane, as shown in Fig. 5, it results in the left part exhibiting high values of voicing quotient, and the right part exhibiting low values, both parts being obliquely separated by a small transition area.

Results show, however, significant differences between the places of articulation. For palato-alveolar fricatives, the glottal chink opening for which the voicing quotient starts to significantly decrease is smaller than for other places of articulation. Also, the lowering of this critical opening seems to be more important for palato-alveolar fricatives. The vowel context seems to have little influence on the voicing quotient. Indeed, for each place of articulation, the shapes of the voicing quotient values for the three vowel contexts are very similar.

2. Spectral centroid

The spectral centroid as a function of phonatory conditions shows distinct areas, as evidenced in Fig. 6. At the bottom left, where the chink opening and the subglottal pressure are small, the spectral centroid lies between 1000 and 1500 Hz. At the top right, when both the glottal chink and the subglottal pressure are large, the spectral centroid is much higher, and lies between 4700 Hz for palato-alveolar fricatives, up to 6200 Hz for alveolar fricatives. In these areas, the spectral centroid is relatively stable in regards with variations of the phonatory configurations. The values in this region depend on the place of articulation considered: alveolar fricatives have the highest values of spectral centroid, around 6 kHz, then the labiodental fricatives have a spectral centroid around 5.8 kHz, and finally, the palato-alveolar fricatives have a spectral centroid around 4.7 kHz. These values are in agreement with data observed in natural speech by Jongman *et al.*[2] for English, and Lonchamp for French[41]. The alveolar fricatives of English and French speakers exhibit the higher spectral centroid than other fricatives, whereas palato-alveolar fricatives have the lowest spectral centroid. Same data also showed that, like in the presented simulations, voiced fricatives exhibit lower spectral centroids than their voiceless counterpart. A small transition area may be seen. In this range, small variations of chink opening or subglottal pressure leads to

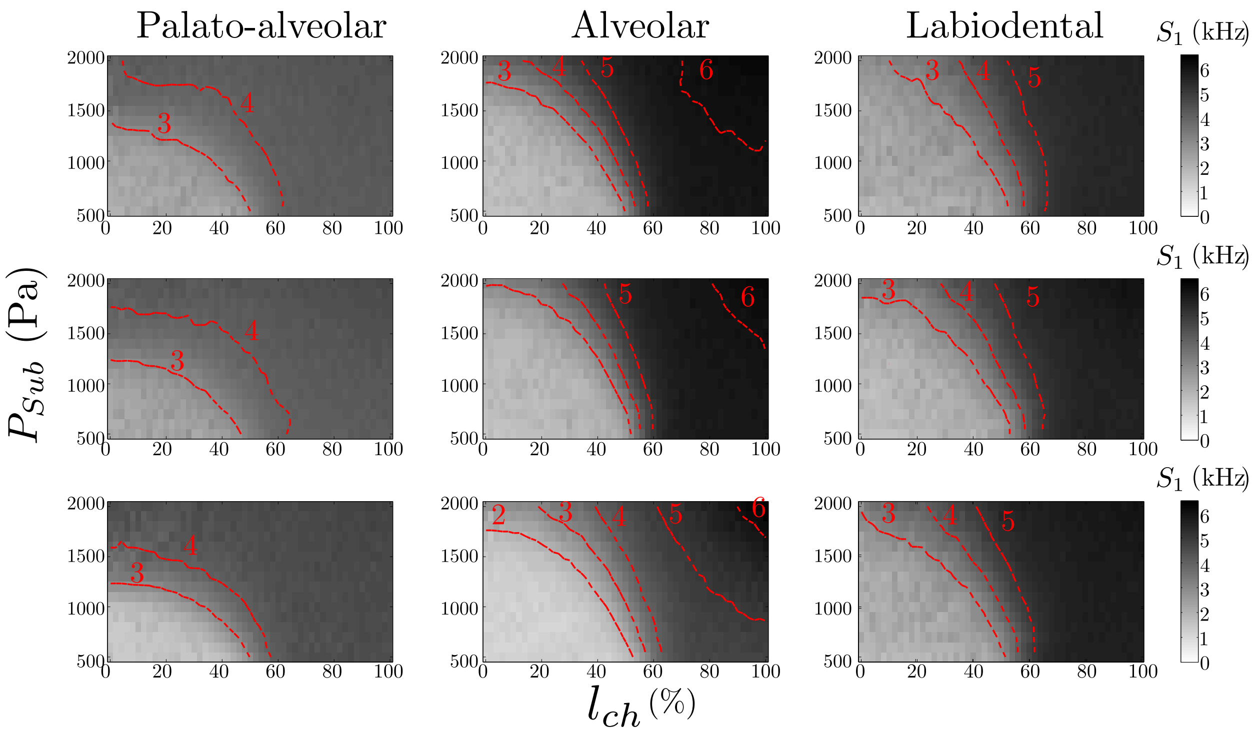


Figure 6. Spectral centroid of simulated voice signals as a function of the subglottal pressure P_{Sub} and the glottal chink opening l_{ch}. Each column of figures corresponds to a place of articulation. From left to right: palato-alveolar fricatives /ʃ,ʒ/, alveolar fricatives /s,z/, and labiodental fricatives /f,v/. Each row of figures corresponds to a vowel context, /i,a,u/, from top to bottom. Contour lines, expressed in kHz, are represented by dashed lines.

large variations of the spectral centroid.

