An Electropalatographic and Acoustic Study of Consonant-to-Vowel Coarticulation*

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Coarticulatory effects from consonants on vowels are investigated by means of electropalatography and acoustical analysis. The electropalatographic data confirm the validity of an articulatory classification of vowels in a front and a back categories. Moreover, vowels are shown to differ in degree of sensitivity to coarticulatory effects from the adjacent consonants. In general, consonant-dependent effects are larger upon those articulatory regions which do not intervene in the formation of a vowel constriction. Other gestural constraints (e.g., lip rounding for [u]) are called forth to interpret some data in lingual coarticulation. The paper also concludes that the degree of C-to-V coarticulation is influenced by the production requirements on the consonant; that explains why the degree of linguopalatal contact for [i] is more affected by velarized [l] than by other consonants. The electropalatographic data are correlated with acoustic (F2) data.

1. INTRODUCTION

While there is a good number of studies on vowel-to-consonant coarticulation, rather less attention has been paid to the coarticulatory effects of consonants on vowels. A possible rationale for this preference lies in the articulatory constraints used by speakers during the production of the two phonetic categories: on the one hand, vowels are resistant to coarticulation since they are produced by means of global vocal tract shapes and require articulatory control upon the entire tongue body configuration; on the other hand, consonants involve local constrictions and leave articulatory regions free to coarticulate (Fowler, Rubin, Remez, & Turvey, 1980).

Studies on C-to-V coarticulation show that vowels differ in degree of coarticulatory sensitivity. However these studies are almost entirely acoustic (Pols, 1977; Recasens, 1985; Stevens & House, 1963). In the absence of relevant production studies the articulatory correlates of the observed C-to-V effects must be inferred from the acoustic data. Articulatory data (such as those presented in this paper) are needed to gain some more understanding about the production mechanisms used by speakers when uttering CV or VC syllables. They should help to improve current speech production models as well.

A goal of this paper is to show that vowels are subject to coarticulatory effects from consonants in a way which is comparable to V-to-C coarticulatory trends. Thus, it is possible to attribute constriction locations to vowels (Wood, 1979) and generate a model of C-to-V coarticulation according to which some tongue regions are more sensitive to coarticulatory effects than others. The issue is, then, to investigate the size and the nature of the C-to-V effects and to come up with a rationale for such effects which is based on the articulatory properties of the vowels and consonants. An important notion here is that the amount of C-to-V coarticulation for a particular articulator is inversely related to the involvement of that articulator in the formation of the vowel constriction. Accordingly, effects on tongue dorsum activity ought to be much larger for [a] than for [i].

The analysis of coarticulation presented here is both electropalatographic (EPG) and acoustic (F2). An inconvenience with the palatographic
technique is that it provides accurate linguopalatal impressions for front vowels but little or no information for back vowels. This problem becomes less obvious when, as in the present investigation, back vowels are embedded in a consonantal context. In those circumstances consonant-dependent fronting and raising effects upon lingual activity cause linguopalatal contact during the production of the vowel; it thus becomes possible to analyze some C-to-V effects. The relationship between the EPG and the acoustic data is also studied in this paper. Only F2 data will be analyzed in view of the fact that there is a main correlation between the values of this formant, and the degree and location of linguopalatal contact (Fant, 1960).

2. METHOD

The sequences of the speech material conform to the phonology of Catalan. They share the segmental structure ['CVCa] when V1 is unreduced and [CV'Ca] when V1 is reduced. The V1 slot in the ['CVCa] sequences was filled with all the unreduced Catalan vowels, namely, [i], [e], [e], [a], [o], [o] and [u]; only [a] was uttered as V1 in the [CV'Ca] sequences. In all sequences C1 was identical to C2. The following Catalan consonants were chosen in order to analyze a large variety of C-to-V effects: bilabial [p]; apicodental [t]; apicoalveolar or laminoalveolar [s]; lamino-postalveolar [ʃ]; predorso-alveolopalatal [ɲ]; dorsopalatal [j]; front or back dorsovelar [k]; velarized apicoalveolar [l].

