THE INFLUENCE OF AERODYNAMIC CONSTRAINTS ON THE SHAPE AND THE DYNAMICS OF PHONOLOGICAL SYSTEMS

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ABSTRACT

This paper shows the contribution of aerodynamic constraints to understand the phonological phenomena of prominence and stress. Changes in the coordination and timing of glottal and oral gestures affect pressure and flow parameters that explain differences between singleton and geminated ejective and non ejectives fricatives and affricates in Amharic. Finally the effect of nasal airflow during voiced and voiceless fricatives in Guarani is examined.

Keywords: aerodynamics, dynamics, prominence, Guarani, fricatives, Amharic

1. INTRODUCTION

Constraints such as the aerodynamic voicing constraint (AVC) are known to play a role in the shape of the sound pattern of languages [7]. Changes in aerodynamic conditions also contribute to the understanding of some linguistic phenomena and the dynamics of phonological systems. An increase in subglottal pressure (Psg) can always be observed before stressed syllables and before trills [2]. This shows that aerodynamic factors are important to understand prosodic and segmental phenomena. Oral airflow volume velocity and intraoral pressure (Pio) are affected by changes in glottal resistance. This creates conditions determining the production of sounds involving glottalization phenomena. Modifications in the timing and coordination of articulatory gestures have an effect on the aerodynamic parameters of speech production. These changes can modify the acoustic output of sounds. This explains the occurrence of doubly articulated labio-uvular consonants [qɓ] [3], changes in the spectrum of voiceless nasalized sibilants turning into non sibilants, click loss [! > k] [9] and many other phenomena encountered in the world's languages. Pio and Afo (Airflow oral) also play an important role in the production of voice onset time (VOT) in stops. When combined with categorization, these aerodynamic factors account for the phonological identification of stop consonants.

2. SUBGLOTTAL PRESSURE AND PROMINENCE

2.1. Prominence

In a study on stress in French, Benguerel [1] noted that unemphatic stress best correlates with the longer duration of the last syllable of each rhythmic group. Emphatic stress correlates highly with sub-glottal pressure. However, he found that in all cases, there is a rise in Psg on or before every emphatically stressed syllable. This rise is affected by two factors: the action of the lungs and the respiratory system, and the resistance offered to the airstream by the glottis and the articulators. Benguerel also noted that the state of the glottis appears to be one of the two significant parameters affecting Psg. The other one is laryngeal tension. In the case of unemphatic stress, Psg is kept fairly constant and changes in fundamental frequency (f0) are likely produced by laryngeal adjustment. In the case of emphatic stress, sub-glottal pressure is presumably, at least in French, the main cause of variations in fundamental frequency, although in some cases, it may be overridden by laryngeal adjustment. Ladefoged [5] claimed that stress is best described in physiological rather than acoustic terms. He also stated that it is apparent that every stress is accompanied by an increase in Psg. Fant, et al. [4] showed that sound pressure level, Psg, f0 baseline and their temporal pattern are predictable for stress and prominence. This part of the paper presents some results of an integrated study of the role of Psg and other acoustic parameters of perceived prominence in French.

2.2. Method and material

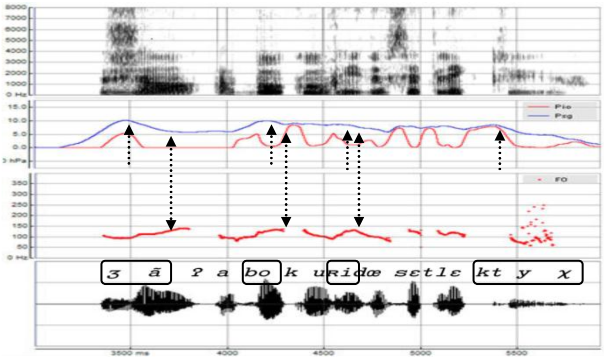
Aerodynamic recordings were made using the Physiologia workstation (Teston and Galindo 1990) linked to a data collection system equipped with different transducers. Oral airflow measurements were taken with a small flexible silicon mask placed against the mouth. Intraoral pressure was recorded with a small flexible plastic tube (ID 2mm) inserted through the nasal cavity into the oro-pharynx. Subglottal pressure (Ps) was measured with a needle (ID 2mm) inserted in the trachea. The needle was placed after local anesthesia with 2% Xylocaine, including the subglottal mucosa. The tip of the needle was inserted, right under the cricoïd cartilage. A plastic tube (ID 2mm) linked to a pressure transducer was connected to the needle. Acoustic recordings were made with a High Fidelity microphone set on the hardware piece equipment connecting the transducers to the computer. Spectrograms and audio waveforms were processed with the signal explorer software.

25 sentences of various types (simple and compound declaratives and interrogatives) have been recorded with 10 subjects of Belgian French (5 women and 5 men).

2.3. Results

An interesting finding of the study, confirming Fant, at al.'s [4] observations in Swedish, is that Psg is often raised well in advance of a stressed syllable and reaches a maximum at the left boundary and then decays at a rate increasing with the prominence. A f0 peak in a stressed vowel is often located in an interval of decaying subglottal pressure (Figure 1).

