CONSISTENCIES AND INCONSISTENCIES BETWEEN EPG AND LOCUS EQUATION DATA ON COARTICULATION

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ABSTRACT

Following a previous study using locus equation (LE) and electropalatographic (EPG) data to examine coarticulation of voiced consonants and vowels in CV syllables [1], the present study examines voiceless stops and fricatives using the same analysis techniques. It is found that when LE data for stops is sampled at the stop burst, rather than at vowel onset, the correlation between LE data on coarticulation and EPG data on coarticulation is quite high. By contrast, results for the fricatives are quite poor. It is suggested that the LE is capable of capturing rather gross differences in coarticulatory resistance, such as that involving a tongue tip rather than a tongue body, but that it is not capable of capturing more subtle differences in coarticulation, such as those involving different coronal articulations. This explanation is supported by work in progress on Australian Aboriginal languages which have up to four coronal places of articulation [2].

1. INTRODUCTION

Locus equations are regression analyses of F2 transition data (with F2 onset plotted as a function of F2 target), and were first used by Lindblom [3] in a spectrographic study of vowel reduction (see [4] for references to other studies on locus equations). It was subsequently suggested by Krull [5, 6] that the slope value derived from locus equations could be used to infer the degree of coarticulation between a consonant and its adjacent vowel, with a slope value of zero suggesting a high degree of coarticulatory resistance and a slope value of one suggesting a high degree of coarticulatory adaptation. The purpose of the current study is to test this hypothesis using electropalatographic (EPG) data on voiceless stops and fricatives in English.

The technique of electropalatography [7] has been used in numerous studies on coarticulation involving different lingual consonants (for some summaries of the literature see [8, 9, 10]). A total contacts measure, which sums the number of electrodes contacted at any particular point in time [8] is used in the present study, as it allows for easy quantification of the variability in contact patterns according to vowel context. In a consonant that is not highly resistant to coarticulation, a high vowel context, such as /i/, would have more contacts than a low vowel context, such as /ɐ/, since the tongue body is higher in the former resulting in more bilateral contact between the tongue and the palate.

2. METHOD

Four female speakers of Australian English served as subjects for the experiment. Stimuli consisted of the consonants /θ s ʃ t k/ combined in CV syllables with the 12 monophthong vowels of Australian English /ɪ e æ ɐ ɔ ʊ ɨ: e: ɐ: o: ʉ: ɜ:/ [11]. CV combinations were placed in the carrier phrase “Doctor __ba”. Since Australian English is non-rhotic, the target syllable was preceded by a schwa. Each speaker produced 5 utterances of each target phrase.

EPG and acoustic data were recorded simultaneously, with each speaker wearing a custom-made artificial palate embedded with 62 electrodes. The palates were designed to interface with the Reading EPG3+ system which was used for the analysis. Data were hand-segmented and labelled using the WAVES+ signal processing system; formants were automatically tracked in this system and hand-corrected. Vowel onset following both the stop and the fricative was labelled at the onset of voicing. The stop burst was labelled separately. All subsequent analysis of data was carried out using the EMU speech database analysis system [12].

Two sets of results will be presented: firstly, means and standard deviations for the total contacts data and for the F2 onset data will be presented. Following this, locus equation results will be presented as well as regression analyses of the EPG data, with total contacts at the (acoustic) consonant midpoint as the dependent variable, and total contacts at the (acoustic) vowel target as the independent variable. The aim of this regression analysis on the EPG data is to make the two sets of data, acoustic and articulatory, more comparable.

3. RESULTS

Tables I and II present means and standard deviations for F2 onset and EPG total contacts respectively. Note that the F2 onset values presented for the stop consonants were taken at stop burst release, not at vowel onset. Although analyses were carried out using both sampling points, it was found that when data were sampled at stop burst release, a much higher correlation between the acoustic and EPG data was obtained. For this reason, stop data sampled at vowel onset will not be considered further.

	Speaker	Mean	S.D.	N
θ	1	1928	319	62
	2	1733	235	61
	3	1836	236	63
	4	1849	150	61
s	1	1983	321	60
	2	1794	207	60
	3	1842	300	61
	4	1909	208	62
ʃ	1	2076	281	60
	2	2051	177	60
	3	2057	322	60
	4	2058	161	62
t	1	2041	234	62
	2	2035	145	60
	3	1913	166	60
	4	2101	127	60
k	1	1956	395	60
	2	2064	508	60
	3	1983	439	63
	4	2040	492	60

Table 1: Means and standard deviations for F2 onset data (in Hz) for four female speakers of Australian English. Note that for the stop consonants, F2 onset is measured at stop burst release rather than at vowel onset.

