AN ACOUSTIC ANALYSIS OF V-TO-C AND V-TO-V: COARTICULATORY EFFECTS IN CATALAN AND SPANISH VCV SEQUENCES

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Abstract. V-to-C and V-to-V coarticulatory effects in $F_2$ frequency are studied for Catalan and Spanish VCV sequences with vowels and consonants involving different degrees of articulatory constraint on tongue-dorsum activity. The findings reported in this paper indicate that coarticulatory effects decrease with the degree of articulatory constraint, for the following groups of consonants and vowels: [i]>[i]; [e]>[e]; [u], [o]>[u]; [a]>. Differences in anticipatory vs. carryover coarticulation were also found to be strongly dependent on the degree of articulatory constraint associated with the intervening consonants and vowels. Overall, results suggest that coarticulatory effects are deeply related to the control mechanisms involved in the production of articulatory gestures.

Introduction

The main purpose of this paper is to show the need for a theory of coarticulation that accounts for coarticulatory effects in terms of the constraints (i.e., requirements) imposed on the articulators during the production of gestures for adjacent phonemes. According to gestural models of coarticulation, coarticulatory effects occur as long as the articulatory requirements for an ongoing gesture do not conflict with those for adjacent gestures (Öhman, 1966). In an effort to characterize the notion of articulatory conflict, evidence will be provided here in support of the hypothesis that the degree of compatibility between a given gesture and adjacent gestures decreases with the degree of articulatory constraint. Thus, highly constrained gestures ought to block coarticulatory effects to a larger extent than gestures specified for lesser degrees of articulatory constraint. Data from the literature support this view. For instance, Lubker and Gay (1982) have shown that the lip rounding gesture for [u:] allows lesser coarticulatory effects in Swedish than in American English because of being subject to higher articulatory requirements; thus, [u:] shows more lip protrusion and an earlier lip rounding onset in Swedish vs. American English in line with the fact that Swedish has more distinctive rounded vowels than English. Also, Recasens (1984a) showed for Catalan that coarticulatory effects on the degree of dorsopalatal contact for palatal, alveolopalatal, and

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Alveolar consonants vary inversely with the constriction degree; thus, coarticulatory effects decrease with an increase of the requirements imposed upon the tongue dorsum to make contact at the surface of the hard palate.

First, acoustic data will be presented that suggest that the degree of V-to-C and V-to-V coarticulation in VCV sequences is inversely related to the degree of articulatory constraint for the consonantal gesture. For this purpose, coarticulatory effects will be analyzed for the following consonants showing contrasting degrees of articulatory constraint on tongue-dorsum activity: (1) velarized apicoalveolar lateral [l] vs. non-velarized apicoalveolar lateral [l]; (2) apicoalveolar trill [r] vs. apicoalveolar tap [r]; (3) velar approximant [y] vs. bilabial approximant [β] and dental approximant [ɔ]. Among these consonants tongue-dorsum activity is subject to a higher degree of articulatory constraint for [l] vs. [l], [r] vs. [r], and [y] vs. [β] and [ɔ]: higher articulatory control over tongue-dorsum activity for [l] vs. [l] results from the fact that, while the two realizations involve apicoalveolar contact, only [l] is articulated with postdorsal constriction at the velopharyngeal region and predorsal lowering (Recasens, 1985); higher demands on tongue-dorsum activity for [r] vs. [r] are reflected by some backing of the tongue dorsum and, presumably, some degree of dorsopharyngeal constriction for the trill (see, for Spanish, Navarro Tomás, 1970) to allow the execution of several apicoalveolar vibrations; finally, [y] is subject to a higher degree of tongue-dorsum constraint than [β] and [ɔ] in accordance with the fact that, for [y], the tongue dorsum is fully involved in the formation of a constriction at the palatovelar or velar regions.

