A model of lingual coarticulation based on articulatory constraints

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The magnitude and temporal extent of consonantal and vocalic coarticulation are reported for VCV sequences with two vowels (/i/, /a/) and seven consonants (/p/, /n/, dark /l/, /s/, /ʃ/, /ɲ/,/k/). Different degrees of articulatory constraint, or DAC values, are assigned to the consonants and vowels based on knowledge of their articulatory properties, in particular, the degree of involvement of the tongue dorsum in closure or constriction formation. Mean results on dorsopalatal contact and $F2$ frequency for five speakers of the Catalan language are presented. Predictions based on the DAC value for consonants and vowels account satisfactorily for the C-to-V effects (e.g., those for /ɲa/ are more prominent that those for /pi/); moreover, vowel-dependent effects tend to be negatively correlated with the DAC value for the consonant (e.g., they are more prominent when the intervocalic consonant is /p/ than when it is dark /l/). V-to-C effects are also conditioned by the tongue-dorsum position for the consonantal gesture. Coarticulatory directionality trends reveal that the extent to which the vowel-dependent tongue-dorsum activity may be anticipated is closely linked to the mechanico-inertial constraints associated with the tongue dorsum during consonantal production; this observation explains the salience of the vowel-dependent anticipatory effects in VCV sequences favoring C-to-V anticipation and of the vowel-dependent carryover effects in VCV sequences giving special weight to C-to-V carryover.
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INTRODUCTION

Two general principles of segmental overlap in a phonetic string have been proposed in the literature: The extent to which a vowel falls short of its target (i.e., the amount of undershoot) increases with the distance between the articulatory targets for the vowel and for the adjacent consonant (Stevens *et al.*, 1966), and coarticulation on consonants affects mostly those articulators which are not involved in closure or constriction formation (Öhman, 1966). There is, however, no model that predicts how much coarticulation is allowed by a given phonetic segment, or the extent to which a particular phonetic segment is likely to affect the surrounding segments in the speech chain. The aim of this paper is to present such a model by examining the relative salience of the C-to-V, V-to-C, and V-to-V coarticulatory effects in Catalan VCV sequences with several consonants (bilabial stop /p/, alveolar nasal /n/, dark alveolar lateral /l/, alveolar fricative /s/, alveolopalatal fricative /ʃ/, alveolopalatal nasal /ɲ/, velar stop /k/) and vowels (high front /i/, low back /a/). Our work is mostly concerned with tongue-dorsum activity[1] since two of the variables under investigation, i.e., dorsopalatal contact and $F2$, are known to be positively correlated.[2]

Spatiotemporal patterns of tongue-dorsum coarticulation should be of general interest for theories of articulatory control in speech production in so far as they have received less attention than those for more mobile articulators such as the lips or the velum (e.g., Krakow, 1989; Boyce, 1990) presumably because it was believed that labial and velar coarticulation would be more extensive than lingual coarticulation. In many respects the coarticulatory patterns presented in this paper ought to have a universal status (although some coarticulation aspects may differ across languages; Beddor and Yavuz, 1995) and may prove useful in predicting the frequency of occurrence of some assimilatory processes (i.e., it may turn out that phonetic segments more prone to undergo assimilations exhibit prominent coarticulatory effects along the relevant articulatory dimensions).

A. Articulatory constraint

In the present study phonetic segments are characterized in terms of articulatory gestures. An articulatory gesture is an actively controlled movement toward a presumed target configuration (e.g., lip rounding for rounded vowels, tongue-dorsum raising for palatal articulations) (Browman and Goldstein, 1986). Phonetic segments may be produced with one or two lingual gestures and thus with one or more lingual articulators (e.g., the tongue tip for /t/, the tongue tip and the tongue dorsum for dark /l/). The biomechanics of the lingual articulator(s) may cause some displacement on other tongue regions. Thus the strength of the coupling effects between the tongue tip or the tongue blade and the tongue dorsum should increase with an increase in the retraction and the extent of the apicolaminal closure or constriction, for alveolopalatals versus alveolars and for laminoalveolars versus apicoalveolars.

These notions are clearly related to a core concept within our descriptive framework, i.e., degree of articulatory constraint (DAC).[3] The formulation of the concept DAC derives from assumptions about the degree of involvement of the speech articulators in the formation of a closure or constriction based on information obtained from experimental production data, e.g., data on articulatory displacement and linguopalatal contact. As shown below, the consonants and vowels of interest in this paper will be assigned different DAC values depending on the degree of tongue dorsum constraint during their production. The DAC scale proceeds from a DAC minimum of 1 to a DAC maximum of 3, where the number of levels could be any other than 3; the assignment process of DAC values to vowels does not differ from that used for consonants and implies that vowels may exhibit constriction locations along the vocal tract (Wood, 1979).

Dorsals, i.e., alveolopalatals /ʃ/ and /ɲ/, palatal /i/, velar /k/, and dark /l/, are maximally constrained and thus specified for a maximal DAC value (DAC=3). Considerable tongue-dorsum involvement in the production of all these consonants renders them highly constrained: Alveolopalatals and palatals are articulated with active tongue dorsum raising toward the palatal zone where they cause large amounts of contact (Recasens, 1990; Recasens and Romero, 1997) and dorsovelars share similar kinematic properties; the production of dark /l/ involves two lingual gestures, i.e., tongue tip raising for a primary apicoalveolar closure and active tongue postdorsum retraction for a secondary dorsopharyngeal constriction (Sproat and Fujimura, 1993).

Labial /p/ is minimally constrained and thus specified for a minimal DAC value (DAC=1). This is so since the tongue body may not be required to achieve an articulatory target. Its obvious correlate in the vowel class is /ə/ which appears to be more sensitive to contextual effects than other vowels (Dutch: Bergem, 1994; English: Kondo, 1994) although it has been reported to exhibit an articulatory target at a neutral tongue position (Browman and Goldstein, 1992).

