Vowel-to-vowel coarticulation in Catalan VCV sequences

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Electropalatographic and acoustical data on vowel-to-vowel (V-to-V) coarticulatory effects were obtained for Catalan VCV sequences, with the consonants representing different degrees of tongue-dorsum contact (dorsopalatal approximant [j], alveolo-palatal nasal [ɲ], alveolo-palatal lateral [ʎ], and alveolar nasal [n]). Results show that the degree of V-to-V coarticulation in linguopalatal fronting and $F2$ frequency varies monotonically and inversely with the degree of tongue-dorsum contact, carryover effects being larger than anticipatory effects. The temporal extent of coarticulation also varies with the degree of tongue-dorsum contact, much more so for anticipatory effects than for carryover effects. Overall, results indicate that V-to-V coarticulation in VCV sequences is dependent on the mechanical constraints imposed on the tongue dorsum to achieve dorsopalatal closure during the production of the intervening consonant. Moreover, anticipatory effects, but not carryover effects, involve articulatory preprogramming.

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INTRODUCTION

Studies on coarticulation address the question of how the phonemic string is produced in running speech. The failure to discover a one-to-one mapping between phonemes and articulatory targets suggests that the invariant production units involve patterns of spatial and temporal coordination among several articulators (see, for example, Bell-Berti and Harris, 1981). Fowler (1980) and Fowler *et al.* (1980) have proposed that coarticulation results naturally from such coordinated patterns of articulatory activity. According to these researchers, the process of speech production is executed by means of coordinative structures, namely, muscle groupings organized functionally to actualize linguistic units in fluent speech. The constraints on articulatory movement imposed by the coordinative structure define those articulatory dimensions along which adjustment to context may take place. Thus in light of this approach, coarticulatory effects ought to be predictable from constraints on articulatory displacement. In the present study, evidence was obtained for systematic variability in transconsonantal vowel-to-vowel coarticulatory effects as a function of the degree of tongue-dorsum contact for the intervening consonant.

Öhman (1966) has proposed a model to account for V-to-V coarticulation across bilabial, alveolar, and velar stops in VCV sequences. In this model, VCV coarticulatory effects are interpreted as reflecting an underlying V-to-V tongue movement with a superimposed consonantal constriction, which is actualized by commands directed towards different regions of the tongue. Öhman distinguishes at least three separate tongue regions that can be independently controlled: regions that shape the whole tongue body (used for the production of vowels), the apical region (used for the production of alveolars), and the dorsal region (used for the production of velars). Tongue regions left uncontrolled by these consonantal commands can conform to the underlying diphthongal gesture, thus allowing for V-to-V coarticulation.

Öhman's interpretation has the interesting implication that degree of coarticulation should vary with the constraints exerted upon the kinematics of the different tongue dimensions under control. Thus, for instance, it could be that the production of place categories other than bilabial, alveolar, and velar imposes restrictions upon tongue activity so severe as to almost prevent V-to-V coarticulation from occurring. In fact, there is evidence from the literature that palatal articulations block V-to-V coarticulation to a large extent. Thus it has been found for Russian palatalized consonants (produced with a primary constriction plus some raising of the tongue dorsum towards the palate) that formant transitions are barely influenced by the quality of the transconsonantal vowel (Öhman, 1966; Purcell, 1979). Also, data on V-to-C coarticulation show that English [j] (Lehiste, 1964; Stevens and House, 1964) and Italian [ʎ] (Bladon and Carbonaro, 1978) are highly resistant to effects from the surrounding vocalic environment.

The prediction tested in the present study was that the degree of V-to-V coarticulation in VCV sequences varies monotonically and inversely with the degree of tongue-dorsum contact required for the production of the consonant. Thus for consonants produced with varying degrees of constraint on tongue-dorsum displacement towards the palate, more tongue-dorsum contact ought to allow less transconsonantal coarticulation, and less tongue-dorsum contact, larger transconsonantal coarticulatory effects. Moreover, degrees of tongue-dorsum contact and degrees of transconsonantal coarticulation ought to vary in comparable amounts.

The dorso-palatal approximant [j], the alveolo-palatal nasal [ɲ], the alveolo-palatal lateral [ʎ], and the alveolar nasal [n] in Catalan (a Romance language spoken in Catalonia, Spain) were chosen for analysis. The degree of tongue-dorsum contact associated with these consonants varies in the order [j] > [ɲ] > [ʎ] > [n], as traditionally described and according to a survey of palatographic recordings from the literature across different Romance languages and contextual conditions (e.g., Haden, 1938; Rousselot, 1924,1925). Thus in a language with this set of consonants, [j], [ɲ], [ʎ], and [n] ought to show increasing degrees of V-to-V coarticulation. This hypothesis is based on the assumption that articulatory control during the production of [j], [ɲ], and [ʎ] is primarily exerted upon tongue-dorsum raising towards the hard palate. On these grounds, the dorso-palatal [j] ought to show maximum degree of tongue-dorsum constraint and minimum degree of V-to-V coarticulation since all muscular activity is directed towards this gesture; less tongue-dorsum constraint and more V-to-V coarticulation should occur for alveolo-palatals (more so for [ʎ] than for [ɲ]) since muscular activity is directed simultaneously towards tongue-blade contact and tongue-dorsum contact.

Another purpose of this investigation was to assess (1) the relative strengths of V1-to-V2 (carryover) versus V2-to-V1 (anticipatory) effects, and (2) the temporal extents of these coarticulatory effects.

Data on coarticulation in asymmetrical VCV sequences (mainly English) with consonants involving lingual closure show large anticipatory and carryover effects during closure and along the VC and CV transitions (see, for review, Parush *et al.*, 1983). However, small and unsystematic anticipatory (English: Kent and Moll, 1972; German: Butcher and Weiher, 1976) and carryover (English: Gay, 1974) V-to-V effects have been reported in the steady-state vowel portion. Several studies show that carryover effects are larger than anticipatory effects for English (Bell-Berti and Harris, 1976; Gay, 1974). In this study, the relative salience of transconsonantal anticipatory versus carryover effects in the formant transitions and in the steady-state vowel are investigated for Catalan.

If the anticipatory process reflects articulatory preprogramming and the carryover process is primarily due to mechanical inertia constraints, anticipatory effects should be more sensitive than carryover effects to the temporal aspects of coarticulation. Recent evidence shows that this is the case for English (Parush *et al.*, 1983). The present study also investigates this issue for Catalan, as well as the extent to which V-to-V temporal effects are dependent on or independent of the degree of dorsal contact required for the production of the consonant.