Some data from the literature are relevant here. Acoustic data (F2) for English show indeed that "dark" [l] is highly resistant to V-to-C effects during closure (American English: Lehiste, 1964; RP British English: Bladon & Al-Bamerni, 1976), more so than "clear" [l] (Bladon & Al-Bamerni, 1976). Also, larger V-to-V coarticulatory effects on tongue-dorsum activity have been reported across labial and alveolar consonants (Catalan: Recasens, 1984b; American English: Carney & Moll, 1971; Swedish: Öhman, 1966) than across velar consonants (German: Butcher & Weiher, 1976); these data are consistent with articulatory data (Catalan: Recasens, 1984a, 1984b) and acoustic data (American English: Lehiste, 1964; Stevens & House, 1963) showing that palatal consonants allow less coarticulatory effects on tongue-dorsum activity than labials and alveolars.

The issue as to whether vowel-dependent effects in VCV sequences can or cannot extend into the transconsonantal vowel is of interest here as well. Thus, while it was found in several early works that such effects do not extend beyond the period of consonantal closure (Gay, 1974, 1977) or the period of transconsonantal vowel transitions (Öhman, 1966; Carney & Moll, 1971), more recent acoustic evidence for English and other languages (Magen, 1984; Manuel & Krakow, 1984) reveals that vowel-dependent effects can also extend into the steady-state period of the transconsonantal vowel.

It will also be shown that the degree to which an F2 difference between two vowels can be traced beyond consonantal closure or consonantal constriction depends on the degree of articulatory constraint for the transconsonantal vowel. Thus, some vowels have been reported to be more resistant than others to V-to-V effects. In a series of experiments, Gay (1974, 1977) found [i] to be more resistant than [a] to differences in jaw opening and tongue body height caused by contrasting consonants and vowels in
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VCV sequences. Similarly, Carney and Moll (1971) found no anticipatory V-to-V effects in tongue-dorsum activity at the steady state period of V1=[i]. These articulatory data accord well with acoustic data. Thus, [i] has been found to be more resistant than [a] to V-to-V coarticulatory effects in $F_2$ frequency in Japanese (Magen, 1984), and in Swahili and Shona (Manuel & Krakow, 1984).

I will also analyze differences in nature between anticipatory and carryover coarticulatory effects. It is commonly accepted that carryover effects are more dependent than anticipatory effects on mechanical constraints, and that anticipatory effects are mainly timing effects resulting from articulatory preprogramming. Accordingly, contrasting V-to-V coarticulatory effects among consonants showing different degrees of articulatory constraint (such as the ones included here) ought to take place at the carryover level but less so--or not at all--at the anticipatory level. Thus, consonants subject to large degrees of constraint are expected to block V-to-V carryover coarticulation to a larger extent than consonants subject to less considerable articulatory requirements; on the other hand, a smaller contrast--or no contrast at all--between V-to-V coarticulatory effects for both sets of consonants is expected at the anticipatory level. In line with this hypothesis, differences in V-to-V coarticulation for Catalan consonants (palatals, alveolopalatals, and alveolars) involving different degrees of tongue-dorsum constraint were found to occur to a larger extent at the carryover level than at the anticipatory level (Recasens, 1984b).

Attention will also be paid to differences in magnitude between anticipatory and carryover effects. While carryover effects have generally been found to be larger than anticipatory effects in English (MacNeilage & DeClerk, 1969) and Catalan (Recasens, 1984a, 1984b), anticipatory effects have been shown to exceed carryover effects in Japanese (Magen, 1984), and in Swahili and Shona (Manuel & Krakow, 1984). This paper investigates the extent to which differences in the magnitude of anticipatory vs. carryover coarticulation follow from differences in the degree of constraint involved in the production of articulatory gestures.

Method

$F_2$ frequency data were collected for three sets of consonants, [l]-[x], [r]-[r], and [p]-[b]-[y], in all possible symmetrical and asymmetrical [V'CV] combinations with V=[i], [a]. Speakers of two different languages, Catalan and Spanish, were chosen in order to test coarticulatory effects for [l] vs. [x], given the fact that the alveolar lateral consonant is known to be velarized ("dark") in Catalan ([x]) and non-velarized ("clear") in Spanish ([l]) (Badia, 1951; Navarro Tomas, 1970). According to these two literature sources, the other phonetic categories tested in the experiment (the tap [r], the trill [r], the approximants [b], [a] and [y], and the vowels [i] and [a]) show the same or highly similar articulatory characteristics in both languages.