An intermediate degree of tongue-dorsum constraint and thus an intermediate DAC value (DAC=2) can be tentatively assigned to phonetic segments for the production of which the tongue dorsum is not directly involved in closure or constriction formation but is subject to coupling effects with the primary articulator. This would be the case for alveolars /n/ and /s/ (in accordance with tongue blade raising for these consonants causing some tongue dorsum raising to occur; Kent and Moll, 1972; Lindblom, 1983) and for low back /a/ (in view of the tongue root retraction gesture for this vowel bringing about some concomitant tongue dorsum lowering).

In addition to the place of articulation and interarticulatory coupling, the manner of articulation may also affect the DAC specification for consonants. Thus, the precise formation of a medial groove for fricatives (e.g., Stone *et al.*, 1992) should render /s/ more constrained than nonfricative alveolars which would cause this consonant to exhibit a DAC value of 3 instead of 2.

To summarize, the DAC scale ranks phonetic sound categories from maximally to minimally constrained as follows: /ʃ/, /ɲ/, /i/, /k/, dark /l/, (/s/) (DAC=3)>/n/, /a/, (/s/) (DAC=2)>/p/, /ə/ (DAC=1). It needs to be emphasized that this is a preliminary DAC classification which could be improved with a more accurate formulation of the articulatory constraints for consonants and vowels.

B. Specific coarticulatory effects

1. C-to-V coarticulation

DAC values should have a bearing on the extent to which a given segment will influence adjacent segments, and the final outcome will also depend on the DAC value for the contextual segment and whether the constraints involved are compatible or opposing. Within this framework, a first goal of this study is to investigate the prominence of the consonant-to-vowel effects (C-to-V) in the three scenarios described below and to determine interactions between the magnitude and the temporal extent of C-to-V coarticulation (Sec. II A).

The first scenario is at work when C and V are produced with comparable articulatory trajectories, as for /ɲi/, /ni/, and /la/ since /ɲ/, /n/, and /i/ involve tongue-dorsum raising (as a consequence of coupling between the tongue tip and the tongue dorsum for /n/) and /l/ and /a/ are produced with tongue-dorsum lowering. Little C-to-V coarticulation is expected to occur for /ɲi/ and /ni/ since both phonetic segments are either specified for the same DAC value (i.e., DAC=3 for /ɲ/ and /i/ in the sequence /ɲi/) or the vowel is more constrained than the consonant (i.e., DAC=3 for /i/ and DAC=2 for /n/ in the sequence /ni/). Some C-to-V effects should occur when the consonant is more constrained than the vowel especially if highly constrained (i.e., DAC=3 for /l/ and DAC=2 for /a/ in the sequence /la/). An interesting research topic is to find out whether such effects will be more or less salient than those occurring in CV combinations of antagonistic phonetic segments exhibiting the same DAC relationship (as for /ɲa/ below).

C and V are produced with opposing articulatory trajectories in a second scenario, as for /ɲa/, /na/, and /li/ where /ɲ/, /n/, and /i/ involve tongue-dorsum raising and dark /l/ and /a/ involve tongue-dorsum lowering. The sequence /ɲa/ should show some C-to-V coarticulation since the DAC value for the consonant (DAC=3) exceeds that for the vowel (DAC=2). In principle, little C-to-V coarticulation is expected to occur if both segments are specified for the same DAC value, i.e., 2 in the sequence /na/ or 3 in the sequence /li/. It deserves to be seen, however, whether constriction requirements for consonants yield C-to-V effects in these circumstances and whether these effects increase with the degree of antagonism between C and V (i.e., for /li/ vs /na/).

One of the two adjacent phonetic segments is specified for DAC=1 in a third scenario, as for /pi/ where the consonant involves no tongue dorsum activation. This segmental combination should yield minimal C-to-V effects.

2. Vowel-dependent coarticulation

The coarticulatory analysis presented in this paper also examines the salience of the vowel-dependent effects as a function of the seven consonants of interest (Sec. II B). For that purpose, the magnitude of the effects from /i/ vs /a/ will be measured during the consonant (V-to-C), and their size and temporal extent as well as the interaction between the two will be computed along the fixed transconsonantal vowel /i/ or /a/ (V-to-V).[4]

Tongue-dorsum related data in the literature are in accordance with the prediction that coarticulatory sensitivity for consonants and vowels is inversely related to their DAC value. Using the same dataset as in the current study, V-to-C effects in symmetrical VCV sequences reported in Recasens *et al.* (1995) show that variability for consonants proceeds in the progression labials>dentoalveolars >alveolopalatals, dark /l/ and /s/; many other production studies reveal the same trend [see Recasens (in press) for a review]. On the other hand, the degree of coarticulatory sensitivity for vowels decreases for /ə/>/a/>/i/ (Kiritani *et al.*, 1977; Recasens, 1985, 1991a). More tongue-dorsum coarticulation for velars than other dorsal consonants is in agreement with their showing a palatovelar constriction in front vowel contexts and a velar one in back vowel contexts (Swedish: Öhman, 1966; American English: Kent and Moll, 1972). This finding does not run against consonantal segments specified for a high DAC value allowing little vowel coarticulation but appears to be due to the consonant and the vowel not being able to achieve adjacent tongue-dorsum targets unless the consonantal constriction moves toward that for the vowel (Wada *et al.*, 1970).

As indicated by data in the literature (Gay, 1974, 1977; Carney and Moll, 1971; Recasens, 1984, 1987, 1989), the relationship between coarticulatory sensitivity and DAC becomes more complex when V-to-V effects are accounted for. It appears that the occurrence of these effects is conditioned not only by the DAC specification for the intervocalic consonant but also by that of the fixed vowel. The prediction will be tested that consonant-dependent differences in V-to-V coarticulation (e.g., for effects across bilabials exceeding those across alveolopalatals) should occur when the fixed vowel is not highly constrained (e.g., /a/) but could be cancelled out if the fixed vowel is specified for a maximal DAC value (e.g., /i/).

While DAC is a potential predictor of coarticulatory sensitivity, the present study will also test for a large number of consonants whether articulatory position determines the articulatory dimension along which coarticulation occurs (Sec. II B 3). Preliminary data from the literature indicate that C-to-V effects on high vowels involve tongue lowering while those on low vowels cause the tongue dorsum to raise and that V-to-C effects are determined by the target lingual position for the consonant (Recasens, 1987, 1991a, b). Thus the fact that the production of /ɲ/ (also /k/) requires the achievement of a dorsal closure justifies why this consonant allows larger tongue-dorsum raising and fronting effects associated with V2=/i/ in the sequence /aɲi/ than tongue-dorsum lowering and backing effects associated with V2 =/a/ in the sequence /iɲa/; also, consonants produced with active tongue-dorsum lowering such as dark /l/ are more sensitive to lowering effects associated with following /a/ in the sequence /ila/ than to raising effects exerted by following /i/ in the sequence /ali/.