I. METHOD

A. Articulatory analysis

Electropalatographic (EPG) data were collected for the Catalan consonants [j], [ɲ], [ʎ], and [n] in all possible VCV combinations with V = [i], [a], and [u]. All combinations can occur in running speech in Catalan. The utterances were embedded in a Catalan frame sentence "Sap__poc," meaning "He knows __just a little." A single speaker of Catalan (speaker Re, the author), also fluent in Spanish, English, and French, repeated all utterances ten times with the artificial palate in place while the electropalatographic signal and the corresponding acoustic signal were recorded on tape for later analysis.

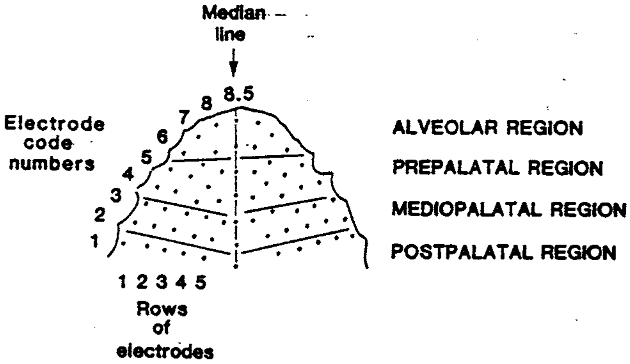

FIG. 1. Electropalate.

A mouth cast for speaker Re was used to build the artificial palate. The artificial palate is a 2-mm-thick device made of acrylic resin, equipped with 63 small gold electrodes evenly distributed over its surface, as shown in Fig. 1. Patterns of linguopalatal contact were tracked over time (1 frame = 15.6 ms) on a display panel with an array of 63 lamps in an analogous configuration; as the tongue touches an electrode, the corresponding lamp lights up. Electrodes were reproduced on the panel in a two-dimensional display (as in Fig. 1) which does not account for the vaulting of the subject's palate. Detailed information about this palatographic system (Rion Electropalatograph model DP-01) is available in Shibata (1968) and Shibata *et al.* (1978).

The electrodes are arranged in five semicircular rows. For purposes of data interpretation, they were grouped into articulatory regions and sides, taking advantage of their equidistant arrangement in parallel curved rows on the artificial palate. As shown in Fig. 1, the surface of the palate was divided into four articulatory regions (alveolar, prepalatal, mediopalatal, and postpalatal) and into two symmetrical sides (right and left) by a median line traced along the central range of electrodes. This division into articulatory areas on the palatal surface is based on anatomical considerations (Catford, 1977).

For each VCV utterance, data were tabulated from onset to offset of palatal contact, for a variable number of on electrodes on each side of the palate. To tabulate the placement of on electrodes frame by frame, every electrode was given a code number in each semicircular row for each side of the palate, starting from the backmost electrode up to the frontmost electrode. Electrodes placed on the median line were assigned to both sides; thus row 1 had 8.5 electrodes, row 2 had 7.5, etc. (see Fig. 1). Given the fact that contacts were always made first at the rear of the palate (except for the sequence [uʎu], as discussed in Sec. II) and that back electrodes stayed on during the entire production, the number of on electrodes in each row was equivalent to the code number of the frontmost on electrode. Therefore, a recording of each code number for each row in each frame simultaneously indicated the amount of linguopalatal contact and the degree of linguopalatal fronting for that row at that moment in time. For data interpretation, means were obtained by averaging the number of on electrodes in each row frame by frame across repetitions of the same sequence lined up according to the point of maximum contact (PMC). The PMC for a token was considered to be in the frame that presented the highest number of on electrodes.

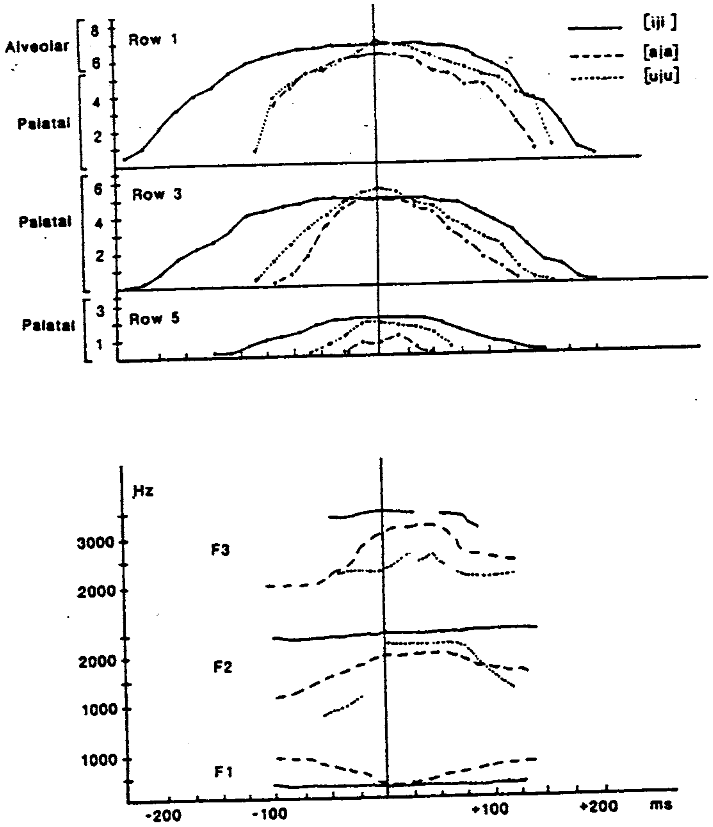

FIG. 2. Trajectories of articulatory dynamics over time (in ms) for [j] in contrasting symmetrical environments lined up at PMC (for [aja] and [uju]) and at the MC midpoint (for [iji]) (speaker Re). Top: trajectories for the frontmost contacted electrode on rows 1 (tongue sides), 3 (between the tongue sides and center of the tongue dorsum), and 5 (center of the tongue dorsum) of the right side of the palate; electrode code numbers and articulatory regions have been given for each row. Bottom: trajectories for $F1$, $F2$, and $F3$ in Hz.