All VCV sequences were embedded in Catalan and Spanish sentences about eight or nine syllables long and with the same stress pattern; in all cases the two vowels were adjacent to the stop consonant [t]. Each utterance was repeated ten times by two speakers of Eastern Catalan from the region of Barcelona and two speakers of Castilian Spanish from Madrid. Acoustic recordings were digitized at a sampling rate of 10 kHz, after preemphasis and low-pass filtering. An LPC (linear prediction coding) program included in an
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ILS (Interactive Laboratory System) package was used for spectral analysis. F$_2$ measurements were taken at eleven equidistant points in time as detected visually on spectrographic displays of each VCV sequence:

1. Onset of V1
2. Equidistant point between (1) and (3)
3. V1 midpoint, at half distance between (1) and (5)
4. Equidistant point between (3) and (5)
5. Onset of consonantal closure or constriction
6. Equidistant point between (5) and (7)
7. Offset of consonantal closure or constriction
8. Equidistant point between (7) and (9)
9. V2 midpoint, at half distance between (7) and (11)
10. Equidistant point between (9) and (11)

All consonants chosen for analysis allow airflow and, thus, display formant structure during the periods of closure or constriction. Measurements for points (5) and (7) were taken at the moment in time showing a sudden shift in F$_2$ frequency and intensity level (as determined on overall amplitude displays) from the endpoint of the V1 transitions into the consonant (point 5), and from the consonant into the V2 transitions (point 7).

Overall, 12,320 measurements were taken (28 sequences x 11 points in time x 10 repetitions x 4 speakers). Data were averaged across repetitions at each point in time, for each VCV sequence and for each speaker.

Results

1. Consonants [l] and [±]

1.1 Coarticulatory effects during closure. Data on F$_2$ were collected at the closure period (measurement point (6)) of [l] and [±] to test the following issues: (a) whether [±] is articulated with more dorso-velopharyngeal constriction than [l]; (b) whether differences in the degree of constriction between the two consonants are inversely related to the degree of V-to-C coarticulation. It was predicted that a more considerable degree of dorsal constriction for [±] than for [l] ought to cause a lower F$_2$ (Fant, 1960) since F$_2$ is inversely related to the degree of tongue backing. In addition, a more constricted tongue dorsum configuration for [±] than for [l] ought to allow less V-to-C coarticulation and, thus, less vowel-dependent F$_2$ variability.

Figure 1 shows F$_2$ data at the midpoint of the closure period of intervocalic [l] and [±] separately for each vocalic environment and for each speaker. The figure shows a lower F$_2$ for Catalan [±] (speakers DR and PL) than for Spanish [l] (speakers FM and CA) in all four VCV environments. These data suggest that [±] is produced with a more considerable degree of tongue-dorsum backing than [l] in all VCV contextual conditions, since F$_2$ is inversely dependent on the degree of tongue-backing and pharyngeal constriction (Fant, 1960).

The figure also shows a larger degree of vowel-dependent F$_2$ variability for [l] in Spanish than for [±] in Catalan, thus indicating that the tongue dorsum is more resistant to changes in the articulatory configuration of the
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adjacent vowels during the production of [i] vs. [l]. According to the figure, differences in F₂ between the two consonantal realizations increase as the number of adjacent high front vowels increases in the progression [iCi] > [iCa], [aCi] > [aCa]. This finding argues for different coarticulatory strategies during the production of adjacent [i] and [l] (Spanish) vs. adjacent [i] and [l] (Catalan). On the one hand, tongue-dorsum activity for [l] is largely overridden by the tongue-dorsum fronting and raising gesture for [i], as suggested by the presence of a high F₂ (between 2000 and 2500 Hz) during closure in the sequence [iili]; on the other hand, the tongue-dorsum backing and lowering gesture for [l] overrides the tongue-dorsum fronting and raising gesture for [i], as suggested by the presence of a low F₂ (about 1300-1500 Hz) during closure in the sequence [ili].

In summary, differences in the degree of vowel-dependent F₂ variability during consonantal closure (for [l]>[i]) are inversely related to differences in the degree of tongue-dorsum constriction (for [i]>[l]). These data suggest that [l] is more sensitive than [i] to coarticulatory effects from the vocalic environment because the tongue-dorsum is less constrained to perform the velarization gesture.

