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COARTICULATORY PATTERNS AND DEGREES OF COARTICULATORY RESISTANCE IN CATALAN CV SEQUENCES*

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This paper is an extensive acoustic analysis of V-to-C and C-to-V coarticulatory effects in Catalan CV sequences for 18 consonants and 8 vowels. Data indicate that Catalan phonemes differ as to the degree of resistance to coarticulation and suggest strongly that differences in coarticulatory resistance follow from differences in degree of articulatory constraint. A theory of coarticulation is proposed that accounts for coarticulatory effects in terms of the articulatory constraints involved in the production of gestures for adjacent phonemes, independently of considerations about the linguistic nature of the phonemic units under control. It is argued that such a theory is more likely to explain patterns of coarticulatory activity arising from compatible and conflicting gestures than previous coarticulation models.

INTRODUCTION

Studies on coarticulation often fail to reveal an invariant correspondence between phonemes and their phonetic realization. They show, instead, that the articulatory and acoustic manifestation of consonants and vowels varies with phonetic context. The present study seeks to understand how consonant–vowel (CV) coarticulatory patterns reflect the coprogramming process of adjacent consonants and vowels in running speech. An extensive acoustic analysis of formant frequencies is carried out for all possible Catalan consonants (as measured at CV-transition starting points) and vowels (as measured at the quasi-steady-state period) in symmetrical CVC environments. The goal of the study is to account for V-to-C and C-to-V coarticulatory effects, and to provide an articulatory interpretation for the acoustic data. I will evaluate this goal in the framework of theories of coarticulation; emphasis will be given to those models that have been better formulated in order to account for coarticulatory effects between adjacent consonants and vowels.

According to the target-based model of coarticulation advocated by Stevens and his coworkers (Stevens and House, 1963; Stevens, House and Paul, 1966) phonemic invariance for vowels and consonants is preserved through ideal acoustic targets and articulatory configurations primarily specified in terms of places of constriction. As a consequence of the inertia of the articulatory system, the overlap of muscular commands for successive phonemes causes the articulators to fall short of such targets (undershoot).

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The extent to which deviation occurs increases with the articulatory and acoustic distance between targets for adjacent phonemes.

It was, however, reported in later works that acoustic invariance is the exception rather than the rule, and that, as the finding that anticipatory effects may extend beyond adjacent segments shows, coarticulation results from active control on the articulatory structures and not only from their mechanical properties (Öhman, 1966; MacNeilage and DeClerk, 1969). To account for these facts, gesture-based models were proposed such as Henke's (1966) and Öhman's (1966). Invariance in the two models is specified for different regions of the vocal tract; coarticulation arises as long as the articulatory requirements for an ongoing gesture are compatible with those for adjacent gestures. In Öhman's (1966) model articulatory compatibility is possible because vowels and consonants are different classes of articulatory gestures; while vowels represent overall vocal tract shapes, articulatory control for consonants of different places of articulation is exerted towards specific articulators, thus leaving uncontrolled regions free to coarticulate. A stronger version of this model has been proposed by Fowler (1980) and Fowler, Rubin, Remez and Turvey (1980) according to which consonantal gestures are overlaid on an underlying string of vowel-to-vowel gestures, thus rendering possible transconsonantal vowel-to-vowel coarticulatory effects (see Tuller and Kelso, 1984, for a review of recent supporting evidence).

The present paper intends to show that Öhman's and Fowler's gestural models are too general to account for a large number of articulatory types and coarticulatory patterns. Thus, for instance, Kent (1983) has stated the fact that coarticulation can also occur between phonemic units that are very similar in motor performance, e.g., consonants showing tongue-tip and tongue-blade contact. Another reason for reconsidering these models arises from the fact that they account mainly for consonants such as labial and dentoalveolar stops, which leave large regions of the vocal tract free to coarticulate with adjacent vowels, thus allowing considerable coarticulatory effects. There are, however, also examples of consonants which are highly resistant to vowel coarticulation because of requirements to constrain larger regions of the vocal tract. This appears to be the case for the velarized apicoalveolar [ɫ] (Bladon and Al-Bamerni, 1976) and the bilabio-dorsovelar [w] (Lehiste, 1964). Also, dorsal consonants such as alveolo-palatals and palatals impose a large degree of constraint upon the tongue body, thus preventing, to a large extent, vowel-dependent coarticulatory effects (Recasens, 1984a, 1984b). It is also known that English fricatives oppose stops in blocking coarticulation in tongue-dorsum activity (Carney and Moll, 1971), tongue-blade activity (Bladon and Nolan, 1977), and jaw opening (Amerman, Daniloff and Moll, 1970).

In the light of these remarks, it seems that a better understanding of coarticulatory processes ought to be gained from an analysis of the interactions between articulatory structures that makes no assumptions as to the vocalic or consonantal nature of the phonological segments under control. According to this view, it will be shown that contrasting vowels and consonants differ as to the extent to which they allow context-dependent effects to occur and, thus, can be categorized according to contrasting degrees of stability (Stevens and House, 1963) or resistance (Bladon and Al-Bamerni, 1976) to coarticulation. Differences in coarticulatory resistance will be shown to depend on differences in constraint on the articulators involved. Thus, the degree to which coarticulatory effects are allowed by a given gesture is expected to vary inversely with the degree of articulatory constraint. On these grounds, consonants such as [ɫ], [w] and palatals ought to allow lesser coarticulation than labials, dentals and alveolars because they are constrained for larger vocal-tract regions. Also, data will be reported arguing for different degrees of articulatory resistance for vowels as a function of degree of articulatory constraint.