One Catalan speaker (the author) uttered the sequences ten times in the carrier sentence Diu ___ (“He says ___”). The overall number of sequences was 640 (8 vowels x 8 consonants x 10 repetitions). Simultaneous electropalatographic and acoustic recordings were made. The electropalatographic system (Rion Electropalatograph model DP-01) is equipped with 63 equidistant electrodes arranged in five semicircular rows (see Figure 1) and enables the recording of one pattern of contact every 15.6 ms. The distance between adjacent electrodes on the artificial palate used in the experiment reported here varies between 5 and 6 mm. Electrodes have been given a code number for each side of the palate, starting from the backmost electrode up to the frontmost electrode; thus, there are 8 electrodes on row 1, 7 on row 2, etc. It can be seen that the number of electrodes decreases as the rows become more central. Rows have also been numbered from 1 (peripheralmost row) through 5 (centralmost row). The figure also shows that some electrodes fall along a median line and, more specifically, that the two backmost electrodes on that line are not associated with any of the five semicircular rows. A division in articulatory zones (alveolar, prepalatal, mediopalatal, postpalatal) has been superimposed upon the surface of the electropalate.

![Figure 1. Electropalate.](image-url)
The EPG frame corresponding to the vowel midpoint (as detected on waveform displays) was selected for measurement. A valid criterion was the averaging of the number of “on” electrodes on each row across repetitions. Each average number corresponds to the point of maximal fronting since all electrodes behind the frontmost electrode on each row were always “on” for all the vowels in all the consonantal contexts. Three F2 measurements were taken at the vowel midpoint by means of an LPC analysis program available in the ILS (Interactive Laboratory System) package; F2 data presented in this paper represent averages across repetitions.

3. ELECTROPALATOGRAPHIC DATA

3.1 Vowel-dependent linguopalatal configurations

3.1.1 Articulatory characteristics

Figure 2 displays linguopalatal contact for each vowel in the context [pVp]. Since the bilabial stop involves no active tongue movement during its production it should have a minimal effect upon the tongue movement of the adjacent vowel.

Electrodes have been coded on the vertical axis; rows have been coded on the horizontal axis. The contour lines in the figure connect the points of maximum linguopalatal fronting on each row. Linguopalatal contact takes place over the area between the contour lines and the sides of the figure. The vertical line along the median line of electrodes separates patterns of linguopalatal contact at the right and left sides of the artificial palate; the division in articulatory zones coincides with that in Figure 1.

The place of maximum constriction for the front vowels ([i], [ɛ] and [ε]) in the figure is towards the mediopalate and postpalate and involves the tongue dorsum. The figure also shows a decrease of contact area all over the palatal surface in the progression [i]>[ɛ]>[ε], which is in agreement with X-ray data for several languages (Wood, 1982). These three front vowels differ in the degree of contact along the front/back and right/left dimensions: the tongue sides achieve the alveolar zone for [i], hardly so for [ɛ] and not at all for [ε]; central contact decreases in the same progression (i.e., [i]>[ɛ]>[ε]). Therefore, tongue fronting decreases with decreasing tongue height. These EPG data are consistent with the view that the fronting and raising of the tongue body for the production of front vowels are executed by means of a single gesture (also Harshman, Ladefoged, & Goldstein, 1977).

Figure 2. Linguopalatal contact for each vowel in the context [pVp].
The vowels [a], [o], and [u] are articulated farther back on the palatal surface; indeed, frontmost contact in this case hardly reaches the prepalate. Those are therefore back vowels. It can also be seen that the linguopalatal traces for [o] and [a] lie behind those for [a] and [u]. Thus it appears that vowels which are articulated with an upper pharyngeal constriction (i.e., [o] and [a]) show less palatal contact than those that are articulated either at the lower pharynx (i.e., [a]) or at the velar region (i.e., [u]). A rationale for this contrast is to be found in the overall tongue body configurations (see, for example, X-ray diagrams in Fant, 1960): the front dorsum is lowered and retracted during the production of [u], [a] and [o], and lowered but not retracted during the production of [a]. As a result of these mechanisms the front dorsum for [a] is flat and more fronted than for back rounded vowels. Larger front dorsum contact for [u] than for [a] and [o] is consistent with a higher position of the jaw and tongue body.

The linguopalatal configuration for the schwa is more similar to that for back vowels (particularly [a]) than to that for front vowels. This is so because no raising of the front dorsum is required for the production of [a], particularly when the schwa is coarticulated with a low vowel (i.e., V2=[a]).

