

Aerodynamic features of French fricatives

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Abstract

The present research investigates the aerodynamic features of French fricative consonants using direct measurement of subglottal air pressure by tracheal puncture (Ps) synchronized with intraoral air pressure (Po), oral airflow (Oaf) and acoustic measurements. Data were collected from four Belgian French speakers' productions of CVCV pseudowords including voiceless and voiced fricatives [f, v, s, z, ʃ, ʒ]. The goals of this study are: (i) to predict the starting, central, and releasing points of frication based on the measurements of Ps, Po, and Oaf; (ii) to compare voiceless and voiced fricatives and their places of articulation; and (iii) to provide reference values for the aerodynamic features of fricatives for further linguistic, clinical, physical and computational modeling research.

Index Terms: Aerodynamics; Fricatives; Belgian French; Subglottal pressure; Intraoral pressure; Oral airflow.

1. Introduction

Previous contributions [1–8] have pointed out the difficulty of explaining the aerodynamics of the initial boundaries of fricatives in speech. Predicting the starting point of fricative sounds is a complex task involving many aerodynamic factors, including the ratio between subglottal air pressure (Ps) and intraoral air pressure (Po), the amount of oral airflow (Oaf) passing through the glottis, and the dimension of the constriction in the vocal tract. These factors are variable depending on the musculature adjustments “that control the relevant articulatory and laryngeal structures” and “by forces on these structures due to the intraoral pressure” [5: 381]. So, whether for the voiceless vs. voiced nature of sounds, the dimension of the constriction area, or the airflow velocity needed to generate frication, direct measurements of the aerodynamic components can help to understand the frication phenomena.

Existing phonetic studies are mostly based on predictions of fricatives' aerodynamics from a static midpoint (e.g., [3, 5, 8]). Predicting fricative aerodynamics can be problematic, and, as pointed out in [4: 45], it is necessary to precisely predict the point where frication begins. It is crucial to establish both the temporal boundaries for frication start and release, as well as the aerodynamic fluctuation between these two points, to accurately describe how aerodynamics phenomena evolve temporally to achieve audible frication (for voiceless fricatives) and audible friction and voicing (for voiced fricatives).

The present study aims to provide references on the aerodynamic features of French fricatives based on direct and synchronized measurements of Ps, Po, and Oaf of voiceless and voiced frication for French fricatives [f, v, s, z, ʃ, ʒ]. Measurements of the start (Fs), mid (Fm), and release (Fr)

points of frication will be presented. This research compares voiceless and voiced fricatives and their respective places of articulations to illustrate the aerodynamic factors affecting optimal frication in the production of voiceless fricatives, and optimal frication during voicing, in the production of voiced fricatives.

2. Methodology

2.1. Experimental setup

The experimental procedure follows the same conditions as presented in [9: 79-80], in which synchronous recordings of Ps, Po, Oaf, and the acoustic signal (Ac) were measured. French intervocalic voiceless fricatives [f, s, ʃ] and voiced fricatives [v, z, ʒ] were collected from four Belgian-French speakers (2 females, SF1 and SF2; 2 males, SM3 and SM4). Speakers were asked to read CVCV pseudowords containing each of the fricatives listed above and where V was the vowel [a]. They were asked to repeat the pseudowords five times in a short carrier sentence [F₁VF₂V CV F₃VF₄V VCV], e.g. [fafa₁di'fafa'ākə]. Speakers read the list at a normal speech level, in terms of speed and intensity. Aerodynamic measurements were taken from the fourth fricative; F₄.

2.2. Methods of data collection

The recording procedure preserved the rights and welfare of human research subjects, in respect of the ethical committee's rules at the Erasme Hospital, Université Libre de Bruxelles [10]. Ps was measured by tracheal puncture using a needle inserted in under the cricoid cartilage. The needle placement was made after administering 2% Xylocaine injection for local anesthesia. A plastic tube linked to a pressure transducer was connected to the needle. Po measurements were obtained using a small tube inserted into the oropharynx through the nasal cavity. Oaf data were collected with a rubber mask placed over speakers' mouth. The acoustic signal was recorded with an AKG C 419 directional microphone positioned at a stable distance of 4 cm from the rubber mask. The Ps and Po tubes, the Oaf mask, and the microphone were connected to the Physiologia workstation [11]; a multiparameter data acquisition system allowing simultaneous recording of the speech signal and various aerodynamic parameters. The data acquisition and signal processing were handled with PHONEDIT Signaix [12].