A study of CV coarticulatory patterns for such an extensive corpus of data will also allow testing as to whether coarticulatory effects can be interpreted as a function of differences in articulatory compatibility between articulatory gestures. Thus, in line with previous models, Bell-Berti and Harris (1981) state that coarticulation can occur as long as the activity of a given articulator does not conflict with the dynamic requirements of other articulators during the production of the phonemic sequence. A major problem for theories of coarticulation has been to come up with a convincing formulation of the notion of articulatory conflict. It will be shown in the present paper that articulatory gestures for given phonemes differ as to the degree of compatibility with respect to adjacent gestures. Thus, it is claimed that the degree of constraint determines the extent to which an articulatory gesture conflicts with an adjacent gesture. This view is consistent with several findings in the literature. For instance, lip rounding is subject to lesser coarticulatory effects in Swedish than in American English because of being subject to higher articulatory requirements (Lubker and Gay, 1982); also, coarticulation on tongue-dorsum activity for alveolo-palatal and palatal consonants in Catalan was found to decrease with an increase in the requirements on the tongue dorsum to achieve palatal contact (Recasens, 1984a). In addition to highly compatible gestures, such as those used for tongue placement during the production of labial consonants and vowels, coarticulatory effects will be analyzed between highly conflicting gestures, such as those invoked during the production of velarized [ɫ] and [w] vs. high front vowels, and of palatal consonants vs. low and back rounded vowels.

METHOD

To study coarticulatory effects within CV syllables, recordings were made of CV_1CV_2 sequences for all possible symmetrical CV_1C combinations in Catalan. V2 was always [ə] for a stressed V1 and always [a] for an unstressed V1. Stressed V1 were [i e ɛ a ɔ o u] and unstressed V1 was [ə]. Consonants were [p b t d k g c ɟ f s z ʃ ʒ j ʎ r w l]. The phonetic symbol [l] from here on stands for velarized [ɫ]. Unstressed vowels [i u] were not included since they were found to show a highly similar formant structure to stressed [i u]. Nasal consonants were not included since they cause vowel nasalization and, thus, introduce important modifications in the spectral configuration of the vowel (see for a similar procedure, Stevens and House, 1963). Other sequences were excluded, namely, those with [ɾ], since [ɾ] cannot occur in absolute initial position in Catalan, and [ˈjijə] and [ˈwuwə], which are difficult to pronounce for speakers of this language.

Words were embedded in the carrier sentence *Sap* ____*poc* ‘He knows ____ just a little.' They were uttered three times by three speakers of Eastern Catalan from the Barcelona region. Overall, 1278 sequences (142 tokens × 3 repetitions × 3 speakers) were recorded and analyzed.

Data were digitized at a sampling rate of 10 kHz, after preemphasis 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. The three lowest spectral peaks were calculated using a transfer-function polynomial of order 14. Each speech frame contained 200 samples representing 20 msec of speech. Analyses were performed every 3 msec.

All sequences were processed. Measurements in Hz were taken for the first three formants ($F1$, $F2$ and $F3$) at the CV transition starting point and at the midpoint of the V1 steady-state period as determined visually on spectral displays over time. Frequencies at the starting point of the formant transitions were taken as consonantal values; formant frequencies at the vowel steady-state period were taken as vocalic values. Measurements were not taken for VC transitions and, thus, will not be discussed.

V-to-C and C-to-V effects are analyzed. It needs to be stated that the direction of the coarticulatory effects (clearly anticipatory for V-to-C effects, and anticipatory and carryover for C-to-V effects) is of no direct interest in the present paper. For interpretation purposes, consonants were grouped as follows: labials (L) ([p b f]), dentals and alveolars (DA) ([t d s z]); palatals (P) ([c ɟ ʃ ʒ ʎ j]); velars (V) ([k g]); labiovelar ([w]). Data for alveolars [l] and [r] were tabulated independently from data for other alveolar consonants in view of the fact that they are produced with a quite different vocal-tract configuration (see RESULTS, *Vowel-to-consonant effects*). Thus, in the exposition, unless specified, the category of dentals and alveolars does not refer to [l] and [r].

In the RESULTS section, differences in degree of coarticulatory resistance will be determined for consonants and vowels, as inferred from a measure of the standard deviation values for each formant across coarticulatory conditions (see, for an analogous procedure, Stevens and House, 1963, and Bladon and Al-Bamerni, 1976). An analysis of CV coarticulatory effects will be performed to single out those production mechanisms that lead to differences in degree of cross-phonemic coarticulatory resistance. Effects will be analyzed with reference to the literature on acoustic theory of speech production, and on articulation of vowels and consonants. Special consideration will be given to coarticulatory trends arising from compatible and conflicting gestures.

RESULTS

Vowel-to-consonant effects

To study V-to-C effects at the starting point of the vowel transitions, mean formant frequencies are given in Figure 1 for each consonantal category as a function of vowel context, averaged across speakers and repetitions. Table 1 shows mean formant frequencies and standard deviations for each consonantal category across vowels, speakers and repetitions.