It will also be investigated whether there is an inverse correlation between the vocalic effects and the consonantal effects, and thus whether context-dependent sensitivity for a given phonetic segment varies inversely with coarticulatory aggression on the adjacent phonetic segments (Fowler and Saltzman, 1993).

C. Coarticulatory directionality

A novelty of the present investigation is to analyze the relative prominence of the anticipatory direction (right-to-left) and the carryover direction (left-to-right) for the consonantal and the vocalic effects in VCV production. This analysis will be carried out with reference to the DAC value for the phonetic segments involved and will evaluate whether coarticulatory direction is conditioned by the gestural demands for the intervocalic consonant (Sec. II C). There is some evidence in the literature in support of the notion that the prominence of the anticipatory and carryover component of consonantal coarticulation varies with the lingual requirements for the consonant and determines the directionality of the vocalic effects [see Recasens (in press) for a review]. Evidence on C-to-V coarticulation reveals that, among consonants specified for a high DAC value, some exert more prominent carryover than anticipatory effects (dorso-alveolopalatals, in line with tongue-dorsum activity proceeding more slowly at consonantal release than at consonantal onset) while others require a strong anticipatory component (dark /l/, in line with strong demands on the formation of a double lingual constriction). Within this framework the direction of the vocalic effects shows the following trends whose validity will be tested in the present paper: On the one hand, vowel-dependent carryover effects exceed vowel-dependent anticipatory effects across consonants exerting more prominent carryover than anticipatory C-to-V coarticulation; on the other hand, consonants requiring a strong anticipatory component allow more prominent vowel-dependent anticipatory than carryover effects or exhibit a significant reduction of the latter in comparison to the former. Special attention will be given to those consonants (bilabials, dentoalveolar stops, fricatives, clear /l/) which have been reported to favor either coarticulatory direction in previous studies.

I. METHOD

A. Articulatory and acoustic analysis procedure

$F2$ and linguopalatal contact data were collected for /iCi/, /aCa/, /iCa/, and /aCi/ with stress on the first syllable.[5] As indicated in the Introduction, the consonants were /p/, /n/, (dark) /l/, /s/, /ʃ/, /ɲ/, and /k/. Sequences were read five times each by five Catalan speakers (DR, JP, JS, DP, JC). In Catalan, unstressed /a/ (i.e., V2 in the sequences of the present study) is realized as [ə] systematically. Differences in quality

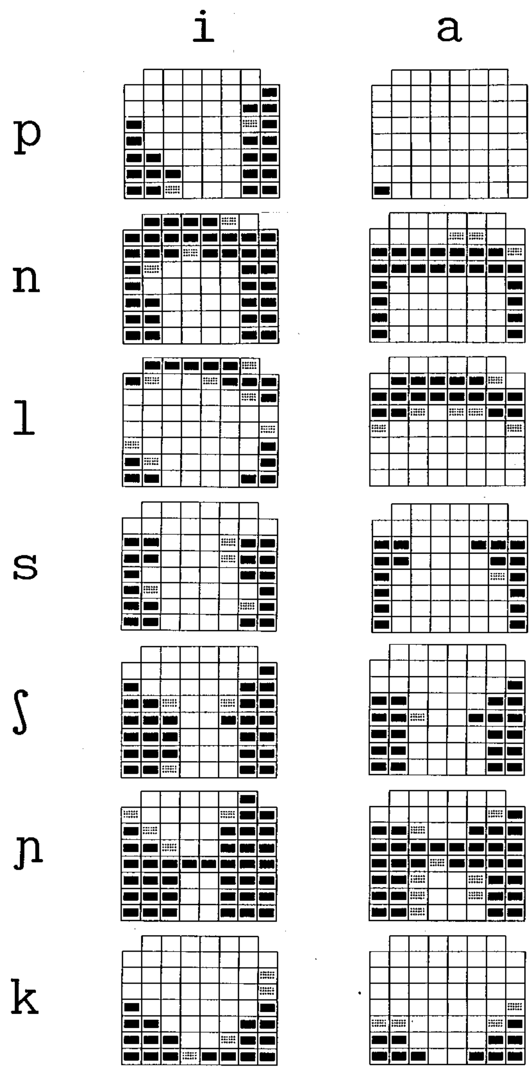

FIG. 1. Linguopalatal configurations at consonantal midpoint for different consonants in symmetrical VCV sequences (speaker DR). Data have been averaged across repetitions. Percentages of electrode activation: (black) 80%–100%; (dotted) 40%–80%; (white) less than 40%.

between V1 and V2 do not render the /aCa/ sequences fully symmetrical, although we will refer to them as such all throughout the paper.[6]

Linguopalatal contact was gathered every 10 ms using artificial palates equipped with 62 electrodes [Reading electropalatographic (EPG) system; Hardcastle *et al.*, 1989]. Figure 1 displays average linguopalatal configurations for each consonant. The four front rows at the top of each EPG display belong to the alveolar zone (extending from the teeth to the alveolar ridge) and the four back rows belong to the palatal zone (from the alveolar ridge back to the soft palate). The graphic representations in the figure do not capture the fact that the distance between adjacent rows is smaller at the former zone than at the latter.

The EPG data reported in this paper will be expressed in Qp values, where Qp stands for the percentage of contact activation over the palatal zone, i.e., number of activated palatal electrodes/total number of palatal electrodes. The Qp index has been computed using the four back rows of the artificial palate in the case of /l/ but the three back rows in the case of /n/, /s/, /ʃ/, and /ɲ/, since a central closure or constriction at the frontmost row of the palatal zone is generally absent for the alveolar lateral but frequently present for the two nasals and for the two fricatives.[7] The Qp index for /k/ and /p/ has also been calculated without taking into account the aforementioned row given that the contact pattern at the three back rows of the artificial palate provides an adequate and sufficient articulatory characterization of velars and bilabials in the context of /i/.