2.3. Fricatives segmentation and measurements

The data collected were segmented by hand with PHONEDIT Signaix [12]. To assess the aerodynamic boundaries of frication, temporally-related outlines of airflow and air pressure (Oaf, Ps, and Po) were placed in three aerodynamic distinct points: the starting point (Fs), the releasing point (Fr),

and the midpoint (Fm) of frication. Midpoint measurements were included to illustrate time-related aerodynamic phenomena that delineate frication. The acoustic waveform and the spectrogram, specifically the onset and offset of full formant structure of surrounding vowels, were used for segmentation purposes. For example, as shown in Figure 1, Fs of the [f] fricative is signaled by a small drop in Ps (1c), an increase in Po (1d), and a positive peak of Oaf (1e). Fr is indicated by a small drop in Ps (1c), an increase in Po (1d), and a positive peak of Oaf (1e). The consonant [f] is also signaled by a low gravity center with a frequency spectrum covering a region between 4000-8000 Hz (1b).

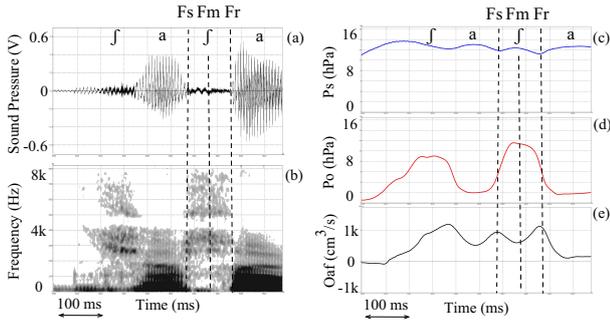


Figure 1: (a) audio waveform, (b) spectrogram (wide-band), (c) Ps, (d) Po, and (e) Oaf for the voiceless palatal fricative [f].

2.4. Data measures and analysis

Aerodynamic measures were extracted by hand using PHONEDIT Signaix [12]. Air pressures (Ps and Po) were quantified in hPa (1 hPa=1.019 cm H₂O). From these measurements, the following pressure differential were calculated: (i) $\Delta Ps/Po$ for voiceless and voiced fricatives, in the Fs, Fm, and Fr points; (ii) $\Delta Poral = Po - Pa$ (where Pa is the atmospheric pressure = 1013.25 hPa). Oaf was quantified in cm³/s. It should be noted that Ps values are measured relative to atmospheric pressure (Pa) [13]. Thus, for a given Ps the pressure value above Pa was considered. For example, a Ps of 7.15 hPa equals 1013.25 hPa + 7.15 hPa. Po is also measured relatively to Pa. $\Delta Ps/Po$ yields small values for voiceless fricatives since the glottis is open and imposes little or no resistance on the pulmonic airflow. In total, 1080 measurements were extracted for the present study: 4 speakers, 6 fricative consonants, 5 repetitions, 3 frication points (Fs, Fm, Fr), 3 aerodynamic features (Ps, Po, and Oaf).

3. Results

3.1. Voiceless fricatives

As shown in Figure 2 (example of the [f] fricative consonant), the aerodynamic initiation of voiceless fricatives is characterized by a mid $\Delta Ps/Po$ (see Fs in Table 1) and a low $\Delta Poral$. These differentials are due to overall high Ps (8.18 hPa; range 4.87–11.67 hPa; n=56 measurements) and low Po (2.61 hPa; range 0.46–5.61 hPa; n=56), associated with a medium peak of Oaf (580 cm³/s; range 300-960 cm³/s; n=56). As illustrated in Figure 2 the frication midpoint of the consonants Fm is characterized by high $\Delta Poral$ and low $\Delta Ps/Po$. These differentials are generated by overall high Ps (8.48 hPa; range 5.04–10.93 hPa; n=56) and overall high Po