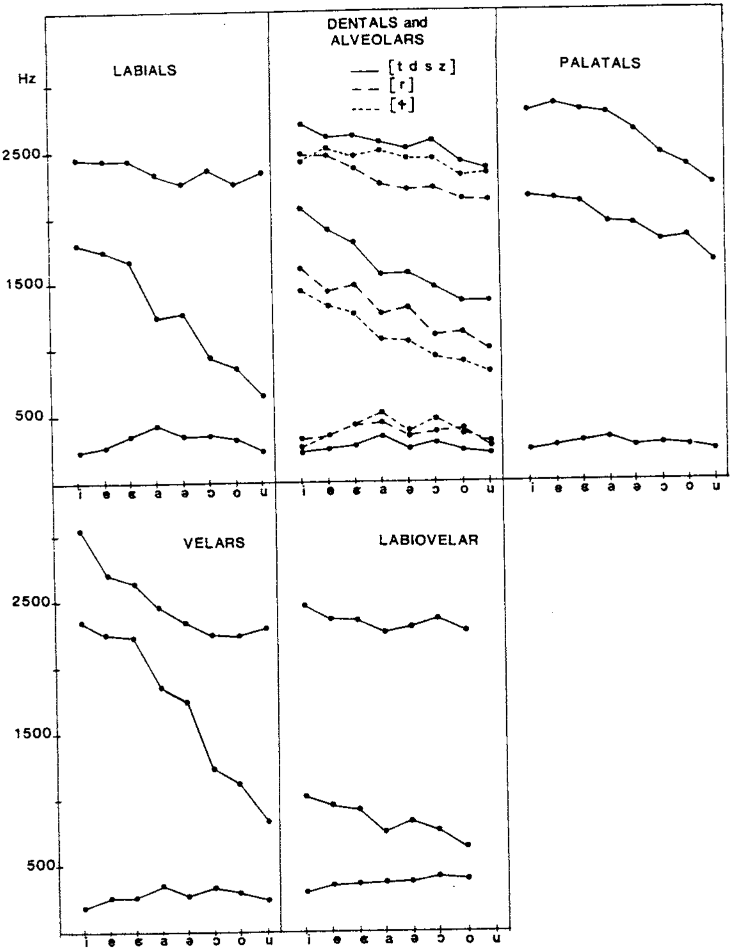

Fig. 1. Vowel-to-consonant effects at the starting point of the vowel transitions. Formant frequencies for *F*1, *F*2 and *F*3 are given for consonants of different articulatory characteristics. Data have been averaged across speakers and repetitions.

As a general trend, at vowel onset, *F*2 and, to a lesser extent, *F*3 for all consonants vary with *F*2 and *F*3 for the vowel (Figure 1). Formant frequencies decrease in the following progression: front vowels of decreasing degree of constriction at the palate ([i], [e], [ɛ]), low pharyngeals ([a]), and, for increasing degrees of lip rounding, upper pharyngeals ([ɔ], [o]) and velars ([u]). *F*2 frequency values for the Catalan schwa are close to those for [a]. On the other hand, *F*1 frequency decreases with increasing degrees of vowel height and lip rounding in the following progression: low vowels ([a]),

TABLE 1

Formant-frequency values and standard deviations (in Hz) for consonants of different articulatory characteristics across vowel contexts measured at the starting point of the vowel transitions. Data have been averaged across speakers and repetitions. Consonantal categories have been labeled as follows:

L (labials), DA (dentals and alveolars), P (palatals), V (velars), [r], [l] and [w]

		L	DA	P	V	r	l	w
*F*1	$\bar{X}$	312	263	261	289	369	384	357
	σ	69	41	34	52	58	81	46
*F*2	$\bar{X}$	1276	1639	1944	1706	1290	1109	832
	σ	432	255	173	597	208	220	134
*F*3	$\bar{X}$	2359	2552	2619	2500	2285	2425	2336
	σ	74	110	227	277	137	75	71

mid low vowels ([ɛ], [ɔ]), mid high vowels ([e], [o]), and high vowels ([i], [u]). *F*1 frequency characterizes Catalan schwa as a mid vowel.

While there are strong V-to-C effects, consonants differ as to the degree of resistance to vowel coarticulation. As shown by standard deviation values in Table 1, the degree of cross-vocalic variability in *F*1, *F*2 and *F*3 frequencies at the starting point of the vowel transitions differs for consonants of contrasting articulatory characteristics. Thus, for instance, standard deviations show large *F*2 variability for velars and labials (thus, highly sensitive to vowel effects) and small *F*2 variability for palatals and [w] (thus, highly resistant to vowel effects), dentals and alveolars falling in between. I will next comment on different degrees of coarticulatory resistance for contrasting consonants and show how they arise from differences in constraint on the articulatory structures involved in their production. Reference will be made to the acoustic outcome of compatible and conflicting gestures.

Second formant frequencies. According to the table, velars and labials allow the highest degree of vowel-dependent $F2$ variability of all Catalan consonants (also, for American English, Stevens *et al.*, 1966). Large $F2$ variability for velars is associated with the articulatory differentiation between two consonantal allophones, namely palatovelars preceding front vowels, and back velars preceding back vowels (Swedish: Öhman, 1966; Fant, 1973; American English: MacNeilage and DeClerk, 1969; Kent and Moll, 1972; German: Butcher and Weiher, 1976). Accordingly, at the acoustic onset of the vowel, a high degree of articulatory compatibility is expected between the consonantal and vocalic gestures. In line with data in Figure 1 and Fant's (1960) indications, as for palatals, palatovelars show a high $F2$ with front vowels as a result of a complete dorsopalatal closure and a wide pharyngeal passage. A lower $F2$ for back velars at the onset of back vowels is dependent on a large cavity in front of the velar place of articulation, with considerable jaw opening for [a] (American English: Kent and Moll, 1972) and lip rounding for rounded vowels. Large $F2$ variability and, thus, high degree of vowel-compatibility for labials is consistent with free positioning of the tongue body for all vowels during closure (American English: Carney and Moll, 1971) since no tongue constriction is required for the production of these consonants. Labials show a lower $F2$ than velars (and, mostly, than the other consonantal categories except for [w]) because of a smaller lip-opening area (Fant, 1960).

Dentals and alveolars (including [r] and [ɫ]) allow less $F2$ variability than velars and labials (see Table 1), as for American English (Stevens *et al.*, 1966). While tongue-body coarticulation for these consonants is well documented in the literature (Swedish: Öhman, 1966; American English: Carney and Moll, 1971; German: Butcher and Weiher, 1976; Catalan: Recasens, 1983), it may be that lesser coarticulation occurs because of the physical coupling between tongue tip and tongue body (Kent and Moll, 1972; Lindblom, 1983). It is suggested that this articulatory constraint results in more fronting of the tongue body (and, thus, a lower $F2$) with back vowels than for labials and back velars, and lesser dorsopalatal contact (at the sides of the palate only; see Recasens, 1983) (and, thus, a lower $F2$) with front vowels than for palatovelars.