The acoustic data were recorded at a 20-kHz sampling rate. $F2$ values were obtained at the same temporal intervals as the EPG data using LPC (25-ms Hamming window, 12 coefficients) and visual inspection of spectrographic displays on a Kay CSL analysis system. The latter method was applied instead of the former when an unsatisfactory resolution was provided by the all-pole peak picking LPC method, i.e., at the VC boundary of VCV sequences with nasal consonants (because of the presence of spectral discontinuities associated with nasal poles and zeros) and during the consonantal period in VCV sequences with fricatives /s/ and /ʃ/ (because of the presence of frication noise at low spectral regions). $F2$ frequencies were measured using a cursor moving in 20-Hz steps after careful inspection of the spectrographic patterns by two experimenters.

An EPG criterion was used in order to determine the consonantal boundaries for /l/ and for /n/ and /ɲ/, i.e., from onset to offset of central alveolar contact for the lateral and of complete closure for the nasal stops. However, the segmentation of /s/, /ʃ/, /p/, and /k/ was performed on waveform and spectrographic displays, from onset to offset of the frication noise for the two fricatives (it was often hard to identify a well-defined period based on the degree of constriction narrowing on the linguopalatal contact patterns) and from offset of V1 formant structure to closure offset at the stop burst for the two stops (bilabial /p/ shows no lingual activity and complete closure /k/ was not visible when occurring behind the palatal zone).

B. Criteria for measuring coarticulatory effects

Coarticulatory effects were calculated in size (C-to-V, V-to-C, V-to-V) and temporal extent (C-to-V, V-to-V) according to the measurement criteria summarized next.

1. C-to-V coarticulation

C-to-V temporal effects were taken to occur during the period when a significant consonant-related acoustic or articulatory difference extends into the vowel. In order to obtain such effects, Qp and $F2$ frequency values were first computed for all repetitions of /iCi/ and /aCa/ for each speaker in 10-ms steps starting at the consonantal onset back to V1 onset and at the consonantal offset until V2 offset. No data were collected for Qp effects from /l/ on /a/ since little or no linguopalatal contact occurs along this vowel in this consonantal environment. The resulting values were then compared statistically (one-way ANOVAs, Scheffé; $df_{bg}=1$, $df_{wg}=4$) with a measure of steady-state V1 of the same symmetrical VCV sequence type for studying C-to-V1 an-

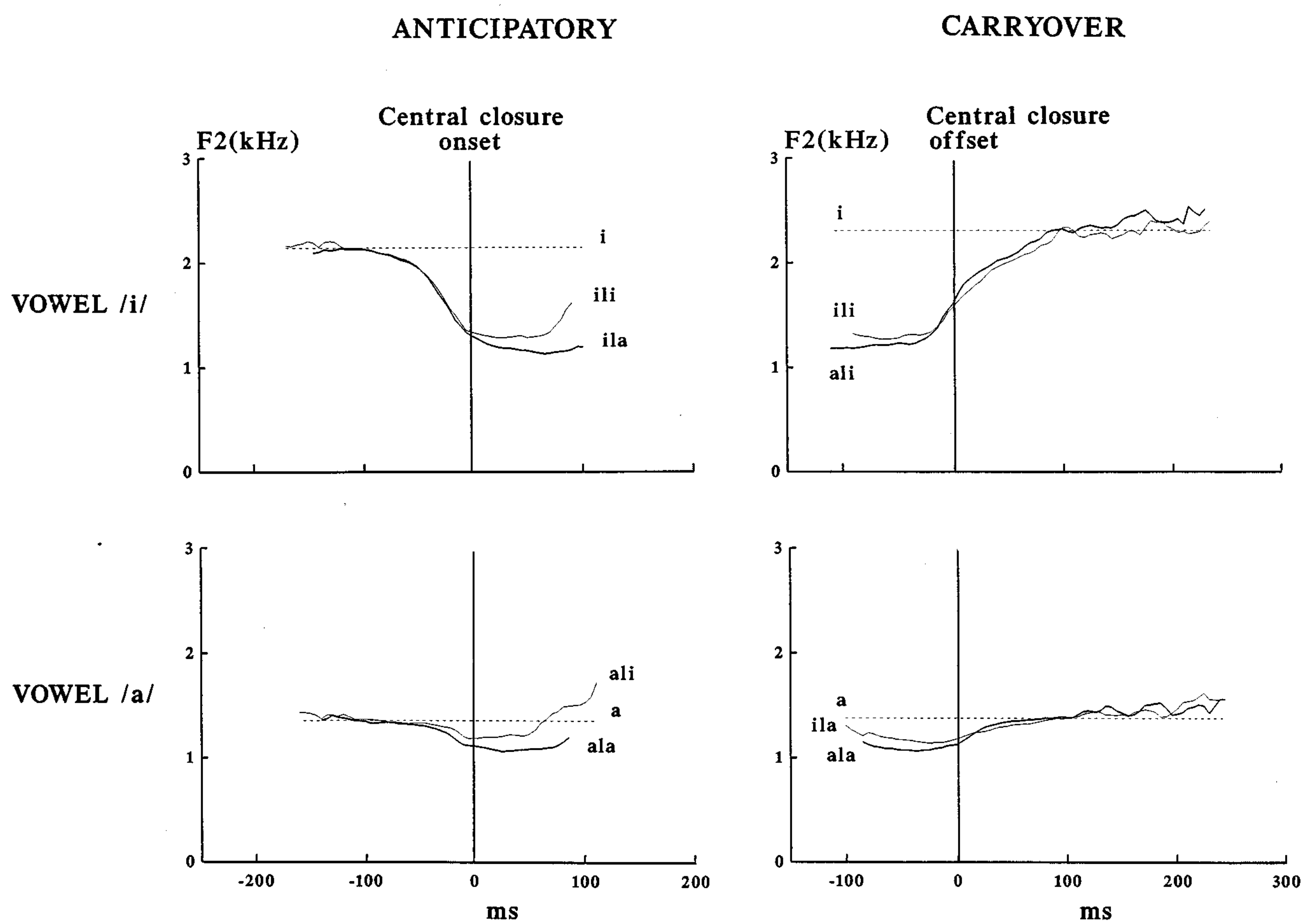

FIG. 2. $F2$ trajectories showing anticipatory effects (left) and carryover effects (right) in a single repetition of /VIV/ sequences with fixed /i/ (top) and fixed /a/ (bottom). Data correspond to speaker JP. The zero point on the x axis occurs at /l/ central closure onset for the anticipatory effects and at central closure offset for the carryover effects. See text for details.