Similarly to the voicing quotient, the vowel context seems to have no significant influence on the spectral centroid of the simulated fricative. However alveolar and palato-alveolar fricatives simulated in the /u/ context exhibit slightly different patterns of spectral centroid values than for /i/ and /a/ context. For palato-alveolar fricatives, the high values (above 4 kHz) are reached for smaller chink opening and smaller subglottal pressure than for other places of articulation.

This may be explained by the fact that when the subglottal pressure and the chink opening are small, the aerodynamics conditions are not fulfilled to generate a frication noise, so that the simulated speech signal contains only periodic, or voiced components. In that case, the energy is mainly concentrated in the low frequency range, hence a low spectral centroid. Then, when the chink opening and the subglottal pressure are sufficiently large to generate a frication noise (central region), noisy components arise in the simulated speech signals. This has for effect to enhance the high frequency range of the spectrum. Hence the rise of the spectral centroid. A slight increase of either the subglottal pressure or the chink opening in this regime leads to a decrease of the voiced component level, and an increase of the noise level, hence the rise of the spectral centroid. When the voiced components have disappeared, at high values of the chink opening and subglottal pressure, and when the simulated signals contain only noise, the spectral centroid reaches its maximal value, since the low frequency domain of the spectrum is significantly weakened by the absence of the voiced contributions. This is confirmed by the similarities between the pattern of voicing quotient values in Fig. 5 and that of spectral centroid values in Fig. 6.

3. Spectral spread

The plot of the spectral spread as a function of P_{Sub} and l_{ch}, shown in Fig. 7, also highlights the presence of areas that are related to both the voicing quotient and the spectral centroid. Again, the palato-alveolar fricative exhibits a different behavior than other places of articulation. For alveolar and labiodental fricatives, the spectral spread values at the bottom left corner is low, and then suddenly increases to reach a maximum around 3.5 kHz. At the top right corner, the spectral spread is also low, with values at the same order of magnitude than at the bottom left corner. Similarly to the bottom left corner, these values are relatively stable. These three areas are approximately located at the same place than the three areas of the spectral centroid. Palato-alveolar fricatives presents smaller values of the spectral spread, and they are relatively constant independently of the position in the $l_{ch} - P_{Sub}$ plane.

Similarly to the spectral centroid, the existence of three different regimes, as well as their characteristics may be explained by the presence, or not, of the frication noise. In the low opening and low subglottal pressure conditions, the absence of frication noise yields to an almost purely harmonic spectrum with a marked spectral slope. Hence a small spectral spread. As long as no frication noise is generated, the spectral shape remains the same independently of the values of the chink opening and the subglottal pressure. As soon as the frication noise is generated, the spectrum of the simulated fricative is enhanced in the high frequency domain. At the same time, the voiced component is still predominant in