Standard deviation values are smaller for [r] and velarized [ɫ] vs. [t d s z], thus indicating higher degree of coarticulatory resistance to vowel effects. High stability for [ɫ] has also been reported for "dark" [ɫ] in English (American English: Lehiste, 1964; RP British English: Bladon and Al-Bamerni, 1976). It is suggested that lesser coarticulation at vowel onset results from a higher degree of articulatory constraint on the tongue body for the consonant. For [ɫ], a more constrained tongue body is related to the formation of two simultaneous places of articulation, namely, at the alveolar region (by means of an apical contact) and at the pharyngovelar region (by means of a dorsal constriction), with a more pronounced concave shape of the tongue predorsum than for other alveolars (Barnils, 1933; Recasens, 1983). This gesture causes a lower $F2$ for [ɫ] than for [t d s z], which is inversely related to a narrower pharyngeal constriction and a larger cavity system behind the place of alveolar closure (Fant, 1960). For the apico-alveolar trill [r], it may be that high requirements are imposed by speakers on tongue body activity to facilitate the production of the trill. Thus, similarly to [l], [r] is articulated with more backing of the tongue body (and, thus, a lower $F2$) than [t d s z], some concave positioning of the tongue predorsum and, presumably, some dorsopharyngeal constriction (see also, for Spanish, Navarro Tomás, 1970).

These articulatory descriptions suggest that the degree of coarticulatory resistance for [l] and [r] at vowel onset results rather from a requirement to constrain the overall tongue configuration than from separate commands to make an apical contact and a dorsal constriction. Thus, differently from Russian (Öhman, 1966), it can not be argued that the formation of the dorsopharyngeal constriction for [l] and [r] in Catalan is related to a command for the actualization of a velar vowel substrate, since no palatalized/velarized distinction is found for consonants in this language. Presumably, as for [w], simultaneous commands on two separate tongue regions would make [l] and [r] more resistant to coarticulation. However, as shown in Figure 1, [l] and [r] allow coarticulatory effects from front vowels which are comparable (though less apparent) to those for [t d s z]; thus, it may be stated that the tongue-dorsum fronting and raising gesture for the vowel is not completely overridden by a conflicting gesture involving a retracted and lowered tongue-dorsum placement, as for [l] and [r].

Palatal consonants and labiovelar [w] show the lowest degree of $F2$ variability of all Catalan consonants (see Table 1). For palatals, small V-to-C coarticulatory effects (American English: Lehiste, 1964; Stevens *et al.,* 1966; French: Chafcouloff, 1980; Catalan: Recasens, 1984a) are due to the severity of the constraints on tongue-dorsum raising to achieve dorsopalatal contact. As for palatovelars, a higher $F2$ for palatal vs. other consonants is associated with a wide pharyngeal passage and a large degree of dorsal contact at the hard palate (Fant, 1960). At vowel onset, the consonantal gesture prevents, to a larger extent than dentals and alveolars, coarticulation from vowels involving conflicting gestures, such as tongue-dorsum lowering and backing, as indicated by an $F2$ placement between 1600 and 2000 Hz at the onset of back vowels. To account for such a high degree of coarticulatory resistance it cannot be argued, analogously to [l] and [r], that the formation of dorsopalatal contact for Catalan alveolopalatals [c ɟ ʃ ʒ ʎ] is associated with a command for the actualization of a palatal vowel substrate, as for Russian palatalized consonants (Öhman, 1966). Good evidence for this arises from the fact that, while both consonantal sets involve simultaneous raising of the front and dorsal regions of the tongue, alveolopalatals show larger dorsal contact towards the center of the palatal region than palatalized consonants (Catalan: Recasens, 1984a; Russian: Vihman, 1967).

Analogously to other languages (American English: Lehiste, 1964; French: Chafcouloff, 1980), small V-to-C coarticulatory effects for the Catalan labiovelar [w] may be associated with the high requirements imposed by speakers to execute a bilabial constriction and a dorsovelar constriction simultaneously. A low $F2$ for [w] is dependent on a large cavity in front of the tongue constriction, as for labials and back velars with back rounded vowels, but with more lip rounding. At vowel onset, the consonantal gesture prevents, to a large extent, coarticulation from vowels involving conflicting gestures, such as tongue fronting and lip unrounding, as indicated by an $F2$ placement at about 1000 Hz at the onset of front vowels.

Third formant and first formant frequencies. According to Table 1, palatal and velar consonants show a higher degree of *F*3 variability than the other Catalan consonants. For palatals and palatovelars with front vowels, a small front cavity and a highly constricted dorsopalatal passage give rise to a high *F*3. At the onset of back vowels, an *F*3 decrease is observed for palatals and back velars with rounded vowels, and for back velars but not for palatals with [a]. Thus, while the two consonantal categories appear to be equally sensitive to lip-rounding effects, palatals are more resistant than velars to conflicting gestures, such as tongue retraction (Recasens, 1984a) and jaw opening (American English: Kent and Moll, 1972).

A lower degree of *F*3 variability for other consonants than for palatals and palatovelars is mainly associated with a lower *F*3 at the onset of front vowels, given an analogous low *F*3 for all the consonants at the onset of back rounded vowels due to lip-rounding effects. A lower *F*3 for dentals and alveolars vs. palatals and palatovelars with front vowels results, presumably, from a lesser degree of dorsopalatal constriction, assuming a highly analogous front-cavity size (Fant, 1960). At the onset of [a], *F*3 is lower for dentals and alveolars vs. palatals but not velars in accordance with less jaw opening during closure for [ata] vs. [aka] in English (Kent and Moll, 1972). Overall, dentals and alveolars (including [l] and [r]) allow a small degree of *F*3 variability at vowel onset, consistent, as for palatals, with a highly invariant place of articulation and a considerable resistance to conflicting jaw-lowering effects. Little *F*3 coarticulation for [p b f] and [w] at vowel onset shows that the degree of bilabial closure for labials and of labiovelar constriction for labiovelars remains highly constant across vowel conditions.