ticipation and of steady-state V2 for studying C-to-V2 carryover. For each repetition of a given symmetrical VCV sequence, steady-state vowel values were established at the highest Qp and $F2$ for /i/ and at the lowest Qp and $F2$ for /a/, starting at the vowel midpoint backward in the case of V1 and at two-thirds of the vowel duration onward in the case of V2. Those maxima were found either at a single temporal frame or along a plateau lasting several frames; the selection of a different temporal criterion for V1 and V2 is justified by the fact that (sentence-final) V2 was longer than V1 and the V2 steady-state period was located further away from the consonantal period than the V1 steady-state period. The steady-state V1 and V2 values for each VCV sequence type represent the average across values for the individual repetitions of that sequence. The last significant difference obtained in the statistical analysis procedure ($p<0.05$) was taken to be the onset of C-to-V1 anticipatory coarticulation when the vowel being measured was V1 and the offset of C-to-V2 carryover coarticulation when the vowel subject to measurement was V2. Onsets and offsets of the C-to-V effects for each VCV sequence type were separately averaged across speakers; the resulting averages will be used as a measure of C-to-V temporal coarticulation in this paper.[8]

Figure 2 exemplifies the method of analysis of the C-to-V effects exerted by dark /l/ on /i/ (top) and on /a/ (bottom). A dotted line has been traced at the estimated $F2$ value for the steady-state portion of V1 and for that of V2. A statistical comparison between the steady-state value and all other $F2$ frequency values along V1=/i/ of the sequence /ili/ (top left) yields a significant difference starting at the 0 temporal point at central closure onset back to -80 ms. The application of the same procedure to V2=/i/ yields a 80-ms long C-to-V effect after the 0 temporal point at central closure offset (top, right). Anticipatory and carryover effects on /a/ (bottom) were found to last until -70 ms and 40 ms, respectively.

The largest Qp or $F2$ difference between V1 or V2 of a symmetrical VCV sequence and the steady-state vowel value is taken to be the (positive or negative) size of a C-to-V effect. This maximal size difference usually occurs near closure onset for the anticipatory C-to-V effects and near closure offset for the carryover C-to-V effects. C-to-V size effects reported in this paper correspond to average values across repetitions and speakers for each symmetrical VCV sequence. In Fig. 2 the size of the C-to-V anticipatory effect for V1=/i/ (i.e., the largest $F2$ difference between steady-state V1=/i/ and V1=/i/ of /ili/) amounts to 811 Hz, while that of the C-to-V carryover effect for V2=/i/ equals 736 Hz. As for the /a/ condition, C-to-V size effects measure 243 Hz (anticipatory) and 254 Hz (carryover).

2. V-to-C coarticulation

V-to-C effects were measured in Qp and $F2$ size at the midpoint of the consonantal period for all consonants except for /p/ and /k/ (since oral stops exhibit no formant structure-during closure). Differences were obtained for the sequence pairs /iCi/–/iCa/ and /aCi/–/aCa/ (anticipatory coarticulation) and /iCi/–/aCi/ and /iCa/–/aCa/ (carryover coarticulation), and averaged across speakers and repetitions. This experimental setting allows studying the extent to which /a/ affects the consonant when /i/ stays constant (in the sequence pairs /iCi/-/iCa/ and /iCi/–/aCi/) and how much V-to-C coarticulation is exerted by /i/ when the fixed vowel is /a/ (in the sequence pairs /aCa/–/iCa/ and /aCa/–/aCi/). Differences (positive) were computed when /i/ caused a higher Qp or $F2$ than /a/ at the consonantal midpoint. V-to-C coarticulation values reported in this paper correspond to averages across differences for each speaker; negative values (i.e., when /a/ yielded a higher Qp or $F2$ than /i/) were equated to zero in this averaging procedure. Data for each type of VCV pair were submitted to one-way ANOVAs Scheffé ($df_{bg}=1$, $df_{wg}=4$) with vowel context as the independent variable and were considered to be significant at the $p<0.05$ significance level.

3. V-to-V coarticulation

V-to-V temporal effects occur during the period along which a significant vowel-dependent articulatory or acoustic difference extends into the transconsonantal vowel. In order to single out such effects, Qp and $F2$ frequency differences as a function of /i/ vs /a/ (for /i/>/a/) were calculated for the same VCV pairs given in Sec. I B 2 every 10 ms, starting at consonantal onset back to V1 onset and from consonantal offset until V2 offset. Essentially the sequence pairs with symmetrical /iCi/ allow studying the effect of /a/ along fixed /i/ and those with symmetrical /aCa/ allow measuring the effect of /i/ along fixed /a/. Those differences were submitted to one-way ANOVAs Scheffé ($df_{bg}=1, df_{wg}=4$) at each temporal point during fixed V1 for studying V-to-V anticipation and during fixed V2 for studying V-to-V carryover. The last significant difference ($p<0.05$) counting backward during V1 was taken to be the onset of a V2-to-V1 anticipatory effect and the last one counting onward during V2 was taken to be the offset of a V1-to-V2 carryover effect. Data on V-to-V temporal coarticulation presented in this paper refer to the mean onset and offset times of the V-to-V effects across speakers for each VCV sequence pair.

Figure 2 illustrates the procedure for measuring V-to-V coarticulation. V2-to-V1 anticipatory effects occur when a significant difference between the pairs of $F2$ trajectories /ili/–/ila/ (top left) and /ali/–/ala/ (bottom left) extends before the 0 temporal point at central closure onset; significant tests for these trajectories yielded 0 ms for the former sequence pair and -40 ms for the latter. On the other hand, V1-to-V2 carryover effects take place when a significant difference between the $F2$ trajectory pairs /ili/–/ali/ (top right) and /ila/–/ala/ (bottom right) extends after the 0 temporal point at central closure offset; significant effects for both pairs were nonexistent (0 ms).

