Aerodynamic characteristics of onset and coda fricatives

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ABSTRACT

This paper explores the differences in the aerodynamic characteristics for syllable onset and coda fricatives. Such differences may account for the weakening (*i.e.*, loss, aspiration or gliding) of syllable final fricatives found in a variety of languages. Simultaneous oropharyngeal pressure, airflow and audio-signal were obtained for two American English speakers. Aerodynamic and acoustic analysis showed that coda fricatives exhibit (i) a slower P_o build-up, (ii) a lower pressure peak, (iii) a delayed onset of audible frication, and (iv) a lower intensity of frication vis-à-vis onset fricatives. In order to provide high flow for frication, voiceless fricatives show a larger glottal opening (*i.e.*, a larger increase in flow) at the end of the preceding vowel in coda than onset position, suggesting compensatory maneuvers. It is argued that the aerodynamic data are compatible with a reduced oral gesture for coda fricatives, which may make it more difficult to meet the aerodynamic requirements for audible frication.

1. INTRODUCTION

Differences between syllable initial and syllable final consonants have been found for a number of articulatory parameters (*e.g.*, velum lowering and lip displacement [1], linguo-palatal contact size [2], tongue retraction [3], etc). This paper explores the differences in the aerodynamic characteristics for syllable onset and coda fricatives. Such differences may account for the weakening (*i.e.*, loss, aspiration or gliding) of syllable final fricatives found in a variety of languages. Examples of syllable final fricatives being lost or weakened include diachronic -- *e.g.*, Latin *nos* , *vos* > Italian, Rumanian *noi, voi*, French *nous, vous* [s]> ø 'we, you'; Latin *mesnata* > Catalan *mainada* 'kids'; English *sæh, bisig̊* > *saw, busy* -- and synchronic data -- Spanish dial. *desde, dos* [h] 'since, two', Standard Catalan *esma*> Balearic dial. *ejma* 'nerve'; English *yes* > *yeah*; *of, have* [v]> ø. Weakened syllable final fricatives are either preconsonantal or prepausal. If a vowel follows, the fricative is resyllabified as an onset and is maintained (*e.g.*, French *nous* [z] *allons*; Spanish *dos* [s] *amigos*; English *of* [v] *all*).

It is known that fricatives have tight positional, aerodynamic, and time constraints *vis-à-vis* stops; they allow lesser articulatory and aerodynamic variation than other segment types [4, 5] and they are more likely to decay if the precise postural and aerodynamic requirements are not met. The rate of flow (U) needed to generate turbulent noise depends on the area (A) of the constriction and the difference in the pressures (ΔP) of the cavities on both sides of the constriction, $U = A(\Delta P)^{0.5}$ (such that the larger the difference in pressure and the smaller the aperture area, the larger the rate of flow and the higher the amplitude of the resulting friction). If the aerodynamic conditions for generating audible turbulence in coda fricatives are not met, due to a decreased oral gesture, articulatory overlap and/or a reduced oral pressure build-up (due to time constraints or a lower rate of transglottal flow), the resulting sound may be interpreted as a glide or the fricative may be perceptually missed.

In this paper we explore the aerodynamic characteristics of syllable onset and syllable coda -- prepausal and preconsonantal -- fricatives to examine whether the conditions for creating turbulent airflow are more difficult to achieve in syllable coda *vs* onset position. Coda fricatives before a pause may fail to achieve audible frication due to lowered subglottal pressure utterance-finally [6]. Coda fricatives before a consonant (*e.g.*, [s#g]) have been found to show less and shorter linguo-palatal contact than onset fricatives (*e.g.*, [g#s]) [2]. This suggests a decreased gesture syllable finally. A more open oral constriction for coda *vis-à-vis* onset fricatives would offer relatively lower resistance to the air flowing out of the oral cavity, such that the air pressure in the mouth would build up at a lower rate and audible frication would be achieved later. Thus, a decreased oral gesture for coda fricatives would result in (1) a slower oral pressure build-up, (2) a lower pressure peak, and (3) a delayed onset of audible frication. A lower rate of transglottal flow in coda than in onset position would predict the same aerodynamic and acoustic effects. Alternatively, coda fricatives in preconsonantal position may not have sufficient time to build up oropharyngeal pressure and achieve the pressure drop across the oral constriction necessary for audible frication due to articulatory overlap of the upcoming consonant. If time constraints due to overlap are at work in coda *vis-à-vis* onset fricatives, we would expect (1) no difference in the rate of oral pressure build-up, (2) a lower pressure peak, and (3) audible friction would be achieved at about the same time in coda and onset fricatives.

