

Locus Equations and the Degree of Coarticulation of Arabic Consonants

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Abstract

The intent of the present study is to investigate the information for place of articulation provided by locus equations, using Moroccan speakers of Modern Standard Arabic. Locus equations are straight-line regression function fits to co-ordinates derived by relating onsets of F_2 transitions of different vowels to their corresponding steady states. Ten subjects produced CVCVC(VC) tokens, the first consonant of each was one of the following list: (/f/, /ð/, /ðʕ/, /s/, /sʕ/, /d/, /dʕ/, /t/, /tʕ/, /ʃ/, /h/, /ʒ/). Each initial consonant was followed by one of the six vowels (/i/, /æ/, /u/, /i:/, /æ:/, /u:/). The present study attempted to explore to what extent locus equations can distinguish between different consonants varying in place and manner of articulation. The findings are of two kinds. On the one hand, locus equations do not reflect certain place-of-articulation distinctions when many consonants varying both in place and manner of articulation are taken into consideration. On the other hand, locus equations are successful in distinguishing place between pharyngealized and non-pharyngealized consonants. Pharyngealized consonants (/ðʕ, dʕ, sʕ, tʕ/) emerged as a totally distinct class, having the flattest locus equation slopes of all consonants.

Review of the Literature

Locus equations have been investigated as 'relational invariants' capable of signalling consonantal place of articulation by Sussman [1989, 1991, 1994] and Sussman et al. [1991, 1992, 1993]. Locus equations are straight-line regression function fits to co-ordinates derived by relating onsets of F_2 transitions of different vowels to their corresponding steady states. Locus equations, expressed as $F_2 \text{ onset} = k \times F_2 \text{ vowel} + c$ (where k and c are slope and intercept, respectively), were originally proposed by Lindblom [1963]. Lindblom [1963] derived locus equations from one Swedish speaker producing initial /b, d, g/ in the context of eight different vowels. The slope of the locus equation lines varied according to place of articulation with /g/ > /b/ > /d/.

Neary and Shammass [1987] replicated the linearity and distinctiveness of locus equations using Canadian English speakers and proposed that they can be 'partial in-

variants'. Krull [1988, 1989], following up research in locus equations with Swedish speakers, pointed out that the amount of coarticulation at the consonant-vowel boundary can be indicated by the slope of the locus equation line. Steep slopes indicate maximal coarticulation of the consonant with the following vowel (i.e. minimal coarticulatory-resistance of the consonant articulation to vowel effects). Flat slopes, on the other hand, indicate absence of vowel coarticulatory effects (i.e. maximal coarticulatory-resistance of the consonant articulation).

Sussman et al. [1991] extended locus equations to American English. Sussman et al. [1991] used 10 male and 10 female speakers producing CVC tokens with initial /b, d, g/ in the context of 10 vowels. They reported significant differences in the slopes as a function of place of articulation with labial /b/ having the steepest slope (0.89), dental /d/ the flattest (0.42), and velar /g/ an intermediate slope (0.72). Further, discriminant analyses showed 93% correct classification for these consonants by place when using only slopes as predictor variables, and 100% correct classification with slopes and intercepts as predictor variables.

Locus equations have also been extended to languages such as Thai, Urdu and Cairene Arabic in Sussman et al. [1993], and Spanish in Celdran and Villalba [1995]. Apart from the crosslinguistic comparisons, the study of Sussman et al. [1993] showed that there was a difference (though not statistically significant) in locus equation slopes for retroflex /d/ and non-retroflex /d/ in Urdu, and for pharyngealized /dʕ/ and non-pharyngealized /d/ in Cairene Arabic.

Recently, there has been a debate concerning the generality of locus equations as a phonetic descriptor of consonantal place. Originally, the locus equation metric was restricted to describing place for stop consonants only. However, Fowler [1994] extended the metric beyond this original scope to compare slope and intercept for different places across manner classes. She presented three lines of evidence (from spontaneous errors of speech production, hierarchy of phonological features, and perception) in favour of the orthogonal¹ character of place features to manner features, leading her to suggest that 'any invariant for stop place must be an invariant for place of articulation in general' [Fowler, 1994, p. 598]. One argument cited by Fowler [1994] is based on the study of Bond and Garnes [1989, cited in Fowler, 1994] reporting the occurrence of mishearings in which both manner and place features are misheard. Another argument relates to error patterns in which 'place is involved, not place within distinct manner classes' (p. 598).

In her critical study, Fowler [1994] investigated six consonants varying in place and manner of articulation: /b, v, ð, d, z, ʒ, g/ in 10 speakers of American English. Fowler [1994] questioned locus equations as a general classifier of place of articulation. When manner of articulation varied, locus equations did not accurately reflect consonantal place. More specifically, she found that /z/ and /d/ which share place of articulation, had distinct locus equation slopes (0.42 and 0.47, respectively). In another critical study using acoustic and EPG data [Crowther, 1994] locus equations had difficulty distinguishing /b/, /d/ and /g/, when coarticulation was an independent variable.

¹ In certain phonetic theories [e.g. Lindau and Ladefoged, 1986] features like 'place of articulation' are not necessarily orthogonal to manner. Their proponents' view concerning place of articulation is also different: they do not think there are discrete places of articulation. The cover feature 'place' is of course used in the present study in a phonological sense for the simple comparison and grouping of sounds.

In a preliminary study, Sussman [1994] compared locus equation parameters for consonants differing in place and manner. Scatterplots of locus equation coefficients (slope \times y intercept) revealed three non-overlapping clusters: a labial group /b, p, m/, an alveolar group /t, d, n, z/ and a velar group /k, g/. In a study carried out with a large speaker population, Sussman and Shore [1996] called into question the criticism of Fowler [1994]. Twenty-two speakers produced stimulus words containing five coronals /t, d, n, s, z/ spanning different manner features. Results showed that the three consonants /d, z, n/ had statistically similar slope (0.40, 0.38 and 0.48, respectively). Voiceless /t/ and voiced /d/ also had similar slopes when F_2 onset for /t/ was taken at the first visible resonance during the aspiration interval. Unlike Fowler [1994], for Sussman and Shore [1996] emphasis should be put on the sufficient contrast between obstruent place categories captured by locus equations rather than the manner-class-induced variability.