Analogously to the C-to-V effects, the size of a V-to-V effect is taken to be the largest Qp or $F2$ frequency difference and usually occurs near closure onset for the anticipatory direction and near closure offset for the carryover direction. When this difference was not significant, the size of the V-to-V effect was taken at the first temporal frame showing the expected coarticulatory difference. V-to-V size effects reported in this paper correspond to averages across speakers and repetitions. In the data of Fig. 2, the size of V-to-V anticipation is 35 Hz (/ili/–/ila/) and 79 Hz (/ali/–/ala/), and that of V-to-V carryover amounts to 0 Hz (/ili/–/ali/) and to 54 Hz (/ila/–/ala/).

C. Other statistical analyses

The size and the temporal extent of the consonantal and vocalic effects for the different consonants across speakers were also submitted to one-way ANOVAs (Scheffé) in order to determine the existence of consonant-dependent significant differences ($df_{bw}=6, df_{wg}=28$; $p<0.05$). For that purpose, negative C-to-V size effects were transformed into positive values and separate tests were conducted for the anticipatory and for the carryover component in each vowel condition.

Four correlation analyses involving the consonantal effects or the vocalic effects were separately performed for each vowel condition and coarticulatory direction across consonants and speakers: between the size and the temporal extent of the C-to-V effects; between the size and the temporal extent of the V-to-V effects; between the size of the V-to-C effects and the size of the V-to-V effects; between the size of the V-to-C effects and the temporal extent of the V-to-V effects. The purpose of this analysis was to investigate whether an increase in magnitude for a given coarticulatory effect was matched by an increase in duration and, less importantly, if V-to-C and V-to-V effects were strongly correlated. Four other correlations were carried out between the consonantal effects and the vocalic effects which should bear on the issue of whether vocalic coarticulation varies inversely with the DAC value for the consonant: between C-to-V size and V-to-C size; between C-to-V size and V-to-V size; between C-to-V size and V-to-V time; between C-to-V time and V-to-V time. In this paper positive or negative correlations will be taken to occur when the r value is relatively low (equal or larger than 0.70, whether significant or not) so as to make sure that no meaningful interactions between coarticulatory effects are left out.

II. RESULTS

A. C-to-V coarticulatory effects

Figure 3(a) and (b) displays Qp and $F2$ data on C-to-V coarticulation for all seven consonants and the two vowels /i/ [Fig. 3(a)] and /a/ [Fig. 3(b)]. Effects are plotted separately for C-to-V size and temporal extent and for the anticipatory direction (A; stippled bars) and carryover direction (C; black bars). The height of the bars indicates whether C-to-V effects are larger/smaller (size effects) and longer/shorter (temporal effects).[9] For example, according to Fig. 3(a), the anticipatory and carryover effects in dorsopalatal contact (Qp) from

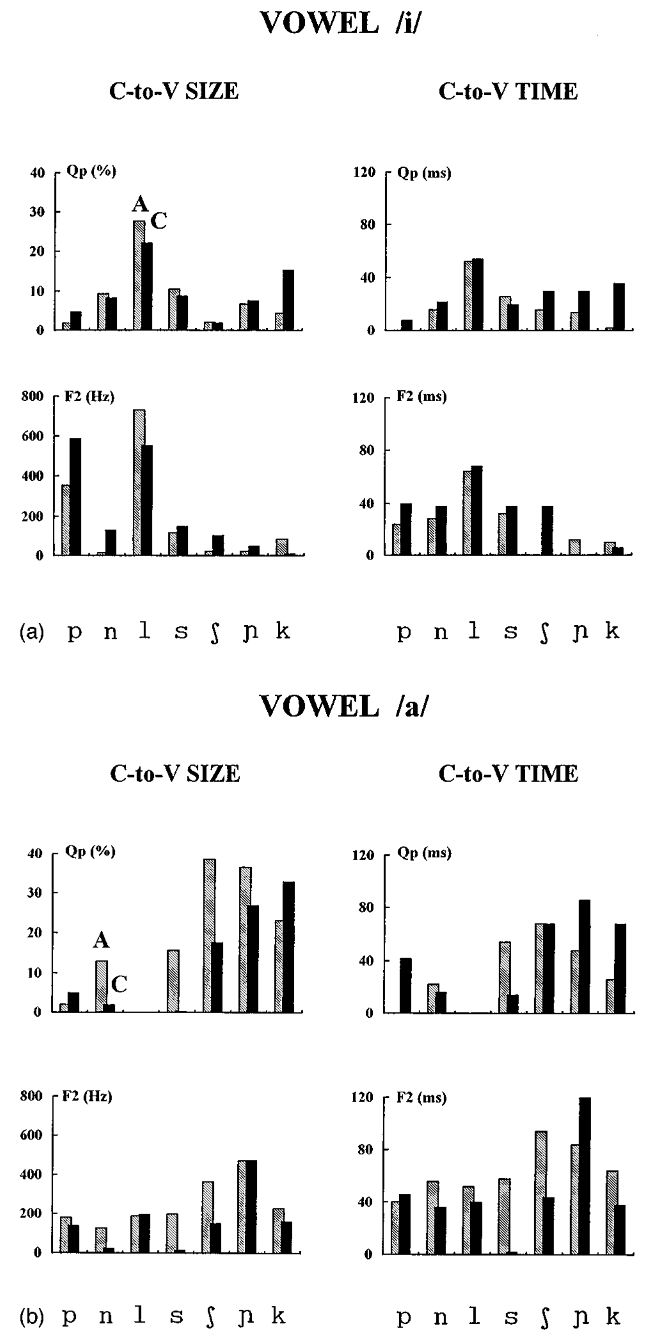

FIG. 3. (a) Mean C-to-V effects across repetitions and speakers for each consonant when the contextual vowel is /i/. Size effects in % of electrode activation and in Hz (left) and temporal effects in ms (right) are plotted separately for Qp (above) and $F2$ (below), and for each coarticulatory direction, i.e., anticipatory (stippled bars) and carryover (black bars). (b) Same representation as in (a) when the fixed vowel is /a/.