2. METHOD

Simultaneous oropharyngeal pressure (P_o), airflow and audio-signal were obtained for two American English speakers (RS and JL) reading sequences containing symmetrical CVC nonsense syllables where C = voiceless and voiced fricatives, [f, s, ʃ, v, z, ʒ], and V = mid vowels [ɛ] and [ɑ]. Each coda fricative (CV__) was compared with its

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corresponding onset fricative (__VC) in the same word, *e.g.* **fef**. The CVC syllables were read in prepausal ('Say __##') and in preconsonantal position (Say__ Bess'). A total of 576 fricatives (6 repetitions x 6 fricatives x 2 syllable positions x 2 boundary conditions x 2 vowels x 2 speakers) were produced and analyzed. The aerodynamic and acoustic data were recorded with the PCquirer (Scicon) data acquisition system. The audio signal was digitized and sampled at 12kHz, the dc channels were sampled at 1kHz. P_o was obtained by a catheter introduced at the side of the mouth and bent behind the rear molars and connected to a pressure transducer. The volume flow from the mouth was collected simultaneously with a Rothenberg mask, using one of the outlet holes in the mask for the pressure tube. The pressure and the airflow signals were low-pass filtered at 50 Hz.

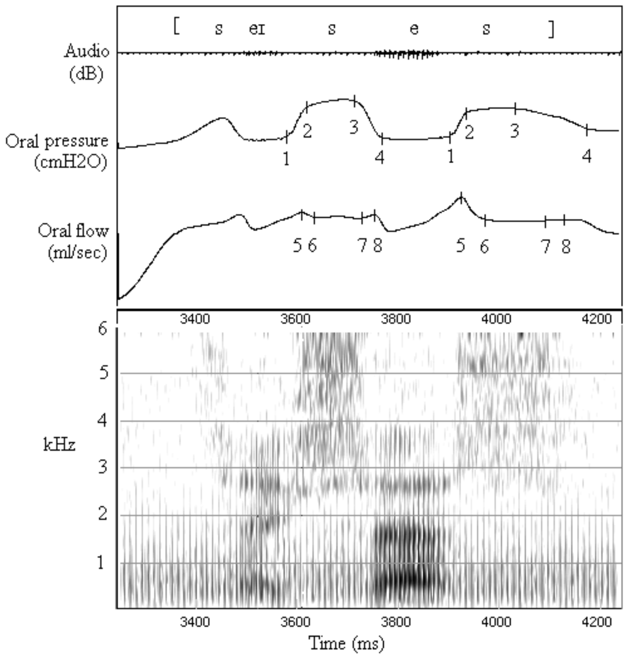

Fig. 1. Aerodynamic and acoustic data for 'Say ses'. Annotation points for onset and coda [s] are indicated. See text for details.

Measurements of the duration and magnitude of pressure and airflow variations were made for onset and coda fricatives at the following annotated points, illustrated in Fig.1: (1) onset of P_o build-up; (2) offset of P_o build-up; (3) onset of P_o release; (4) offset of P_o release; (5) first peak of flow; (6) first valley of flow; (7) second valley of flow; (8) second peak of flow. If no peak of airflow was present, but a plateau, flow measurements were made at the plateau midpoint. The rate of P_o build-up (or slope) was calculated for each token by dividing the difference in pressure between onset and offset of P_o rise (measurements (1) and (2)) into the time difference between these two points. Measurements at time (3) were used as the value for peak oral pressure since, after a sharp rise, oral pressure tended to plateau towards higher values. The time between onset of P_o build-up and onset of audible frication was measured with the help of spectrograms. Assuming oral airflow is an indirect measure of glottal area, the magnitude of the flow peak at the VC transition (point 5) was measured to examine whether coda fricatives show a larger glottal opening (*i.e.*, a larger increase in flow) than onset fricatives, in order to provide high airflow for frication. The data allow us to observe the timing of aerodynamic and acoustic events and relate them to inferred articulatory gestures.