1.2 Coarticulatory effects over time. Pairs of sequences were lined up for all eleven points in time (see Method section) to study V-to-V anticipatory and carryover effects. Anticipatory effects for the sequence

![Figure 1. F₂ data at the midpoint of the closure period of [l] (right) and [l] (left) in the vocalic environments [iCi], [iCa], [aCi] and [aCa]. Data are displayed for the Catalan speakers DR and PL ([i]), and for the Spanish speakers FM and CA ([l]).](image-url)
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Pairs [iCiJ]-[iCaJ] and [aCaJ]-[aCiJ] were measured at points (1) through (8); carryover effects for the sequence pairs [iCiJ]-[aCiJ] and [aCaJ]-[iCaJ] were measured at points (4) through (11). Coarticulation was considered to occur when an observable difference between [i] and [a] in F2 frequency caused an analogous difference to occur during the production of the consonant and the transconsonantal vowel. Coarticulatory effects in F2 frequency at all intermediate points in time between (1) and (8) (anticipatory effects), and between (4) and (11) (carryover effects) were submitted to a t-test procedure; only significant effects at the p < 0.01 level of significance were chosen for data interpretation.

Graph bars in Figure 2 show significant coarticulatory effects over time for [l] and [t]. Anticipatory effects are plotted on each bar above the horizontal line for temporal frames 1 through 8, and carryover effects are plotted on each bar below the horizontal line for temporal frames 4 through 11; effects are displayed separately for consonants [l] and [t], fixed vowels

![Fixed V](image)

**Figure 2.** Significant V-to-V coarticulatory effects in F2 frequency from [i] vs. [a] along the closure period of [l] and [t], and the transconsonantal vowels [i] and [a]. Anticipatory effects have been plotted above the horizontal line along V1C (points in time 1 through 8); carryover effects have been plotted below the line along CV2 (points in time 4 through 11). Data are displayed separately for the consonants [l] and [t], the fixed vowels [i] and [a], and the four speakers DR, PL, FM, and CA. Asterisks have been placed at intermediate temporal frames showing nonsignificant V-to-V coarticulatory effects.
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[ɪ] and [a], and different speakers. Let us consider, for example, the data for speaker DR. The onset of the V2-dependent anticipatory effects (above the line) for [ɪiɪ] vs. [iɪa] occurs about the offset of closure (point in time 7); on the other hand, the onset of V2-dependent anticipatory effects for [aɪɪ] vs. [aɑa] occurs at V1 midpoint (point in time 3). At the carryover level (below the line), the offset of the V1-dependent carryover effects occurs later when V2= [a] (about offset of closure; point in time 7) than when V2= [ɪ] (about onset of closure; point in time 5).

In general, significant V-to-V effects occurred continuously in time from point (8) back to onset of anticipatory coarticulation, and from point (4) until offset of carryover coarticulation. Occasionally, nonsignificant effects were found at intermediate time frames. Thus, data for speaker FM in the context [VCi] show significant carryover effects at frames 4 to 6 and at frame 9, but nonsignificant carryover effects at the intermediate frames 7 and 8. These two intermediate points in time showing nonsignificant V-to-V effects are indicated with asterisks in Figure 2 (see also Figure 6).

Figure 2 shows larger V-to-V effects for Spanish [ɪ] than for Catalan [i]. Carryover effects are consistently larger for [ɪ] (speakers FM and CA) than for [i] (speakers DR and PL); thus, while carryover effects for [ɪ] usually last until V2 offset, those for [i] do not extend into V2. Anticipatory effects, on the other hand, are usually somewhat larger for [ɪ] (Spanish speakers) than for [i] (Catalan speakers), but can show the same onset time for the two consonantal realizations (speakers DR, FM and CA; context [aCV]). Overall, [ɪ] allows larger V-to-V effects than [i], much more so at the carryover level than at the anticipatory level.