These data show that there is a good correlation between the EPG traces, and a front and a back class of vowels. Recent production studies using other analysis techniques confirm the validity of this articulatory division (Alfonso & Baer, 1982; Baer, Alfonso, & Honda, 1988).

3.1.2 Variability of linguopalatal contact and linguopalatal asymmetry

Figures 3 through 10 show linguopalatal contact in number of “on” electrodes for all the Catalan vowels as a function of all the adjacent consonants. Moreover Table 1 gives the means and standard deviations (SD) for all the vowels across consonantal contexts on each row of electrodes, both at the left and at the right sides of the palate. Empty slots in the table represent mean values smaller than .5. SD values give an estimate of the variability in degree of linguopalatal fronting on each row.

The means show the existence of asymmetry in degree of palatal contact for all vowels on all rows. As it can also be seen in the figures, the number of “on” electrodes on the right side of the palate is always larger than that on the left side. These data indicate that lingual asymmetry does not only occur for consonants (Hamlet, Bunnell, & Struntz, 1986; Marchal & Espesser, 1989) but also for vowels.

Table 1. Means and SD values in number of “on” electrodes across consonantal contexts. Data are given for each row of electrodes (1 through 5) on the right (RS) and left (LS) sides of the palate.

<table>
<thead>
<tr>
<th></th>
<th>Row 1</th>
<th>Row 2</th>
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<td>X</td>
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<td>SD</td>
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<tr>
<td>[i]</td>
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<td>.5</td>
<td>4.8</td>
<td>.5</td>
<td>3.8</td>
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<tr>
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<td>.4</td>
<td>5.8</td>
<td>.7</td>
<td>5.1</td>
</tr>
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<td>.6</td>
<td>4.3</td>
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</tr>
<tr>
<td>[e]</td>
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<td>.5</td>
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<td>LS</td>
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<td>LS</td>
<td>3.8</td>
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<td>RS</td>
<td>1.9</td>
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<tr>
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<td>1.7</td>
<td>4.7</td>
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<td>3</td>
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</tbody>
</table>
Figure 3. Linguopalatal configuration for [i] as a function of consonantal environment.

Figure 4. Linguopalatal configuration for [e] as a function of consonantal environment.
The SD values allow grouping the vowels into two categories, front and back. The group of front vowels (i.e., \([i, e, e']\)) always shows SD values below 1; Figures 3, 4 and 5 show indeed little variability in the configuration of the contour lines as a function of consonantal context. The group of back vowels (i.e., \([a, o, u]\), on the other hand, often shows SD values above 1; Figures 6, 7, 8 and 9 show large degrees of linguopalatal variability across consonantal environments.

In the case of front vowels, the fact that SD values are equally low on all rows suggests that the entire tongue dorsum is subject to a high degree of constraint. This finding is consistent with current hypotheses about the production of \([i]\). X-ray data reported by Perkell and Nelson (1985) show similar contextual variability for pellets positioned at the blade and the mediodorsum; small variability in vertical displacement suggests that those two lingual regions are positioned as a unit during the articulation of the vowel \([i]\). Kiritani et al. (1977) also found less context-dependent variability at the blade and mediodorsum than further back in the tongue for the Japanese vowels \([a, o, u]\). Moreover SD values are higher for \([u]\) than for \([a, o]\) and \([o]\) (see Figures 6 through 9. Also Recasens, 1985; Stevens & House, 1963). A rationale for the large degree of variability exhibited by \([u]\) is associated presumably with the lip rounding gesture (see § 3.2.3).

SD values are also very high for the schwa. Indeed, Figure 10 shows a great deal of consonant-dependent variability in linguopalatal contact. This is an expected trend since \([a]\) is unconstituted and should be highly sensitive to changes in the vocal tract configuration induced by the surrounding consonants.

### 3.2 Consonant-dependent effects in linguopalatal contact

#### 3.2.1 General characteristics

Figures 3 through 10 indicate that the size of the SD values given in Table 1 depends on the articulatory relationship between particular consonants and particular vowels. In order to find out more about the precise effect of consonants on vowels, the following procedure was applied.
Figure 6. Linguopalatal configuration for [a] as a function of consonantal environment.

Figure 7. Linguopalatal configuration for [o] as a function of consonantal environment.
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**Figure 8.** Linguopalatal configuration for [ɔ] as a function of consonantal environment.