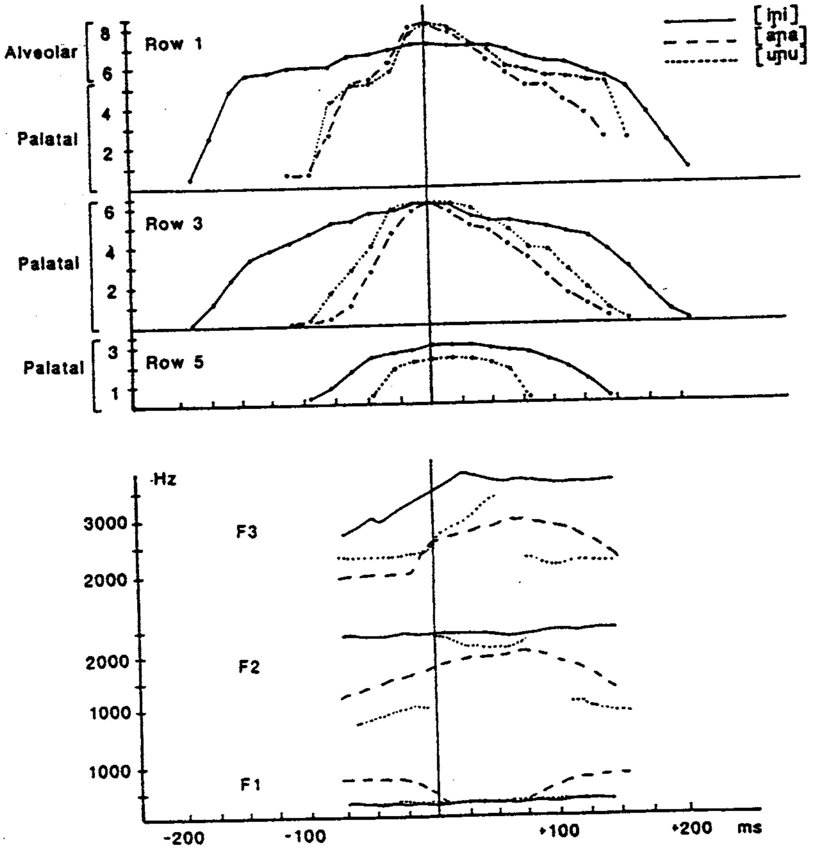

FIG. 3. Trajectories of articulatory dynamics over time for [ɲ] in contrasting symmetrical environments lined up at PMC (speaker Re). Top: EPG data; bottom: acoustical data. See Fig. 2 for details about the displays.

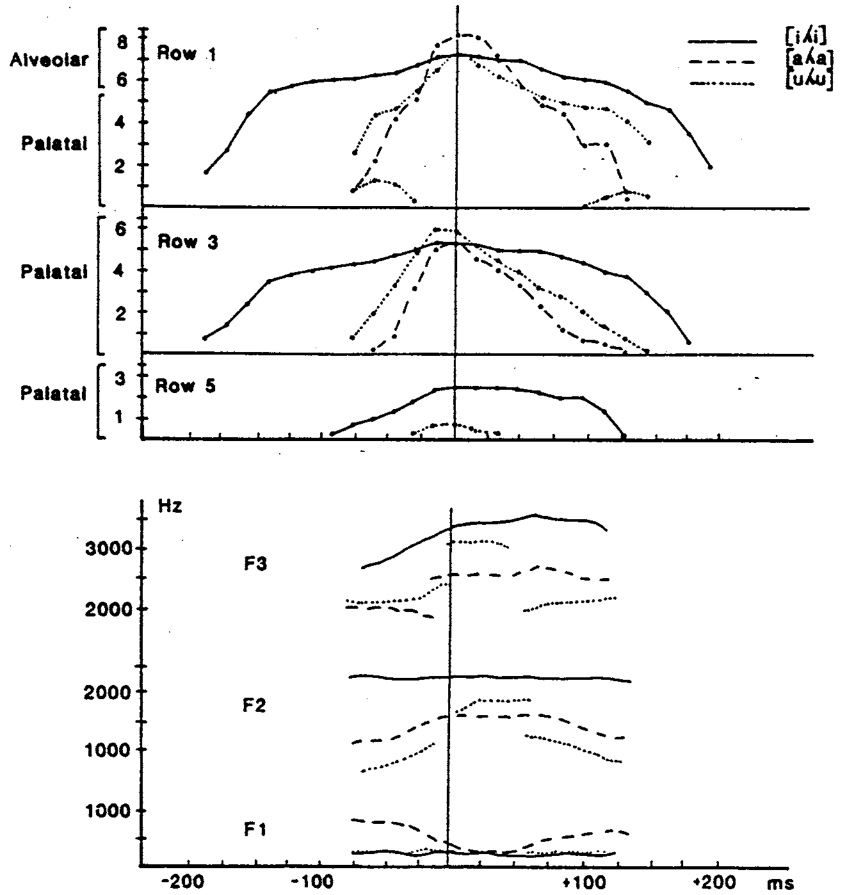

FIG. 4. Trajectories of articulatory dynamics over time for [ʎ] in contrasting symmetrical environments lined up at PMC (speaker Re). Top: EPG data; bottom: acoustical data. See Fig. 2 for details about the displays.

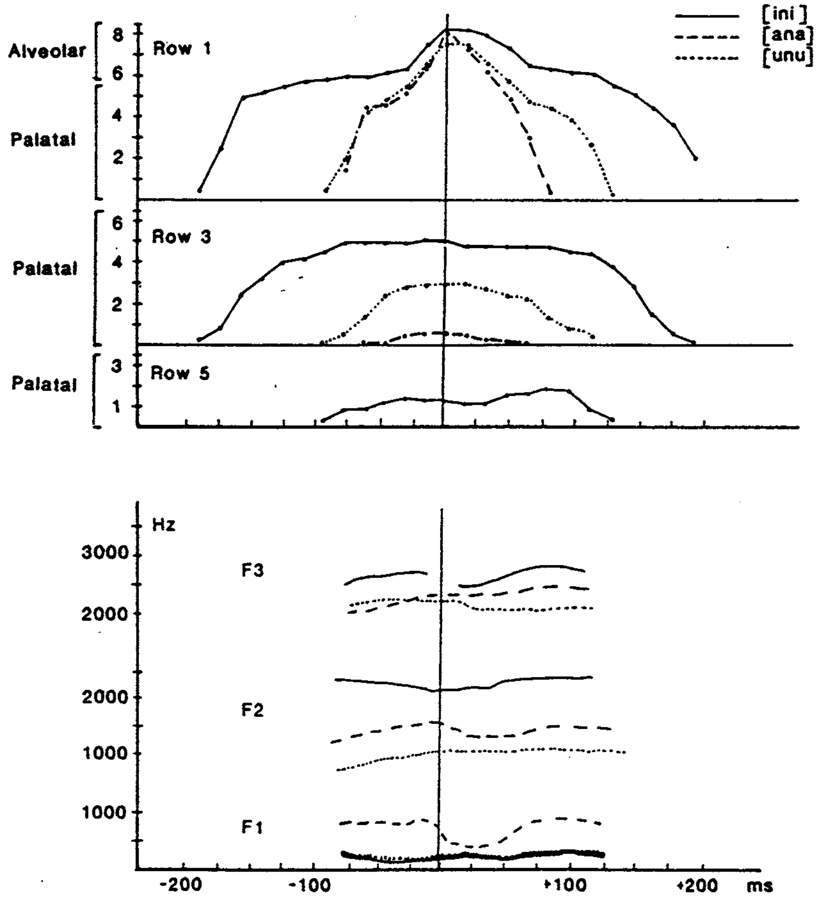

FIG. 5. Trajectories of articulatory dynamics over time for [n] in contrasting symmetrical environments lined up at PMC (speaker Re). Top: EPG data; bottom: acoustical data. See Fig. 2 for details about the displays.