The intent of this study is to further investigate the information for place of articulation provided by locus equations using Moroccan speakers of Standard Modern Arabic. Two important questions of interest are the following: First, to determine how well locus equations can reflect place of articulation in an expanded phonetic inventory. The inventory includes consonants belonging to different place categories: labial /f/, interdental /ð/, alveolars /t, d, s/, pharyngealized alveolars /d^h, s^h, t^h/, postalveolar /ʃ/, uvular /ħ/ and pharyngeal /ħ/. The alveolar category spans different manner classes: voiced stop /d/, voiceless stop /t/ and voiceless fricative /s/. If locus equations hold as general place descriptors, then the slopes and y intercepts should not be statistically different across the alveolar category. Locus equation coefficients should also remain distinctive for the different fricative place categories. Second, to explore whether pharyngealized /d^h, s^h, t^h/ consonants can statistically be distinguished from their non-pharyngealized cognates /d, t, s/. There are three reasons why we are interested in the last question. First, in a preliminary study, locus equations derived from data of 4 speakers significantly distinguished pharyngealized /d^h, s^h/ from non-pharyngealized /d, s/. Second, Sussman et al. [1993] reported that the locus equation for pharyngealized /d^h/ was slightly different from that of non-pharyngealized /d/. Third, in a perceptual study, F_2 onset transition was found to be a critical acoustic cue distinguishing pharyngealized /s^h/ from non-pharyngealized /s/ [Yeou, 1995].

Method

Subjects

The subjects were 10 male Moroccan graduate students of linguistics and phonetics (mean age=29). They are all native speakers of Arabic. The data for one of the subjects were subsequently discarded for his failure to distinguish between /ð/ and /d/. That left data from 9 subjects.

Materials

The material consisted of word and nonsense word CVCVC(V) sequences. The first consonant of each was one of the following list: /f/, /ð/, /d^h/, /s/, /s^h/, /d/, /d^h/, /t/, /t^h/, /ʃ/, /ħ/, /ħ/. Each initial consonant was followed by one of the six vowels /i/, /æ/, /u/, /i:/, /æ:/, /u:/. All the items ended in /nun/ to maximize the number of real words in the inventory. The subjects were asked to produce five repetitions of each item in a carrier phrase format, written in Arabic orthography on ten sheets of paper (qa:ħe __ mærrætæjni: 'He said the word two times'). A total of 360 tokens per subject were analysed (12 consonants \times 6 vowels \times 5 repetitions).

Table 1. Locus equation slope values, y intercepts, and R²s for the set of 12 consonants across 9 speakers

	ð			d			s			t		
	slope	y inter	R ²	slope	y inter	R ²	slope	y inter	R ²	slope	y inter	R ²
<i>Non-pharyngealized consonants</i>												
S ₁	0.54	732	0.93	0.51	837	0.79	0.48	794	0.82	0.65	598	0.91
S ₂	0.46	731	0.93	0.46	908	0.92	0.44	830	0.89	0.59	724	0.91
S ₃	0.54	811	0.93	0.45	1,128	0.93	0.56	779	0.81	0.69	784	0.93
S ₄	0.31	1,080	0.61	0.50	843	0.87	0.47	882	0.82	0.69	533	0.89
S ₅	0.47	879	0.87	0.57	695	0.87	0.59	662	0.84	0.70	492	0.72
S ₆	0.50	785	0.85	0.44	1,038	0.66	0.61	767	0.80	0.70	573	0.95
S ₇	0.34	1,108	0.57	0.41	1,080	0.90	0.66	576	0.97	0.65	636	0.88
S ₈	0.52	873	0.87	0.50	958	0.85	0.68	600	0.94	0.69	571	0.97
S ₉	0.46	880	0.90	0.48	936	0.88	0.56	779	0.87	0.58	700	0.90
Mean	0.46	875	0.83	0.48	936	0.85	0.56	741	0.86	0.66	623	0.90
	ð ^v			d ^v			s ^v			t ^v		
	slope	y inter	R ²	slope	y inter	R ²	slope	y inter	R ²	slope	y inter	R ²
<i>Pharyngealized consonants</i>												
S ₁	0.20	702	0.41	0.41	446	0.75	0.38	550	0.85	0.35	598	0.75
S ₂	0.20	675	0.75	0.39	730	0.87	0.31	626	0.81	0.33	724	0.87
S ₃	0.24	761	0.81	0.25	1,037	0.60	0.29	776	0.50	0.40	784	0.76
S ₄	0.14	990	0.28	0.33	895	0.75	0.33	729	0.37	0.38	533	0.79
S ₅	0.28	801	0.72	0.30	804	0.51	0.35	701	0.60	0.43	492	0.76
S ₆	0.23	812	0.61	0.21	1,062	0.64	0.42	663	0.83	0.39	573	0.95
S ₇	0.14	738	0.72	0.14	931	0.20	0.26	694	0.59	0.22	636	0.45
S ₈	0.31	771	0.61	0.39	748	0.86	0.43	689	0.90	0.44	571	0.90
S ₉	0.21	750	0.70	0.33	895	0.75	0.35	701	0.81	0.36	668	0.87
Mean	0.22	778	0.62	0.31	839	0.66	0.35	681	0.70	0.37	678	0.79
	f			j			ʒ			h		
	slope	y inter	R ²	slope	y inter	R ²	slope	y inter	R ²	slope	y inter	R ²
<i>Other consonants</i>												
S ₁	0.92	-31	0.99	0.64	618	0.91	0.99	-8.5	0.98	0.53	754	0.40
S ₂	0.93	41.1	0.96	0.41	991	0.89	0.81	225	0.98	0.60	661	0.92
S ₃	0.91	119	0.99	0.59	879	0.88	0.98	96.1	0.91	0.68	641	0.92
S ₄	0.90	97.3	0.99	0.57	714	0.73	0.91	127	0.97	0.57	710	0.88
S ₅	0.92	108	0.96	0.60	645	0.91	0.86	183	0.85	0.83	401	0.72
S ₆	0.95	24.4	0.99	0.70	613	0.91	0.94	77.2	0.92	0.71	576	0.89
S ₇	0.96	9.5	0.99	0.73	537	0.96	0.90	38.6	0.97	0.85	539	0.93
S ₈	0.89	34	0.99	0.71	568	0.96	0.85	106	0.98	0.71	354	0.98
S ₉	0.93	65	0.97	0.6	680	0.93	0.90	110	0.96	0.67	650	0.90
Mean	0.92	61	0.98	0.62	694	0.90	0.90	106	0.95	0.68	587	0.84