**Figure 9.** Linguopalatal configuration for [u] as a function of consonantal environment.
In the first place, an index of linguopalatal fronting was obtained for each vowel in each consonantal context; for that purpose, the average number of “on” electrodes was calculated for each row across the right and left sides of the palate. Secondly, each index of linguopalatal fronting was subtracted from the fronting index in the neutral context \(pVp\). Results are plotted on Figures 11 through 18. The figures show the amount of deviation in number of electrodes for each vowel with respect to the neutral \(pVp\) context as a function of row number and consonantal context. Positive effects reflect an increase in linguopalatal contact with respect to the linguopalatal configuration in the \(pVp\) context; negative effects reflect a decrease in contact with respect to the neutral configuration. The magnitude of the deviation can be interpreted as a measure of the degree of C-to-V coarticulation.

In the case of the front vowels [i], [e] and [e] (Figures 11, 12 and 13) the number and size of the positive effects (i.e., effects in tongue dorsum raising and/or fronting) are not too different from those corresponding to the negative effects (i.e., effects in tongue dorsum lowering and/or backing). Moreover the contribution of the negative effects decreases as the vowel becomes lower while the contribution of the positive effects increases in the same progression. A low palatal vowel can become higher when adjacent to consonants which are produced with a higher tongue dorsum position; effects on a high palatal vowel, on the other hand, are mainly lowering effects.

Back vowels [a], [o], [o] and [u] (Figures 14 through 17) reveal a different pattern of C-to-V coarticulation. Firstly, there are almost no negative effects in this case: while velar [k] and velarized alveolar [l] mainly cause negative effects, all the remaining consonants cause an increase in degree of linguopalatal contact. As discussed in § 3.2.3, these coarticulatory effects accord well with the low positioning of the front dorsum of the tongue for back vowels, and the placement of that tongue region for the adjacent consonants (i.e., low in the case of [k] and velarized [l], and quite high in the case of dentoalveolars and palatals). Effects on the peripheral rows are larger for the higher vowels [o] and [u] than for the lower vowels [o] and [a]; they reflect tongue fronting and may very well be associated with a considerable lip rounding gesture during the vowel. Effects on the central rows 4 and 5 are only found for [u] consistently with the fact that fronting the tongue body during a high back vowel should involve an increase in dorsopalatal contact.

**VOWEL [ɔ]**

![Diagram](https://via.placeholder.com/150)

*Figure 10. Linguopalatal configuration for [ɔ] as a function of consonantal environment.*
Figure 11. Amount of deviation in number of electrodes for [i] with respect to the neutral context [pVp] as a function of row number and consonantal context.

Figure 12. Amount of deviation in number of electrodes for [e] with respect to the neutral context [pVp] as a function of row number and consonantal context.
Figure 13. Amount of deviation in number of electrodes for [e] with respect to the neutral context [pVp] as a function of row number and consonantal context.

Figure 14. Amount of deviation in number of electrodes for [a] with respect to the neutral context [pVp] as a function of row number and consonantal context.
Figure 15. Amount of deviation in number of electrodes for [ɔ] with respect to the neutral context [pVp] as a function of row number and consonantal context.

Figure 16. Amount of deviation in number of electrodes for [ɔ] with respect to the neutral context [pVp] as a function of row number and consonantal context.
The schwa (Figure 18) shows a similar pattern to that exhibited by [u] except for the rarity of negative effects and the presence of large positive effects at the center of the palatal surface. The front dorsum is thus more sensitive to coarticulation for the schwa than for back vowels. That tongue region is subject to less articulatory requirements for vowels which are unconstricted than for those which are produced with one or more articulatory constrictions.

Next I will analyze the C-to-V effects in more detail.

3.2.2 Effects on front vowels

3.2.2.1 Dental, alveolar and postalveolar consonants. Dental [t] causes a decrease of contact at the central palate for the vowel [i], which is consistent with the absence of contact at that same articulatory zone during the production of [t] (see Recasens, 1984). The more open vowels [e] and [ɛ] show an increase of contact at the peripheral rows when adjacent to the dental stop; this contact increase should be associated with the apicodental articulation (with simultaneous laminoalveolar contact) of the consonant as opposed to the lowered position of the blade and predorsum for the two vowels.