Figure 1: Spectrogram, (Psg), (Pio), f0 and audio waveform for the sentence [ʒãʔabokuʁidœsɛtlɛktyχ] 'Jean a beaucoup ri de cette lecture'. Simple arrows indicate Psg rise, double arrows fall of Psg and rise of f0. Stressed syllables are squared.



These observations confirm that Psg has an important role in prominence. In French most stressed syllables have a rise in f0 and a concurrent drop in Psg. This suggests a slight opening or relaxation of the glottis to produce a stressed syllable. This is likely explained by Titze's [11] claim that there is a ratio between the amplitude of vibration of the vocal folds and their length. The ratio is bigger when the vocal folds are short and relaxed. Therefore the pattern of prominence in French is made by an increase of glottal resistance (R=P/U) followed by a relaxation of the glottis, both phases not being symmetrical. These results confirm Ladefoged [5] and Benguerel's [1] claim stress is best described in physiological rather than in acoustic term.

3. VOT AND GLOTTAL LAG IN AMHARIC

Amharic a Semitic language spoken in Ethiopia has a series of geminated consonants in its phonological inventory. One important point about these consonants is to understand the features by which they are characterized. Ladefoged and Maddieson [6] note that unlike a sequence of consonants, geminates may not be separated by an epenthetic vowel or other interruption; neither will one half of them undergo a phonological process by itself. Amharic which has fricative and affricate geminates, plain and ejective, is an interesting case to test these claims. Ladefoged and Maddieson [6] say that geminate affricates are clearly different from an affricate sequence. Geminates are expected to have one long stop closure followed by one fricative portion.

3.1. Method and material

Section 2.2 describes the method. Five Amharic speakers took part in the experiments. Only one took part in the Psg measurements. A set of words presented in table 1 was pronounced in a short carrier sentence and in isolation by the speaker.

Table 1: Amharic words used in the experiment.

Fricatives		Affricates	
[kasa]	'compensation'	[kalitʃa]	'witch doctor'
[ləwəsə]	'knead flour for bread'	[t'ətʃ':i]	'drankard'
[kəsəl]	'charcoal'	[atʃ'a]	'equal'
[bəs:a]	'he pierced'	[lutʃ'a]	'smooth air'
[s'əs'ət]	'regret'		
[k'is':il]	'adjective'		

3.2. Results

Mean values of duration measurements for the six speakers are given in table 2 and 3. Aerodynamic data given below are mean values of 6 measurements for the speaker who participated in the Psg experiment.

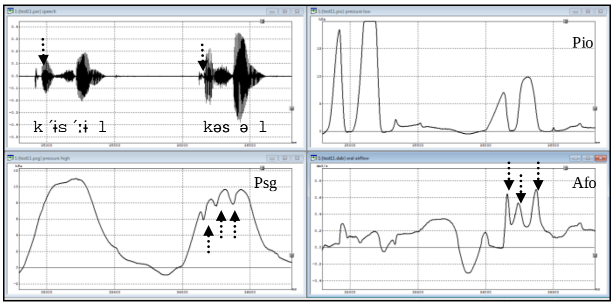
Table 2: Duration and mean Psg and Pio values (n=6) for alveolar fricatives in Amharic.

	s'	s	s':	s:
Duration ms	103.5	123.9	162.9	197.7
Pio	19.9	10.5	19.9	10.7
Psg	10.5	10.7	9.2	10.5

Table 3: Duration and mean Psg and Pio values (n=6) for palatal affricates in Amharic.

	tʃʼ	tʃ	tʃʼː
Duration ms	124.8	195.3	263.4
Pio	19.9	9.2	19.9
Psg	11.6	10.3	10.7

Figure 2: Audio waveform, Psg, Pio and Afo of the words [kəsəl] 'charcoal' and [k'ɨs'ːɨl] 'adjective'. Arrows on the audio waveform show the VOT without noise for [k'] and the VOT with noise of [k]. Arrows on Psg show pressure drops after the burst of [k'] at the start and end of the fricative [s'ː] and the glottal lag at the end of [s'ː]. Arrows on Afo show increases of airflow at the end of [k] at the start and end of [s'ː].



Acoustic measurements show that ejectives are shorter than their plain counterpart. In the case of affricates, there is a gradual increase of the duration of the stop and frication noise: [tʃʼ] (94.3 ms + 30.5 ms) < [tʃ] (139.5 ms + 55.8 ms) < [tʃː] (196.4 ms + 67 ms). Aerodynamic measurements show that there does not seem to be much difference in Ps between the ejectives and affricates except for [s'ː] and [tʃʼ]. Pio is at 19.9 for ejectives because the maximum value was reached. The maximum was fixed at 20 hPa during the experiments which was clearly not enough. Of course this does not allow to say anything about differences between ejectives but it shows that Pio is at least twice aslarge for ejectives compared to plain consonants. Figure 2 shows an interesting finding about the difference between ejectives and plain fricatives. The coordination between glottal gestures (closure and opening) is different in both cases. Ejective fricatives are charaterized by a glottal closure at the start, contrary to what happens with plain fricatives where there is an openning. This is visible on the Psg and Afo curves where before and after the plain fricative there is a drop in Psg and an increase in Afo. (Note that the same is true for the VOT when plain and velar ejective stops are compared as it is shown by the difference between [k] and [k']). At the end of the ejective fricative the glottis remains closed until the next vowel and there is no drop in Psg. This is not the case for the plain fricative where the constriction's release produces a drop in Psg before the following vowel. Drops in Psg corresponds to an increase in Afo.