Procedures

The utterances were recorded in a sound-attenuated room using an Electret microphone and a Sony DTC 670 DAT tape-recorder. The recorded signal was digitized at 16 kHz sampling rate via a 16-bit analog-to-digital converter. UNICE software (version 1.60, LIMS) was used for all editing, display, playback and measurement procedures. Spectral measurements were taken from three sources: direct read-outs from wide-band spectrographic displays, linear predictive coding (LPC) analyses, and fast Fourier transforms.

Acoustic measurements of F_2 (at vowel onset and at vowel 'midpoint') were taken from five tokens of each speaker. Following Sussman et al. [1991] the midpoint was the vowel steady state; for U-shaped or U-inverted formant patterns, it was the value at the minimum or maximum points. If there was a monotonic change in frequency, the formant value at the temporal midpoint was taken. Generally, vowel onset was identified as the onset of voicing in the vowel following the consonant release. Other cues were also adopted to establish vowel-consonant boundaries: (1) changes in the amplitude of F_1 and F_2 ; (2) visual identification of the first visible change in the overall amplitude of the waveform, and (3) visual identification of the friction noise/burst offset.

Results

One hundred and eight locus equation scatterplots were generated (12 consonants \times 9 subjects). Each consonant regression function was derived from 30 two-point coordinates spanning 6 vowel contexts and 5 repetitions. Locus equation slopes, y intercepts, and R^2 values (calculated for each subject and averaged) are shown in table 1 for the set of 12 consonants.

The Three Consonants /f, s, χ/

Before taking into consideration all consonants, consider how locus equation slopes vary with place of articulation in three fricative consonants: a labial /f/, a dental /s/ and a uvular /χ/. This provides a comparable experimental condition on the basis of which locus equations have been proposed as a descriptor of place of articulation: the labial /b/, the dental /d/ and the velar /g/ [Sussman et al., 1991]. An uvular consonant, /χ/, is taken since there is no velar fricative in Arabic. The mean slopes for /f/, /s/, and /χ/ were 0.92, 0.56, and 0.90, respectively (see fig. 1 for mean locus equation scatterplots for these three consonants). The slope values for labial /f/ and dental /s/ compare with the mean slope values for labial /b/ and dental /d/ of Sussman et al. [1991] and Fowler [1994]. In Sussman et al. [1991, from fig. 2] the slopes for /b/, /d/, and /g/ were 0.91, 0.54, and 0.66, respectively; and in Fowler [1994, from her fig. 1], they were 0.80, 0.48, and 0.71, respectively. So the general tendency that a labial has a steeper slope than a dental is replicated. Fowler's [1994] explanation for this tendency is that since a labial does not involve the tongue body as a main articulator, the tongue is free to coarticulate with the vowel. For a dental, however, the tongue is the main articulator for both the consonant and the vowel, so the consonant can resist vowel-induced coarticulation. Surprisingly, uvular /χ/ which also involves the tongue in its articulation has a steeper slope than /s/. A possible explanation is that since in Arabic there is no contrasting velar /x/, uvular /χ/ can admit of more vowel coarticulation; there would be no perceptual confusion between a fronted /χ/ or a backed /χ/. This explanation is similar to that given by Fowler [1994] for velar /g/ in English which has a steeper slope, although it is articulated with the tongue.