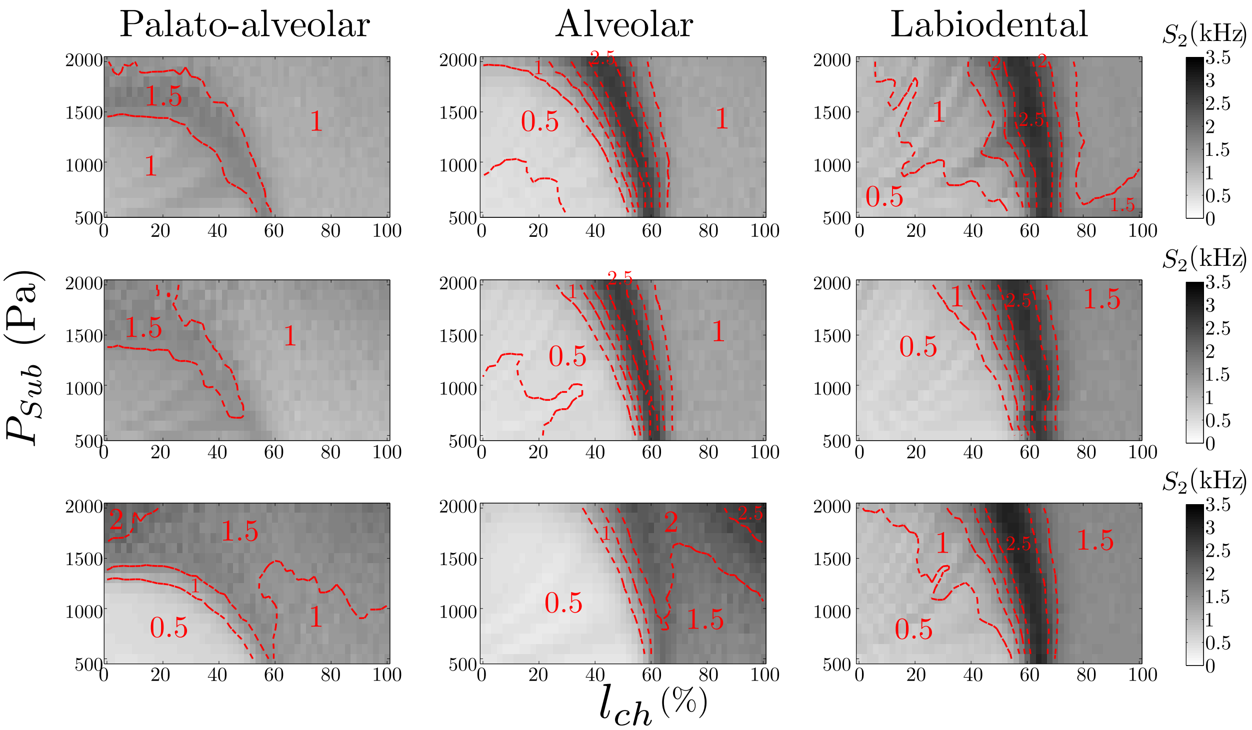


Figure 7. Spectral spread of simulated voice signals as a function of the subglottal pressure P_{Sub} and the glottal chink opening l_{ch}. Each column of figures corresponds to a place of articulation. From left to right: palato-alveolar fricatives /ʃ,ʒ/, alveolar fricatives /s,z/, and labiodental fricatives /f,v/. Each row of figures corresponds to a vowel context, /i,a,u/, from top to bottom. Contour lines, expressed in kHz, are represented by dashed lines.

the low frequency range. As a consequence, the spectral spread is large, since the signal contains energy both in the low frequency domain (voiced component) and in the high frequency domain (noisy component). The spectral spread value is very sensitive to the balance between the voiced component energy level and the noise level, hence quick changes in the spectral spread values in the central area. Finally, when values of both subglottal pressure and the chink opening are large enough so that there is no voiced components in the simulated fricative any longer, the spectrum in the low frequency domain is significantly weakened so that the energy is concentrated in the mid- and high-frequency domains, hence smaller values of the spectral spread.

The alveolar fricative in the /u/ context shows smaller spectral spreads than in other contexts. This is in agreement with measurements presented by Shadle and Mair[42], where spectral spread of /s/ in /usu/ context were smaller than in /asa/ and /isi/ contexts. The same paper also reported that spectral spread of /ʃ/ in /uʃu/ were significantly larger than in /aʃa/ and /iʃi/ contexts, while spectral spread of /f/ is at the same value independently of the vowel context. These observations are also verified by our simulations.