3.3. Discussion

The comparison between plain and ejective fricatives show some important differences. Compared to the constant noise of plain fricatives, frication noise increases towards the end for ejective fricatives. This is due to the larynx elevation which is necessary to produce the ejective.

In the case of [s'ː] the larynx's elevation is delayed as it can be seen on the audio waveform which shows an increase in the frication noise towards the end. As the air resources within the oral cavity are not extensible it seems at first sight difficult to produce a geminated ejective fricative. The larynx's elevation with a closed glottis expels all the air from the oral cavity for the singleton ejective fricative. In order to produce a geminate ejective fricative there seems to be a delay in the larynx's elevation which suggests that this is under control by the Amharic speakers. This delay is visible on the audio waveform which has very low frication noise for about 2/3rd of the time. Other important differences relate to the coordination of glottal and oral gestures in plain and ejective stops. The ejective has a VOT without noise which suggests that the glottis is still closed when the oral constriction is released. A similar coordination seems to be present at the end of the fricatives. There is a glottal lag at the end of the ejectives fricatives because when the constriction is released the glottis is still closed. This can be seen at Figure 2 where there is a drop in Psg at the end of the plain fricatives which is not the case for the ejective. The fact that the glottis is closed for the ejective fricatives can also be seen at the start. There is a drop of Psg at the start of fricatives due to a wider glottal opening permiting an increase in the airflow volume velocity necessary to generate the frication noise. This triggers a drop of Psg and an increase in AFo as can be seen at Figure 2. This is not the case for ejective fricatives as the glottis is closed. This confirms that frication noise of ejective fricatives is only produced by the available air resources in the oral cavity between the sealed glottis and the constriction. These phenomena raise some fundamental questions on the control and coordination of articulatory gestures. These are about the kind and degree of control that speakers exert on articulations. Data about the affricates, plain and ejective, confirm Ladefoged and Maddieson's [6] claims about the unity of geminates. It is the increase in duration of the stop that makes the main difference between these sounds rather than an increase in the duration of frication noise.

4. GUARANI

4.1. Introduction

Guaraní a language belonging to the Tupi language family shows interesting phenomena about nasalization. When nasalized voiced fricatives lose their frication, voiceless fricatives have their frication noise affected and their spectrum becomes more flat. These observations have been predicted by Ohala & Ohala [8] and by Shosted [9] who showed that the following changes are to be expected when fricatives become nasalized: [v] > [ʋ], [s] > [θ], [ɣ] > [ɦ]. Aerodynamic measurements were made to check these predictions.

4.2. Method and material

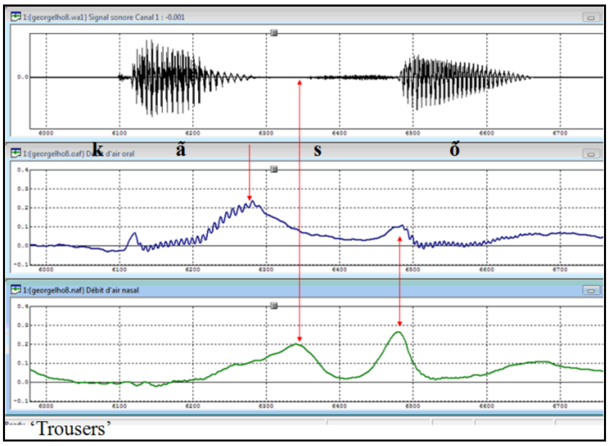
The method is similar to that described in section 2.2 except that an EVA2 portable workstation was used instead of Physiologia. Data come from 6 Guaraní speakers from the same rural area of Paraguay (2 women and 4 men). A set of words and sentences chosen from Suarez & Suarez [10] completed by other new data was recorded (5 times each word in isolation and in a carrier sentence).

4.3. Results

In nasalized words when a nasal vowel precedes a fricative (voiced or voiceless), the velum often closes after the glottis opening gesture that takes place at the start of the fricatives. This triggers a strong peak of nasalization at the end or after the vowel. Most the airflow goes through the nose at this time because the oral constriction is already in place. This 'late' velum closure alters the frication that may be reduced or delayed as can be seen on the audio waveform in Figure 3.

The Guarani data suggest that the timing and coordination of velum and oral gestures triggers effects on aerodynamic parameters. These can in turn shape changes in the phonological pattern of languages.

Figure 3: Audio waveform; Afo and Nasal airflow (Afn), in dm^3/s, of the word [kãsõ]. The single arrow on the Afo shows the peak of airflow at the start of the fricative. Double arrows show the start of Afn decrease and frication noise; simultaneous peaks of Afo and Afn at the constriction's release.



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