Larger significant V-to-V effects occur when the fixed vowel is [ɑ] than when the fixed vowel is [i] for the two Spanish speakers and for the Catalan speaker DR; the Catalan speaker PL shows the same degree of coarticulation for the two fixed vowels. For those three speakers, anticipatory effects show an earlier onset when V1= [ɑ] (at V1 midpoint) than when V1= [i] (during closure). Carryover effects, on the other hand, may show a later offset time when V2= [ɑ] than when V2= [i] (speakers DR and FM) or the same offset time for the two fixed V2 (speakers CA and PL). Thus, overall, fixed [ɑ] allows larger V-to-V effects than fixed [i], more so at the anticipatory level than at the carryover level.

Differences in magnitude between anticipatory and carryover effects appear to be mainly dependent on the degree of articulatory constraint for the intervocalic consonant. Thus, while "clear" [ɪ] allows larger carryover than anticipatory effects, "dark" [i] shows only a slight contrast between the extent in time of anticipatory vs. carryover coarticulatory trends.

In summary, the degree of V-to-V coarticulation appears to be inversely correlated, as for V-to-C effects during closure, with the degree of tongue-dorsum constraint for the consonant; coarticulatory differences between [ɪ] and [i] occur consistently at the carryover level but much less so at the anticipatory level. Also, carryover effects are manifestly larger than anticipatory effects for [ɪ] but not for [i]. Consistent differences in the temporal extent of V-to-V coarticulation occur for fixed [ɑ] vs. fixed [i]; thus, fixed [ɑ] allows larger V-to-V effects than fixed [i], more so at the anticipatory level than at the carryover level.
2. Consonants [ɾ] and [r]

2.1 Coarticulatory effects during closure. Figure 3 shows $F_2$ data at the midpoint of the closure period of intervocalic [ɾ] and [r] for each speaker. As for [l] and [ɾ], differences in $F_2$ frequency are plotted separately for the environments [iCi] (1), [iCa] (2), [aCi] (3) and [aCa] (4).

The figure shows a lower $F_2$ for [ɾ] than for [ɾ] in all four VCV environments for all speakers. As for [i] vs. [l], this $F_2$ contrast is associated with more tongue-dorsum backing and predorsum lowering for [ɾ] than for [ɾ] (see Introduction).

The figure also shows a larger degree of $F_2$ variability for [ɾ] than for [ɾ] for all speakers. The tongue dorsum is, thus, less resistant to changes in the articulatory configuration of the adjacent vowels during the production of [ɾ] vs. [ɾ]. Analogously to data for [l] and [ɾ], differences in $F_2$ between [ɾ] and [ɾ] increase as the number of adjacent high front vowels increases in the progression [iCi] > [iCa], [aCi] > [aCa]. This finding argues for different coarticulatory strategies during the production of adjacent [l] and [ɾ] vs. adjacent [i] and [ɾ]. On the one hand, as for [l], tongue-dorsum activity for [ɾ] is largely overridden by the tongue-dorsum fronting and raising gesture for [ɾ], as suggested by the presence of a high $F_2$ (about 2000 Hz) during closure in the sequence [iri]; on the other hand, as for [ɾ], the
tongue-dorsum backing and lowering gesture for [r] overrides the tongue-dorsum fronting and raising gesture for [i], as suggested by the presence of a low F2 (below 1500 Hz) during closure in the sequence [iri].

In summary, differences in the degree of vowel-dependent F2 variability during consonantal closure (for [r]>[r]) are inversely related to differences in the degree of tongue-dorsum constraint for the consonant (for [r]>[r]). Thus, [r] is more sensitive than [r] to coarticulatory effects from the vocalic environment in line with differences in the degree of control over tongue-dorsum activity between the two consonants. Consonants [r] and [r] require contrasting degrees of tongue-dorsum constraint, which may be associated with the execution of several vibrations for the trill as opposed to only one vibration for the tap.

2.2 Coarticulatory effects over time. Figure 4 displays significant coarticulatory effects over time for [r] and [r]. The figure shows larger significant V-to-V effects for [r] than for [r] for speakers DR, FM, and CA;

![Figure 4](image)

Figure 4. Significant V-to-V coarticulatory effects in F2 frequency from [i] vs. [a] along the closure period of [r] and [r], and the transconsonantal vowels [i] and [a]. Anticipatory and carryover effects are displayed analogously to those in Figure 2. Data are represented separately for speakers DR, PL, FM, and CA. Speaker PL, however, shows larger effects for [r] than for [r]. Carryover effects are consistently larger for [r] than for [r] for all speakers. However, differences in the extent of anticipatory coarticulation between the
two consonants are highly systematic: thus, while speakers DR and CA usually show an analogous onset time of anticipatory effects for \([r]\) and for \([r]\); speaker FM may show an earlier onset time for \([r]\) than for \([r]\) and speaker PL always shows an earlier onset time for \([r]\) than for \([r]\). Overall, \([r]\) allows larger V-to-V coarticulatory effects than \([r]\), much more so at the carryover level than at the anticipatory level.