B. Influence of the cross-sectional area of the supraglottal constriction

1. Voicing quotient

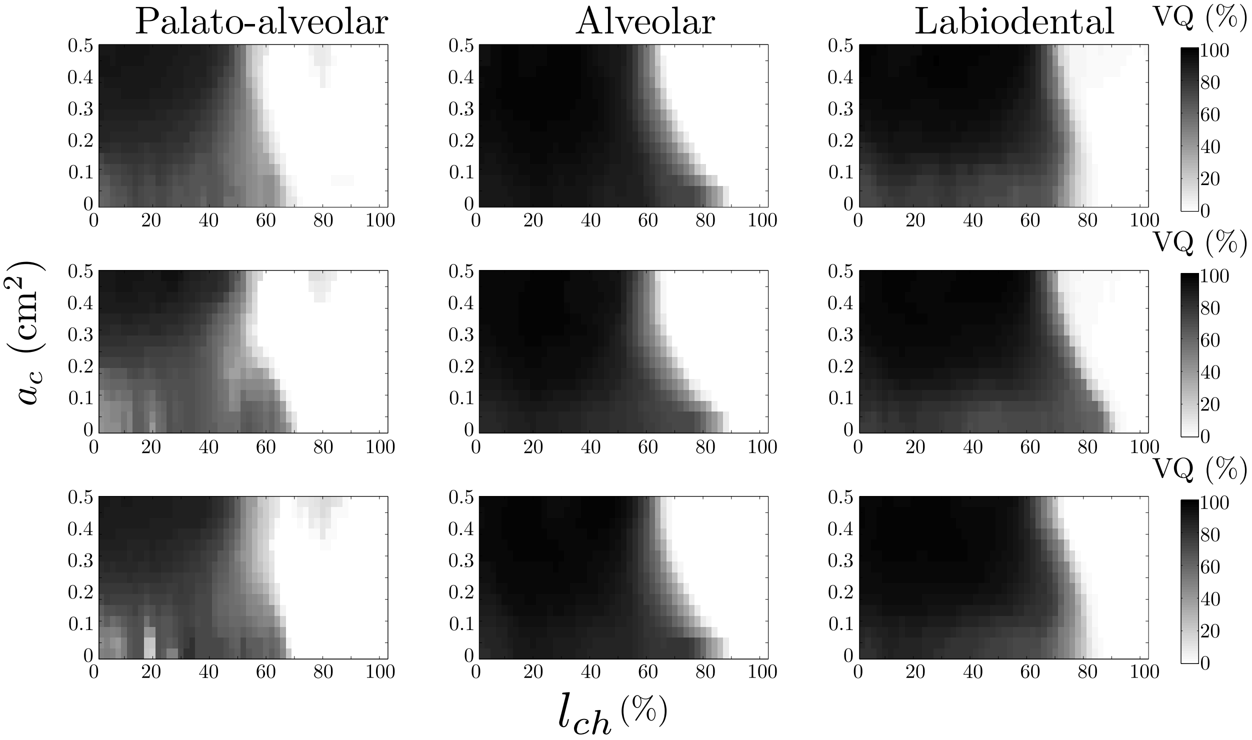


Figure 8. Voicing quotient of simulated voice signals as a function of the supraglottal constriction area a_c and the glottal chink opening l_{ch}. Each column of figures corresponds to a place of articulation. From left to right: palato-alveolar fricatives /ʃ,ʒ/, alveolar fricatives /s,z/, and labiodental fricatives /f,v/. Each row of figures corresponds to a vowel context, /i,a,u/, from top to bottom.

The voicing quotient as a function of the chink opening l_{ch} and the supraglottal constriction area a_c is shown in Fig. 8. As expected, the voicing quotient is high for small chink opening l_{ch}, then dramatically decreases at a critical chink opening, and vanishes for large values of l_{ch}. The influence of the supraglottal constriction area is limited when a_c is larger than 0.3 cm^2. Under this value, a_c has a more marked influence, and more specifically for alveolar and labiodental fricatives: the value of l_{ch} above which the voicing quotient vanishes increases as a_c decreases. For labiodental fricatives, it depends on the vowel context, as this is more marked for the context /a/ than for the other contexts /i/ and /u/.

2. Spectral centroid

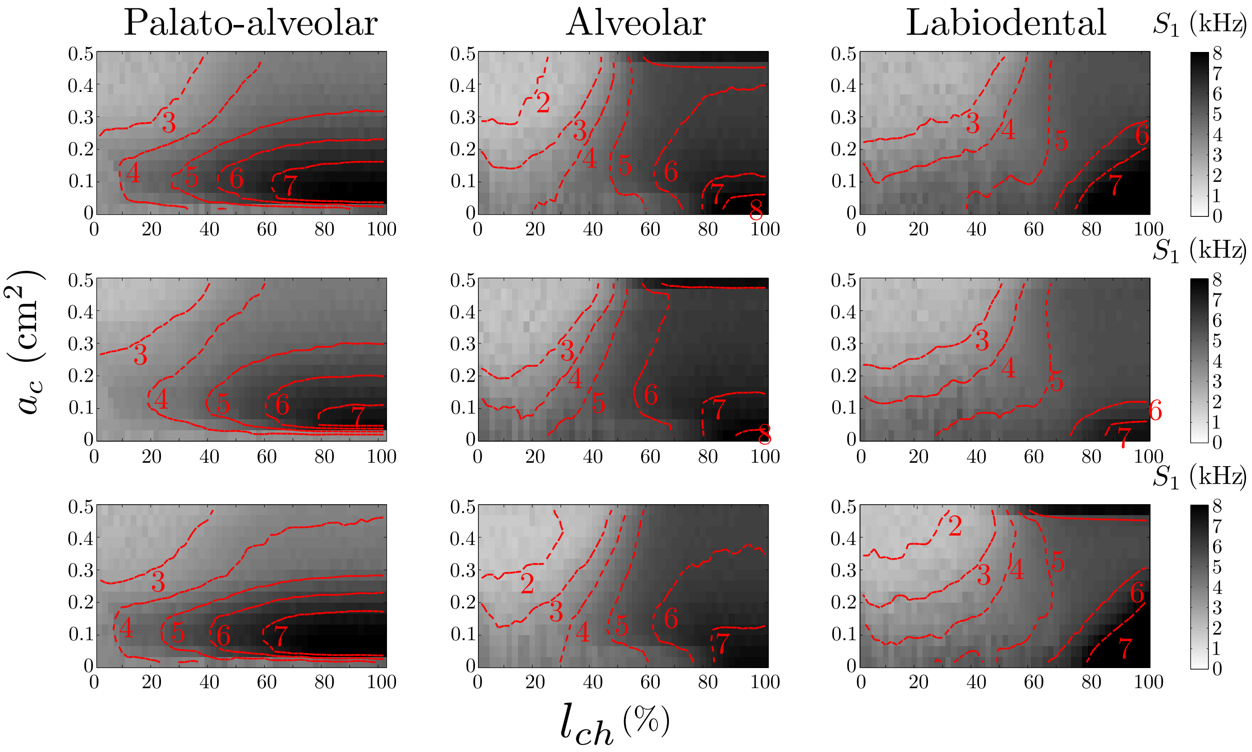


Figure 9. Spectral centroid of simulated voice signals as a function of the supraglottal constriction area a_c and the glottal chink opening l_{ch}. Each column of figures corresponds to a place of articulation. From left to right: palato-alveolar fricatives /ʃ,ʒ/, alveolar fricatives /s,z/, and labiodental fricatives /f,v/. Each row of figures corresponds to a vowel context, /i,a,u/, from top to bottom. Contour lines, expressed in kHz, are represented by dashed lines.