Alveolar [s] and postalveolar [ʃ] cause similar effects on [i]. On the one hand, rows 2 and 3 show some increase of contact; X-ray data reported by Carney and Moll (1971) also indicate that the predorso-mediadorsal constriction for [i] in the sequence [hiza] is narrower than that in the sequence [hiva]. On the other hand, the other rows (1, 4 and 5) show some decrease of contact; in an EPG study, Ohala and Kawasaki (1979) also found that [s] causes some loss of contact at the central rows of the artificial palate during the production of the vowel [i]. These C-to-V effects in linguopalatal contact suggest that the two fricative consonants are subject to the following articulatory requirements: (a) achievement of a laminal constriction, as suggested by the increase in contact on rows 2 and 3 during the vowel; (b) concave shaping of the medial groove, as suggested by the decrease in contact on rows 4 and 5 during the vowel. Indeed, contrary to traditional descriptions, there is good evidence for the primary place of constriction for [ʃ] being rather lamino-postalveolar than palato-alveolar (Hála, 1962; Konecná and Zawadowski, 1951; Recasens, 1986), and for alveolar [s] being rather laminal than apical (for British English, Bladon & Nolan, 1977; for Catalan, Recasens, 1986). The cross-contextual stability of the medial groove configuration for [s] and, more so, [ʃ] is also documented (for American English, Carney, & Moll, 1971; for Catalan, Recasens, 1986).

When adjacent to the more open front vowels [e] and [ɛ], coarticulatory effects associated with the formation of the primary constriction (for both consonants) and with the shaping of the medial groove (for [s]) are still found. In addition, [ʃ] causes some increase of dorsal contact at the central rows since this consonant is produced with some tongue dorsum raising, and the tongue dorsum position for [e] and [ɛ] is now lower than that for [i]. On the other hand, [s] causes some positive coarticulatory effects at the periphery (row 1) since the tongue front is higher for this consonant than for the vowels [e] and [ɛ].

3.2.2.2 Velarized alveolar consonant. The consonant [h] in Catalan is produced with a double articulation, namely, a primary apicoalveolar closure and a secondary dorsal constriction at the velar region or at the upper pharynx. A large cavity is found between these two places of articulation since the tongue dorsum is actively lowered at that vocal tract location (see Giles & Moll, 1975, and Fant, 1960, for similar realizations of velarized [h] in American English and in Russian, respectively).

When adjacent to front vowels, this consonant has a negative effect on all rows. Notice moreover that coarticulation is larger at the central rows than at the periphery of the palatal surface. Ohala and Kawasaki (1979) also found a decrease of central contact for [i] when adjacent to American English [t]. Overall, these data reflect the existence of antagonistic tongue dorsum mechanisms during the articulation of front vowels and velarized [h]: while front vowels require fronting and raising of the tongue dorsum, velarized [h] requires tongue dorsum lowering to bring about a “dark” acoustic quality and lowering of the sides of the tongue to allow lateral airflow.

3.2.2.3 Alveolopalatal, palatal and postpalatal consonants. These three consonantal categories are all produced with dorsal contact in the centropalatal zone. Their precise place of articulation is as follows (see Recasens, 1984, 1986 for the same speaker): postalveolo-prepalatal with the predorsum in the case of alveolopalatal [p]; prepalato-mediopalatal with the predorsum and mediodorsum in the case of palatal [j]; postpalatal with the postdorsum in the case of postpalatal [k] (i.e., fronted [k] with adjacent front vowels).
Figure 17. Amount of deviation in number of electrodes for [u] with respect to the neutral context [pVp] as a function of row number and consonantal context.

Figure 18. Amount of deviation in number of electrodes for [ə] with respect to the neutral context [pVp] as a function of row number and consonantal context.
When adjacent to [i] the three consonants cause a decrease of contact at the peripheral rows, more so for [j] and [k] than for [n]. This effect is consistent with the fact that the two former consonants are produced with less dorsal fronting than the latter. Moreover, [n] (but not [j] nor [k]) causes some increase of contact at the centropalatal zone. This finding is not in agreement with cross-consonantal differences in place of articulation; thus, negative effects ought to be larger for [n] than for [j] and front [k] if lingual pressure is higher at the front palate for [n], and at the mediopalate and postpalate for [j] and front [k]. Instead, these data suggest that articulatory control for [n] is exerted upon the entire tongue dorsum and is not directed towards the front dorsum only.