3. RESULTS

3. 1 AERODYNAMIC RESULTS

One-way ANOVAs showed that the aerodynamic characteristics of fricatives (slope of P_o build-up and peak P_o pressure) in the [ɛ] and [ɑ] context did not differ significantly for any of the two speakers, thus values for the two vowels were pooled.

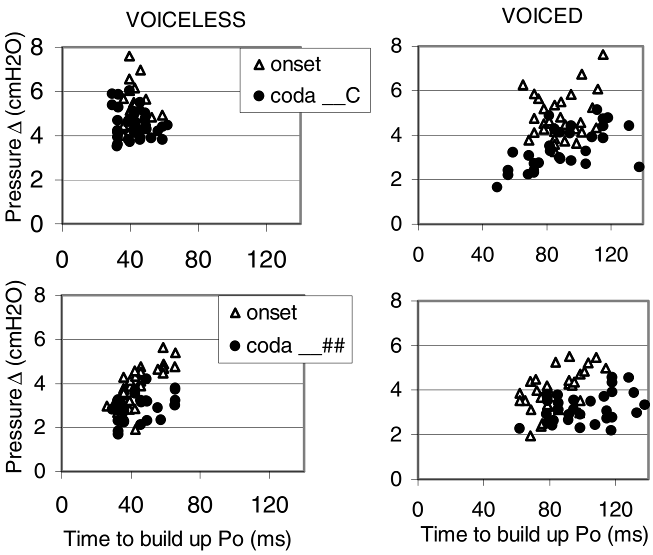

Fig. 2. Increase in P_o as a function of time for onset and coda voiceless (left) and voiced (right) fricatives. Preconsonantal coda fricatives are shown at the top, and prepausal fricatives at the bottom. Speaker RS.

Fig. 2 shows the rate of P_o build-up (or slope) in terms of increase in P_o (on the ordinate) as a function of time (on the abscissa) for onset and coda fricatives. Thus tokens plotted in the upper left quadrant of each graph exhibit a steep oral pressure build-up (or a high value for slope, *i.e.*, a large pressure increase in a short time), whereas tokens in the lower right quadrant show a slow P_o build-up (or a low value for slope, *i.e.*, a small P_o increase in a long time). Fig. 2 shows that onset fricatives reach higher P_o values than coda fricatives in a similar time (in the voiceless series) or in a shorter time (in the voiced series) which results in a faster rate of P_o build-up (or slope) for onset as opposed to coda fricatives in all conditions. Comparison of fricatives in preconsonantal and prepausal context (top and bottom panels) shows a larger pressure increase in preconsonantal than in prepausal position, most likely due to reduced subglottal pressure prepausally. Fig. 2 also illustrates that voiced fricatives (right) take about twice as long as voiceless fricatives (left) to build up oral pressure, due to the reduced flow of air through the vibrating vocal folds.

Two-factor ANOVAs were performed for each individual speaker to evaluate the effects of syllable position (onset *vs* coda) and boundary type (preconsonantal *vs* prepausal) on rate of P_o build-up (*i.e.,* slope). The results are shown in the left column of Table I(a). For both speakers the main effects of syllable position and boundary type were significant at the $p<0.01$ level. Interaction effects were not significant. The ANOVA results indicate that coda fricatives show a significantly slower P_o build-up than onset fricatives, both prepausally and preconsonantally, and that fricatives before a pause exhibit a significantly lower rate of P_o build-up than preconsonantally.

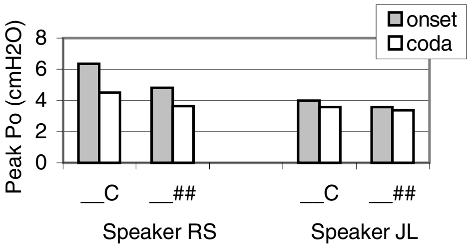

Fig. 3. Mean peak oral pressure values for onset fricatives and coda fricatives in preconsonantal (__C) and prepausal (__##) context for speakers RS and JL.