B. Acoustical analysis

Four repetitions of all VCV combinations from this and two other male Catalan speakers (Bo and Ca), also fluent in Spanish, were recorded for acoustical analysis. They were digitized at a sampling rate of 10 kHz, after pre-emphasis and low-pass filtering. An LPC (linear predictive coding) program included in the ILS (Interactive Laboratory System) package available at Haskins Laboratories was used for spectral analysis. Dynamic trajectories for the three lowest spectral peaks from onset to offset of voicing as detected in the waveform displays were reproduced on tracing paper and averaged across repetitions of the same VCV utterance lined up according to PMC. To identify PMC in the acoustic wave for speaker Re, EPG data were also digitized at a sampling rate of 20 kHz, with no previous pre-emphasis or filtering. Labeling procedures were executed by means of WENDY (Haskins Laboratories Wave Editing and Display system). For speakers Bo and Ca, for whom no EPG data were available, PMC was estimated by visually identifying the $F1$ frequency minimum in the transition from the first vowel to the consonant. This procedure was chosen on the grounds that, of all the spectral characteristics present in the acoustical display of the utterances under study, such a point was found empirically to match PMC for speaker Re.

For each consonant, articulatory and acoustical data are presented as a function of time, considering first the general production characteristics in symmetrical VCV environments, and subsequently V-to-V coarticulatory effects in asymmetrical VCV environments. In the articulatory domain, patterns of contact in the palatal region (mediopalate and postpalate) that reflect tongue-dorsum activity are of particular concern; in the acoustic domain, $F2$ frequencies that, for palatal and alveolar consonants, reflect changes in the size of the back cavity behind the primary constriction and in degree of palatal constriction (Fant, 1960) are emphasized.

II. RESULTS

A. General production characteristics

VCV utterances involving [j], [ɲ], [ʎ], and [n] were found to exhibit different patterns of linguopalatal contact and contrasting $F2$ patterns. Such patterns were correlated with different degrees of tongue-dorsum contact required for the production of each consonant, with [j] > [ɲ] > [ʎ] > [n].

1. Articulatory data

Trajectories of linguopalatal contact in VCV symmetrical environments for [j], [ɲ], [ʎ], and [n] with V = [i], [a], and [u] are displayed in the top panels of Figs. 2–5. Each trajectory represents an average over ten repetitions. Each panel provides data on linguopalatal contact (vertical axis) over time (horizontal axis). Data have been displayed for three rows of electrodes on the right side of the palate, namely, row 1 (contact with the tongue sides), row 3 (contact with the region between the tongue sides and the center of the tongue dorsum), and row 5 (contact with the center of the tongue dorsum). Linguopalatal contact has been plotted in terms of the code numbers for any on electrodes on each row starting from the backmost electrode (1) up to the frontmost electrode (8.5 for row 1, 6.5 for row 3, 3.5 for row 5). As explained in Sec. I, the plot of each trajectory over time represents the frontmost contacted electrode. For all consonants, contact is cumulative from back to front such that the frontmost electrode is also a good representation of total amount of contact. For [uʎu] (see Fig. 4), the tongue did not always make contact with electrode 1 on row 1 of the artificial palate presumably because of the positioning of the tongue sides required to allow lateral airflow. Time has been measured in ms frame by frame. The lineup point for VCV sequences with [ɲ], [ʎ], and [n] is at PMC. Lineup procedures for [VjV] sequences were handled differently: EPG data for [aja] and [uju] showed a single frame (PMC) with maximum contact all over the palatal surface; however, maximum contact for [iji] was found to last for six frames (= 95 ms). To account for this contrast, PMC for [aja] and [uju] was lined up with the midpoint of the period of maximum contact for [iji].

For all consonants in all sequences (see Figs. 2–5), onset of contact occurs earlier at the tongue sides (row 1) and intermediate tongue regions (row 3) than at the center of the tongue dorsum (row 5); analogously, offset of contact occurs later on rows 1 and 3 than on row 5. Displacement along the vertical axis for any row indicates degree of linguopalatal fronting. All sequences show that the degree of linguopalatal fronting increases during the VC period from onset to PMC and decreases during the CV period from PMC to offset. This pattern of displacement over time has been reported in the literature for dorsal articulations such as [j] and velar consonants (Kent and Moll, 1972).

Trajectories for all consonants on row 5 show that [j], [ɲ], [ʎ], and [n] are produced with decreasing degrees of tongue-dorsum contact (see also, the Introduction). Thus the number of on electrodes at PMC on row 5 adding across different vocalic conditions for each consonant varies for [j] (5.3), [ɲ] (5.3), [ʎ] (2.9), and [n] (1.3). Moreover, the vowel [a] shows contact with [j] but not with [ɲ], nor with [ʎ] and [n]. Vowel [u] shows no contact with [n]. Differences in degree of tongue-dorsum contact for alveolo-palatal [ɲ] and [ʎ] versus alveolar [n] are related to the fact that, while the two categories of place of articulation involve alveolar contact, alveolo-palatals but not alveolars are produced with simultaneous raising of the tongue dorsum towards the palatal vault, resulting in lingual contact at the center of the mediopalatal and postpalatal regions.

Table I shows maximum and minimum onset and offset contact values with respect to PMC at the tongue sides (row

TABLE I. Maximum and minimum values of onset and offset time (in ms) for linguopalatal contact at the tongue sides (row 1) and at the center of the tongue dorsum (row 5) for consonants [j], [ɲ], [ʎ], and [n] in symmetrical VCV environments. Data are from one Catalan speaker (Re).

	Onset values		Offset values	
	row 1	row 5	row 1	row 5
[j]	− 220/ − 95	− 140/ − 30	+ 200/ + 140	+ 155/ + 45
[ɲ]	− 185/ − 95	− 95/ 0	+ 200/ + 140	+ 140/ 0
[ʎ]	− 185/ − 80	− 95/ 0	+ 185/ + 125	+ 125/ 0
[n]	− 185/ − 80	− 95/ 0	+ 185/ + 80	+ 125/ 0

TABLE II. Maximum and minimum $F2$ values (in Hz) at PMC for consonants [j], [ɲ], [ʎ], and [n] in symmetrical VCV environments. Data are from three Catalan speakers (Re, Bo, and Ca).

	Speaker Re	Speaker Bo	Speaker Ca
[j]	2350 , 1925	2450 , 2150	2150 , 1925
[ɲ]	2350 , 1775	2450 , 2000	2250 , 1575
[ʎ]	2275 , 1600	2400 , 1850	2000 , 1600
[n]	2210 , 1075	2350 , 1150	2075 , 1100

1) and at the center of the tongue dorsum (row 5), as derived from Figs. 2–5. These values give a good estimate of the duration of the VC period (from onset to PMC) and the CV period (from PMC to offset) of linguopalatal contact. Onset values across rows show the pattern [j] > [ɲ] > [ʎ],[n]; offset values across rows show the pattern [j] > [ɲ] > [ʎ] > [n]. Thus VC, CV, and VCV contact durations decrease as the degree of tongue-dorsum contact for the consonant decreases.