/l/ on /i/ are larger and longer than those exerted by other consonants and the situation for the $F2$ effects is essentially the same as that for the Qp effects referred to.

The numerical values for the coarticulatory effects represented in the figures are presented in Table I (means and standard errors). Size effects in the table are assigned a positive or a negative sign depending on whether the consonant causes an increase or a decrease in the Qp or $F2$ value for the vowel. Thus the table assigns a negative sign to the anticipatory and carryover size effects from /l/ on /i/ meaning that this consonant causes Qp and $F2$ to lower during V1 and V2.

1. /i/ context

According to the predictions in the Introduction section (see Sec. B 1), coarticulation should not be too prominent in sequences made of compatible consonants involving tongue-dorsum raising whether specified for the same DAC value as /i/ (i.e., 3 in the case of alveolopalatals and velars) or for a lower DAC value (i.e., 2 for alveolars excluding /l/). C-to-V effects in Qp and $F2$ in the figure are indeed small and short for alveolopalatals /ɲ/ and /ʃ/ and for velar /k/ although this trend is less clear for the carryover effects in Qp for reasons pointed out in Sec. II C 1 a.[10] According to Table I, these effects are positive (in Qp) and slightly positive or negative (in $F2$) which is in accordance with these consonants being articulated with a similar degree of tongue-dorsum height to that for /i/. Size and temporal effects in Qp and $F2$ for the alveolars /n/ and /s/ are often somewhat more prominent than those for alveolopalatals and velars which does not accord with the DAC value for alveolars being lower than that for /i/. The intermediate status of the C-to-V size effects for /n/ and /s/ is reflected by their being significantly different from those for other consonants in some cases. The negative sign of the C-to-V size effects in Qp and $F2$ for /n/ and /s/ (see Table I) may account for this finding: It appears that the production of these two consonants involves some lowering of the tongue predorsum (presumably because of manner requirements in the case of /s/ and of language-specific constraints in the case of /n/) which renders them not fully compatible with the tongue-dorsum raising gesture for /i/.[11]

Little C-to-V coarticulation was expected to occur as a function of /p/ since bilabials do not involve tongue-dorsum activity ($\mathrm{DAC}=1$) and /i/ is specified for a maximum DAC value (3) (see Sec. B 1). Qp effects for bilabial /p/ in the figure are indeed small and short. C-to-V effects in $F2$ (also in $F3$) for /p/ were unexpectedly large and long; more specifically, size effects were found to be significantly larger than those for most other consonants. This outcome is probably unrelated to tongue-dorsum activity but to $F2$ and $F3$ of /i/ being highly sensitive to variations in lip rounding, i.e., to a protrusion of the lips, a decrease of their area or both (Fant, 1960). The negative sign of the $F2$ size effects in Table I is indeed related to lip closing for /p/; Qp size effects (which could be exclusively attributed to tongue predorsum lowering) are also negative but very small.

One scenario deserves special attention, i.e., the sequence /li/ with the participation of lingual gestures which are at the same time highly constrained (dark /l/ and /i/ are both specified for $\mathrm{DAC}=3$) and antagonistic (the vowel is produced with tongue-dorsum raising and fronting and the consonant with tongue-dorsum lowering and backing) (see Sec. B 1). The figure reveals the existence of large and long C-to-V effects in this case with size effects being significantly larger than those for most other consonants. This coarticulatory outcome indicates that the requirements for a highly constrained consonant override those for a highly constrained vowel when the two phonetic segments are produced with antagonistic lingual gestures. The negative sign

TABLE I. Mean Qp and $F2$ coarticulation values across speakers and repetitions for different consonants when the fixed vowel is /i/. Data are separately displayed for the size and the temporal extent of the C-to-V, V-to-C, and V-to-V effects at the anticipatory and carryover level. Size effects are given in % of electrode activation (Qp) and in Hz ($F2$); temporal effects are given in ms. C-to-V size effects can be positive or negative (i.e., the consonant contributes to a raising or a lowering of the Qp or $F2$ frequency value for the vowel). An asterisk indicates the presence of significant V-to-C size effects ($p<0.05$). A variability measure (se=standard error) is also given.

