INTERSPEECH 2017
August 20–24, 2017, Stockholm, Sweden

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 [F_1VF_2V CV F_3VF_4V VCV], e.g. [fafaˌdiˈfafaˈɑ̃kɔ]. Speakers read the list at a normal speech level, in terms of speed and intensity. Aerodynamic measurements were taken from the fourth fricative; F_4.

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),

http://dx.doi.org/10.21437/Interspeech.2017-285

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 [ʃ] 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 [ʃ] is also signaled by a low gravity center with a frequency spectrum covering a region between 4000-8000 Hz (1b).

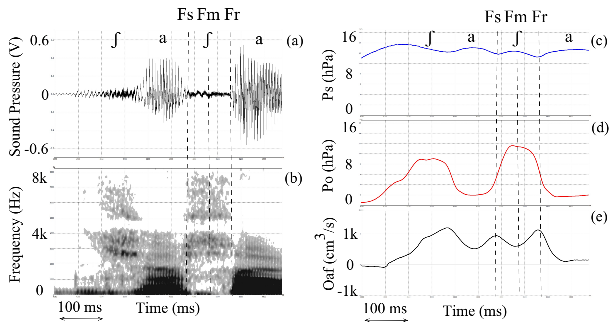

Figure 1: *(a) audio waveform, (b) spectrogram (wide-band), (c) Ps, (d) Po, and (e) Oaf for the voiceless palatal fricative* [ʃ].

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 H_2O). 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 cm^3/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. Δ*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 Δ*Ps/Po* (see F_s in Table 1) and a low Δ*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 cm^3/s; range 300-960 cm^3/s; n=56). As illustrated in Figure 2 the frication midpoint of the consonants Fm is characterized by high Δ*Poral* and low Δ*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 cm^3/s; range 100–810 cm^3/s; n=56). Figure 2 also shows that the voiceless fricatives' end point (F_r) is characterized by a decrease of Δ*Poral* and an increase of Δ*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 cm^3/s; range 270-1070 cm^3/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, ʃ] 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 F_s during intervocalic [f] are a high Δ*Ps/Po* (Table 1) and a low Δ*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 cm^3/s; range 340–816 cm^3/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 Δ*Poral* and low of Δ*Ps/Po* (Table 1). These pressure differentials are associated with a decrease in Oaf (352 cm^3/s; range 29–711 cm^3/s; n=16). At the release point (F_r), Ps is kept constant (Table 2; n=16) and Po increases (Table 3; n=16), causing high Δ*Ps/Po* (Table 1) and low Δ*Poral* differentials, which are associated with a medium peak in Oaf (560 cm^3/s; 290–1064 cm^3/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 Δ*Ps/Po* (Table 1) and a low Δ*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 cm^3/s; range 100–1050 cm^3/s; n=20). The frication midpoint F_m is characterized by a significant increasing of Po (Table 3; n=20) and a constant Ps (Table 2; n=20) that cause both high Δ*Poral* and low of Δ*Ps/Po* (Table 1). These pressure differentials are associated with a decrease in Oaf (290 cm^3/s; range 40–730 cm^3/s; n=20). At the release point F_r, Ps is kept constant (Table 2; n=20) and Po decreases (Table 3; n=20), causing high Δ*Ps/Po* (Table 1) and low Δ*Poral* differentials, which are associated with a medium-low peak of Oaf (460 cm^3/s; 150–920 cm^3/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 Δ*Ps/Po* (Table 1) and a low Δ*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 cm^3/s; range 440–1010 cm^3/s; n=20). The frication midpoint F_m is characterized by a significant increasing of Po (Table 3; n=20) and a constant Ps (Table 2; n=20) that cause high Δ*Poral* and low of Δ*Ps/Po* (Table 1). These pressure differentials are associated with a decrease in

Table 1: Δ*Ps/Po for voiceless fricatives in hPa. Fs (frication start); Fm (frication midpoint); Fr (frication release). SF1 and SF2 are female speakers.*

	[f]			[s]			[ʃ]		
	Fs	*Fm*	*Fr*	*Fs*	*Fm*	*Fr*	*Fs*	*Fm*	*Fr*
SF1	6.48	0.33	6.75	6.54	2.20	1.99	6.33	0.53	4.75
SF2	5.21	0.41	1.98	4.23	1.27	1.69	4.24	1.50	2.19
SM3	3.22	0.41	2.91	3.59	1.23	2.47	4.03	0.77	2.94
SM4	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: *Ps for voiceless fricatives in hPa. Fs (frication start); Fm (frication midpoint); Fr (frication release). SF1 and SF2 are female speakers.*