Coarticulatory patterns on [e] and [e] are similar to those on [i]. Overall, effects at the peripheral rows are mainly negative while those at the central rows are mainly positive. This is the expected trend since all these consonants share a dorsal constriction at the central palate. Positive effects at the center of the palate tend to increase as the vowel becomes lower (see § 3.2.1 for a rationale). As for [i], negative effects at the peripheral rows for these two vowels are less considerable with adjacent [n] than with adjacent [j] and front [k], while positive effects at the central rows show the opposite trend.

3.2.3 Effects on back vowels and the schwa

3.2.3.1 Dental, alveolar and postalveolar consonants. For back vowels, effects at the peripheral rows are positive and quite large, and decrease in the progression [s]>[j]>[t]. Thus the front dorsum is fronted and/or raised during the production of back vowels when adjacent to consonants involving a lingual closure or constriction in the front regions of the vocal tract. Consonantal effects at the center of the palate increase as the vowel becomes higher and, as expected, are larger when the adjacent consonant is [j] than when it is [s] or [t].

Positive effects on [a] reflect coarticulation in tongue dorsum raising. Carney and Moll (1971) report X-ray data showing more tongue-dorsum raising for [a] when adjacent to [s] than to [v] (sequences [hisa] and [hiva]); Gay (1974) reports X-ray data showing similar effects in the progression [t]>[k]>[p] (sequences [VCa]).

There is also evidence for coarticulation in lingual fronting and raising upon back rounded vowels in these consonantal contexts. Stone et al. (1987) report ultrasound data showing a similar tongue dorsum configuration for [i] and [u] in dVd sequences for some speakers of American English; according to X-ray data in Perkell (1969), the vertical distance between the dorsum of the tongue and the mediopalate in the context [hotV] is higher for [u] than for [i] and [e]; X-ray data reported by Carney and Moll (1971) show more fronting for [u] in the sequence [husi] than in the sequence [hufi]; Butcher and Weiher (1976) give EPG data showing lateral contact up to the front alveolar zone (one speaker) and up to the front prepalatal zone (another speaker) in the case of [u] in the sequence [utu]; according to X-ray data reported by Kiritani et al. (1977), the tongue stretches out and becomes flat during the production of [o] and [u] in symmetrical CVC sequences with dentoalveolar consonants.

The chances that the front dorsum configuration for back vowels is affected by the adjacent consonants are high in CVC symmetrical environments, as shown by myself in this paper, and by Stone et al. (1987) and Kiritani et al. (1977). Indeed data collected in other contextual conditions may reveal no consonantal effects. Thus, according to X-ray data from the literature, [u] may be articulated with a similar tongue dorsum configuration at a dorsovelar place of constriction when adjacent to consonants differing in degree of fronting ([udV] and [ugV] (Öhman, 1966); [utV], [upV] and [ukV] (Gay, 1974)). A large degree of variability in linguopalatal contact for [u] is due to lingual fronting effects caused by adjacent consonants articulated at the front of the mouth (see Figure 9). This phenomenon may be associated with lip rounding, which is more considerable for this vowel than for the other back rounded vowels. It can be hypothesized that speakers do not care much about the precise location of the lingual constriction because the spectral properties of [u] are already accounted for by the lip rounding gesture. If so, it seems a natural strategy to allow for C-to-V coarticulation in tongue positioning along the palatal surface.

Larger effects in front dorsum activity when the adjacent consonant is a fricative than when it is a stop may result from the high requirements on the shaping of the tongue body in the case of [s] and [f]. They might also be associated with more anticipatory lip rounding during [s] and [f] than during [t].

Effects on the schwa are similar to those on [u] but not identical, because neither is making strong demands on the tongue. Positive deviations are most peripheral for [t] and most central for [f],
[s] falling in between. These trends reflect presumably the contribution of the blade in the production of [s] and [ʃ], of the dorsum in the production of [ʃ], and of the apex in the production of [t]. Overall effects on [a] reflect quite well the articulatory properties of the adjacent consonant.

3.2.3.2 Velarized alveolar consonant. This consonant causes few coarticulatory effects on the pharyngeal vowels [a], [s] and [o]. When adjacent to [u] and the schwa, it has some negative effect on rows 2 and 3 (more so when V=[u] than when V=[o]) and some positive effect on row 1 (more so when V=[a] than when V=[u]).