Average values for peak oropharyngeal pressure (measurement (3)) for onset fricatives and coda fricatives in preconsonantal and prepausal context are shown in Fig. 3. The female speaker JL shows overall lower P_o values than the male speaker RS, due to net differences in the size of the vocal tract. Both speakers exhibit lower peak P_o values in coda than in onset position in all conditions. Fig. 3 also shows that fricatives in prepausal position show lower peak P_o values than preconsonantally. Two-factor ANOVAs with syllable position (onset *vs* coda) and boundary type (preconsonantal *vs* prepausal) as independent variables, and peak pressure values as the dependent variable, were performed for each speaker separately. The results are shown in the right column of Table I(a). Significant main effects of syllable position and context were found for both speakers. Interaction effects were only significant for speaker RS. Further analyses examined the simple main effect of onset *vs* coda position in prepausal and preconsonantal context separately for this speaker. The differences reached significance in prepausal ($F_{(1,122)}$= 90.04, $p<0.0001$) and preconsonantal context ($F_{(1,123)}$= 75.44, $p<0.0001$), with a larger F-ratio prepausally. The ANOVA results indicate that coda fricatives show significantly lower P_o values than onset fricatives, and that fricatives before a pause exhibit a significantly lower peak pressure than preconsonantally.

Table I. (a-c) Significant differences for the two factors ANOVAS performed for the independent variable on the rows and the dependent variables on the columns for speakers RS and JL. Two asterisks indicate $p<0.01$, one asterisk $p<0.05$.

(a)	RS P_o slope	RS Peak P_o	JL P_o slope	JL Peak P_o
Onset *vs* coda	**	**	**	*
_C *vs* _##	**	**	**	**
Interaction	n.s.	**	n.s.	n.s.

(b)	RS Onset of frication	JL Onset of frication
Onset *vs* coda	*	n.s.
Vd. *vs* vless.	**	**
Interaction	n.s.	**

(c)	RS Peak flow	JL Peak flow
Onset *vs* coda	**	**
_C *vs* _##	**	n.s.
Interaction	n.s.	n.s.

It has been suggested [7] that fricatives involve maintenance of certain aerodynamic parameters over time, rather than achieving certain peak pressure or flow values. Production of fricatives requires sufficient rate of flow through the glottis and sufficient time to build up oropharyngeal pressure behind the oral constriction. The time from onset of the P_o rise to onset of audible frication (*i.e.*, the difference in time between annotation point (1) and onset of acoustic frication) was measured for onset and coda fricatives in the same syllable. Only the results for fricatives in the context 'Say CVC Bess' are presented in Fig. 4. Two-way ANOVAs with syllable position (onset *vs* coda) and voicing (voiced *vs* voiceless) as factors showed that fricative voicing had a significant effect on the time needed to reach audible frication for the two speakers, see Table I(b). As shown in Fig. 4, the average time required to achieve the pressure drop for audible frication in coda position was 43ms for voiced fricatives and 26 ms for voiceless fricatives (very close to the values reported in [5]). Voiced fricatives took approximately 65% longer, vis-à-vis voiceless fricatives, due to glottal impedance and reduced transglottal flow. The simple main effect of syllable position reached significance only for speaker RS, with coda fricatives taking longer to achieve the pressure difference for frication than onset fricatives. No interaction effects were found for this speaker. Speaker JL showed a significant interaction between syllable position and voicing. Further analyses showed that the effect of syllable position reached significance for voiced fricatives ($F_{(1,72)}$= 7.01, $p<0.01$), with coda fricatives taking approximately 27% longer to achieve audible frication than onset fricatives, but not for voiceless fricatives.

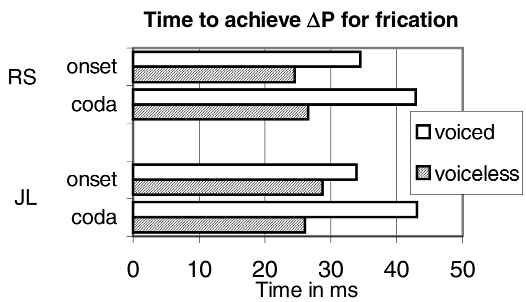

Fig. 4. Mean time needed to achieve the pressure difference at the oral constriction for audible frication for voiced and voiceless onset and coda fricatives (preconsonantal) for speakers RS and JL.

