

Variability and Constancy in the Articulation and Acoustics of Pima Coronals

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# Variability and Constancy in the Articulation and Acoustics of Pima Coronals<sup>1</sup>

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## 1. Introduction

Pima is a Uto-aztecan language spoken in the state of Arizona, U.S.A. and Sonora, Mexico by 11,819 speakers. Pima presents a contrast among denti-alveolar /t̪, d̪, s/, alveolar /d/, post-alveolar /ɖ/ and alveo-palatal /tʃ, dʒ/. Less than 15 % of 452 languages distinguish two coronal stops in place of articulation, according to the UPSID corpus (Maddieson 1984, Maddieson and Precoda 1992). Since the distinction is rather uncommon across languages, our primary goal is to provide a detailed description of the phonetic properties of the sounds involved in this contrast. Based on this description, our study addresses the question about the specific characterization of these consonants. Furthermore, we discuss the classification proposed for related languages, such as Tohono O'odham and Pima Bajo (Escalante and Estrada Fernandez 1993, Saxton 1963). These studies claimed that the contrast between /d̪, s/ and /d, ɖ/ corresponds to a difference between dental and retroflex sounds. However, these studies lack the precise description about how the retroflex sounds are articulated. The term 'retroflex' generally describes an articulation made with the inferior part of the tongue by curling the tip. Nevertheless, the label has been used for quite different articulatory gestures across languages (Ladefoged and Maddieson 1996). In our earlier fieldwork on Pima, we have observed that the articulation of apical sounds might not be well described by the gesture of curling the tongue tip. The detailed articulatory study will shed a light on this issue.

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<sup>1</sup> We would like to thank the five Pima speakers who decided to remain anonymous and collaborated in this project. We acknowledge the authorities at the Gila River Reservation for granting us the permission to do the fieldwork. Without their collaboration this work could not have been possible. We are especially grateful to Mr. Virgil Lewis who has taught us his language and helped us in the preparation for the fieldwork. We wish to thank Jenny Ladefoged and Peter Ladefoged who supervised the fieldwork and guided us through the whole process of this study. This project was supported by a grant from the Institute of American Cultures through the American Indian Center at UCLA and by the Department of Linguistics at UCLA. The first author acknowledges a UC-MEXUS/CONACYT fellowship.

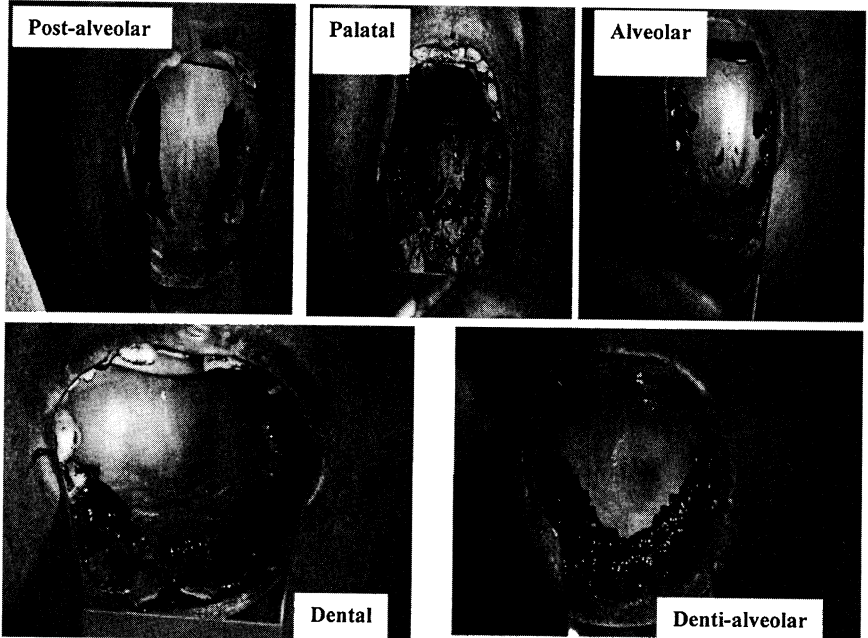
The compression of the coronal consonants in a narrow articulatory space is also relevant to phonetic theory because it allows us to observe the degree of variability and/or constancy in the production of these sounds. Some phonetic theories proposed that the sounds that are perceptually salient or typologically common can show articulatory variability to the extent that the corresponding acoustic parameters show relative constancy (Stevens 1985, 1989, 1998). Similarly, it has been suggested that small phonemic systems demand less perceptual distinctiveness than larger systems (Lindblom 1990). These ideas allow us to predict that a speech sound in a dispersed articulatory space may allow greater articulatory variability than that in a compressed space, as far as its acoustic properties remain constant. Hence, our secondary goal is to examine the correlation between the articulatory and acoustic properties of Pima coronal sounds.