(7.17 hPa; range 4.87–10.93 hPa; n=56), associated with a low peak of Oaf (380 cm³/s; range 100–810 cm³/s; n=56). Figure 2 also shows that the voiceless fricatives' end point (Fr) is characterized by a decrease of $\Delta Poral$ and an increase of $\Delta Ps/Po$. These differentials are generated by overall mid Ps (8.04 hPa; range 5.63–14.60 hPa; n=56) and overall low Po (4.97 hPa; range 2.20–9.85 hPa; n=56), associated with a medium peak in Oaf (560 cm³/s; range 270-1070 cm³/s; n=56). Number of measurements for all voiceless fricative consonants n=504.

The measures illustrated in this section describe the overall aerodynamic features of the [f, s, j] fricatives. The broad aerodynamic air pressure and airflow measurements are due to cross-speaker variation in sound articulation ([5: 33], [6: 53]). Specificities for each place of articulation are illustrated in the following subsections.

3.1.1. Voiceless labiodental fricative [f]

The aerodynamic features required to initiate frication at point Fs during intervocalic [f] are a high $\Delta Ps/Po$ (Table 1) and a low $\Delta Poral$. These differentials are generated by high Ps (Table 2; n=16) and low Po (Table 3; n=16), associated with a medium peak of Oaf (548 cm³/s; range 340–816 cm³/s; n=16). The frication midpoint Fm is characterized by a significant increasing of Po (Table 3; n=16) and constant Ps (Table 2; n=16) that cause high $\Delta Poral$ and low of $\Delta Ps/Po$ (Table 1). These pressure differentials are associated with a decrease in Oaf (352 cm³/s; range 29–711 cm³/s; n=16). At the release point (Fr), Ps is kept constant (Table 2; n=16) and Po increases (Table 3; n=16), causing high $\Delta Ps/Po$ (Table 1) and low $\Delta Poral$ differentials, which are associated with a medium peak in Oaf (560 cm³/s; 290–1064 cm³/s; n=16). Number of measurements for all [f] fricative consonants n=144. The average duration of French [f] is 123 ms.

3.1.2. Voiceless Alveolar [s]

The aerodynamic features required to initiate frication during intervocalic [s] are a high $\Delta Ps/Po$ (Table 1) and a low $\Delta Poral$. These differentials are generated by high Ps (Table 2; n=20) and low Po (Table 3; n=20), associated with a medium peak of Oaf (570 cm³/s; range 100–1050 cm³/s; n=20). The frication midpoint Fm is characterized by a significant increasing of Po (Table 3; n=20) and a constant Ps (Table 2; n=20) that cause both high $\Delta Poral$ and low of $\Delta Ps/Po$ (Table 1). These pressure differentials are associated with a decrease in Oaf (290 cm³/s; range 40–730 cm³/s; n=20). At the release point Fr, Ps is kept constant (Table 2; n=20) and Po decreases (Table 3; n=20), causing high $\Delta Ps/Po$ (Table 1) and low $\Delta Poral$ differentials, which are associated with a medium-low peak of Oaf (460 cm³/s; 150–920 cm³/s; n=20). Number of measurements for all [s] fricative consonants n=180. The average duration of French [s] is 130 ms.

3.1.3. Voiceless Postalveolar [ʃ]

The aerodynamic features required to initiate frication during intervocalic [ʃ] are a high $\Delta Ps/Po$ (Table 1) and a low $\Delta Poral$. These differentials are generated by high Ps (Table 2; n=20) and low Po (Table 3; n=20), associated with a medium-high peak of Oaf (640 cm³/s; range 440–1010 cm³/s; n=20). The frication midpoint Fm is characterized by a significant increasing of Po (Table 3; n=20) and a constant Ps (Table 2; n=20) that cause high $\Delta Poral$ and low of $\Delta Ps/Po$ (Table 1). These pressure differentials are associated with a decrease in

Table 1: $\Delta Ps/Po$ for voiceless fricatives in hPa. *F_s* (friction start); *F_m* (friction midpoint); *F_r* (friction release). *SF1* and *SF2* are female speakers.