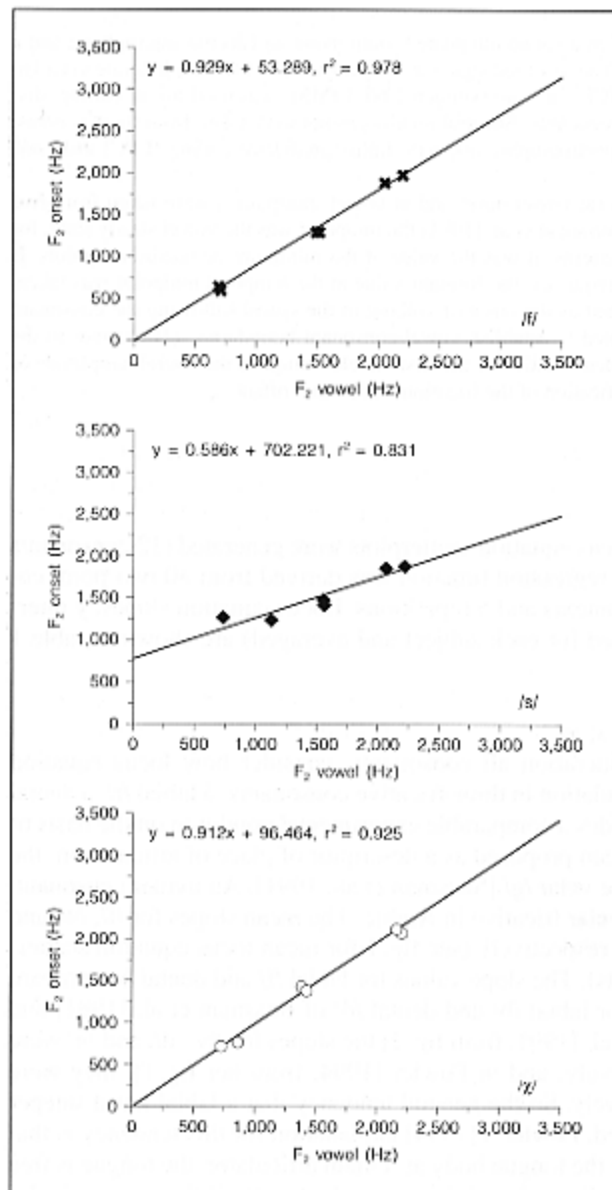


Fig. 1. Locus equation scatterplots for labial /b/, dental /s/, and uvular /x/ averaged across all speakers.

The Set of All 12 Consonants

A repeated-measures ANOVA was performed on the slope values as the dependent variable, the effect of consonant was highly significant [$F(11, 88) = 100.17, p = 0.0001$]. In another repeated-measures ANOVA on the intercept values, the effect of consonant was also significant [$F(11, 88) = 62.95, p = 0.0001$]. In post hoc tests (Fisher PLSD and Scheffé F test), most slope and intercept differences were significant.

One of the main purposes of this study was to determine to what extent locus equations can distinguish consonants belonging not only to different place categories but also to different manner classes. Following Fowler [1994] and Sussman and Shore [1996], if slopes and y intercepts for consonants sharing the same place of articulation, but differing in manner of articulation do not differ significantly, then locus equations can serve as a general descriptor for consonantal place across manner classes. However, locus equation slopes were found to differ statistically for consonants belonging to the alveolar group in the following cases. The slope for /t/ (0.66) was significantly steeper than that for /s/ (0.56) [$t(8)=-3.77$, $p=0.0055$], and than that for /d/ (0.48) [$t(8)=-9.33$, $p=0.0001$].

An explanation might be given for the high slope value obtained for the aspirated /t/ (0.66) in the present study by invoking a measurement limitation rather than a phonetic interpretation. In Sussman and Shore [1996], the traditional procedure for measuring F_2 onsets at the first glottal pulse of the vowel was not followed for aspirated /t/. F_2 onset was taken at the first visible F_2 resonance during the aspiration interval subsequent to the burst release. The mean slope value obtained in their study (/t/ slope = 0.23) is quite different from our value. The same problem seems to be raised by the high slope value for fricative /s/ obtained in the present study as well as in Sussman and Shore [1996] (0.56 and 0.57, respectively). In Sussman and Shore [1996], the slope for /s/ was statistically different from the other alveolars /t, d, z/. They argued that this should not occur if F_2 onset was assessed within the friction interval, which is not possible to do in a systematic and consistent way.

Another method for testing the capability of locus equation metric as a general descriptor of consonantal place is to extend it to continuant-type consonants. One would expect that labial /f/, interdental /ð/, alveolar /s/, postalveolar /ʃ/, uvular /χ/ and pharyngeal /ħ/ should not overlap with each other in a locus equation space. If locus equation coefficients remain distinctive for these different place categories, then their scope is not limited to oral stops.

Analysis of locus equation slopes and y intercepts reveals certain cases where differences in place categories are not captured by locus equation parameters. First, the slope of postalveolar /ʃ/ (0.62) did not differ significantly from that of pharyngeal /ħ/ (0.68) [$t(8)=1.29$, $p=0.094$]. Then, the slopes for alveodental /d/ and interdental /ð/ (0.48 and 0.46, respectively) were statistically not distinct [$t(8)=0.69$, $p=0.511$]. Finally, the labial /f/ and uvular /χ/ had indistinguishable slopes [$t(8)=0.91$, $p=0.388$, with values 0.92 and 0.90, respectively]. The intercepts did not distinguish these pairs of consonants, either. /ʃ/ did not differ from /ħ/ [$t(8)=2.07$, $p=0.071$], /d/ from /ð/ [$t(8)=-0.98$, $p=0.357$], and /f/ from /χ/ [$t(8)=-2.03$, $p=0.077$].

Figure 2 plots locus equation slope by y intercept values obtained from the 9 speakers producing all the consonantal categories of the present study. Inspection of the scatterplot reveals that, in its lower right quadrant of space, there is no clear separation of labial /f/ co-ordinates from uvular /χ/ co-ordinates. There is not a sufficient contrast of postalveolar /ʃ/ co-ordinates (squares) with respect to those of the alveolar group (lozenges).

So it seems that locus equations do not reflect accurately certain place-of-articulation distinctions, as the many examples have shown. This finding might be used against the applicability of locus equations to continuant-type obstruents. Since locus equation coefficients were not distinctive for many continuant place categories, their scope might be considered to be limited. Specification of fricative place of articulation