At vowel onset, the highest *F*1 corresponds to consonants that are articulated with some oral opening, namely, [w] (at the place of velar and labial constrictions), [r] (during the open interval of the trill) and [l] (at the sides of the palate, as for other lateral consonants). The lowest *F*1 is found for consonants that are articulated with a complete lingual closure, namely, dentals and alveolars, palatals, and velars. Standard deviation values in Table 1 show a clear trend for the degree of *F*1 variability to increase with the degree of consonantal opening, at least for consonants involving lingual closure. Thus, contrasting degrees of vowel opening at vowel onset can be better actualized for consonants showing lesser requirements to make a complete lingual closure, as for [l] and [r] vs. palatals, and dentals and alveolars.

Summary. As inferred from acoustic data on *F*1, *F*2 and *F*3 frequencies, vowel-dependent coarticulatory effects at the starting point of CV formant transitions have been shown to vary in line with the requirements imposed by speakers on the vocal-tract configuration for the consonant. Thus, consonants may prevent, to a large extent, vowel-dependent coarticulatory effects from taking place. In particular, vowel effects in oral opening (as shown by *F*1 and *F*3) are largely blocked by consonants showing complete closure. As for coarticulatory trends affecting tongue positioning in the vocal tract (as inferred from *F*2 and *F*3 data), coarticulatory resistance has been found to be positively correlated with large degrees of dorsopalatal contact, the formation of a double place of articulation, and tongue-body–tongue-tip coupling. Consonants differ as to the extent to which they are articulated with reference to one or more of these constraints and, thus, as to the degree of V-to-C coarticulation. The most constrained articulations

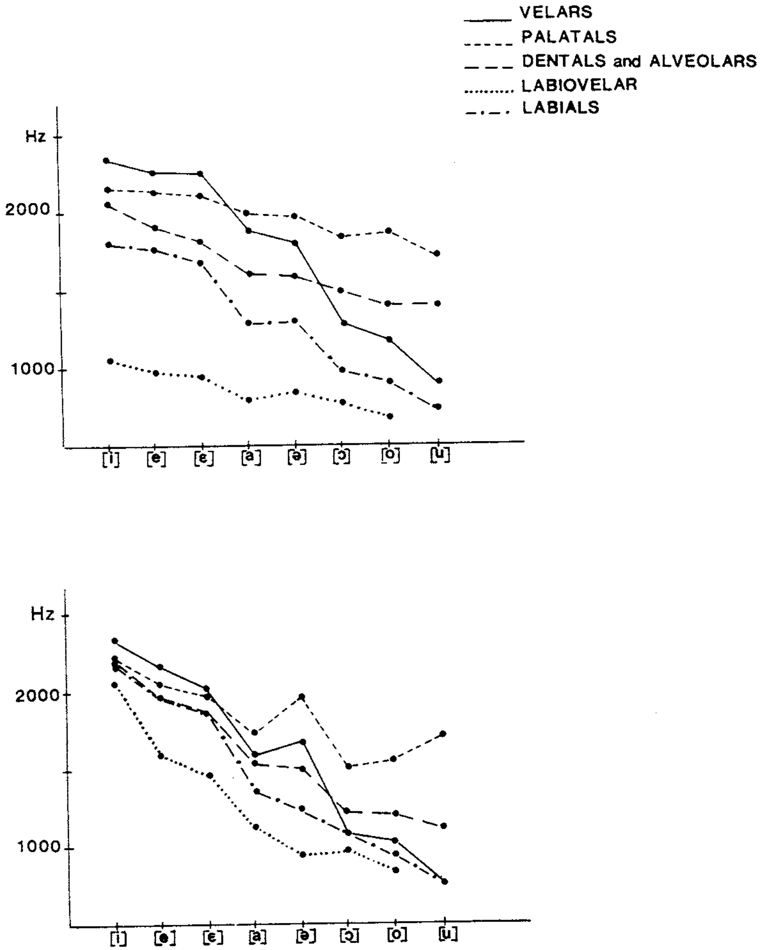

Fig. 2. *F*2 frequency values for vowels at the starting point of the vowel transitions (above) and at the vowel steady-state period (below) as a function of consonants of different articulatory characteristics. Data have been averaged across speakers and repetitions.

are [w] and palatal consonants, which block, to a large extent, vowel effects involving jaw and tongue activity and, for [w], lip rounding as well. The least constrained are velars and labials which allow considerable effects in vowel lowering and fronting and, for velars, lip rounding as well. Dentoalveolar consonants, on the other hand, show that degrees of coarticulation are also sensitive to contrasting degrees of constraint on analogous articulatory gestures. Thus, while [t d s z l r] require apical contact at the dentoalveolar region, the tongue body is more constrained for [l] and [r] vs. [t d s z], thus blocking, to a large extent, tongue fronting and raising effects.