	[f]			[s]			[ʃ]		
	<i>F_s</i>	<i>F_m</i>	<i>F_r</i>	<i>F_s</i>	<i>F_m</i>	<i>F_r</i>	<i>F_s</i>	<i>F_m</i>	<i>F_r</i>
<i>SF1</i>	6.48	0.33	6.75	6.54	2.20	1.99	6.33	0.53	4.75
<i>SF2</i>	5.21	0.41	1.98	4.23	1.27	1.69	4.24	1.50	2.19
<i>SM3</i>	3.22	0.41	2.91	3.59	1.23	2.47	4.03	0.77	2.94
<i>SM4</i>	5.93	0.86	5.26	6.95	1.26	5.07	7.81	1.12	4.18
Av.	5.21	0.50	4.22	5.33	1.49	2.81	5.60	0.98	3.51

Table 2: *P_s* for voiceless fricatives in hPa. *F_s* (friction start); *F_m* (friction midpoint); *F_r* (friction release). *SF1* and *SF2* are female speakers.

	[f]			[s]			[ʃ]		
	<i>F_s</i>	<i>F_m</i>	<i>F_r</i>	<i>F_s</i>	<i>F_m</i>	<i>F_r</i>	<i>F_s</i>	<i>F_m</i>	<i>F_r</i>
<i>SF1</i>	8.48	9.54	8.95	9.70	10.6	10	9.60	10.5	9.85
<i>SF2</i>	5.68	5.57	5.63	5.16	5.39	5.36	4.98	5.04	4.87
<i>SM3</i>	5.49	6.28	5.79	6.36	7.58	7.54	6.22	7.13	7.22
<i>SM4</i>	11.6	11.5	10.9	11.3	11.4	10.4	11.4	11	9.78
Av.	7.83	8.24	7.83	8.14	8.77	8.36	8.06	8.44	7.93

Table 3: *P_o* for voiceless fricatives in hPa. *F_s* (friction start); *F_m* (friction midpoint); *F_r* (friction release). *SF1* and *SF2* are female speakers.

	[f]			[s]			[ʃ]		
	<i>F_s</i>	<i>F_m</i>	<i>F_r</i>	<i>F_s</i>	<i>F_m</i>	<i>F_r</i>	<i>F_s</i>	<i>F_m</i>	<i>F_r</i>
<i>SF1</i>	2.00	9.21	2.20	3.16	8.48	8.10	3.33	10.56	9.85
<i>SF2</i>	0.46	5.16	3.66	0.93	4.12	3.67	0.74	3.54	2.68
<i>SM3</i>	2.27	5.87	2.88	2.77	5.77	5.07	2.20	6.36	4.28
<i>SM4</i>	5.61	10.2	5.71	4.38	10.1	5.38	3.52	6.11	6.21
Av.	2.59	7.72	3.61	2.81	7.14	5.56	2.45	6.64	5.75

Oaf (500 cm³/s; range 220–970 cm³/s; n=20). At the release point *F_r*, *P_s* is kept constant (Table 2; n=20) as *P_o* decreases (Table 3; n=20), causing high $\Delta Ps/Po$ and low $\Delta Poral$ differential, which are associated with increased a medium-high peak of Oaf (650 cm³/s; 360–1210 cm³/s; n=20). Number of measurements for all [f] fricative consonants n=180. The average duration of French [f] is 128 ms.

3.2. Voiced fricatives

As shown in Figure 3 for the [v] fricative consonant, the aerodynamic initiation of voiceless fricatives is characterized by a maximization of $\Delta Ps/Po$ (Table 4) and $\Delta Poral$. These differentials are generated by overall high *P_s* (9.81 hPa; range 5.68–15.25 hPa; n=60 measurements) and overall low *P_o* (3.46 hPa; range 0.91–6.21 hPa; n=60), associated with a low peak in Oaf (range 80–610 cm³/s; n=60). As illustrated in Figure 3, the friction midpoint of the consonants is characterized by a lowered $\Delta Ps/Po$ (Table 4) and an increased $\Delta Poral$. These differentials are generated by overall high *P_s* (9.89 hPa; range 5.57–14.60 hPa; n=60) and overall mid *P_o* (4.03 hPa; range 2.42–6.21 hPa; n=60), associated with low Oaf (range 30–640 cm³/s; n=60). Figure 2 shows that voiced fricatives' end point *F_r* is characterized by comparable $\Delta Ps/Po$ and $\Delta Poral$ differentials, generated by overall high *P_s* (9.87 hPa; range 5.63–14.60 hPa; n=60) and overall mid *P_o* (4.46 hPa; range 2.66–6.21 hPa; n=60), associated with low Oaf (range 80–640 cm³/s; n=60). Number of measurements for all voiceless fricative consonants n=504.