As for \([l]\) and \([t]\), V-to-V effects are systematically larger for fixed \([a]\) than for fixed \([i]\) for all speakers. According to Figure 4, anticipatory effects show an earlier onset time when \(V1=[a]\) (about \(V1\) midpoint or about \(V1\) onset) than when \(V1=[i]\) (during \(C\) closure) for all speakers. Carryover effects may show a later offset time when \(V2=[a]\) than when \(V2=[i]\), or the same offset time for the two fixed \(V2\). Thus, overall, fixed \([a]\) allows larger V-to-V effects than fixed \([i]\), more so at the anticipatory level than at the carryover level.

Differences in magnitude between anticipatory and carryover effects appear to be mainly dependent on the degree of articulatory constraint for the intervocalic consonant. All speakers show larger carryover effects than anticipatory effects when the intervocalic consonant is \([r]\); as for \([r]\), however, while speakers FM and PL show larger carryover effects than anticipatory effects, speakers DR and CA show larger anticipatory effects than carryover effects.

In summary, the degree of V-to-V coarticulation for consonants \([r]\) and \([r]\) appears to be inversely correlated, as for V-to-C effects during closure, with the degree of tongue-dorsum constraint for the consonant; coarticulatory differences between the two consonants occur consistently at the carryover level but much less so at the anticipatory level. Also, carryover effects are manifestly larger than anticipatory effects for \([r]\) but not for \([r]\). Consistent differences in the temporal extent of V-to-V coarticulation occur for fixed \([a]\) vs. fixed \([i]\); thus, fixed \([a]\) allows larger V-to-V effects than fixed \([i]\), more so at the anticipatory level than at the carryover level.

3. Consonants \([\beta]\), \([\delta]\), and \([\gamma]\)

3.1 Coarticulatory effects during consonantal constriction. Figure 5 shows \(F_2\) data at the midpoint of the constriction period of intervocalic \([\beta]\), \([\delta]\) and \([\gamma]\) in the VCV environments \([iCi]\) (1), \([iCa]\) (2), \([aCi]\) (3), and \([aCa]\) (4). Data are displayed separately for each speaker. The figure shows a decrease in \(F_2\) frequency in the progression \([\gamma]>[\delta]>[\beta]\), and a decrease in the degree of vowel-dependent \(F_2\) variability in the progression \([\gamma]>[\delta]>[\beta]\). Obviously, such cross-consonantal differences in \(F_2\) variability do not correspond to differences in the degree of tongue-dorsum constraint. Were that the case, the degree of vowel-dependent \(F_2\) variability would decrease in the progression \([\beta]>[\delta]>[\gamma]\); thus, little \(F_2\) variability for \([\gamma]\) ought to result from the fact that the tongue dorsum is fully involved in the constriction, and considerable \(F_2\) variability for \([\beta]\) ought to result from the fact that the tongue dorsum is left free to coarticulate with the phonetic environment. Instead, cross-consonantal differences in the degree of vowel-dependent \(F_2\) variability reported in Figure 5 can be explained as follows.
3.2 Coarticulatory effects over time. Figure 6 displays significant coarticulatory effects over time for [β], [δ] and [γ]. Asterisks have been placed at intermediate time frames showing nonsignificant V-to-V effects. Overall, significant effects decrease in the progression [δ]>[β]>[γ] for all speakers. The figure shows a clear trend for [γ] to allow shorter carryover
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effects than [β] and [δ]; thus, the offset time of carryover coarticulation occurs about V2 midpoint or about V2 offset for [β] and [δ], and, usually, at an earlier period in time for [γ]. On the other hand, the onset time of anticipatory effects occurs later for [γ] than for [β] and [δ]; however, such cross-consonantal differences in anticipatory coarticulation are less systematic than those observed at the carryover level. Overall, [β] and [δ] allow larger V-to-V coarticulatory effects than [γ], more so at the carryover level than at the anticipatory level.