The absence of coarticulatory effects on pharyngeal vowels is presumably due to the similarity in tongue dorsum configuration between those vowels and velarized [l]; indeed, all these articulations are produced with a back dorsal constriction and a lowered front dorsum. Larger effects on the central rows for [u] than for the schwa are associated with more tongue dorsum raising in the case of [u]; larger effects on the peripheral rows for the schwa than for [u] indicate that the schwa may be more neutral to tongue fronting induced by [l] (see also coarticulatory effects with adjacent [t]).

3.2.3.3 Alveolopalatal and palatal consonants. In this contextual condition, positive coarticulatory effects increase as the vowel becomes higher, mainly at the center of the palate (see § 3.2.1 for a rationale). In all cases except for [a] (which, like [o], shows very small effects) coarticulation is larger at the peripheral rows than at the central rows. This trend suggests that, similarly to adjacent dentoalveolars, adjacent palatal consonants cause some stretching of the front dorsum during back rounded vowels and pull it forward within the oral cavity.

In general, effects on the schwa are as large as on [u]; for that vowel, however, they decrease in the progression 3rd row> 2nd row> 1st row> 4th row> 5th row. Notice also that effects on rows 2 and 3 are higher for the alveolopalatal [n] than for the palatal [j] while those on rows 4 and 5 are larger for the palatal than for the alveolopalatal. In summary, differently from front vowels (see § 3.2.2.3), effects on [a] reflect quite well the place of constriction of the adjacent consonants, which is more fronted and less central for alveolopalatals than for palatals.

3.2.3.4 Velar consonant. This consonant causes slight negative effects on row 1 in the case of back vowels and the schwa, and additional effects on rows 2 and 3 in the case of [u] (negative) and the schwa (positive). The presence of negative effects indicate that [k] with back vowels is produced with a velar place of articulation; thus a very retracted tongue position for the consonant causes some retraction during the vowel when compared to its neutral configuration in the pVp environment.

4. ARTICULATORY-ACOUSTIC RELATIONS

As pointed out in the Introduction, another goal of this study is to establish a correlation between the EPG data and the acoustic data.

Figure 19 shows F2 data for all vowels in all consonantal contexts. Differences between these F2 values and those in the pVp context are not given since F2 for a vowel preceded and followed by p reflects other articulatory factors besides tongue activity. It should also be said that the correlation between the articulatory and acoustic measurements will be necessarily low for those vowels showing little palatal contact since the lingual configuration cannot be inferred with precision from the EPG data in these circumstances.

4.1 Front vowels

A systematic relationship between the F2 data and the EPG data obtains in the case of front vowels with adjacent velarized [l]. In this case, negative C-to-V effects in degree of dorsopalatal contact (see § 3.2.2.2) cause a significant decrease in F2. Wood (1982) has also shown that large openings at the place of the palatal constriction cause dramatic F2 changes while location perturbations along the prepalatal changes while location perturbations along the prepalatal and mediopalatal do not cause appreciable F2 variations.

There may also be a direct relationship between positive C-to-V effects in dorsopalatal contact (EPG data; see § 3.2.2.3) and a high F2 frequency in the case of [e] and [ɛ] when adjacent to alveolopalatal [n], palatal [j] and postpalatal [k]. Of course it could be argued instead that dentoalveolars and labials (but not alveolopalatals and palatals) cause some deviation (i.e., lowering) from the ideal F2 values for those target vowels (Stevens & House, 1963).

Notice that the fricatives [s] or [ʃ] tend to cause a lower F2 frequency than the stop of a similar place of articulation (i.e., [l]) at the midpoint of [i] and [ɛ] (see also Stevens and House, 1963). A rationale for this finding is that fricatives cause some tongue dorsum lowering along the median line during the production of the vowel and thus contribute to an F2 decrease. Some evidence for such effects has been reported in § 3.2.2.1.
4.2 Back vowels and the schwa

Among back vowels, positive C-to-V effects in the EPG data have some clear acoustic consequences (also Stevens & House, 1963). Thus, vocalic F2 is highest when the adjacent consonant involves a palatal constriction, less high when it is articulated in the front of the mouth but shows no contact at the central palate, and lowest when it is a velar or the velarized [h]. Consistently with the data reported here, Wood (1982) has shown that advancing the dorsal constriction for [u] from the back or mid soft palate to the front soft palate or more forward causes a great F2 increase; Maeda (in press) reports a similar finding for the vowel [o]. Notice that this consonant-dependent F2 increase could also reflect lip unrounding during the production of back rounded vowels.