The aerodynamic values illustrated in this section describe the overall aerodynamic features of the [v, z, ʒ] fricatives. As stated above, pressure differentials and airflow are also influenced by the places of articulation [5: 33]. Therefore, the

specificities for each fricative are illustrated in the following subsections.

3.2.1. Voiced Labiodental [v]

The aerodynamic features required to initiate friction during intervocalic [v] are a high $\Delta Ps/Po$ (Table 4) and a low $\Delta Poral$. These differentials are generated by high *P_s* (Table 5; n=20) and low *P_o* (Table 6; n=20), associated with a low peak of Oaf (260 cm³/s; range of 202–344 cm³/s; n=20). The friction midpoint *F_m* is characterized by constant *P_s* (Table 5; n=20), a significant increase in *P_o* (Table 6; n=20) that causes a decrease in $\Delta Ps/Po$ (Table 4), and an increased high $\Delta Poral$. These pressure differentials are associated with a slight decrease in Oaf (200 cm³/s; 34–342 cm³/s; n=20). At the release point *F_r*, *P_s* decreases (Table 5; n=20) while *P_o* increases (Table 6; n=20), causing $\Delta Ps/Po$ (Table 1) and $\Delta Poral$ differentials to be similar. They are also associated with a slight increase in Oaf (270 cm³/s; 143–430 cm³/s; n=20). Number of measurements for all [v] fricative consonants n=180. The average duration of French [v] is 68 ms.

3.2.2. Voiced Alveolar [z]

The aerodynamic features required to initiate friction during intervocalic [z] are a high $\Delta Ps/Po$ (Table 4) and a low $\Delta Poral$. These differentials are generated by high *P_s* (Table 5; n=20) and low *P_o* (Table 6; n=20), associated with a low peak of Oaf (310 cm³/s; range of 110–740 cm³/s; n=20). The friction midpoint *F_m* is characterized by constant *P_s* (Table 5; n=20), a significant increase in *P_o* (Table 5; n=20) that causes a decrease in $\Delta Ps/Po$ (Table 4), and an increased high $\Delta Poral$. These pressure differentials are associated with a slight decrease in Oaf (270 cm³/s; 10–780 cm³/s; n=20). At the release point *F_r*, *P_s* decreases (Table 5; n=20) while *P_o* increases (Table 6; n=20), causing $\Delta Ps/Po$ (Table 1) and $\Delta Poral$ differentials to be similar. They are also associated with an increase in Oaf (310 cm³/s; 60–740 cm³/s; n=20). Number of measurements for all [z] fricative consonants n=180. The average duration of French [z] is 63 ms.

3.2.3. Voiced Postalveolar [ʒ]

The aerodynamic features required to initiate friction during intervocalic [ʒ] are a high $\Delta Ps/Po$ (Table 4) and a low $\Delta Poral$. These differentials are generated by high *P_s* (Table 5; n=20) and low *P_o* (Table 6; n=20), associated with a low peak in Oaf (360 cm³/s; range of 80–740 cm³/s; n=20). The friction midpoint *F_m* is characterized by constant *P_s* (Table 5; n=20), a significant increase in *P_o* (Table 6; n=20) that causes a decrease in $\Delta Ps/Po$ (Table 4), and an increased high $\Delta Poral$. These pressure differentials are associated with a slight decrease in Oaf (300 cm³/s; 40–780 cm³/s; n=20). At the release point *F_r*, *P_s* is kept constant (Table 5; n=20) while *P_o* increases (Table 6; n=20) causing $\Delta Ps/Po$ (Table 4) and $\Delta Poral$ differentials to be similar. They are also associated with a slight increase in Oaf (330 cm³/s; 30–740 cm³/s; n=20). Number of measurements for all [ʒ] fricative consonants n=180. The average duration of French [ʒ] is 65 ms.