Plots of the spectral centroid of the simulated signals as a function of the chink opening l_{ch} and the supraglottal constriction area a_c, shown in Fig. 9, exhibit complicated patterns. The opening of the glottal chink leads to higher values of the spectral centroid. The supraglottal constriction area has also a significant influence on the spectral centroid. Basically, a small a_c leads to a high value of the spectral centroid. However, for palato-alveolar fricatives, there is local maximum, at $a_c = 0.1$ cm^2. It results in low values of the spectral centroid at the top left corner, and high values at the bottom right corner of the $l_{ch} - a_c$ plane. There is no significant differences according to the vowel context.

3. Spectral spread

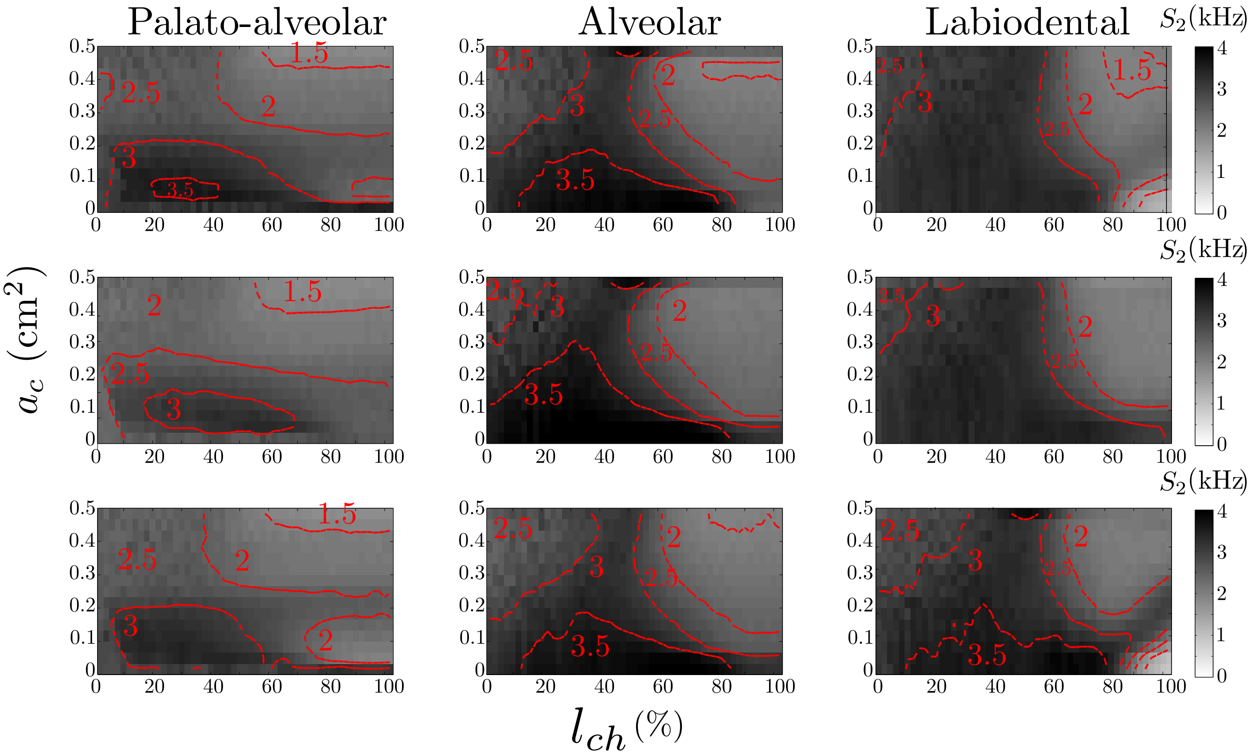


Figure 10. Spectral spread of simulated voice signals as a function of the supraglottal constriction area a_c and the glottal chink opening l_{ch}. Each column of figures corresponds to a place of articulation. From left to right: palato-alveolar fricatives /ʃ,ʒ/, alveolar fricatives /s,z/, and labiodental fricatives /f,v/. Each row of figures corresponds to a vowel context, /i,a,u/, from top to bottom. Contour lines, expressed in kHz, are represented by dashed lines.

Fig. 10 shows the spectral spread as a function of l_{ch} and the constriction area a_c. As a function of the chink opening, and at a given constriction area, one can observe the same behavior than in Fig. 7: the spectral spread is the smallest at both extremities, and reach a maximum in a central area. The spectral spread is also larger for narrow constrictions. Palato-alveolar fricatives have smaller spectral spread than other places of articulation. This is certainly due to the fact that postalveolar fricatives present a predominant peak between 2 and 3 kHz[?] , which concentrates the energy of the spectrum in this frequency domain.