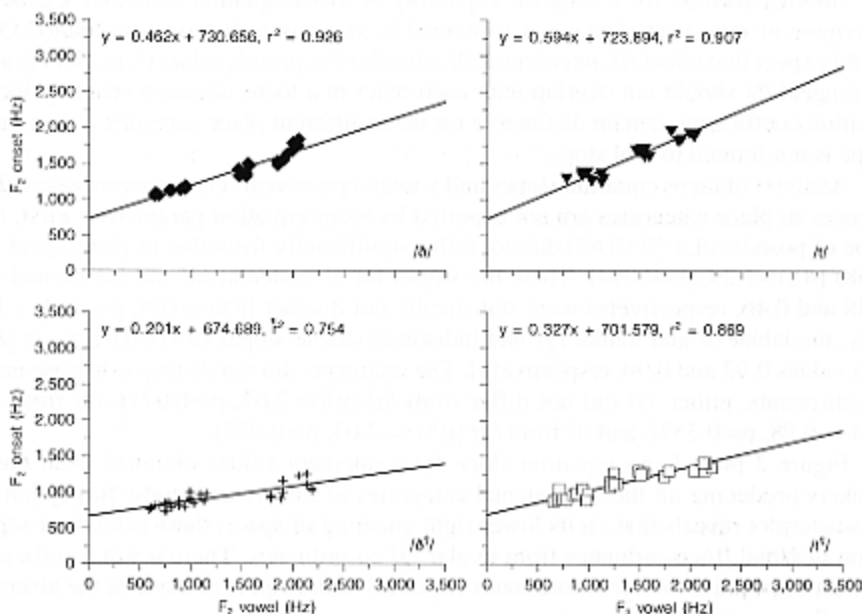
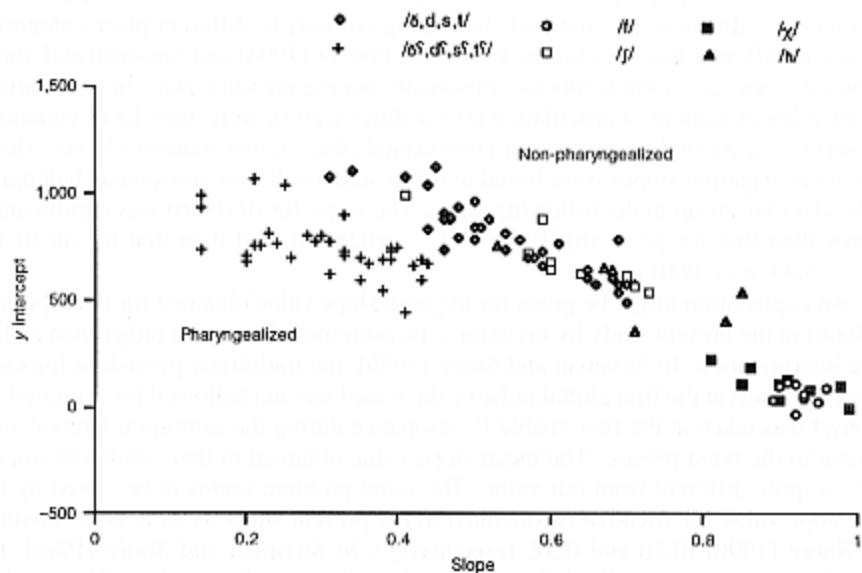


Fig. 2. Locus equation slopes and y intercepts for all 12 consonants across all speakers. Pharyngealized consonants include /ð, d, t, s/ and non-pharyngealized consonants include both the cognates /ð, d, t, s/ and the non-cognates /l, ʒ, h/.

Fig. 3. Locus equation scatterplots for /lʲ/ vs. /l/ and for /hʲ/ vs. /h/ from subject 2.

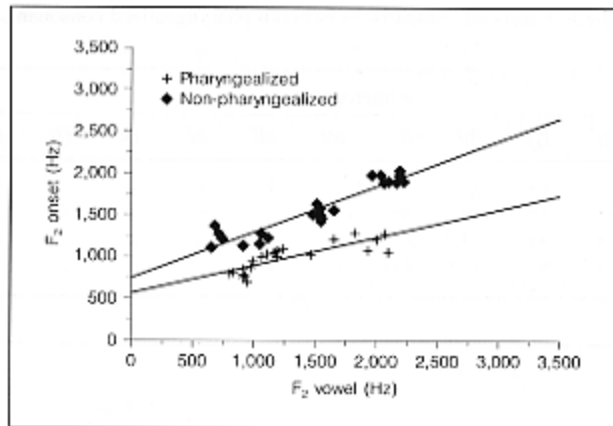


Fig. 4. Locus equation scatterplots for all pharyngealized consonants /d^ɣ, d^ʕ, t^ɣ, s^ɣ/ and their non-pharyngealized cognates /d, d, t, s/ across all speakers.

depends on sufficient information found in the spectral properties of frication noise in /s/ versus /ʃ/ and /z/ versus /ʒ/ [Stevens, 1960; Heinz and Stevens, 1961]. Distinction of uvulars /χ, ʁ/ from pharyngeals /ħ, ʕ/ needs the onset value of F₁, which is found to be higher for pharyngeals [Alwan, 1989; Yeou and Maeda, 1995]. In two perceptual experiments, the onset frequency of F₁ was found to be critical in distinguishing uvulars from pharyngeals, while that of F₂ was not [El-Halees, 1985; Alwan 1989].

The foregoing is not to suggest that locus equations are uninteresting. They demonstrated significant differences involving many slope comparisons for consonants such as /d^ɣ/ and /s^ɣ/ (0.46 and 0.56) versus /t/ (0.92), /ʃ/ (0.62), /χ/ (0.90) and /ħ/ (0.68). Locus equation parameters (slope and y intercept) were successful in distinguishing pharyngealized consonants from non-pharyngealized ones, as is shown below.

Pharyngealized Consonants as a Distinct Class

Table 1 shows that the slopes of pharyngealized consonants /d^ɣ, d^ʕ, s^ɣ, t^ɣ/ are quite flatter than those of their non-pharyngealized cognates /d, d, s, t/. A repeated-measures ANOVA comparing slope values (as the dependent variable) for the two categories showed a highly significant main effect for pharyngealization [F(1, 35)=293.78, p=0.0001]. Post hoc tests (Fisher PLSD and Scheffé F test) showed significant differences between each pair: any pharyngealized consonant vs. any non-pharyngealized one. Figure 3 illustrates representative locus equation scatterplots for two pharyngealized /d^ɣ, t^ɣ/ vs. two non-pharyngealized consonants /d, t/ (from speaker 2).