4. Discussion and Conclusions

The investigation carried out in the present study establishes a standardized reference based on direct measurements describing the aerodynamic features of French fricative

Table 4: $\Delta Ps/Po$ for voiced fricatives in hPa. *Fs* (frication start); *Fm* (frication midpoint); *Fr* (frication release). *SF1* and *SF2* are female speakers.

	[v]			[z]			[ʒ]		
	<i>Fs</i>	<i>Fm</i>	<i>Fr</i>	<i>Fs</i>	<i>Fm</i>	<i>Fr</i>	<i>Fs</i>	<i>Fm</i>	<i>Fr</i>
<i>SF1</i>	9.80	7.01	6.39	8.58	7.51	6.58	8.36	7.54	7.21
<i>SF2</i>	4.14	2.82	2.68	5.12	3.13	2.59	5.29	4.07	3.76
<i>SM3</i>	7.11	4.57	4.01	6.19	4.22	3.73	6.68	4.56	4.17
<i>SM4</i>	10.76	7.99	7.82	10.72	7.69	7.43	11.73	8.86	8.39
Av.	7.95	5.60	5.22	7.65	5.64	5.08	8.02	6.26	5.88

Table 5: *Ps* for voiced fricatives in hPa. *Fs* (frication start); *Fm* (frication midpoint); *Fr* (frication release). *SF1* and *SF2* are female speakers.

	[v]			[z]			[ʒ]		
	<i>Fs</i>	<i>Fm</i>	<i>Fr</i>	<i>Fs</i>	<i>Fm</i>	<i>Fr</i>	<i>Fs</i>	<i>Fm</i>	<i>Fr</i>
<i>SF1</i>	11.13	11.2	11.2	11.37	11.4	11.6	10.61	10.8	10.8
<i>SF2</i>	5.68	5.57	5.63	6.10	6.27	6.40	6.25	6.48	6.42
<i>SM3</i>	8.21	8.25	8.20	8.26	8.52	8.63	8.26	8.52	8.63
<i>SM4</i>	12.68	12.7	12.5	13.89	13.8	13.6	15.25	14.97	14.6
Av.	9.42	9.43	9.41	9.90	10	10	10.1	10.2	10.1

Table 6: *Po* for voiced fricatives in hPa. *Fs* (frication start); *Fm* (frication midpoint); *Fr* (frication release). *SF1* and *SF2* are female speakers.

	[v]			[z]			[ʒ]		
	<i>Fs</i>	<i>Fm</i>	<i>Fr</i>	<i>Fs</i>	<i>Fm</i>	<i>Fr</i>	<i>Fs</i>	<i>Fm</i>	<i>Fr</i>
<i>SF1</i>	1.33	4.21	4.86	2.79	3.96	5.11	2.25	3.26	3.61
<i>SF2</i>	1.33	2.84	3.10	0.97	3.14	3.81	0.96	2.42	2.66
<i>SM3</i>	1.09	3.67	4.19	2.07	4.30	4.90	1.16	3.55	4.16
<i>SM4</i>	1.93	4.70	4.72	3.17	6.17	6.20	3.52	6.11	6.21
Av.	1.42	3.86	4.22	2.25	4.39	5.01	1.97	3.83	4.16

consonants [f, v, s, z, ʃ, ʒ]. In regard to voiceless fricatives, previous aerodynamic studies [3: 92] have shown that maximizing both the pressure differential across the glottis and the intraoral constrictions ($\Delta Ps/Po$) and the pressure differential between the intraoral and the atmospheric pressures ($\Delta Poral$) create optimal conditions for voiceless frication. The direct measurements conducted in this study confirm these findings and develop them further. As shown in Figure 2 ([f] fricative), the aerodynamic initiation of intervocalic voiceless fricatives is characterized by maximum $\Delta Ps/Po$ (see *Fs* columns in Table 1) and minimum $\Delta Poral$. To this extent, high $\Delta Ps/Po$ and low $\Delta Poral$ provide the aerodynamic conditions necessary to initiate frication while a high $\Delta Poral$ is only required to sustain frication.