According to Figure 19, fricatives (i.e., [s]) tend to cause a higher F2 of back vowels than stops of similar articulatory characteristics (i.e., [t]) (also Stevens & House, 1963, for American English).

F2 effects for the schwa are very similar to those observed on the palatal surface. They can be compared to those for [a] and show a larger spread of F2 frequencies across consonantal contexts.

5. SUMMARY AND CONCLUSIONS

Patterns of linguopalatal contact across consonantal contexts show differences in contact size between vowels of different height within the front series ([i], [e], [e]) but not within the back series ([u]> [a]> [o], [o]). This apparent anomaly was attributed to the position of the front dorsum, which is higher for low back vowels than for higher back vowels. A systematic contrast in constriction location on the palatal surface was obtained for front vs. back vowels which is consistent with the tongue regions under active control in the two groups. This grouping of vowels into a front and a back category has been shown to be not only related to patterns of linguopalatal contact but also to patterns of articulatory variability. Variability for [a] is the highest of all vowels.

The finding that [i] is subject to a low degree of variability in palatal contact is consistent with the assumption of [i] being a quantal vowel (Perkell & Nelson, 1985). According to this assumption, tongue front activity shows little variability along the vertical dimension because the sides of the tongue blade are being pushed against and
restrained by the hard palate; on the other hand, horizontal variability at the front and, more so, at the back of the tongue dorsum is caused presumably by contraction of the posterior genioglossus. Moreover, findings reported here suggest that coarticulatory resistance on the entire tongue dorsum is also found when the tongue region under control is the predorsum and/or mediiodorsum instead of the blade.

High cross-consonantal SD values in EPG activity for [u] and [o] suggest a clear trend for the degree of coarticulation to vary inversely with the degree of constraint on tongue dorsum activity. Low SD values for [a], [e] and [i] when compared to those for [u] suggest that lip rounding may play a role in the presence of C-to-V effects.

As shown below, coarticulatory data reported in this paper may be useful to gain some understanding about the nature of the articulatory strategies used by speakers for the production of adjacent vowels and consonants. It should be pointed out in this respect that C-to-V effects are subject to similar production strategies to those observed in V-to-C effects. Analogously to consonants, those lingual regions which are not involved in the formation of a vocalic constriction are left freer to coarticulate than those which are actively involved.

Effects on front vowels are quite small due to the requirements on the tongue dorsum to achieve a palatal constriction. Overall, tongue dorsum raising effects increase as the vowel becomes lower, in line with differences in articulatory constraint. The most significant consonantal effects are those caused by velarized [l], stop vs. fricative dentoalveolars, and alveolopalatal vs. (post)palatais. In general, those articulatory contrasts associated with palatal constriction raise the degree of coarticulation to vary inversely with the degree of constraint on tongue dorsum activity. Low SD values for [a], [o] and [e] lower, in line with differences in articulatory constraint.

The number and size of the positive coarticulatory effects are larger for back vowels and [s] than for front vowels; moreover, differently from front vowels, effects among back vowels increase with vowel height at the periphery and at the center of the palate. Large effects on [a] are found all over the palatal surface, including the central palate. Back vowels and the schwa show large positive coarticulatory effects which reflect raising (typically for [a]) and fronting (typically for rounded vowels) of the tongue dorsum as a function of adjacent dentoalveolar and palatal consonants; [k] and velarized [l] however cause negative or no positive effects. These articulatory differences have an effect on F2 frequency.

Overall, these effects reflect contrasts in degree of articulatory constraint associated with different phonetic segments. Large effects on back vowels from dentoalveolar and palatal consonants show that the constriction requirements on the front dorsum (for the consonant) dominate in the absence of articulatory activity (for the vowel); on the other hand, coarticulatory effects from velarized [l] on back vowels are small since the front dorsum configurations for that consonant and those vowels are highly similar. In the case of front vowels, high requirements on tongue dorsum lowering for velarized [l] override to some extent tongue dorsum raising for front vowels; also, coarticulatory effects from fricatives on front vowels are very precise because fricative production demands high requirements on the tongue configuration.

REFERENCES


**FOOTNOTES**

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†Also Universitat Autònoma de Barcelona, Department de Filologia Catalana, Bellaterra, Barcelona.