In order to provide sufficient airflow to generate frication at the supraglottal constriction, voiceless fricatives show maximum glottal opening and large increments in airflow (the double peaks in flow observed in Fig. 1). Peak flow values before onset and coda voiceless fricatives were compared. The results of the two-way ANOVAs, with syllable position (onset *vs* coda) and context (prepausal *vs*

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preconsonantal) as factors are shown in Table I(c). The ANOVA results showed that coda fricatives exhibit a significantly larger increase in flow vis-à-vis onset fricatives for both speakers. The effect of context was significant for speaker RS, who exhibited lower peak flow values prepausally than preconsonantally, most probably due to decreased subglottal pressure. No interaction effects were found. Peak airflow values for voiceless coda fricatives were in the order of 500-600 ml/sec for speaker RS (lower for the female speaker JL), very similar values to those for [h]. The larger increase in oral flow in coda *vs* onset fricatives most likely reflects a lesser glottal resistance and suggests compensatory maneuvers to achieve generation of turbulence in coda fricatives.

3. 2 ACOUSTIC RESULTS

Acoustic analysis showed that coda fricatives have a lower amplitude of the high frequency noise than fricatives in onset position (average values were 14dB for coda and 22 dB for onset fricatives). The lower P_o build-up for coda vis-à-vis onset fricatives is responsible for a lower particle velocity across the oral constriction, and a lower intensity of friction, which may contribute to decreased audible friction syllable finally.

4. DISCUSSION

Aerodynamic analysis showed that coda fricatives exhibit (i) a slower oral pressure build-up, and (ii) a lower pressure peak, *vis-à-vis* onset fricatives, and they take longer to achieve the pressure drop required for audible frication. The aerodynamic differences between onset fricatives and coda fricatives before a pause could be attributed to decreased subglottal pressure utterance-finally [6], with coda consonants being more sensitive to decreased subglottal pressure than onset consonants in the same syllable. However, the significant differences found between onset fricatives and coda fricatives preconsonantally must reflect syllable position effects. Time constraints, due to articulatory overlap of anticipatory gestures for the upcoming consonant, could explain a reduced oral pressure build-up in coda as opposed to onset fricatives. However, the observed differences in rate of P_o build-up in coda vis-à-vis onset fricatives cannot be accounted for in terms of articulatory overlap. The observed delayed onset of audible friction in coda as opposed to onset fricatives cannot easily be explained by gestural overlap either.

The observed aerodynamic differences in rate and magnitude of P_o build-up between onset and coda fricatives suggest a lesser resistance to flow at the oral constriction for coda fricatives -- resulting in a slower and more reduced P_o rise -- compatible with a reduced oral gesture syllable finally. Acoustic analysis showed that coda fricatives (i) take longer to achieve the pressure difference (or flowrate) required for frication (as predicted from the slower P_o rise), and (ii) result in a lower intensity of frication (rate of flow being proportional to intensity) vis-à-vis onset fricatives. A lower rate of transglottal flow would have similar aerodynamic consequences to those observed; however, there is no principled reason why non-prepausal coda consonants should involve a lower flowrate through the glottis. On the contrary, coda fricatives exhibited a larger increment in oral (and hence, transglottal) flow than onset fricatives, most likely reflecting a lesser glottal resistance to achieve turbulence in coda position.

The observed aerodynamic and acoustic data are compatible with a reduced oral gesture and reduced amplitude of frication for coda as opposed to onset fricatives. A reduced gesture may delay the onset of frication (and thus make it more likely to be affected by overlapping gestures) and/or may endanger the aerodynamic conditions for generating audible turbulence, and the resulting sound may be reinterpreted as a glide, an aspirated [h] or may be perceptually missed, as the historical and present-day processes illustrate. Coda fricatives becoming homorganic glides or approximants is a plausible process because fricatives naturally have onglides and offglides that resemble these glides; the change involved is essentially that the turbulence of the sound disappeared. Final voiceless fricatives becoming aspirated [h] may reflect the large and slightly turbulent airflow escaping through the open glottis before the oral constriction for the fricative has been formed, with failure to achieve audible frication. If turbulence for coda fricatives is diminished and perceptually missed the lexical entry will accommodate to the changing input and sound change will take place.

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