	[f]			[s]			[ʃ]		
	Fs	*Fm*	*Fr*	*Fs*	*Fm*	*Fr*	*Fs*	*Fm*	*Fr*
SF1	8.48	9.54	8.95	9.70	10.6	10	9.60	10.5	9.85
SF2	5.68	5.57	5.63	5.16	5.39	5.36	4.98	5.04	4.87
SM3	5.49	6.28	5.79	6.36	7.58	7.54	6.22	7.13	7.22
SM4	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: *Po for voiceless fricatives in hPa. Fs (frication start); Fm (frication midpoint); Fr (frication release). SF1 and SF2 are female speakers.*

	[f]			[s]			[ʃ]		
	Fs	*Fm*	*Fr*	*Fs*	*Fm*	*Fr*	*Fs*	*Fm*	*Fr*
SF1	2.00	9.21	2.20	3.16	8.48	8.10	3.33	10.56	9.85
SF2	0.46	5.16	3.66	0.93	4.12	3.67	0.74	3.54	2.68
SM3	2.27	5.87	2.88	2.77	5.77	5.07	2.20	6.36	4.28
SM4	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 cm^3/s; range 220–970 cm^3/s; n=20). At the release point F_r, Ps is kept constant (Table 2; n=20) as Po decreases (Table 3; n=20), causing high Δ*Ps/Po* and low Δ*Poral* differential, which are associated with increased a medium-high peak of Oaf (650 cm^3/s; 360–1210 cm^3/s; n=20). Number of measurements for all [ʃ] fricative consonants n=180. The average duration of French [ʃ] 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 Δ*Ps/Po* (Table 4) and Δ*Poral.* These differentials are generated by overall high Ps (9.81 hPa; range 5.68–15.25 hPa; n=60 measurements) and overall low Po (3.46 hPa; range 0.91–6.21hPa; n=60), associated with a low peak in Oaf (range 80-610 cm^3/s; n=60). As illustrated in Figure 3, the frication midpoint of the consonants is characterized by a lowered Δ*Ps/Po* (Table 4) and an increased Δ*Poral.* These differentials are generated by overall high Ps (9.89 hPa; range 5.57–14.60 hPa; n=60) and overall mid Po (4.03 hPa; range 2.42–6.21 hPa; n=60), associated with low Oaf (range 30-640 cm^3/s; n=60). Figure 2 shows that voiced fricatives' end point Fr is characterized by comparable Δ*Ps/Po* and Δ*Poral* differentials, generated by overall high Ps (9.87 hPa; range 5.63–14.60 hPa; n=60) and overall mid Po (4.46 hPa; range 2.66–6.21 hPa; n=60), associated with low Oaf (range 80-640 cm^3/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 frication during intervocalic [v] are a high Δ*Ps/Po* (Table 4) and a low Δ*Poral*. These differentials are generated by high Ps (Table 5; n=20) and low Po (Table 6; n=20), associated with a low peak of Oaf (260 cm^3/s; range of 202–344 cm^3/s; n=20). The frication midpoint Fm is characterized by constant Ps (Table 5; n=20), a significant increase in Po (Table 6; n=20) that causes a decrease in Δ*Ps/Po* (Table 4), and an increased high Δ*Poral*. These pressure differentials are associated with a slight decrease in Oaf (200 cm^3/s; 34–342 cm^3/s; n=20). At the release point Fr, Ps decreases (Table 5; n=20) while Po increases (Table 6; n=20), causing Δ*Ps/Po* (Table 1) and Δ*Poral* differentials to be similar. They are also associated with a slight increase in Oaf (270 cm^3/s; 143–430 cm^3/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 frication during intervocalic [v] are a high Δ*Ps/Po* (Table 4) and a low Δ*Poral*. These differentials are generated by high Ps (Table 5; n=20) and low Po (Table 6; n=20), associated with a low peak of Oaf (310 cm^3/s; range of 110–740 cm^3/s; n=20). The frication midpoint Fm is characterized by constant Ps (Table 5; n=20), a significant increase in Po (Table 5; n=20) that causes a decrease in Δ*Ps/Po* (Table 4), and an increased high Δ*Poral*. These pressure differentials are associated with a slight decrease in Oaf (270 cm^3/s; 10–780 cm^3/s; n=20). At the release point Fr, Ps decreases (Table 5; n=20) while Po increases (Table 6; n=20), causing Δ*Ps/Po* (Table 1) and Δ*Poral* differentials to be similar They are also associated with an increase in Oaf (310 cm^3/s; 60–740 cm^3/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 frication during intervocalic [ʒ] are a high Δ*Ps/Po* (Table 4) and a low Δ*Poral*. These differentials are generated by high Ps (Table 5; n=20) and low Po (Table 6; n=20), associated with a low peak in Oaf (360 cm^3/s; range of 80–740 cm^3/s; n=20). The frication midpoint Fm is characterized by constant Ps (Table 5; n=20), a significant increase in Po (Table 6; n=20) that causes a decrease in Δ*Ps/Po* (Table 4), and an increased high Δ*Poral*. These pressure differentials are associated with a slight decrease in Oaf (300 cm^3/s; 40–780 cm^3/s; n=20). At the release point Fr, Ps is kept constant (Table 5; n=20) while Po increases (Table 6; n=20) causing Δ*Ps/Po* (Table 4) and Δ*Poral* differentials to be similar. They are also associated with a slight increase in Oaf (330 cm^3/s; 30–740 cm^3/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: Δ*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]		
	Fs	*Fm*	*Fr*	*Fs*	*Fm*	*Fr*	*Fs*	*Fm*	*Fr*
SF1	9.80	7.01	6.39	8.58	7.51	6.58	8.36	7.54	7.21
SF2	4.14	2.82	2.68	5.12	3.13	2.59	5.29	4.07	3.76
SM3	7.11	4.57	4.01	6.19	4.22	3.73	6.68	4.56	4.17
SM4	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]		
	Fs	*Fm*	*Fr*	*Fs*	*Fm*	*Fr*	*Fs*	*Fm*	*Fr*
SF1	11.13	11.2	11.2	11.37	11.4	11.6	10.61	10.8	10.8
SF2	5.68	5.57	5.63	6.10	6.27	6.40	6.25	6.48	6.42
SM3	8.21	8.25	8.20	8.26	8.52	8.63	8.26	8.52	8.63
SM4	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]		
	Fs	*Fm*	*Fr*	*Fs*	*Fm*	*Fr*	*Fs*	*Fm*	*Fr*
SF1	1.33	4.21	4.86	2.79	3.96	5.11	2.25	3.26	3.61
SF2	1.33	2.84	3.10	0.97	3.14	3.81	0.96	2.42	2.66
SM3	1.09	3.67	4.19	2.07	4.30	4.90	1.16	3.55	4.16
SM4	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 (Δ*Ps/Po*) and the pressure differential between the intraoral and the atmospheric pressures (Δ*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 Δ*Ps/Po* (see Fs columns in Table 1) and minimum Δ*Poral*. To this extent, high Δ*Ps/Po* and low Δ*Poral* provide the aerodynamic conditions necessary to initiate frication while a high Δ*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 (Δ*Ps/Po*) and the intraoral (Δ*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 Ps combined with a low Po, during Fs. Hence, the initiation of voiced frication requires maximum Δ*Ps/Po* (see Fs columns in Table 4) and minimum Δ*Poral*. Although maximum Δ*Ps/Po* is the main factor that generates audible voicing during the beginning of a voiced fricative, the maximization of Δ*Poral* and a moderate lowering of Δ*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 Δ*Ps/Po* decreases as Δ*Poral* increases (up to ~85% of Δ*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].