Figure 4 presents group mean locus equations obtained across all speakers for the two categories: pharyngealized consonants /d^ɣ, d^ʕ, t^ɣ, s^ɣ/ and their non-pharyngealized cognates /d, d, t, s/. It can be seen that the locus scatterplots for these categories are quite distinct and non-overlapping. Pharyngealized consonants have flatter slopes and relatively lower intercepts. This finding is consistent with the preliminary results of Sussman et al. [1993], who found that pharyngealized /d^ɣ/, in comparison with /d/, has a flatter locus equation slope and a lower intercept.

Table 2. Results of Fisher PLSD and Scheffé F tests on comparisons between pharyngealized consonants and non-pharyngealized ones for slope and y intercepts

	Slope								y intercept							
	/f/	/ð/	/d/	/t/	/s/	/ʃ/	/tʃ/	/h/	/f/	/ð/	/d/	/t/	/s/	/ʃ/	/tʃ/	/h/
/ð/	**	**	**	**	**	**	**	**	**	-	*	*	-	-	**	*
/d/	**	*	**	**	**	**	**	**	**	-	-	*	-	*	**	*
/t/	**	*	*	**	**	**	**	**	**	*	**	-	-	-	**	-
/s/	**	*	*	**	**	**	**	**	**	*	**	-	-	-	**	-

* $p < 0.05$, ** $p < 0.01$; - = non-significant.

Furthermore, inspection of figure 2 which plots locus equation slope by intercept for all consonants across all speakers reveals a sufficient separability of pharyngealized consonants from any non-pharyngealized consonants (whether they be their cognates or not). Pharyngealized consonants constitute, then, a distinct non-overlapping class having the flattest slopes of all consonants. The results of post hoc tests (Fisher PLSD and Scheffé F test) used to analyse differences between the two consonantal categories for slope and y intercept values are shown in table 2. All slope comparisons were significant (at either $p = 0.01$ or $p = 0.05$) and more than half of the intercept comparisons were significant.

The Haskins-Type Consonantal Locus

Since pharyngealized consonants are characterized by having the flattest locus equation slopes of all consonants, they would be expected to be somehow closer to the traditional Haskins-'locus' concept [Delattre et al., 1955]. Before dealing with the relationship between locus equation slopes and the 'invariant locus', we examine Krull's [1988] figure which illustrates the information on the degree of CV coarticulation that locus equation slopes can provide [see also Sussman et al., 1993]. Figure 5 illustrates two extreme cases of the degree of coarticulation: In figure 5a steep slopes are indicative of maximal coarticulation of the consonant with the following vowel (i.e. minimal coarticulatory resistance of the consonant gesture), while in figure 5b flat slopes indicate absence of vowel coarticulatory effects (i.e. maximal coarticulatory resistance of the consonantal gesture).

The latter extreme case is indicative of an invariant consonantal locus that is not dependent on the articulation of the adjacent vowel. This provides a condition that would correspond to the 'virtual locus' concept. Figure 5c shows that the coarticulatory behaviour of pharyngealized consonants comes closer to the ideal case in figure 5b, by virtue of their flatter slope. So pharyngealized consonants constitute a class of consonants that resist most to the coarticulatory influence from the neighbouring vowels, and thus reflect a more stable consonantal locus across all vowel contexts. A 'virtual locus' concept would possibly be realized for these consonants.

As in Sussman et al. [1991] 'locus' values were derived from locus equation plots by computing the intersection point of the locus equation regression line with the 45-degree diagonal indicating that the frequencies of F_2 onset and F_2 vowel are equal. Computation of the intersection point was done by relating the locus equation as

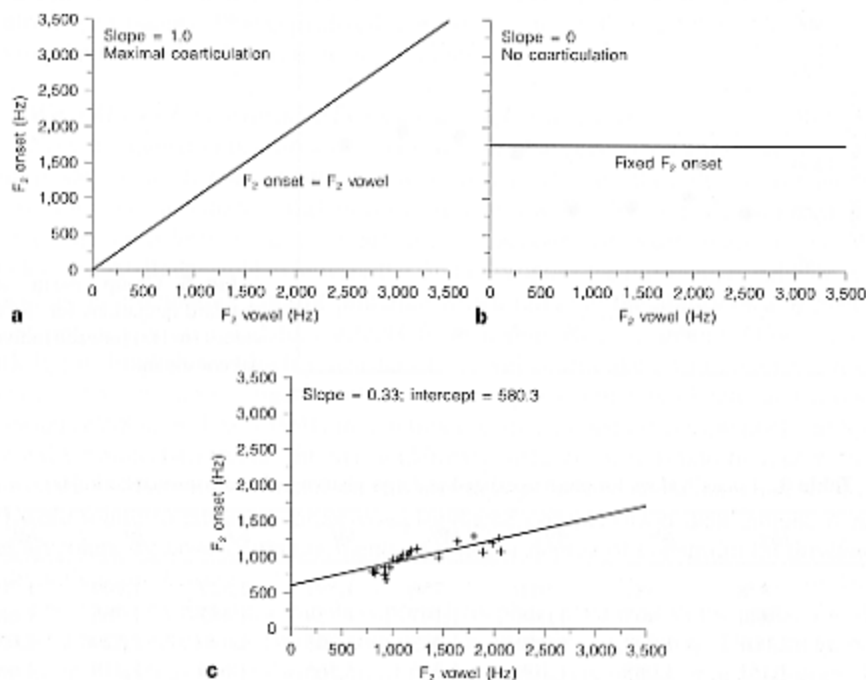


Fig. 5. Schematic representation of two extreme cases of the degree of coarticulation indicated by locus equation slopes. **a** Maximal coarticulation. **b** Absence of coarticulation. **c** Coarticulatory behaviour of pharyngealized consonants.

expressed in the function $y = ax + b$ to the function $y = x$ (where $x = F_2$ vowel and $y = F_2$ onset).