The trajectories give information about velocity of linguopalatal displacement over time. Velocity of displacement can be obtained by dividing the total displacement for a given movement by the time required to execute the movement (Kuehn and Moll, 1976). Accordingly, velocity increases as duration decreases and degree of displacement remains constant. Trajectories for the sequences [aCa] and [uCu] in Figs. 3–5 show that, for consonants involving fronted alveolar contact ([ɲ], [ʎ], and [n]) and, thus, similar degrees of tongue-tip and/or tongue-blade displacement—the time to achieve and release alveolar constriction (see row 1) decreases for [ɲ] > [ʎ] > [n]. Therefore, velocity of displacement for this articulatory gesture increases as the degree of tongue-dorsum contact for the consonant decreases. On the other hand, velocity decreases as degree of displacement decreases and duration increases. This is the case for [j] versus all other consonants; thus [j] is articulated with a lesser degree of alveolar fronting and involves greater VCV contact duration. Overall, at the tongue sides, the velocity of displacement appears to be inversely related to the degree of tongue-dorsum contact.

In summary, several patterns of fronting, duration, and velocity of linguopalatal contact vary with the degree of tongue-dorsum contact for [j] > [ɲ] > [ʎ] > [n].

2. Acoustic measurements

Table II reports maximum and minimum $F2$ values for [j], [ɲ], [ʎ], and [n] at PMC in symmetrical environments for speakers Re, Bo, and Ca. Overall, $F2$ values for all speakers decrease for [j] > [ɲ] > [ʎ] > [n], namely, as the degree of tongue-dorsum contact decreases. Moreover, since $F2$ is dependent on the back cavity behind the place of constriction for [j] and [ʎ], its frequency decreases (for [j] > [ʎ]) as that cavity becomes larger (for [ʎ] > [j]). $F2$ for the nasal consonants [ɲ] and [n] is presumably pharynx-cavity dependent, as indicated by an $F2$ continuation from the first vowel into the consonant in Figs. 3 and 5 (bottom) and given the fact that,

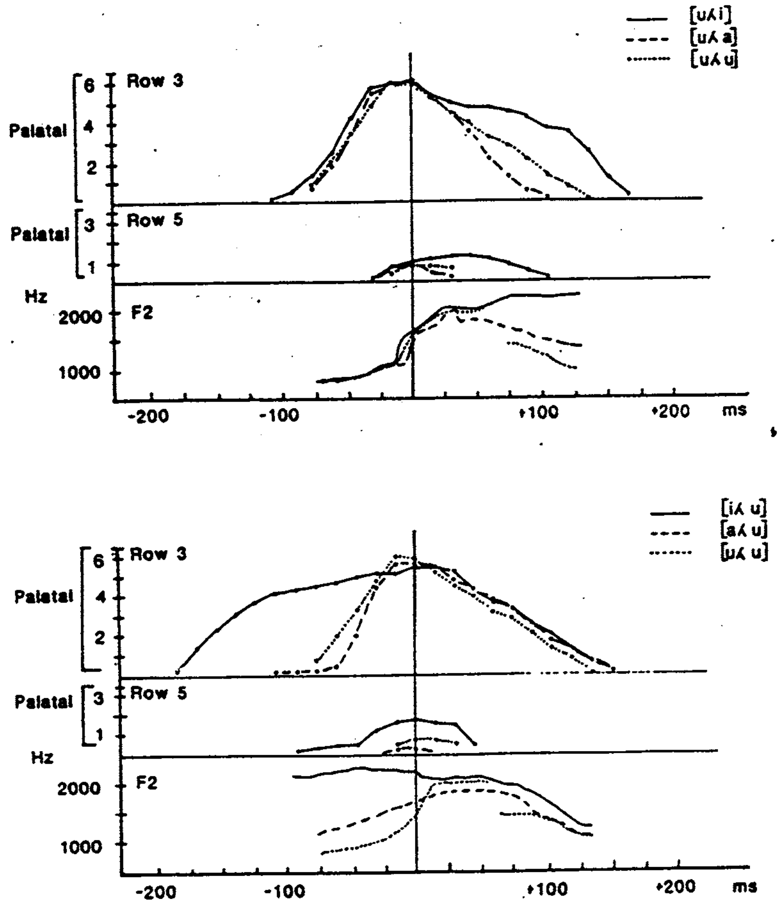

FIG. 6. Top: EPG data (two upper panels) and $F2$ data (lower panel) on anticipatory effects over time for sequences [uʎV] lined up at PMC. Bottom: EPG data (two upper panels) and $F2$ data (lower panel) on carryover effects over time for sequences [Vʎu] lined up at PMC. Data correspond to speaker Re; EPG data correspond to rows 3 and 5 on the right side of the palate.

for nasal consonants, the mouth cavity behind the constriction acts as a shunting cavity. On these grounds, the pharynx-cavity size for [ɲ]and [n] ought to be smaller than the whole mouth-pharynx system for [j] and [ʎ] and, thus, cause a higher $F2$; however, acoustical data reported in Table II show that this is not the case. Also, if, as revealed by the area functions of Russian [n] and [n] reported by Fant (1960), Catalan [ɲ] and [n] are produced with similar pharynx-cavity size, these two consonants ought to show similar $F2$ frequencies; however, acoustical data reported in Table II show a much higher $F2$ for [ɲ] than for [n]. In the absence of x-ray data on vocal tract configurations for these two Catalan consonants, it can only be stated with confidence that $F2$ differences for [j], [ɲ], [ʎ], and [n] are inversely related to differences in degree of tongue-dorsum contact.

The same $F2$ relationship holds during the consonantal steady-state period for all speakers. This is exemplified by the displays of formant trajectories for speaker Re, lined up at PMC with the EPG data in Figs. 2–5 (bottom). The steady-state period for [j], [ɲ], [ʎ], and [n] lasts roughly from PMC up to + 75 ms. Thus little change in $F2$ frequencies appears to be taking place during the consonantal steady-state period and, presumably, in degree of tongue-dorsum contact.

In summary, as for the EPG data, $F2$ trajectories show frequency values that vary with the degree of tongue-dorsum contact for [j] > [ɲ] > [ʎ] > [n].

B. Coarticulation

It was also found that the extent of V-to-V coarticulatory effects for [j] < [ɲ] < [ʎ] < [n] is inversely related to the different degrees of tongue-dorsum contact.