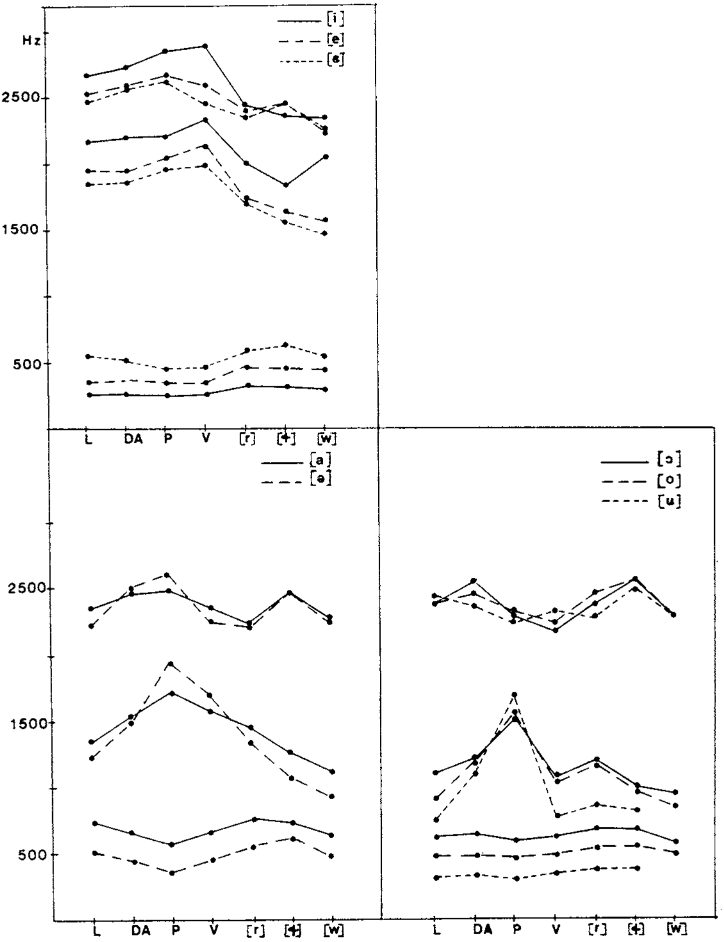

Fig. 3. Consonant-to-vowel effects at the vowel steady-state period. Formant frequencies for *F*1, *F*2 and *F*3 are given for three different sets of vowels (front vowels; [a], [ə]; back rounded vowels). Data have been averaged across speakers and repetitions. Consonantal categories have been labeled as follows: L (labials), DA (dentals and alveolars), P (palatals), V (velars), [r], [l] and [w].

Consonant-to-vowel effects

*F*2 coarticulatory effects for different vowels and consonants (except for [l] and [r]) are displayed in Figure 2 at the starting point of the vowel transitions (above) and at the vowel steady-state period (below), across speakers and repetitions. A comparison between the two displays shows that, although to a lesser extent, cross-consonantal *F*2 differences at the vowel steady-state period are highly similar to those present at the

TABLE 2

Formant-frequency values and standard deviations (in Hz) for vowels across consonantal contexts measured at the vowel steady-state period. Data have been averaged across speakers and repetitions

		[i]	[e]	[ɛ]	[a]	[ɔ]	[o]	[u]	[ə]
*F*1	$\bar{X}$	283	405	541	670	607	474	315	486
	σ	27	53	59	63	36	23	24	79
*F*2	$\bar{X}$	2114	1869	1771	1420	1129	1071	980	1376
	σ	160	211	204	209	194	249	374	363
*F*3	$\bar{X}$	2613	2509	2444	2368	2362	2368	2338	2351
	σ	233	141	132	109	136	108	104	159

starting point of the transitions. Thus, significant traces of the consonantal gesture can be said to occur during the articulation of the vowel.

To study C-to-V effects at the vowel steady-state period, mean formant frequencies are given in Figure 3 for three sets of vowels as a function of consonantal context, averaged across speakers and repetitions. The vowels have been grouped according to contrasting coarticulatory patterns in *F*2 frequency, for front vowels (pattern 1), low back vowel [a] and schwa (pattern 2), and back rounded vowels (pattern 3). Table 2 shows mean formant frequencies and standard deviations for each vowel across consonants, speakers and repetitions.

While, as shown in Figure 2, there are strong C-to-V effects, vowels differ as to the degree of resistance to consonant coarticulation. As shown by standard-deviation values in Table 2, the degree of cross-consonantal variability in *F*1, *F*2 and *F*3 frequencies at the vowel steady-state period differs among vowels. A comparison between Table 1 and Table 2 shows, moreover, that the degree of *F*2 coarticulation is not vowel- vs.

consonant-specific but rather phoneme-specific. This finding is not consistent with the view that vowels and consonants are subject to contrasting coarticulatory effects because of different types of articulatory gestures (see INTRODUCTION). I will next comment on different degrees of consonantal resistance for contrasting vowels and show how they arise from differences in their production. The acoustic outcome of conflicting and compatible gestures will also be taken into account.

Second-formant frequencies. According to Table 2, [i] shows the highest degree of coarticulatory resistance of all Catalan vowels. Small *F*2 variability for [i] has also been reported for American English (Stevens and House, 1963) and Dutch (Pols, 1977), thus, confirming, as for palatal consonants (see Table 1), that articulations involving a large tongue-dorsum raising gesture towards the palate block, to a large extent, coarticulation upon tongue-body activity. As shown in Figure 3 (pattern 1), *F*2 frequency for front vowels varies directly with the degree of dorsopalatal constriction and pharyngeal width (Wood, 1982a) for the consonant. A high *F*2 is caused by palatals and palatovelars, which are produced with a dorsopalatal closure and a wide pharyngeal passage; a low *F*2 is caused by [ɫ] and [ɾ], which are articulated by means of an articulatory configuration in conflict with that for front vowels, with a lowered predorsum and some pharyngeal narrowing. While tongue-dorsum lowering and pharyngeal narrowing during the production of front vowels with adjacent [ɫ] and [ɾ] cause a noticeable *F*2 decrease, a retraction of the place of constriction towards the rear of the palate (with additional lip rounding) for [i] adjacent to [w] does not result in an appreciable *F*2 lowering (also, for American English, Lehiste, 1964). These data for [i] are consistent with Stevens' (1972) predictions that changes in constriction location along the palatal region cause negligible spectral changes.