Group mean 'locus' values along with their standard deviations for pharyngealized and non-pharyngealized consonants are given in table 3 and illustrated in figure 6. Pharyngealized consonants have lower 'locus' values than non-pharyngealized ones (with range values: 996–1,192 and 1,625–1,844 Hz, respectively). It can clearly be seen from figure 6 that the consonantal 'loci' of pharyngealized consonants are quite distinct and do not overlap with those of their non-pharyngealized cognates. A two-tailed *t* test indicates that the difference between the two 'loci' is highly significant [$t(35) = 23.16$, $p = 0.0001$]. Moreover, as standard deviation values are quite respectable, these 'loci' can be considered to be reliable invariant-like descriptors of place category. The consistency of the derived 'loci' for pharyngealized consonants and their non-pharyngealized cognates could be considered in the spirit of Delattre et al. [1955]. The mean 'locus' value for /d/ was 1,794 Hz, which is very close to the 1,800-Hz value reported in the Delattre et al. [1955] synthesis study. Also, the average 'locus' for pharyngealized /sʕ/ (= 1,047 Hz) closely agrees with the F_2 resonance frequency (= 992 Hz) calculated from an idealized acoustic model for the production of /sʕ/ [Yeou, 1996].

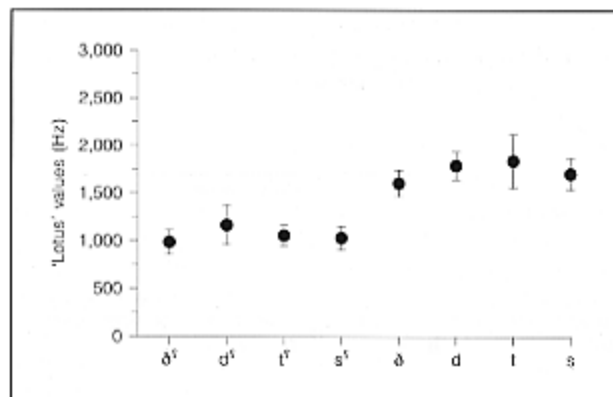


Fig. 6. Group mean and standard deviations for 'locus' values (in Hz) for each individual consonant.

Table 3. 'Locus' values for pharyngealized and non-pharyngealized consonants (in Hz)

	/δʰ/	/sʰ/	/tʰ/	/dʰ/	/δ/	/s/	/l/	/d/
S ₁	878	887	911	756	1,591	1,527	1,709	1,708
S ₂	844	907	1,048	1,197	1,354	1,482	1,766	1,681
S ₃	1,001	1,093	1,240	1,383	1,763	1,770	2,529	2,051
S ₄	1,151	1,088	1,108	1,336	1,565	1,664	1,719	1,686
S ₅	1,112	1,078	1,040	1,149	1,658	1,615	1,640	1,616
S ₆	1,055	1,143	1,133	1,344	1,570	1,967	1,910	1,854
S ₇	858	938	972	1,001	1,679	1,694	1,817	1,831
S ₈	1,117	1,209	1,191	1,226	1,819	1,875	1,842	1,916
S ₉	949	1,079	1,044	1,336	1,630	1,770	1,667	1,800
Mean	996	1,047	1,076	1,192	1,625	1,707	1,844	1,794
SD	119	111	103	203	133	157	271	137

The typical lowering of 'locus' values for pharyngealized consonants can be thought of as reflecting a fixed articulatory place of production or an invariant articulatory gesture, i.e. pharyngealization. Pharyngealization involves a rearward movement of the back in the tongue towards the pharyngeal wall and a depression of the tongue's palatine dorsum, resulting in a widened oral cavity. This seems to account for the low 'locus' values obtained for pharyngealized consonants.

Discussion

The present study attempted to explore to what extent locus equations can distinguish between different consonants varying in place and manner of articulation. Findings confirm earlier ones in two ways. On the one hand, locus equations do not reflect certain place-of-articulation distinctions when many consonants varying both in place and manner of articulation are taken into consideration. On the other hand, locus equa-

tions are successful in distinguishing place between pharyngealized and non-pharyngealized consonants. Pharyngealized consonants emerged as a totally distinct class, having the flattest locus equation slopes of all consonants.

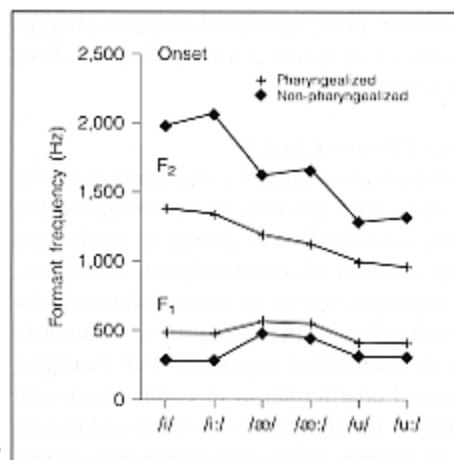
What Makes Pharyngealized Consonants a Distinct Class?

Now the question that arises is: why should pharyngealized consonants have the flattest slopes of all consonants? In other words, why are they the consonants that resist most to coarticulatory influences from the vowels? Before giving an explaining answer, let us briefly review an interpreting account of coarticulation resistance. Bladon and Al-Bamerni [1976] were the first to propose the term 'coarticulation resistance' as an articulatory control principle which refers to the ability of a segment to resist potentially coarticulatory effects from neighbouring segments. For example, dark [ɫ] in English was highly resistant to vowel coarticulation in comparison with clear [ɫ̥]. Extensive investigation of coarticulatory resistance has been carried out by Recasens [1984a, b, 1987, 1991] in a number of studies, using consonants from Spanish and Catalan. Differences in coarticulatory resistance were found to vary with the consonant's differential demand on the articulators involved. Palatals and velarized [ɫ̥] were found to admit of lesser vowel-induced coarticulation than labials, dentals and alveolars, because of requirements of a larger degree of constraint on the tongue body in their production.