1. Articulatory data

Trajectories of linguopalatal contact were plotted for contrasting second vowels (V2) to study anticipatory coarticulation and for contrasting first vowels (V1) to study carryover coarticulation. All VCV sequences except [ijV] and [Vji] were lined up according to PMC. For [ijV] sequences, in which the period of maximum contact lasts for several frames, the onset of the period of maximum contact was taken as the lineup point in measuring anticipatory effects; for [Vji] sequences, for the same reasons, the offset of the period of maximum contact was taken as the lineup point in measuring carryover coarticulation. Coarticulation was considered to occur when an observable difference between two vowels in fronting of linguopalatal contact caused an analogous difference to occur on the other side of the lineup point, and such a difference was found to be statistically significant at some moment in time. Since the main concern was to measure the correlation between degree of tongue-dorsum contact and degree of transconsonantal coarticulation, only data from rows 3 and 5 were selected for analysis in view of the fact that those rows show contact in the palatal region exclusively. The analysis procedure chosen to study V-to-V coarticulatory effects is described below.

Figure 6 shows anticipatory effects for [uʎV] (top, two upper panels) and carryover effects for [Vʎu] (bottom, two upper panels) on rows 3 and 5 at the right side of the palate. For the anticipatory condition, differences in linguopalatal fronting can be observed during V2 on rows 3 and 5 as [i] > [u] > [a]. On row 3 such differences cancel out during the period of maximum contact but appear between V1 onset and 15 ms before PMC as V2 = [i] > [u], [a]; two-tailed t tests show that anticipatory effects for V2 = [i] > [u] (but not for V2 = [i] > [a]) are significant ($p < 0.05$) between − 60 and − 30 ms. No significant anticipatory effects occur on row 5.

For the carryover condition, differences in linguopalatal fronting can be observed during V1 on rows 3 and 5 as [i] > [u] > [a]. Differences cancel out during the period of maximum contact (on row 3 but not on row 5) but appear during V2 (as V1 = [i],[a] > [u] on row 3 and as V1 = [i] > [u] > [a] on row 5). They were found to be significant for V1 = [i] > [u] on rows 3 and 5 ($p < 0.01$) and for V1 = [i] > [a] on row 5 ($p < 0.001$) between PMC and V2 offset.

TABLE III. EPG data on significant anticipatory (V2-to-V1) effects for different degrees of tongue-dorsum fronting. The magnitude of the effects is plotted for different levels of significance (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). Onset of coarticulation (in ms before PMC) occurs at the number preceding / or at V1 onset if no number is present; offset of coarticulation (in ms before PMC) ocurs at the number following / or at PMC if no number is present.

	V1=[i]			V1=[a]			V1=[u]		
	Ci>Ca	Ci>Cu	Cu>Ca	Ci>Ca	Ci>Cu	Cu>Ca	Ci>Ca	Ci>Cu	Cu>Ca
[j]	/-140*	—	—	/***	/***	—	/-30***	/30**	—
[ɲ]	—	—	/-75*	—	—	/-30*	—	—	—
[ʎ]	/-140**	—	—	/-30*	—	/-30*	—	-60/-30*	—
[n]	/-140**	/-140**	—	/***	/***	-45/***	-60/***	-60/***	—

TABLE IV. EPG data on significant carryover (V1-to-V2) effects for different degrees of tongue-dorsum fronting. The magnitude of the effects is plotted for different levels of significance (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). Onset of coarticulation (in ms after PMC) occurs at the number preceding / or at PMC if no number is present; offset of coarticulation (in ms after PMC) occurs at the number following / or at V2 offset if no number is present.

	V2=[i]			V2=[a]			V2=[u]		
	iC>aC	iC>uC	uC>aC	iC>aC	iC>uC	uC>aC	iC>aC	iC>uC	uC>aC
[j]	——	——	——	/***	——	/***	——	——	——
[ɲ]	/+30*	——	+95/ +125***	/***	——	/***	/***	——	+30/***
[ʎ]	/***	/***	——	/***	/+65*	/***	/***	/**	——
[n]	+95/**	/***	——	/***	/***	/***	/+95***	/***	/***

This procedure was used to analyze effects between all possible VCV pairs in all coarticulatory conditions for all consonants reported in this study. Any possible coarticulatory effect on rows 3 and 5 on both sides of the palate, as determined visually from the plottings for all contextual combinations of VCV pairs, was tested frame by frame by means of the *t*-test procedure. Transconsonantal anticipatory effects (Table III) and carryover effects (Table IV) are reported for all consonants in all vocalic environments. For each VC context (Table III) and CV context (Table IV), the magnitude of the significant coarticulatory effects and the onset and offset times of such effects are given for pairs of V2 (Table III) and V1 (Table IV) differing in degree of linguopalatal fronting. The magnitude of the significant coarticulatory effects is plotted for different levels of significance (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$); data correspond to the largest significant effects on rows 3 and 5 on any of the two sides of the palate. Onset and offset times of the significant coarticulatory effects are plotted in ms. The number of ms before / indicates onset time (as for − 60 in the case of [uʎi] versus [uʎu]) and the number of ms after / indicates offset time (as for − 30 in the case of the same pair of sequences). No number before / indicates onset of coarticulation at V1 onset (anticipatory effects) and at PMC (carryover effects), and no number after / indicates offset of coarticulation at PMC (anticipatory effects) and at V2 offset (carryover effects).

a. Anticipatory effects (Table III). The data show that, as expected, the instances and the degree of significance of the anticipatory effects decrease for [n] > [j] and for [n] > [ʎ] > [ɲ] as tongue-dorsum contact increases. However, [j] shows more contact and more (not less, as expected) coarticulation than [ɲ] and [ʎ]. According to Table III, large anticipatory effects for [j] occur for [aCV] and [uCV] when V2 = [i] versus [a], [u]; given that [i] and [j] are produced with a highly similar articulatory configuration, it could be that, during V1, the speaker shows greater fronting for V2 = [i] versus [a], [u] to make sure that the upcoming consonant will be produced with a very salient gesture so that it can be articulatorily and perceptually distinguishable from V2 = [i]. Data on $F2$ (see Sec. II B *2a*) suggest strongly that the same effects occur for this speaker and others when [j] is preceded by V1 = [i]. This strategy supports the view that the process of anticipatory coarticulation is regulated by articulatory preprogramming.

The onset time of the anticipatory effects always occurs at V1 onset for consonants that involve large tongue-dorsum contact ([j] and [ɲ]) and at different moments in time before PMC (at V1 onset, − 60 and − 45 ms) for consonants that involve less tongue-dorsum contact ([n] and, to a lesser extent, [ʎ]). Offset time values show that anticipatory effects can cancel out about the period of closure for articulations that show large tongue-dorsum contact (at 30 ms before PMC for [j], [ɲ], and [ʎ]; at the onset of V1 = [i] about − 140 ms), but not for articulations that show small tongue-dorsum contact ([n]).