## 2. Method

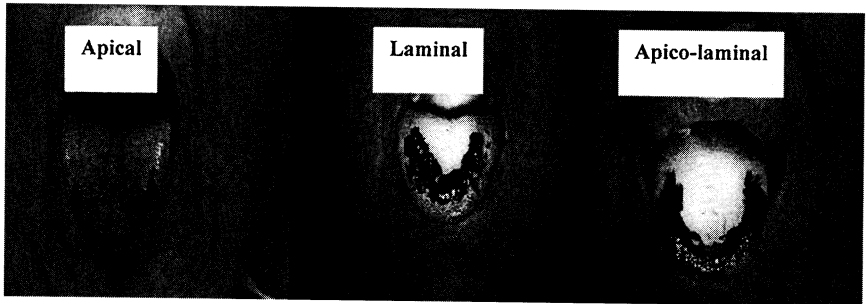
**Data collection and subjects.** The corpus investigated consisted of six words containing the target segments in a /...VCV.../ context (where V is [-high]). Subjects were asked to repeat each word three times. The materials were collected in fieldwork in the Gila River reservation. Three female and three male native speakers of Pima, ranging from 40-60 years of age participated in this study. Audio data were recorded using digital audio tapes and digitized at a 22,050 Hz sampling rate. Video data were recorded in a digital camera and transferred to a computer.

**Articulatory Measurements.** To record articulatory data, we adopted the method of static palatography (Anderson 2000, Dart 1993, Ladefoged to appear, among others). In order to obtain palatogram data, the tongue of a speaker was coated with a colored substance (an innocuous mixture of charcoal and olive oil) so that when the sound being studied was articulated, there was an imprint of the articulation on the roof of the mouth. This imprint was reflected in a mirror and captured as a video image. In linguograms, the process was reversed. The roof of the mouth was coated, and the imprint on the tongue (reflects the location of linguo-palatal contact) was recorded as a video image. In order to relate palatographic/linguographic images to the actual articulation, a life-size dental impression was made of each speaker's palate and cast in plaster. For each still frame, measurements from the vertical and horizontal axes were calibrated according to the measurements of the life-size casts for each speaker. For palatograms, data were classified as post-alveolar, palatal, dental, denti-alveolar and alveolar according to the measurements and visual inspection of the images compared to the plaster casts. Figure (1) illustrates representative palatograms of each category. For linguograms, data were classified as apical, laminal and apico-laminal according to visual inspection of the images. Figure (2) shows typical examples of the three categories.

(1) Classification of palatograms



(2) Classification of linguograms



**Acoustic Measurements.** Several measurements were obtained to perform acoustic analyses. We measured the centroid frequency and spectra of fricatives and affricates, formant transitions, stop burst release amplitude for stops and durational properties. The centroid frequency for fricatives were obtained from FFT spectra computed over a 25 ms window in a frequency range of 1000 Hz to 10000 Hz. Spectral properties were obtained from FFT spectra using a 1024 point frame, which amounted to 46 ms window. Formant transitions (F1, F2, F3, F4) of the surrounding vowels were obtained. Vowel formants were measured at the

offset of the preceding vowel and the onset of the following vowel. The formants at the steady state of vowels were also measured as a reference point. Relative ‘vowel-burst’ amplitude was calculated from the difference between the maximum amplitude of the vowel and the peak stop burst amplitude. Various analyses of durational properties were obtained fricative duration, voice onset time, stop closure duration and rate of voicing during the acoustic closure were measured.

### 3. Results

#### 3.1. Articulation

**Stops.** The results regarding the production of stops are summarized in Table (3).

/t/ and /d/ were articulated as dental or denti-alveolar and laminal or apico-laminal. /d/ was articulated as alveolar or post-alveolar; most speakers articulated /d/ as apical, except for the two who pronounced it with the tongue blade.