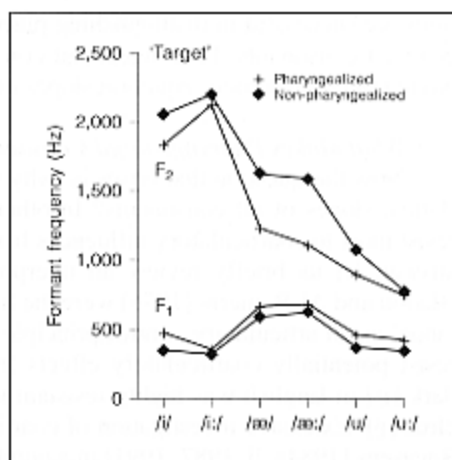
The same explanation can be applied to pharyngealized consonants, for they impose a high requirement on the tongue body in their articulation. The tongue body constraint is related to the formation of two simultaneous places of articulation: (1) a primary articulation at the dental/alveolar region by means of apical contact, and (2) a secondary articulation at the pharyngeal region by means of dorsoradical contact [Ali and Daniloff, 1972; Ghazeli, 1977]. Pharyngealized consonants pattern analogously to velarized [ɫ̥]. As was said earlier, [ɫ̥] was one of the consonants that were highly resistant to vowel coarticulatory effects in English and in Catalan. This is because production of [ɫ̥] also involves a high constraint on the tongue body in terms of a double place of articulation, one at the alveolar region and the other at the pharyngovelar region.

Farnetani [1990] remarked in her review of the literature on coarticulation that segments that are highly resistant to coarticulation are also those that induce strongest coarticulatory effects on the neighbouring segments. As a matter of fact, pharyngealized consonants are known to exert strong backing coarticulation effects generally on more than one adjacent segment, be it a vowel or a consonant. An example is the considerable lowering of F_2 at the onset of the front vowels /i:/, /i/, reflecting the high resistance of pharyngealized consonants to conflicting gestures, namely tongue fronting and raising.

To further investigate the effect of pharyngealized consonants /ð^v, d^v, s^v, t^v/ on the following vowels, we have measured the frequency of the first formant (F_1) at the onset of the vowel and at the steady state to complement the F_2 measurements. Vowels in the context of the non-pharyngealized correspondents /ð, d, s, t/ were also measured to provide a comparable condition. Overall, 405 sequences were processed spanning 8 consonants × 5 repetitions × 9 speakers. For interpretation purposes consonants of direct interest were grouped into two categories: (a) pharyngealized /ð^v, d^v, s^v, t^v/ and (b) non-pharyngealized /ð, d, s, t/. Figure 7 gives average F_1 and F_2 frequencies at the onset of the vowel, and figure 8 at the vowel steady state.



7



8

Fig. 7. Formant frequencies for F₁ and F₂ in Hertz for eight vowels plotted as a function of two different categories of consonants: pharyngealized /ð^h, d^h, s^h, t^h/ vs. non-pharyngealized /ð, d, s, t/. Data were averaged across repetitions and speakers.

Fig. 8. Values of F₁ and F₂ in Hertz for eight vowels as a function of two different categories of consonants: pharyngealized /ð^h, d^h, s^h, t^h/ vs. non-pharyngealized /ð, d, s, t/.

It can clearly be seen from figures 7 and 8 that pharyngealized consonants influence to a large degree the articulation of all the vowels. This influence is reflected by a lowering of F₂ and a raising of F₁, relatively both at vowel onset and at steady state. When examining in detail both figures 7 and 8, several general observations emerge as to the extent of coarticulatory effects induced by pharyngealized consonants. First, the influence of the pharyngealization gesture is more extensive at the beginning of the vowel than at the steady-state period. Still traces of this gesture occur significantly during the vowel. Second, the extent of pharyngealized consonant-to-vowel effects differs from one vowel to another: (a) The low vowels /æ, æ:/ oppose the other vowels in showing the influence of pharyngealized consonants similarly both at vowel steady state and onset. The reason for this is that the articulation of /æ, æ:/ is naturally more compatible with the pharyngealization gesture than the high vowels /i:, i, u:, u/. (b) The short vowels /i, u/ show the effects of pharyngealization more obviously than the long vowels /i:, u:/. The time factor seems to play a role here: duration is known to affect coarticulation.

The findings of this study are not meant to suggest that locus equations invariably and uniquely specify the place-of-articulation distinction between pharyngealized consonants and non-pharyngealized ones. This distinction certainly relies on other cues. For instance, the contrast between pharyngealized /s^h/ and non-pharyngealized /s/ in the context of the vowel /i:/ is based on the integration of both the onset F₁ transition and the onset F₂ transition [Yeou, 1995]. The noise friction provides yet another source of information for this distinction. In addition, there are other important cues that may contribute to the contrast between the other pharyngealized and non-pharyngealized consonants, such as the burst noise for the /t^h/ - /t/ contrast, and the spectral consonantal characteristics for the /ð^h/ - /ð/ contrast.

One interesting aspect of locus equations as a source of place information for the pharyngealized/non-pharyngealized distinction is the following: they express the dynamics of the F_2 transition which is a critical acoustic cue for the perception of this distinction, and which is basically similar for all pharyngealized consonants. The fact that these pharyngealized consonants (voiced and voiceless fricatives and stops) are clustered as a separate and non-overlapping class is an interesting finding.

From the point of view of locus equations, the pharyngealized/non-pharyngealized contrast is seen differently. Traditional accounts of this contrast have focused on the coarticulatory influence of pharyngealized consonants on the adjacent vowels. The inverse direction, that is the differential coarticulatory effects of vowels on pharyngealized consonants and non-pharyngealized ones, has been overlooked. The present study showed two related findings: (1) Since pharyngealized consonants have the flattest locus equation slopes, they are the most resistant to coarticulatory effects from the adjacent vowels. This seems to be due to their double articulation, which represents a high constraint on the tongue body. (2) Because pharyngealized consonants highly resist coarticulation from adjacent vowels, they induce a considerable coarticulatory influence on these vowels.

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