Overall, it appears that consonants that involve low requirements on tongue-dorsum activity (as for [n]) show a small degree of tongue-dorsum contact and allow large transconsonantal anticipatory effects with different onset times before PMC. On the other hand, as tongue-dorsum contact increases (as for [ʎ] and [ɲ] but not for [j], for reasons stated above), consonants allow small transconsonantal anticipatory effects with a fixed onset time at V1 onset.

These coarticulatory phenomena suggest that the magnitude and the temporal extent of transconsonantal anticipatory coarticulation in VCV sequences is controlled by anticipatory preprogramming with reference to the mechanical constraints on articulatory activity required for the production of the consonant.

b. Carryover effects (Table IV). The instances and the degree of significance of the carryover effects decrease (for [n] > [ʎ] > [ɲ] > [j]) inversely and monotonically with the degree of tongue-dorsum contact (for [j] > [ɲ] > [ʎ] > [n]). For all consonants (except for [j], for reasons indicated in Sec. II B *1a*), carryover effects are larger than anticipatory effects; also, while anticipatory and carryover effects occur from front versus back vowels, carryover effects among back vowels are much larger than anticipatory effects.

Contrary to anticipatory coarticulation, no contrasting timing effects are found among different consonants; thus, carryover coarticulation extends generally from PMC up to V2 offset.

These coarticulatory phenomena suggest that transconsonantal carryover coarticulation in VCV sequences results from mechanical inertia constraints on articulatory activity required for the production of the consonant and involves no articulatory programming.

2. Acoustic measurements

$F2$ trajectories for pairs of VCV sequences for speakers Re, Bo, and Ca were lined up according to the same procedure used to study coarticulatory effects for EPG data. Carryover effects for [j] could be measured only for speaker Re since no reference point was available for lineup procedures for speakers Bo and Ca. To detect transconsonantal effects, a procedure analogous to that for EPG data was used; thus, effects were considered to occur when observable frequency differences between two vowels caused analogous differences to occur at some moment in time on the other side of the lineup point. This method of analysis is exemplified below.

Figure 6 shows anticipatory effects for [uʎV] (top, lower panel) and carryover effects for [Vʎu] (bottom, lower panel). Data correspond to speaker Re and have been lined up at PMC with EPG data for the same speaker. For the anticipatory condition, differences in $F2$ frequency can be observed during V2 as [i] > [a] > [u]. Anticipatory effects for V2 = [i] > [a] and V2 = [i] > [u] occur between − 15 ms and PMC; they never exceed 250 Hz. No differences for V2 = [a] > [u] take place before PMC.

For the carryover condition, differences in $F2$ frequency can be observed during V1 as [i] > [a] > [u]. Carryover effects for V1 = [i] > [a] and V1 = [i] > [u] occur between PMC and V2 offset; the largest magnitude for the two effects is found between 250 and 500 Hz. No effects take place after PMC for V1 = [a] > [u].

Coarticulatory effects on $F2$, as determined visually from the plottings for all contextual combinations of VCV pairs, are reported in Tables V (anticipatory effects) and VI (carryover effects) analogously to Tables III and IV. The magnitude of the coarticulatory effects is plotted for different magnitude levels (*0–250 Hz, **250–500 Hz, *** more than 500 Hz); onset and offset times are reported in ms.

TABLE V. Acoustical data on significant anticipatory (V2-to-V1) effects for differences in $F2$ frequency. The magnitude of the effects is plotted for different magnitude levels (*0–250 Hz, **250–500 Hz, *** more than 500 Hz). Temporal effects are indicated as for the EPG data (see Table III).

	V1 = [i]			V1 = [a]			V1 = [u]		
	Ci>Ca	Ci>Cu	Ca>Cu	Ci>Ca	Ci>Cu	Ca>Cu	Ci>Ca	Ci>Cu	Ca>Cu
[j]									
Re	/*	/*	—	/*	/*	/*	/**	/**	—
Bo	/*	/*	—	-15/*	-15/*	—	—	—	—
Ca	/*	/*	—	—	—	—	—	—	—
[ɲ]									
Re	/*	/*	—	—	—	—	/*	/*	—
Bo	/-25*	—	—	-70/-25*	—	—	—	—	—
Ca	/*	/*	—	—	/*	/*	—	—	—
[ʎ]									
Re	/*	/*	—	/*	/*	—	-15/*	-15/*	—
Bo	-15/*	-40/**	—	/*	/*	—	—	-25/*	—
Ca	/-15*	/-15*	—	-15/*	—	—	—	—	—
[n]									
Re	—	—	-55/*	-40/*	/**	/*	-50/**	-50/-10*	—
Bo	—	—	—	/*	-45/*	—	/*	/*	—
Ca	/*	/*	—	-45/*	-55/*	—	—	-25/*	—

TABLE VI. Acoustical data on significant carryover (V1-to-V2) effects for differences in $F2$ frequency. The magnitude of the effects is plotted for different magnitude levels (*0–250 Hz, **250–500 Hz, *** more than 500 Hz). Temporal effects are indicated as for the EPG data (see Table IV).

		V2=[i]			V2=[a]			V2=[u]		
		iC>aC	iC>uC	aC>uC	iC>aC	iC>uC	aC>uC	iC>aC	iC>uC	aC>uC
[j]	Re	/*	/*	—	/+75*	—	—	/+50*	/+50*	—
	Bo	—	—	—	—	—	—	—	—	—
	Ca	—	—	—	—	—	—	—	—	—
[ɲ]	Re	/**	/*	—	/**	+80/**	+80/*	+80/**	+80/**	—
	Bo	/+50*	—	—	/**	+65/**	—	/+25*	—	—
	Ca	/**	—	—	/**	+80/*	—	/**	+70/**	—
[ʎ]	Re	/+85**	/+85***	—	/***	/***	—	/**	/**	—
	Bo	/+40**	—	—	/**	+50/*	—	/+50*	/+50**	—
	Ca	/+65*	—	—	/**	/*	—	/***	/***	—
[n]	Re	—	—	—	/***	/***	/+65**	/***	/***	/+50**
	Bo	/+55***	/+45***	/+45**	/***	/***	/+40*	/+75***	/+75***	/+75**
	Ca	/**	/+65***	/+50*	/+125**	/+125*	—	/+125**	/***	/**

a. Anticipatory effects (Table V). Similar to the EPG data, the magnitude of the coarticulatory effects increases slightly as tongue-dorsum decreases for [ɲ] > [ʎ] > [n], while [j] shows similar effects to [ʎ]. As for the EPG data, speaker Re (but not speakers Bo and Ca) shows large anticipatory effects for [Vji] versus [Vja], [Vju] when V1 = [a] and [u] as a result of tongue-dorsum reinforcement before PMC. Moreover, the same strategy is used by all speakers for all palatal consonants when V1 = [i], including speaker Re who did not show anticipatory effects during the articulation of this V1 on the surface of the palate.