Figure 6. Significant V-to-V coarticulatory effects in F2 frequency from [i] vs. [a] along the constriction period of [β], [δ] and [γ], and the transconsonantal vowels [i] and [a]. Anticipatory and carryover effects are displayed analogously to those in Figures 2 and 4. Data are represented separately for speakers DR, PL, FM, and CA. Asterisks have been placed at intermediate temporal frames showing nonsignificant V-to-V coarticulatory effects.

Larger V-to-V effects are systematically found for fixed [a] than for fixed [i] for all speakers. This trend occurs both at the anticipatory level and at the carryover level: while effects for fixed [i] are seldom found before V1 offset (anticipatory) and after V2 onset (carryover), effects for fixed [a] often reach V1 onset (anticipatory) and V2 offset (carryover). Thus, fixed [a] allows larger V-to-V effects than fixed [i], both at the carryover level and at the anticipatory level.

Small differences in magnitude between anticipatory and carryover effects occur as a function of the intervocalic consonant ([γ] vs. [β] and [δ]). Therefore, while anticipatory effects are usually larger than carryover
effects when $C=[\gamma]$, carryover effects are usually larger than anticipatory effects when $C=[\beta]$ and $[\delta]$. Also, while speakers DR and PL favor anticipatory over carryover coarticulation, speakers FM and CA show larger carryover than anticipatory effects.

In summary, $[\gamma]$ is more resistant than $[\beta]$ and $[\delta]$ to V-to-V effects, more so at the carryover level than at the anticipatory level. Moreover, contrary to $[\beta]$ and $[\delta]$, $[\gamma]$ does not favor carryover effects over anticipatory effects. Fixed vowel $[a]$ allows larger V-to-V effects than fixed vowel $[i]$, analogously to data reported for $[1]$, $[i]$, $[r]$ and $[r]$.

**Summary and Conclusions**

Data reported in the Results section reveal that the degree of V-to-V coarticulation in $F_2$ frequency varies inversely with the degree of articulatory constraint on tongue-dorsum activity for the intervocalic consonant. Thus, effects decrease inversely with the degree of tongue-dorsum constraint, for $[l]>[i]$, $[r]>[r]$ and $[\beta]$, $[\delta]>[\gamma]$. Moreover, V-to-C coarticulatory effects during the periods of consonantal closure and constriction have also been found to decrease for $[l]>[i]$ and $[r]>[r]$. As suggested in the Introduction, a velarization gesture for $[i]$ (vs. $[l]$) and for $[r]$ (vs. $[r]$), and a tongue-dorsum raising gesture for $[\gamma]$ (vs. $[\beta]$ and $[\delta]$), cause a high degree of resistance to V-to-V effects in $F_2$ frequency.

The degree of V-to-V coarticulation appears to be related to the articulatory characteristics of the fixed vowel as well. Thus, fixed $[i]$ allows smaller effects than fixed $[a]$ from transconsonantal $[a]$ vs. $[i]$. These results indicate that $[i]$ is more resistant that $[a]$ to changes in tongue height and jaw opening.

This paper shows that transconsonantal anticipatory effects can extend all the way back to V1 onset and that transconsonantal carryover effects can last uninterruptedly until V2 offset. Differences in the degree of carryover vs. anticipatory coarticulation appear to be largely dependent on the nature of the articulatory gestures involved in the production of the VCV sequence. Separate trends have been found in this respect for contrasting intervocalic consonants and for contrasting fixed vowels:

1. Differences in V-to-V coarticulation among consonants subject to different degrees of tongue-dorsum constraint are larger at the carryover level than at the anticipatory level. This finding confirms the view that V-to-V carryover effects are more dependent than V-to-V anticipatory effects on the mechanical constraints involved during the production of the intervocalic consonant. It also accords well with the fact that while unconstrained $[l]$, $[x]$, $[\beta]$, and $[\delta]$ allow larger carryover than anticipatory effects, highly constrained $[i]$, $[r]$ and $[\gamma]$ show systematic differences between anticipatory and carryover trends.