As for the pattern 2, low pharyngeal [a] shows an analogous degree of *F*2 variability to that for other mid open and open vowels, while [ə] shows a high degree of *F*2 variability. *F*2 for [a] increases with an increase in the width of the lower pharyngeal constriction and, thus, with tongue fronting and a front cavity reduction (Fant, 1960; Wood, 1982b). Thus, while consonants involving conflicting tongue fronting, such as palatals, cause a high *F*2 frequency, consonants showing a pharyngeal constriction, such as [ɫ], cause a low *F*2. A higher *F*2 for alveolars and velars vs. labials is consistent with Gay's (1974, 1977) finding for English that [a] shows more tongue height and less jaw opening with [t] and [k] vs. [p]. Lowest *F*2 for [a] with [w] is presumably related to lip rounding for the consonant.

The pattern of consonantal effects upon *F*2 of [ə] is similar to that for [a]. Consonant-dependent frequency displacements are larger for the schwa. Thus, e.g., palatal consonants cause a higher *F*2, and [ɫ] and [w] cause a lower *F*2. The schwa is, therefore, highly sensitive to coarticulatory effects from the adjacent consonants in line with the fact that, for a vowel articulated with an idealized open tube, any constriction difference along the vocal tract has a marked effect on all formant frequencies (Fant, 1960; Mrayati and Carré, 1976).

Table 1 shows that cross-consonant *F*2 variability among back rounded vowels increases with lip rounding for the vowel. Thus, standard deviations for [u] are the largest of all Catalan vowels. Also Stevens *et al.* (1966) found larger *F*2 coarticulation for [u] than for other English vowels. *F*2 for these vowels is directly dependent on a widening of the passage at the tongue constriction and lip unrounding effects (Wood, 1982b), and, thus, tongue fronting and a front-cavity reduction. Accordingly, as shown by pattern 3, *F*2 is generally low for consonants showing a velar and/or pharyngeal constriction, namely [w], [l], [r] and back velars, or no tongue constriction, namely, labials, and higher for consonants showing a more forward place of constriction, namely, dentals and alveolars (for [u] but much less so for [ɔ] and [o]), and palatals.

Two possible explanations are given to account for large *F*2 effects caused by palatal consonants on back rounded vowels. It could be that these consonants cause a considerable advancement of the place of dorsal constriction for the vowel, thus originating a vocal tract configuration analogous to that for front high and mid rounded vowels in line with the fact that such realizations have no phonemic status in Catalan. A considerable *F*2 increase could also be due to lip unrounding effects (Fant, 1960; Ladefoged and Bladon, 1982), consistent with Wood's (1982b) finding and Stevens' (1972) quantal theory that advancing the tongue constriction along the soft palate causes little *F*2 raising. This hypothesis is in accord with the fact that *F*2 displacement increases with lip rounding for the vowel and, thus, is larger for [u] vs. [ɔ], [o].

The sequences [wi] and [j c ɟ ʃ ʒ] + [u] involve highly constrained, conflicting gestures, namely, lip rounding and dorsovelar constriction for [w] and [u], vs. lip unrounding and dorsopalatal constriction for [i] and palatal consonants. *F*2 shows, however, different coarticulatory effects; thus, while the [w] gesture blocks, to a large extent, coarticulation due to following [i], the gesture for [u] is greatly overridden by the effects of a preceding and a following palatal consonant. It could be argued that this is so because, while [w] is only subject to anticipatory effects, [u] is subject to simultaneous anticipatory and carryover effects involving the same consonant. Notice, however, that under analogous circumstances, similar effects occur for *F*2 on [i] from preceding and following [l] (Figure 3) vs. [l] from following [i] (Figure 1). Therefore, it is not likely that coarticulatory direction plays a major role in determining a larger degree of *F*2 coarticulation for [u] vs. [w]. Instead, this contrast is to be explained in terms of differences in degree of articulatory constraint used by speakers to execute the bilabial and dorsovelar gestures in both cases. Thus, larger effects on [u] vs. [w] are due to the fact that [u] is produced with a lesser constrained labiovelar constriction, as suggested by a lesser degree of lip rounding, and, perhaps, a wider dorsovelar constriction than [w].

Third-formant and first-formant frequencies. As for palatal consonants, *F*3 is largely dependent on the size of the constriction passage and on the front cavity size for [i], and becomes more dependent on the entire vocal tract as the width of the palatal constriction increases for [e] and [ɛ] (Fant, 1960). Table 2 (pattern 1) indicates a higher degree of *F*3 variability for [i] vs. [e] and [ɛ]. Large *F*3 lowering effects from [r] and [l] on [i] reveals that this formant is more sensitive than *F*2 to changes in the size of the palatal constriction (Fant, 1960); also, differently from *F*2, a low *F*3 for [i] with [w] results from the fact that *F*3 is highly sensitive to small degrees of lip rounding (Fant, 1960; Ladefoged and Bladon, 1982) and of retraction of the place of constriction along the palate (Wood, 1982a). *F*3 for [a] (pattern 2) is also front-cavity dependent and, thus, shows analogous coarticulatory effects to *F*2; similarly to *F*2, *F*3 for [ə] is quite sensitive to coarticulatory effects from the surrounding consonants. A low *F*3 for back rounded vowels (pattern 3), is due to fronting of the tongue dorsum constriction along the soft palate with adjacent velar and palatal consonants (Wood, 1982a), and to additional lip rounding with adjacent [w] (Fant, 1960); a higher *F*3 for these vowels results from a reduction in front-cavity size because of tongue-tip raising caused by adjacent dental and alveolar consonants (including [l] and [r]) (Japanese: Kiritani, Itoh, Hirose and Sawashima, 1977; American English: MacNeilage and DeClerk, 1969).