(3) Stop articulation

		SPK 1 (f)	SPK 2 (f)	SPK 3 (f)	SPK 4 (m)	SPK 5 (m)	SPK 6 (m)
/t/	Palato-gram	Denti-alveolar	Denti-alveolar	Dental	Denti-alveolar	Denti-alveolar	Denti-alveolar
	Linguo-gram	Laminal	Apico-laminal	Laminal	Apico-laminal	Laminal	Apico-laminal
/d/	Palato-gram	Dental	Denti-alveolar	Denti-alveolar	Denti-alveolar	Denti-alveolar	Denti-alveolar
	Linguo-gram	Laminal	Laminal	Laminal	Laminal	Laminal	Apico-laminal
/d/	Palato-gram	Post-alveolar	Alveolar	Alveolar	Alveolar	Post-alveolar	Alveolar
	Linguo-gram	Apical	Apical	Apical	Laminal	Laminal	Apical

**Fricatives.** /s/ was articulated as denti-alveolar or alveolar and laminal whereas /ʃ/ was consistently post-alveolar and it was produced with the tongue tip for most of the speakers, although two speakers produced it with the blade. The channel width was consistently wider in /ʃ/ than in /s/, as shown in Table (4).

(4) Fricative articulation

	/s/		/ʃ/	
	Palatogram	Linguogram channel width (cm)	Palatogram	Linguogram channel width (cm)
SPK1 (f)	Denti-alveolar	Laminal (0.8)	Post-alveolar	Laminal (0.7)
SPK2 (f)	Alveolar	Laminal (0.4)	Post-alveolar	Apical (0.8)
SPK3 (f)	Denti-alveolar	Laminal (0.7)	Post-alveolar	Laminal (0.8)
SPK4 (m)	Alveolar	Laminal (n/a)	Post-alveolar	Apical (n/a)
SPK5 (m)	Denti-alveolar	Laminal (0.6)	Post-alveolar	Apical (0.95)
SPK6 (m)	Denti-alveolar	Apico-laminal (0.6)	Post-alveolar	Apical (0.8)

**Affricates.** As seen in Table (5) /tʃ/ was consistently produced as laminal. It showed wider variation in place of articulation, ranging from denti-alveolar to palatal. /dʒ/ was also consistently produced as laminal. It also showed a great deal of variation in place of articulation, ranging from alveolar to palatal.