Like for the spectral centroid, there are no significant differences among the different vowel contexts.

V. MINIMAL LENGTH OF THE GLOTTAL CHINK

In this section, two adimensional quantities are defined according to the method explained in Sec. III C: l_1 is the minimal length of the glottal chink from which frication noise is generated, namely the boundary between $\mathcal{A}$ and $\mathcal{B}$, and l_2 is the minimal length of the glottal chink from which the noise component is predominant over the voiced component, namely the boundary between $\mathcal{B}$ and $\mathcal{C}$. A third quantity is $\Delta l = l_2 - l_1$, which is the width of regime $\mathcal{B}$.

A. Effect of the subglottal pressure

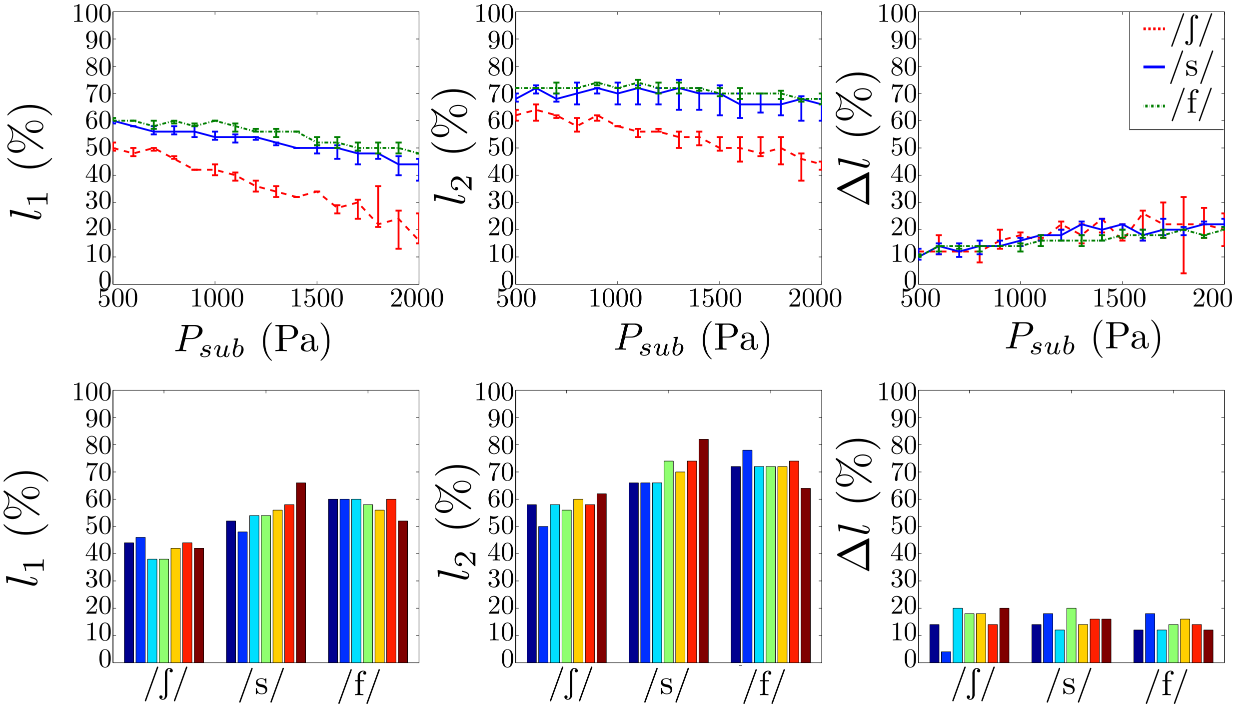


Figure 11. Top: median values of l_1, l_2, and Δl as a function of P_{sub} for the three fricatives. Bottom: values of l_1, l_2, and Δl at $P_{sub} = 1000$ Pa for each extracted area function. For each group of 7 area functions, they correspond to the following vowels /i,ɛ,a,o,u,y,ø/, respectively.

Fig. 11 shows the median value of l_1, l_2, and Δl as a function of P_{sub} for the three places of articulation, as well as the median absolute deviation. Increasing the subglottal pressure has for main effect to decrease both l_1 and l_2. This is due to the fact that when P_{sub} is high, the low-frequency component of the acoustic volume velocity inside the vocal tract increases as the pressure drop between the subglottal region and the mouth increases. This results in the rise of the Reynolds number, hence smaller minimal lengths. The evolution of l_1 and l_2 as a function of P_{sub} are qualitatively similar for all places of articulation. However, it exhibits quantitative discrepancies, even among a single group of fricatives. For instance, in the /ø/ context, the alveolar fricative presents minimal lengths significantly larger than in other contexts. Also, the median value among the group of palato-alveolar fricatives is the lowest for both l_1 and l_2. This suggests that small variations of the vocal tract geometry, and especially at the supraglottal constriction, may significantly modify the acoustic features of the produced fricative. Interestingly, Δl increases as P_{sub} becomes large: it is 10% for $P_{sub} = 500$ Pa, and goes up to approximately 20% for $P_{sub} = 2000$ Pa. It is also interesting to note that the values are globally very similar for each place of articulation and for each realization. This result suggests that for any articulatory configuration, the chink opening range required to produce voiced fricative depends mostly on the subglottal pressure and is not dependent on the phonological context.