Timing effects can be explained in analogy to the EPG data. For consonants involving a large degree of tongue-dorsum contact ([j] and [ɲ]), onset time of the anticipatory effects occurs at V1 onset; for consonants involving less tongue-dorsum contact ([n] and, to a large extent, [ʎ]), onset of anticipatory coarticulation occurs at different moments in time before PMC (mainly at V1 onset and between − 55 and − 25 ms). Contrary to the EPG data, as for [n], anticipatory effects for palatal consonants last until PMC.

Overall, anticipatory effects on $F2$ are in agreement with anticipatory effects over the surface of the palate (see Sec. II B *1a*) and, therefore, are due to articulatory preprogramming. In some instances, different coarticulatory trends take place in different regions of the vocal tract for the same speaker; thus, articulations that require large degrees of tongue-dorsum contact block coarticulatory effects across the period of closure at the surface of the palate but not at other regions of the vocal tract.

b. Carryover effects (Table VI). As for the EPG data, the magnitude of the coarticulatory effects decreases (for [n] > [ʎ] > [ɲ] > [j]) inversely and monotonically with the degree of tongue-dorsum contact (for [j] > [ɲ] > [ʎ] > [n]). As for the EPG data, for all consonants (except for [j], for reasons indicated in Sec. II B *2a*), carryover effects are larger than anticipatory effects; also, while effects from front versus back vowels occur in the anticipatory and carryover conditions, carryover effects for [n] are much larger than anticipatory effects.

There is some indication that, in the carryover condition, timing may be controlled with reference to the degree of tongue-dorsum constraint required for the production of the consonant. Thus carryover effects end at different moments in time after PMC for consonants produced with small degrees of tongue-dorsum contact ([n] and, to a lesser extent, [ʎ]) and last until V2 offset for consonants produced with large degrees of tongue-dorsum contact ([ɲ]). However, consistent with EPG data on carryover coarticulation, speaker Re does not show this trend with respect to coarticulatory effects common to all the consonants. Onset of carryover effects at + 65/ + 80 ms after PMC for [ɲ] results from the cancellation of differences in $F2$ frequency for V1 = [i] versus [u] during closure due to oronasal coupling.

Overall, carryover effects on $F2$ are in agreement with carryover effects on the surface of the palate (see Sec. II B *1b*); they are due to mechanical inertia constraints on articulatory activity and involve little or no articulatory programming.

III. SUMMARY AND CONCLUSIONS

The articulatory mechanisms that underlie the relationship between degrees of tongue-dorsum contact and degrees of coarticulatory activity are discussed. The dorso-palatal [j] is produced with one articulatory command for the raising of the tongue dorsum while the tongue blade makes no contact with the palate. For alveolo-palatals, two commands are actualized simultaneously: tongue-blade occlusion and tongue-dorsum raising. As a result of this synergistic activity, a large degree of contact is obtained for alveolo-palatals over the entire surface of the palate. Thus the production of [j] versus alveolo-palatals results in more tongue-dorsum constraint since all muscular activity is directed exclusively towards tongue-dorsum raising; for alveolo-palatals, on the other hand, less tongue-dorsum constraint results from the fact that muscular activity towards tongue-dorsum raising is accompanied by tongue-blade activity to make contact at the front of the palatal surface (more so for [ʎ] than for [ɲ]). Alveolar [n] is produced with a command to the tongue tip against the alveolar region and involves no constraint on the tongue dorsum to achieve dorso-palatal contact; in fact, contact with the tongue dorsum for [n] occurs only at the sides of the palate. Data on the degree of linguopalatal fronting and $F2$ frequency reported in this study show that V-to-V coarticulatory effects for [j], [ɲ], [ʎ], and [n] can be predicted from these differences in constraint on the tongue dorsum to achieve dorso-palatal contact. Thus effects have been found to vary monotonically and inversely as a function of such differences in tongue-dorsum constraint.

Transconsonantal effects extended back to V1 onset (anticipatory effects) and up to V2 offset (carryover effects), more so on the surface of the palate (80% of anticipatory and carryover effects for the EPG data) than at other regions of the vocal tract (60% of anticipatory and carryover effects for the $F2$ data). There is evidence from the literature that acoustical measurements can be less sensitive than articulatory measurements to coarticulatory effects (Gay, 1974, 1977).

Directionality of coarticulatory effects has been taken to be inherent in the programming of speech sequences (Kent, 1976). Several findings reported in this study speak to this issue. Carryover effects were found to be larger than anticipatory effects in light of articulatory and acoustical data for most consonants and speakers. From the present study, it can be concluded that this finding reflects a language-specific property of how articulatory programming is organized in Catalan. Evidence for a similar trend has been found for English (Bell-Berti and Harris, 1976; Gay, 1974; MacNeilage and DeClerk, 1969).

The temporal extent of coarticulation was found to vary with differences in tongue-dorsum contact, much more so for anticipatory effects than for carryover effects. Thus EPG data and acoustical data show that onset time of anticipatory coarticulation is determined with higher precision (at V1 onset versus different times before PMC) as the degree of tongue-dorsum contact for the consonant increases; on the other hand, EPG data and, less so, acoustical data show that carryover effects extend up to V2 offset independent of the degree of tongue-dorsum contact for the consonant. This finding is consistent with the view that anticipatory coarticulation results from articulatory preprogramming which, for the set of consonants investigated in this study, operates with reference to the mechanical constraints involved during the production of the consonant. Preprogramming also results in the reinforcement of tongue-dorsum activity during V1 to anticipate the articulatory and perceptual differentiation of a palatal consonant followed by V2 = [i] versus [a], [u].

Data reported in this study support the view that the speech production mechanism involves independent control of different regions of the vocal tract. Thus anticipatory effects on the surface of the palate (EPG data) but not at other regions of the vocal tract ($F2$ data) are blocked about the period of closure for articulations that involve large tongue-dorsum contact.

With respect to alternative models that have been proposed in the literature to explain coarticulation in VCV utterances (syllabic or V-to-C model and cross-syllabic or V-to-V model; see Gay, 1978, for discussion), data reported here show that coarticulation is a context-dependent process in the sense that the extent to which V-to-V effects occur depends on the articulatory mechanisms involved in the production of the entire VCV sequence. The finding that coarticulation can be largely predicted from the degree of constraint involved during the activity of specific articulators suggests that the process of speech production is organized around precisely controlled patterns of articulatory activity. Thus it has been shown that, independent of whether the primary constriction takes place at the palatal and/or alveolar regions, the degree of tongue-dorsum contact needs to be specified with accuracy. These observations are consistent with the view that linguistic units are actualized in running speech by muscle groupings that are synergistically controlled.

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