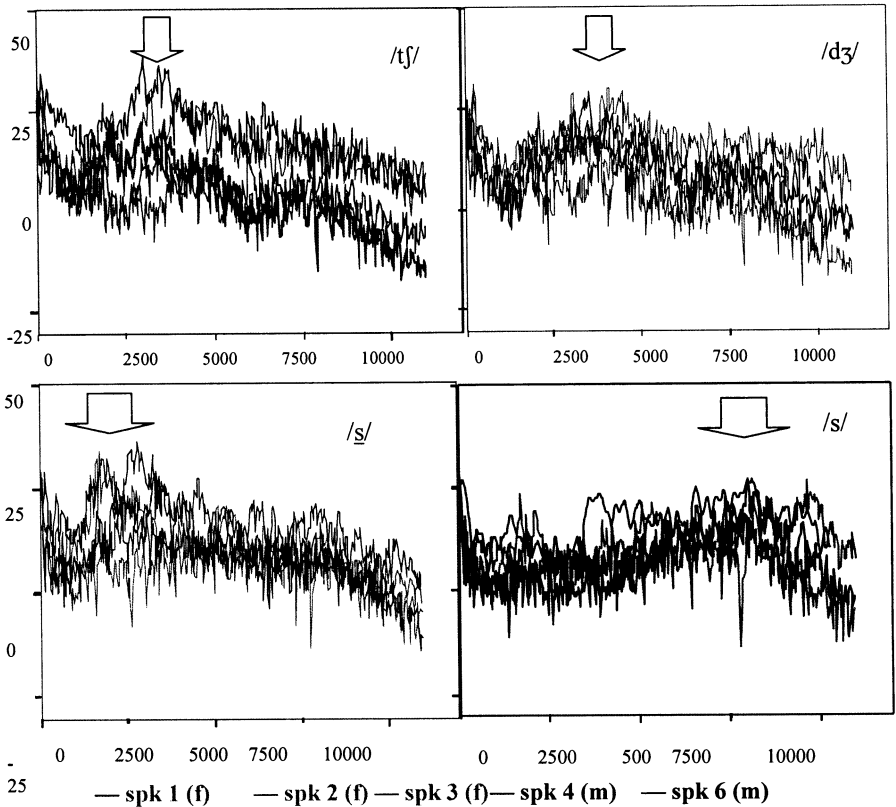
(5) Affricate articulation

	/tʃ/		/dʒ/	
	Palatogram	Linguogram	Palatogram	Linguogram
SPK1 (f)	Alveolar	Laminal	Alveolar	Laminal
SPK2 (f)	Post-alveolar	Laminal	Post-alveolar	Laminal
SPK3 (f)	Post-alveolar	Laminal	Post-alveolar	Laminal
SPK4 (m)	Palatal	Laminal	Palatal	Laminal
SPK5 (m)	Alveolar	Laminal	Alveolar	Laminal
SPK6 (m)	Denti-alveolar	Laminal	Alveolar	Laminal

**3.2 Acoustics**

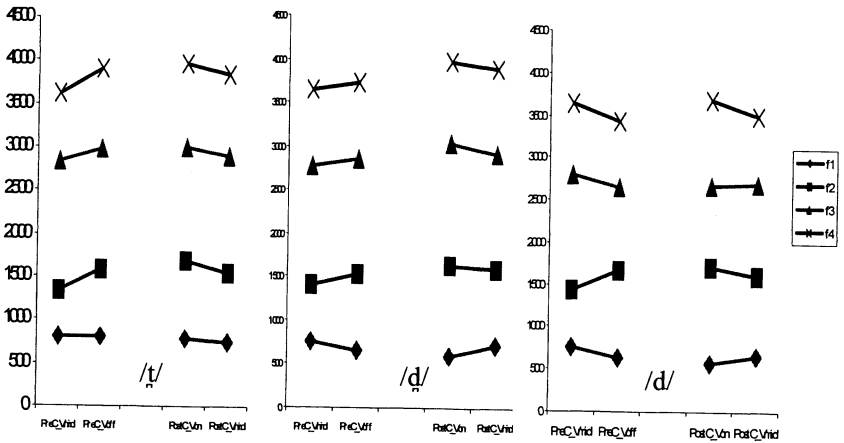
**Spectral Properties.** Affricates /tʃ/ and /dʒ/ showed the greatest amount of amplitude between 2500 and 4000 Hz. The amplitude dropped off in the higher frequencies. The spectrum of /s/ showed the greatest amount of amplitude around 2500 Hz, which went down in the higher frequencies. However, the spectrum of /ʃ/ differed from the others. The amplitude peaks were in the frequencies after 7000 Hz, except for one speaker whose spectrum of /ʃ/ showed more or less flat pattern. Figures in (6) show the results.

## (6) Spectral properties of fricatives and affricates



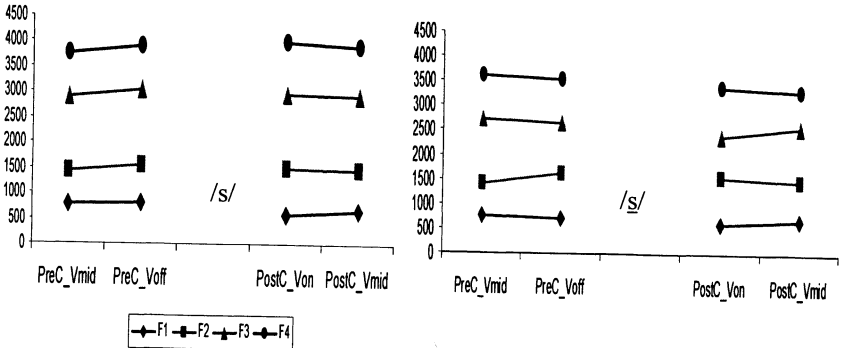
**Formant transitions.** Formant values at the vowel midpoints differed according to the subtle articulatory differences of the surrounding stops: vowels following dental /t/ and /d/ showed higher F3 and F4 than those following alveolar /d/, and vowels preceding alveolar /d/ showed higher F2 than those preceding dentals /t/ and /d/. As shown in Figure (7), these differences further led to different trajectories in formant transitions. Dental /t/ and /d/ raised F3 and F4 of the preceding and following vowels, but alveolar /d/ lowered F3 of the preceding and following vowels.