B. Effect of the cross-section area of the supraglottal constriction

Fig. 12 represents the minimal lengths l_1, l_2, and $\Delta l = l_2 - l_1$, as a function of the cross-sectional area of the supraglottal constriction a_c. The values of the minimal length are still systematically lower for the palato-alveolar fricatives than for the other fricatives. Although very close, they are also smaller for alveolar fricatives than for labiodental fricatives. If a_c is greater than 0.1 cm^2, there is no significant changes in the value of l_1. The same is true for l_2 when a_c is greater than 0.3 cm^2.

Changing the cross-sectional area of the supraglottal constriction seems to be have no significant impact on the required configurations at the vicinity of the glottis if the supraglottal constriction is larger than 0.3 cm^2. This suggests that the area of the supraglottal constriction is not used as a mean to adjust the degree of voicing of the fricative, but is used only to control the acoustic characteristics (noise level and spectral moments).

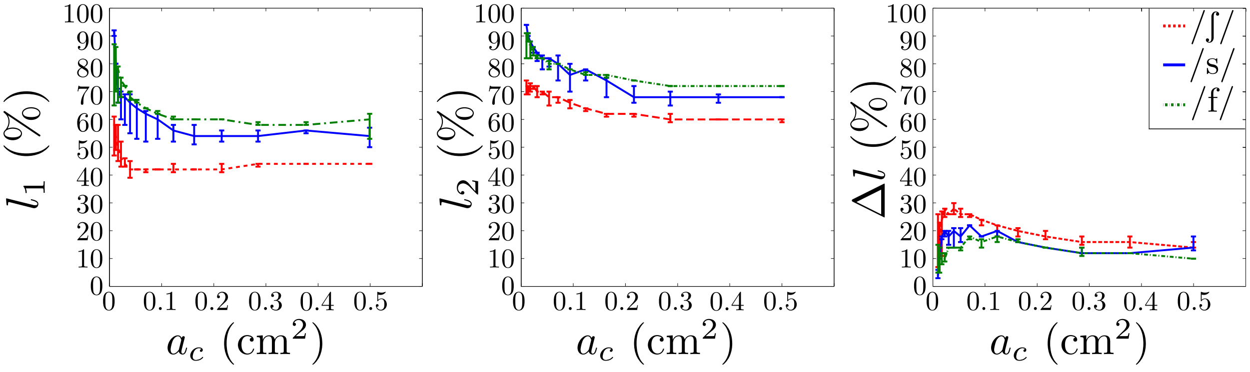


Figure 12. From left to right: l_1, l_2, and Δl, as a function of the supraglottal constriction area a_c, and for the three places of articulation.

C. Discussion

Our simulations give a new point of view about strategies available to implement the voice/unvoiced contrasts of fricatives. Here we exploit the results of our simulations together with the observations of French speakers and German learners of French[43]. In this work dedicated to language learning we recorded sentences with voiced fricatives in a word final position uttered by French and German speakers, and the same words (in an isolated condition) by French speakers to investigate voicing without the influence of the initial vowel of the next word. The final devoicing of voiced fricatives of French by German learners of French allows the differences in the realization of voiced fricatives to be highlighted.

In our simulations, the computed values of l_1 and l_2, whether as a function of the subglottal pressure or the cross-section area of the supraglottal constriction, lead to very small values of Δl, namely under 25 %. In this range, corresponding to regime $\mathcal{B}$, small variations of the vocal tract and the glottal configurations lead to significant modifications of the acoustic characteristics. Consequently, sustaining regime $\mathcal{B}$ to produce voiced fricatives may be very difficult for the speaker, and falling into regime $\mathcal{C}$ is very likely. On the contrary, voiceless fricatives is much easier because it requires to open the glottis sufficiently to be in regime $\mathcal{C}$, which is very stable. However, since the abduction/adduction movement of the vocal folds is relatively slow, the speaker goes from $\mathcal{A}$ to $\mathcal{C}$ by transiting through $\mathcal{B}$ during a short moment, leading to voiced frames in the fricative segment. Then, in order to contrast voiced and voiceless fricatives, the speaker may have several strategies. A first strategy would consist in producing a weak frication noise, i.e. maintaining regime $\mathcal{A}$ for the whole duration of the voiced fricative. Secondly, since the boundary between the voiced and unvoiced regimes is almost vowel independent for each of the places of articulation (Fig. 11), that probably enables the control of this regime to be mastered by a speaker. However, this requires to reduce the duration of the fricative, since $\mathcal{B}$ is very unstable. Our acoustic measurements[43] show that some French speakers (approximately one third for postalveolar fricatives) sustain voicing for the whole fricative even in a final position. This corresponds to one of these two strategies. However, there is a substantial part of French speakers who fail to produce voicing for the whole fricative even if perception tests confirmed that the corresponding fricatives are perceived as voiced. The third production strategy resorts on a less precise control of the chink opening which results in a brief excursion in regime $\mathcal{C}$, hence some unvoiced frames. The abduction/adduction movement corresponding to the devoicing and then revoicing of speech is all the easier since there is a vowel after the fricative as exhibited by Fig. 2. This probably explains why French speakers realize a release vocal schwa (/ə/) after a voiced fricative. This also explains that short voiceless segments of fricatives have been shown to be an acoustic clue for voicing perception[44].