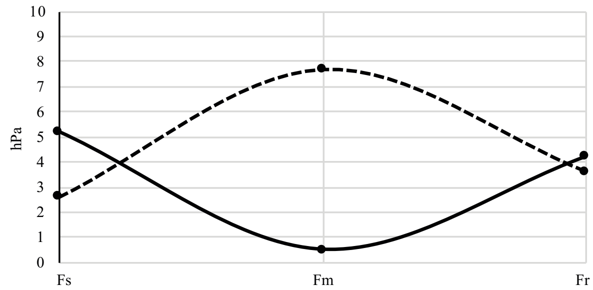

Figure 2: *Time-related start (Fs), mid (Fm), and release (Fr) aerodynamic points of [f].* Δ*Ps/Po (solid line) and* Δ*Poral (dashed line).*

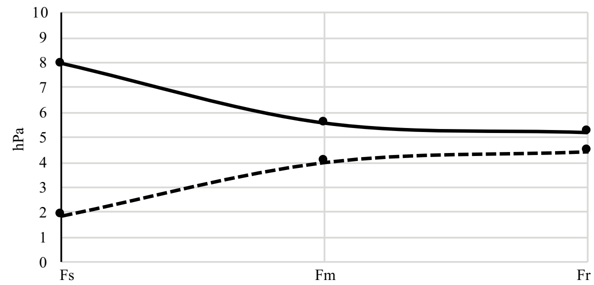

Figure 3: *Time-related start (Fs), mid (Fm), and release (Fr) aerodynamic points of [v].* Δ*Ps/Po (solid line) and* Δ*Poral (dashed line).*

5. Acknowledgements

Work supported by grant DS0707–2015 *ArtSpeech* from The French National Research Agency. We would like to thank Shinji Maeda and Angelique Amelot (LPP, CNRS) who provided insight and expertise that greatly assisted the research, and Nora Fangel-Gustavson (LPP, Paris 3) for proofreading the manuscript.

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