Voiced fricatives, on the other hand, require simultaneous volume adjustments in the cross-sectional area between the glottis and the intraoral constrictions [5: 477]. The vibration of the vocal folds causes a lowering of the flowrate through the glottis and, in turn, a lower Po as compared to that of voiceless sounds [8: 42]. Thus, to provide the ideal aerodynamic conditions for sustaining both voicing and frication, a pressure drop across both the glottal ($\Delta Ps/Po$) and the intraoral ($\Delta Poral$) constrictions must be maintained [11: 53] and maximized as much as possible [3: 92]. Previous aerodynamic studies have indicated a range of Po comprised between 2.94–5.49 hPa (3–5.6 cm H_2O in the original text [8: 85]), needed to cause the pressure drop necessary to sustain simultaneous frication and voicing. These predictions are very accurate, yet only account for voiced fricatives' temporal mid-point, the *Fm*. As shown in Figure 3 ([v] fricative), the direct measurement techniques used in the present study show that the pressure drop, which provides the necessary conditions for

optimal voicing and frication, primarily results from a high P_s combined with a low P_o , during *Fs*. Hence, the initiation of voiced frication requires maximum $\Delta Ps/Po$ (see *Fs* columns in Table 4) and minimum $\Delta Poral$. Although maximum $\Delta Ps/Po$ is the main factor that generates audible voicing during the beginning of a voiced fricative, the maximization of $\Delta Poral$ and a moderate lowering of $\Delta Ps/Po$ are also required to sustain optimal voiced frication at *Fm*, as shown in Figure 4. This second aerodynamic condition is a key factor for favoring frication while allowing voicing to occur. At *Fr* $\Delta Ps/Po$ decreases as $\Delta Poral$ increases (up to ~85% of $\Delta Ps/Po$), causing pressure levels to converge (Figure 2).

This study develops the understanding of optimal aerodynamic conditions in the production of voiceless vs. voiced fricatives and illustrates differences in pressure differentials and airflow due to cross-speaker variation in several places of articulation. The results presented in this study provide reference values of the aerodynamic features of fricatives for ongoing and further linguistics studies, clinical research [14], and physical and computational modeling [15, 16, 17].

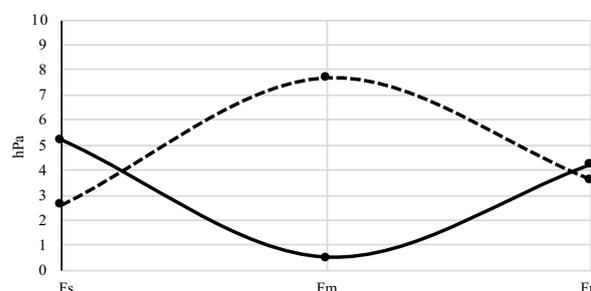


Figure 2: Time-related start (*Fs*), mid (*Fm*), and release (*Fr*) aerodynamic points of [f]. $\Delta Ps/Po$ (solid line) and $\Delta Poral$ (dashed line).

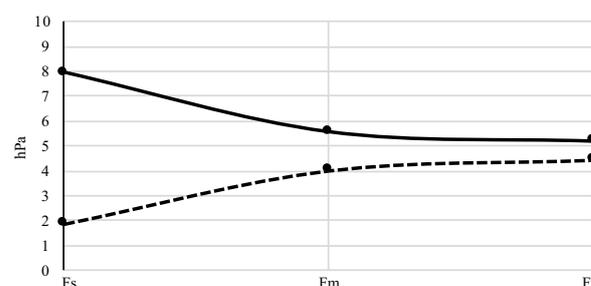


Figure 3: Time-related start (*Fs*), mid (*Fm*), and release (*Fr*) aerodynamic points of [v]. $\Delta Ps/Po$ (solid line) and $\Delta Poral$ (dashed line).

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6. References

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