For all vowels, *F*1 increases with an increase in degree of oral opening for the consonant. Thus, it is worth noticing that consonant-dependent variations in *F*1 for the three sets of vowels are a good mirror-image replication of consonant-dependent variations in *F*2 frequency, except for [w], which causes a lowering of all formant frequencies because of lip-rounding effects. As for coarticulatory effects at the CV transition onset (see p. 105), standard-deviation values in Table 2 show a clear trend for the degree of *F*1 variability to increase with the degree of vowel opening (also, for American English, Stevens and House, 1963). Thus, while [a] allows large *F*1 effects, [i] and [u] allow small effects in oral opening from the adjacent consonants.

Summary. A comparison between degrees of resistance to coarticulatory effects for Catalan vowels shows small differences in *F*2 and *F*3 variability among mid vowels and [a], presumably as a result of the fact that such vowels are controlled for overall vocal-tract configurations. As shown by *F*1 variability, the low vowel [a] opposes the other vowels in being more sensitive to degrees of consonantal opening. Vowels [i], [u] and [ə] show different degrees of formant variability. Vowel [i] behaves like palatal consonants except for being more sensitive to degrees of consonantal opening (as shown by *F*3) presumably because of lesser palatal contact. As shown by all formant frequencies, the schwa is highly compatible with other gestures in line with the fact that no defined vocal-tract shape is needed for the production of this vowel. Lesser articulatory control on the bilabial and dorsovelar constrictions for [u] vs. [w] causes a higher degree of *F*2 sensitivity to lip-unrounding and tongue-fronting effects from consonants.

CONCLUSIONS

This paper shows that consonants and vowels are not necessarily produced by means of articulatory requirements of a different nature (i.e., on an overall vocal-tract shape for vowels, and on specific vocal-tract regions for consonants). Thus, consonants may require a high degree of articulatory control over large regions of the vocal tract, as for [l], [r], [w] and palatal consonants; also, consonants and vowels may be articulated by means of highly analogous gestures, as for [i] and palatal consonants, and [w] and [u]. According to Öhman (1966), a high degree of coarticulatory resistance to vowel effects for palatalized and velarized consonants in Russian is due to additional articulatory requirements imposed by a command towards the actualization of a vowel substrate.

It has been shown, however, that this explanation is not applicable to Catalan since no palatalized–velarized distinction among consonants is found in this language.

It has also been shown that Catalan phonemes differ as to degrees of coarticulatory resistance in line with differences in articulatory constraint. The degree of articulatory constraint explains whether gestures are more or less compatible with respect to coarticulatory effects from adjacent gestures. Thus, highly constrained gestures (such as for the production of palatal articulations and consonants involving two simultaneous places of constriction) override, to a large extent, coarticulatory effects from conflicting gestures, and gestures subject to low degrees of constraint (as for the production of labial consonants and [ə]) become highly compatible with respect to other articulatory gestures. In particular, data on V-to-C coarticulation confirm Öhman's view that, to a large extent, the consonantal gesture overrules the vocalic gesture, if the latter is antagonistic to the former, so that the consonantal constriction can be achieved (Öhman, 1966). On these grounds, it has been inferred from the acoustics that the need to form a palatal constriction prevents effects from back vowels from taking place, and that a constraint to make a bilabial and a dorsovelar constriction explains why [w] is not sensitive to effects from front vowels.

Several examples reported here support the view that the degree of coarticulation allowed by a given articulatory gesture decreases with a decrease in the requirements to perform the gesture. Thus, a larger degree of $F1$ variability to oral-opening effects from adjacent gestures has been found for consonants and vowels involving lesser requirements to perform a closing gesture. Differences in coarticulatory resistance for [l] and [r] vs. [t d s z], [w] vs. [u] and palatal consonants vs. [i] also confirm this hypothesis. It can be argued that Catalan speakers have learned how to differentiate, at the level of production, consonants within each of these three consonantal sets as a function of differences in the degree of articulatory control. Similar cases have been reported in the literature for degrees of lip rounding in rounded vowels (Swedish vs. English: Lubker and Gay, 1982), of dorsopalatal contact in palatal consonants (Catalan: Recasens, 1984a, 1984b), and of dorso-pharyngovelar constriction in "clear" vs. "dark" [l] (English: Bladon and Al-Bamerni, 1976).

I take these results to confirm the need for a theory of coarticulation that accounts for coarticulatory effects in terms of the articulatory constraints involved in the production of gestures for adjacent phonemes, independent of considerations about the linguistic nature of the phonemic units under control. Such a theory, thus, needs to make predictions about the articulatory and spectral consequences of competing articulatory gestures (Harris, 1984). It is claimed that the extent to which coarticulatory effects occur is associated with the degree of articulatory constraint involved in the production of an ongoing gesture. For instance, it has been shown that velarized [ɫ] is more resistant than "clear" [l] to coarticulatory effects from adjacent vowels. Differences in degree of articulatory constraint on tongue-body activity for the two consonants in the sequence [iCi] cause a strong $F2$ decrease during the production of C = [ɫ] but essentially no frequency change when C = [l] is being produced. In asymmetrical VCV sequences, the extent to which vowel-dependent coarticulatory effects extend into the transconsonantal vowel will, however, not only depend on the degree of constraint exerted upon the articulatory configuration for the consonant but for the transconsonantal vowel as well.

Thus, while such effects will be largely blocked when C = [ɫ], effects across [l] will be more or less apparent depending on whether the transconsonantal vowel is specified for higher (e.g., [i]) or lower (e.g., [ə]) degrees of coarticulatory resistance.

This study shows that some understanding about the nature of the production constraints on articulatory activity can be gained from an acoustic analysis of the coarticulatory effects between adjacent consonants and vowels. Candidates for production constraints presented here need to be validated with additional articulatory data. Further articulatory and acoustic analyses on other languages will allow testing whether such production constraints are universal or language-specific.

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