	Speaker	Mean	S.D.	N
θ	1	8.51	3.17	62
	2	0.86	0.86	61
	3	5.17	1.99	63
	4	14.37	2.16	61
s	1	21.45	3.14	60
	2	16.10	3.01	60
	3	24.63	1.65	61
	4	21.95	1.06	62
ʃ	1	25.16	2.24	60
	2	22.36	3.67	60
	3	26.21	2.10	60
	4	23.88	2.13	62
t	1	35.56	4.04	62
	2	29.00	2.32	60
	3	30.40	2.67	60
	4	24.11	1.82	60
k	1	15.98	3.92	60
	2	9.83	2.80	60
	3	14.87	4.48	63
	4	20.61	5.35	60

Table 2: Means and standard deviations for total electrodes contacted (maximum possible = 62) at consonant midpoint for four female speakers of Australian English.

It can be seen that there is very little difference in F2-onset variability for the fricatives. For speakers 1 and 2, /ʃ/ seems to show less variability, while for speakers 3 and 4 it is /θ/. Results for the stops, by contrast, are quite consistent, with /t/ having the least variability of all the consonants presented, and /k/ having the most variability. In the total contacts data, the stop pattern is not so clear since the variability in velar contacts is not fully reflected due to limitations of the artificial palate. The expected pattern is clearest for speaker 4, who had the most fronted velar articulation, whereas the expected pattern is not evidenced for speaker 2 who had the most retracted velar articulation (these articulation strategies are reflected in the mean number of total contacts for these speakers, with a higher mean suggesting a more fronted articulation for the velar). By contrast, the fricative total contact data can be expected to be more reliable, and here we see inconsistencies with the F2 onset data. For speaker 1 it would appear that /ʃ/ has the least variability (consistent with her acoustic data) whereas for speaker 2 it would appear to be /θ/ (inconsistent with her acoustic data). For speakers 3 and 4, it would appear /s/ has slightly less variability than the other two fricatives. Thus, there are few parallels between the F2 and EPG data on fricatives.

Tables III and IV present regression analyses of the F2 data (= locus equations) and of the EPG data. Perhaps the first aspect to note is the very high r^2 values in the LE analysis and the very low r^2 values in the EPG analysis. This suggests a highly linear relationship between the consonant and the vowel in the acoustic data, but a situation in the EPG data where the vowel contributes little to the variability in consonant production. These trends are repeated in the slope values, which are a more direct measure of how the consonant varies according to vowel context.

The only exceptions to the above observations are /t/ in the LE data and /k/ in the EPG data. In the acoustic data, the lower slope values for /t/ reflect the more fixed "locus" for this consonant when measured at stop burst release. By contrast, /k/ has a significantly higher slope value for all speakers, suggesting that its "locus" is not as fixed due to the greater variability in production of this consonant. In the EPG data, the higher slope values for /k/ show that a regression analysis of the total contacts picks up on the variability according to vowel context which is obscured by a simple means and standard deviations analysis of the total contacts data.

	Speaker	y-int.	Slope	r^2
θ	1	771	0.61	0.89
	2	898	0.47	0.83
	3	983	0.46	0.84
	4	1138	0.39	0.85
s	1	798	0.62	0.90
	2	999	0.45	0.77
	3	748	0.59	0.87
	4	1068	0.46	0.84
ʃ	1	988	0.56	0.86
	2	1393	0.35	0.61
	3	869	0.62	0.86
	4	1262	0.42	0.85
t	1	1796	0.14	0.13
	2	1896	0.08	0.10
	3	1809	0.07	0.07
	4	1849	0.15	0.38
k	1	1043	0.49	0.52
	2	725	0.78	0.79
	3	757	0.62	0.75
	4	662	0.79	0.75

Table 3: locus equation data for all speakers. Locus and y-intercept values are in Hertz. Note that F2 onset for stops is taken at stop burst release.