2. On the other hand, differences in V-to-V coarticulation between fixed $[i]$ and $[a]$ can be larger at the anticipatory level than at the carryover level. A closer look at differences in the temporal extent of coarticulation reveals that carryover effects for fixed V2=$[i]$ and $[a]$ can either last until consonantal closure or constriction, or extend into V2; on the other hand, while anticipatory effects for fixed V1=$[i]$ usually start during consonantal closure or constriction, anticipatory effects for fixed
V1=[a] usually start at V1. Thus, while the onset of anticipatory coarticulation appears to be dependent on the articulatory characteristics of V1, the offset of carryover coarticulation is, to a large extent, independent of the articulatory nature of V2.

In summary, all these findings suggest that coarticulatory effects are deeply related to the control mechanisms involved during the production of adjacent articulatory gestures. The $F_2$ data presented here allow us to formulate the following model in order to explain coarticulatory effects on tongue-dorsum activity along VCV sequences.

At the carryover level, V1-dependent effects are found to vary inversely with the degree of tongue-dorsum constraint involved during the production of the CV2 sequence; thus, for example, V1-dependent effects do not extend beyond consonantal closure in [Vra] and [Vri] sequences, but usually extend until V2 offset in [Vla] and [Vri] sequences. On the one hand, after closure, little carryover V-to-V coarticulation is allowed by consonants requiring a high degree of articulatory constraint (e.g., as for [i] and [r]); moreover, the temporal extent of V1-dependent transconsonantal coarticulatory effects is blocked even more if V2 is highly constrained (e.g., as for [i]). On the other hand, for CV2 syllables showing a low degree of tongue-dorsum constraint (e.g., as in the sequences [Vla] and [Vra]), V1-dependent effects are allowed to last until V2 offset.

Anticipatory effects appear to be temporal effects in so far as their onset is programmed to occur before the periods of consonantal closure or consonantal constriction. To a large extent, they are independent of the degree of tongue-dorsum constraint associated with the intervocalic consonant. However, the onset of V2-dependent anticipatory coarticulation is highly dependent on the degree of tongue-dorsum constraint exerted upon V1; thus, anticipatory effects have been consistently found to begin during closure when V1=[i], but at V1 when V1=[a]. In summary, the onset time of anticipatory effects for a given gesture is programmed to occur at V1 unless V1 entails conflicting articulatory requirements. In that respect, anticipatory effects in tongue-dorsum opening for V2=[a] show a late onset time if V1 requires a highly resistant tongue-dorsum raising gesture (i.e., when V1=[i]); on the other hand, however, tongue-dorsum raising for V2=[i] shows an early onset time when V1=[a], since the articulatory gesture for [a] is not resistant to tongue-dorsum raising for [i].

In addition to other findings reported in the literature (see Introduction), these data suggest that speakers use different degrees of constraint for different gestures, and that the extent to which the articulatory activity for adjacent gestures overlaps in running speech follows from those differences in degree of constraint. Thus, a theory of coarticulation that makes high predictions about the nature of coarticulatory effects ought to be based on appropriate notions about the degree of constraint required by phonemic gestures. Differences in articulatory constraint operate differently at the carryover and anticipatory levels: while carryover effects appear to be inversely related to the degree of articulatory constraint for the entire CV2 sequence, anticipatory effects are dependent on the degree of constraint for V1, but are largely independent of the degree of constraint for the intervocalic consonant.
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Overall, the view according to which V-to-V coarticulation in VCV sequences is possible because adjacent consonants and vowels involve different classes of gestures (Ohman, 1966; Fowler, 1980) is far too simple. According to this view, V-to-V coarticulation occurs because vowels entail articulatory control over the positioning of the entire tongue body, while consonants involve articulatory control over the tongue articulator on which closure or constriction depend. Instead, it seems that V-to-V coarticulation proceeds according to contrasting degrees of constraint associated with gestures for adjacent phonemes; thus, for example, no carryover V-to-V effects are expected to occur for a highly constrained CV2 sequence. This view needs to be tested with further data from a good sample of different consonants and vowels, as well as different speakers and languages.

References