(7) Formant transitions of vowels surrounded by stops



Regarding the contrasts in fricatives, our results showed that denti-alveolar /s/ raised the F3 and F4 of the preceding and following vowels, whereas post-alveolar /s/ lowered the F3 of the preceding and following vowels. Post-alveolar /s/ lowered the F4 of the preceding vowel as well. Vowels that preceded denti-alveolar /s/ showed lower F2 than those which preceded post-alveolar /s/, as shown in Figure (8).

(8) Formant transitions of vowels surrounded by fricatives

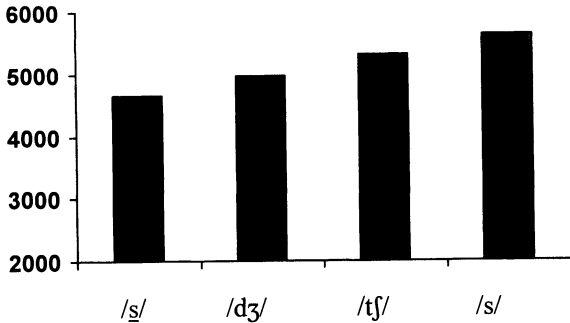


The observed formant transition patterns of /tʃ/ and /dʒ/ were similar to that of /s/, in that they both lowered the F3 of the preceding and following vowels.

**Centroid frequency for fricatives.** The centroid frequency of /s/ was higher than those of /s/, /tʃ/ and /dʒ/ as in Figure (9). A *t*-test result showed that the difference between /s/ and /s/ was statistically significant ( $p < .001$ ).

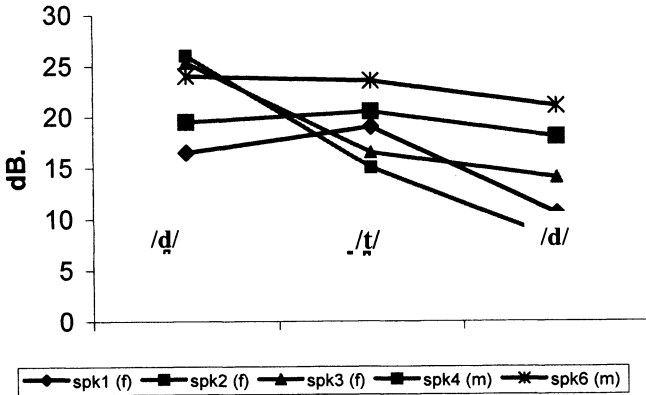
(9)

**centroid frequency**



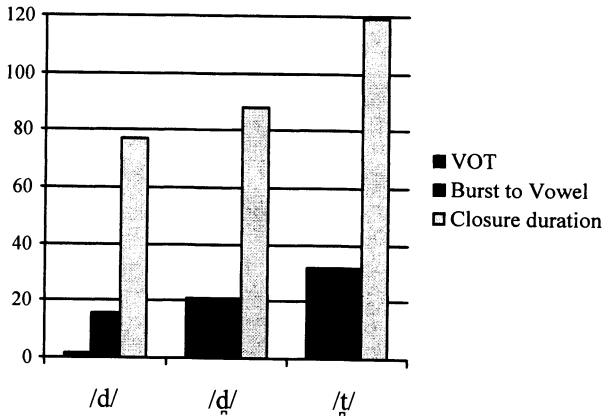
**Amplitude difference between vowel maxima and stop burst.** Vowel-burst differences were smaller (higher amplitude burst) for alveolar /d/ than for dentals /d̪/ and /t̪/. An overall significant difference was found between /d̪/ and /d/ ( $p = .0002$ ), /t̪/ and /d/ ( $p = .03$ ) but not between /d̪/ and /t̪/.