	Speaker	y-int.	Slope	r^2
θ	1	6.47	0.27	0.40
	2	0.60	0.09	0.15
	3	4.12	0.20	0.35
	4	13.91	0.07	0.02
s	1	19.96	0.15	0.17
	2	14.93	0.27	0.16
	3	24.44	0.02	0.01
	4	21.52	0.05	0.11
ʃ	1	25.49	-0.03	0.01
	2	22.48	-0.02	0.00
	3	26.48	-0.03	0.01
	4	23.67	0.02	0.01
t	1	35.72	-0.02	0.00
	2	29.23	-0.06	0.01
	3	30.79	-0.05	0.02
	4	24.34	-0.03	0.01
k	1	13.13	0.41	0.52
	2	7.74	0.58	0.60
	3	11.04	0.61	0.57
	4	16.62	0.63	0.46

Table 4: Regression analyses for EPG data (total contacts - all rows). Total vowel contacts are taken at the acoustic vowel target, and total consonant contacts are taken at the consonant midpoint.

The extremely low (and with one exception, negative) slope values for /t/ and /ʃ/, coupled with the low r^2 values for this consonant, suggest that these consonants are highly resistant to coarticulation. There is, moreover, the possibility of some target overshoot (indeed, this is supported by an examination of the raw palatographic data) whereby there is more contact at consonant midpoint in the low-vowel context than in the high-vowel context.

Overall, fricative slope values are very low. The lowest slope values are for /ʃ/ for all four speakers. /θ/ has the highest slope value for speakers 1, 3 and 4, whereas for speaker 2 it is /s/. By contrast, an examination of the LE slope values shows very little consistency, again, between the two sets of data. For speakers 1 and 2, /ʃ/ has the lowest slope value, whereas for speakers 3 and 4 it is /θ/. There are similar mismatches for the other fricatives in the results of each individual speaker.

The overall correlation of LE slope values and EPG slope values is 0.98 for the stop consonants taken at stop burst release ($t = 12.17$, $df = 6$, $p = 0$) and 0.10 for the fricative consonants ($t = 0.32$, $df = 10$, $p =$ n.s.). Although tables of results are not presented here due to lack of space, significance tests on the regression data [13] show that differences between the stop consonants are highly significant in both the EPG and the LE data, whereas for the fricatives, differences that are significant for one speaker in one set of data are not necessarily so for the same speaker in the other set of data. As was seen above, some of the relative values between the three fricatives can even be reversed for the two sets of data.

4. CONCLUSION

There is very little correlation between the EPG and locus equation data on voiceless fricatives in English with regards to coarticulation. This parallels the results from an earlier study on voiced fricatives [1]. There is a high correlation, however, between the locus equation data and the EPG data on voiceless stops in English, provided that F2 onset is measured at stop consonant release, rather than vowel onset.

Whilst it is possible that the turbulence noise of the fricative obscures any formant transition into the following vowel, there are alternative interpretations of the poor fricative results. One explanation is that whilst a locus equation analysis can infer the relative coarticulatory differences between consonants with different active articulators (such as the alveolar and velar stops in English, which use tongue tip and tongue body articulations respectively) it can not do so for consonants which involve the same, or nearly the same, active articulators (such as the apical and laminal fricatives in English). This interpretation is supported by work on Australian languages, which have up to four coronal places of articulation: lamino-dental, apico-alveolar, apico-postalveolar and lamino-palatoalveolar [2].

Another interpretation is that coarticulatory differences between consonants are simply not always encoded in the acoustic signal. Work in progress, which uses RMS energy and the first spectral moment (or “centre of gravity”) in the fricative to examine spectral variability, suggests that when lip-rounded vowels are excluded from the analysis, there are very few correlations between the articulatory data and the spectral data. These results echo those of Soli [14, 15], who found that listeners were able to identify the following vowel from the sibilant fricative alone when the vowel was /i/ or /u/ (with the exception of /ʃi/, which contained lip-rounding in the fricative portion), but not when it was /a/. Thus, the spectra of voiceless fricatives are sensitive to lip-rounding, which affects the cavity anterior to the constriction at which turbulence is generated, but perhaps not so sensitive to tongue-body movement, which affects the cavity behind the constriction.

Overall, it would seem that both the fricatives and the alveolar stop /t/ are quite resistant to coarticulation, and it is the velar /k/ which exhibits the greatest coarticulation with the following vowel.

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