The first and second strategies have been observed in some French speakers for producing voiced fricatives in final position[43]. Interestingly, these strategies are used by 27 % of the speakers for /ʒ/, by 62 % of the speakers for /z/, and by 75% of the speakers for /v/. In regards with the results presented in this paper, this makes sense since palato-alveolar is the place of articulation that systematically presents the shorter region $\mathcal{A} - \mathcal{B}$ (smaller values of l_1 and l_2), followed by alveolars, and by labiodentals. Hence difficulties to maintain these regimes.

VI. CONCLUSION

The paper has presented a numerical study about the influence of the glottal chink opening, along with various configurations of the supraglottal constriction, on several acoustic features of produced fricatives. Simulations used a recent glottal chink model that is connected with the classic 1D wave solver based on a transmission line circuit analog framework. It is, to the best of our knowledge, the first study about the acoustic impact of fine glottal configurations, such as partial abduction and incomplete closure of the glottis, on the production of voiced fricatives.

Simulations have highlighted the existence of three distinct regimes of fricative production, depending on the amount of frication noise that is generated. The first regime, labeled $\mathcal{A}$ in this paper, corresponds to an almost purely voiced signal, corresponding to an approximant consonant, where the DC component of the volume velocity in the vocal tract is too low to generate a frication noise with a significantly high acoustic level. In this regime the spectral centroid and the spectral spread are relatively low, and small variations of speaker configurations, such as the glottal chink opening, or the geometry of the supraglottal constriction, do not significantly modify the spectral features. The second regime, labeled $\mathcal{B}$, corresponds to the situation where the voiced and the frication noise components of the speech signal have similar energy. In regime $\mathcal{B}$, the spectral centroid and the spectral spread are higher than in the first regime, because of the presence of the noise component that enforces the high frequency domain of the uttered voice. Unlike regime $\mathcal{A}$, small variations of the speaker configurations significantly modify the acoustic features. Finally, the third regime, labeled $\mathcal{C}$, corresponds to voiceless fricatives, i.e. when the frication noise component is predominant over the voiced component. In regime $\mathcal{C}$, like in regime $\mathcal{A}$, the spectral features are very stable in regards with variation of the speaker configurations. However, unlike in regime $\mathcal{A}$, the spectral centroid is high and the voicing quotient is almost null. The existence of these regimes has been evidenced for each of the three places of articulation of French fricatives.

In the articulatory-phonatory space, regime $\mathcal{B}$ is the one with the smallest extent, confirming the fact that voiced fricatives are a difficult-to-produce class of consonants, because of the very specific aeroacoustic conditions required. Simulations have shown that the range of chink opening for producing voiced fricatives do not vary significantly with the place of articulation, nor with the phonological context, and nor with the geometry of the supraglottal constriction. On the contrary, this range varies with the subglottal pressure: the greater the pressure the longer the range of the chink opening.

In terms of articulatory strategy, regime $\mathcal{B}$ is not suitable to sustain fricatives, hence several alternatives to contrast voiced fricative with voiceless fricatives: i) staying in $\mathcal{A}$ by favoring the voicing over the frication noise, or ii) reducing the length of the fricative segment to maximize the proportion of the amount of time in $\mathcal{B}$ in relation to the whole fricative segment. The latter strategy, although used by many speakers[44], may lead to inappropriate coordination between the articulatory configurations and the configurations at the glottis.

This may explain the presence of final devoicing in fricatives, which is frequently observed in many languages[10,45], or the partial devoicing of voiced fricatives[43].

The presented study also shows that the consideration of the partial glottis abduction in articulatory synthesis is important to simulate natural running speech. However, there is still a lack of experimental measurements of the precise time evolution of the glottal opening, which limits the use of realistic time scenarios of the coordination between the vocal tract and the glottis. External lighting and sensing photo-glottography (ePGG) data, in addition to articulatory gestures, should be acquired in the next future in order to thoroughly study the tract-glottis coordination.

Finally, the proportion of direct and fine control by the speaker on the chink opening, due to active muscle control, over that of the fluid-structure interactions resulting from the aeroacoustic conditions is not fully comprehended yet. Possible future improvements of glottis models that account for the potential uncontrolled chink opening, due to fluid-structure interactions at the vicinity of the glottis, would be a step forward the full comprehension of the production of voiced fricatives.

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