(10) Amplitude difference between vowel maxima and stop burst



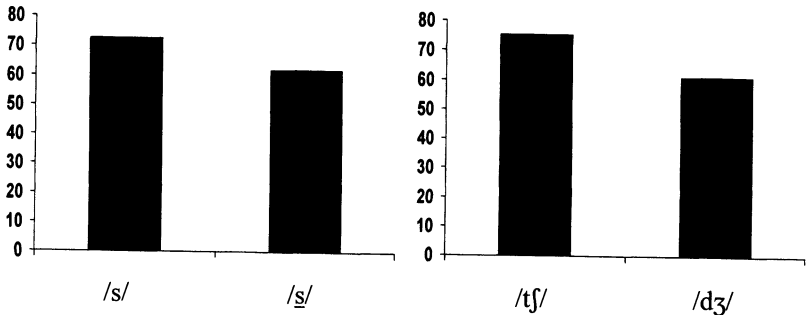
**Stop durations.** The mean burst to vowel duration value of /d/ (15.6 ms) was shorter than that of /d̪/ (20.9 ms) and /t̪/ (32.1 ms). The difference /d/ and /t̪/ was significant. The mean VOT value of /d/ (1.8 ms) was shorter than that of /d̪/ (20.9 ms) and /t̪/ (32.1 ms). There was a significant difference between /d/ and /t̪/. The mean closure duration value of /d/ (77.2 ms) was shorter than that of /d̪/ (87.7 ms) and /t̪/ (119.5 ms). There was a significant difference between /d/ and /t̪/, and between /d̪/ and /t̪/. The results are summarized in (11).

(11) Acoustic durations for stop consonants



**Fricative durations.** The duration of /s/ was longer than that of /s̥/, but the difference was not significant. The closure duration for /t̥f/ was significantly longer than that of /d̥ʒ/ ( $p < .05$ ). There was no significant difference in the duration of frication between /t̥f/ and /d̥ʒ/. The results are summarized in (12).

(12) fricative duration closure duration for affricates



#### 4. Discussion

The phonetic description provided in this study showed that /t̥/, /d̥/, and /s/, the sounds which were previously categorized as dentals, are produced with dental or denti-alveolar constriction using the tongue blade. In contrast, /d/ was articulated with the tip or the blade of the tongue against the alveolar ridge or in the post-alveolar region. /s̥/ had its point of constriction in the post-alveolar region and the tongue contact was made either by the tip or the blade. Palatal sounds

/tʃ/ and /dʒ/ were produced with the tongue blade, and their places of articulation ranged from denti-alveolar to palatal.

Previous descriptions of O'odham languages (Saxton 1963) considered /d/ and /s/ as retroflex sounds. Our results indicate that a more accurate account of these sounds should describe them as retracted articulations, which, at the phonetic level, should be differentiated from the retroflex sounds made by curling the tongue tip back (Ladefoged and Maddieson 1996).

The results showed a correlation between the place of articulation and the tongue contact. In stops, dentals and denti-alveolars involved laminal contact, whereas alveolars tended to involve apical contact. In fricatives, alveolar fricatives involved laminal contact, and post-alveolars tended to involve apical contact. The generalization emerging from these observations is consistent with the cross-linguistic patterns observed by Ladefoged and Maddieson (1996): fronter points of constriction involve tongue blade contact and more posterior points of constriction involve tongue tip contact.

The results also indicated that there is a correlation between place of articulation and formant transitions of the surrounding vowels. Alveolar /d/ lowers F3 into the transition of the following vowel. It is due to the fact that the larger front cavity formed when the tongue tip is raised and retracted produces smaller F3 and F4. Post-alveolar /s/ produced a dramatic lowering of F3 of the adjacent vowel transitions, as opposed to /s/ that triggered a slight raising on the adjacent vowel formant transitions. Our findings were consistent with previous analyses of coronal consonants (Anderson 2000, Dart 1993, Gordon *et al.* to appear, Stevens 1998) suggesting that the lowering effect of /s/ is concomitant to the larger sublingual resonance of the consonant.

Our findings showed a correlation between burst amplitude and the active articulator. The burst amplitude was lower for laminal stops (/t/, /d/) than apicals (/d/) due to the prolonged obstruction of the oral cavity caused by the gradual release of the tongue. This observation is consistent with the reports of previous studies of apicality in Malayalam (Jongman *et al.* 1985) and in Tiwi (Anderson and Maddieson 1994).

The results showed a robust correlation between the place of articulation and the energy distribution of fricatives. That is, when the front cavity length was smaller, both centroid frequency and locus of spectral noise were concentrated at higher frequencies (Stevens 1998).

We also found a strong correspondence between articulatory variation and spectral shape constancy of friction noise. The results showed that regardless of the intra-speaker variation found in the articulation of fricatives and affricates, its acoustic properties remained constant. This observation may indicate that acoustic stability of the location of amplitude peak is more important for the overall perception.

Overall, our results seem to suggest that even a language like Pima, which has phonological contrasts within a limited articulatory space, does not impose strict

demands on articulatory precision to the extent that the target acoustic signal is produced.

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