			C to V				V to C		V to V			
			Anticipatory		Carryover		Anticipatory	Carryover	Anticipatory		Carryover	
	Vowel /i/		Size	Time	Size	Time	Size		Sice	Time	Size	Time
Qp	/p/	$\bar{X}$	−1.83	0.00	−4.83	8.00	26.67*	31.00*	3.00	0.00	11.67	70.00
		se	*1.52*	*0.00*	*1.78*	*5.83*	*1.99*	*1.43*	*1.07*	*0.00*	*1.73*	*16.43*
	/n/	X	−9.33	16.00	−8.33	22.00	13.33*	15.83*	5.50	10.00	5.00	30.00
		se	*2.73*	*10.30*	*3.11*	*10.68*	*1.86*	*1.92*	*1.20*	*10.00*	*1.21*	*20.00*
	/l/	X	−27.63	52.00	−22.13	54.00	13.38*	13.38*	6.50	14.00	4.13	2.00
		se	*0.64*	*3.74*	*3.71*	*12.49*	*3.40*	*3.39*	*2.86*	*14.00*	*2.18*	*2.00*
	/s/	X	−10.50	26.00	−8.83	20.00	8.83*	4.66	2.50	0.00	1.50	0.00
		se	*2.07*	*14.70*	*2.31*	*12.25*	*1.80*	*2.12*	*1.18*	*0.00*	*0.55*	*0.00*
	/ʃ/	X	2.17	16.00	2.00	30.00	4.00	6.83*	1.50	8.00	5.33	28.00
		se	*0.68*	*16.00*	*2.72*	*23.24*	*1.57*	*1.61*	*0.93*	*8.00*	*2.21*	*20.83*
	/ɲ/	X	6.83	14.00	7.67	30.00	0.17	12.83*	1.00	6.00	6.94	23.33
		se	*1.67*	*8.72*	*1.27*	*12.65*	*0.17*	*2.89*	*0.81*	*6.00*	*3.20*	*12.02*
	/k/	X	4.46	2.00	15.33	36.00	11.15*	4.50	3.75	6.00	1.00	0.00
		se	*2.94*	*2.00*	*4.11*	*9.27*	*2.80*	*2.00*	*2.07*	*4.00*	*0.49*	*0.00*
$F2$	/p/	$\bar{X}$	−353.00	24.00	−587.00	40.00	⋯	⋯	89.60	8.00	72.00	18.00
		se	*109.43*	*6.78*	*84.35*	*6.32*			*21.67*	*8.00*	*28.02*	*11.14*
	/n/	X	15.20	28.00	−130.40	38.00	632.13*	646.10*	309.20	26.00	415.60	46.00
		se	*85.40*	*11.58*	*38.15*	*15.30*	*68.32*	*74.20*	*56.94*	*6.78*	*58.52*	*18.60*
	/l/	X	−732.00	64.00	−552.40	68.00	193.32*	86.97*	118.64	12.00	77.96	10.00
		se	*31.29*	*6.00*	*98.84*	*8.60*	*22.34*	*13.81*	*36.49*	*5.83*	*50.44*	*10.00*
	/s/	X	−116.00	32.00	−149.60	38.00	99.20*	137.40*	41.60	2.00	52.80	12.00
		se	*51.74*	*22.67*	*43.90*	*13.56*	*33.11*	*37.26*	*24.68*	*2.00*	*8.62*	*9.70*
	/ʃ/	X	20.80	0.00	−104.00	38.00	104.00	116.40	48.80	0.00	74.00	0.00
		se	*12.99*	*0.00*	*42.01*	*20.35*	*43.67*	*54.59*	*15.56*	*0.00*	*39.28*	*0.00*
	/ɲ/	X	20.80	12.00	−48.80	0.00	22.40	105.48*	26.40	4.00	33.67	0.00
		se	*18.82*	*12.00*	*7.09*	*0.00*	*12.24*	*11.63*	*10.32*	*4.00*	*10.59*	*0.00*
	/k/	X	86.00	10.00	10.40	6.00	⋯	⋯	41.00	8.00	94.20	50.00
		se	*42.17*	*10.00*	*58.25*	*4.00*			*23.11*	*5.83*	*52.44*	*27.93*

of the C-to-V size effects in Qp and $F2$ from /l/ on /i/ (Table I) reveals that the consonant contributes to much tongue dorsum lowering during the vowel.

According to Table III, correlations between C-to-V size and C-to-V temporal extent, i.e., $CV_s \times CV_t$, yield high positive r values for Qp and $F2$ and for the anticipatory and for the carryover direction meaning that the duration of the consonantal effect varies with its magnitude in the /i/ context condition. A close correspondence between C-to-V size and temporal extent can be seen for fixed /i/ in Fig. 3(a). Larger effects are also longer (as those for /l/) and smaller effects are also shorter (as those for /p/ in Qp and for alveolopalatals and velars in $F2$).

2. /a/ context

According to predictions in Sec. B 1, prominent consonant-dependent effects on /a/ should occur in scenarios where the consonant and the vowel are produced with opposing articulatory trajectories and the DAC value for the consonant exceeds the DAC value of 2 for /a/. Figure 3(b) shows large and long C-to-V effects in Qp and $F2$ for consonants requiring tongue-dorsum raising and specified for a DAC maximum, i.e., alveolopalatals /ɲ/ and /ʃ/ and velar /k/. These effects are often significantly different from those for other consonants. They are positive (Table II) meaning that the consonant causes tongue dorsum raising to occur during the vowel.

In comparison to alveolopalatals and velars, the size and temporal effects in the figure are usually smaller and shorter for the alveolars /n/, /s/, and dark /l/ and for the bilabial /p/. This is the expected outcome for consonants such as /n/ and /s/ involving different articulatory trajectories from that for the vowel and specified for the same moderate DAC value (see Sec. B 1). In this case, C-to-V effects can be somewhat more prominent than predicted since the tongue-dorsum position for the consonant is higher than that for the vowel (as revealed by Qp and $F2$ effects for /na/ and /sa/ showing a positive sign; see Table II) and consonants tend to override vowels when the two phonetic segments are specified for the same DAC value and are antagonistic (as for /li/). C-to-V effects of little prominence for /p/ accord with this consonant exhibiting a minimal DAC value (see Sec. B 1). These effects often exhibit a negative sign due to lip closing and/or some tongue lowering (Table II). The existence of smaller C-to-V effects in $F2$ (also in $F3$) from /p/ on /a/ than on /i/ is in accordance with predictions in Fant's nomograms relat-

TABLE II. Same contents as in Table I when the fixed vowel is /a/.

			C to V				V to C		V to V			
			Anticipatory		Carryover		Anticipatory	Carryover	Anticipatory		Carryover	
Vowel /a/			Size	Time	Size	Time	Size	Size	Size	Time	Size	Time
Qp	/p/	$\overline{X}$	2.00	0.00	−5.00	42.00	17.17*	21.50*	3.67	30.00	2.83	6.00
		se	*0.50*	*0.00*	*1.97*	*28.00*	*2.91*	*2.89*	*1.87*	*30.00*	*1.76*	*4.00*
	/n/	$\overline{X}$	13.00	22.00	2.00	16.00	9.67*	12.17*	1.83	6.00	1.50	2.00
		se	*0.86*	*2.00*	*1.41*	*16.00*	*3.28*	*1.59*	*0.81*	*4.00*	*1.30*	*2.00*
	/l/	$\overline{X}$	⋯	⋯	⋯	⋯	5.50	4.75	1.28	22.00	2.97	10.00
		se					*1.62*	*1.85*	*0.86*	*22.00*	*1.34*	*7.75*
	/s/	$\overline{X}$	15.67	54.00	−0.33	14.00	6.33*	2.67	2.33	8.00	1.50	0.00
		se	*1.43*	*6.00*	*3.15*	*8.72*	*1.57*	*1.63*	*1.27*	*8.00*	*0.93*	*0.00*
	/ʃ/	$\overline{X}$	38.50	68.00	17.67	68.00	0.17	2.17	1.50	0.00	0.33	0.00
		se	*2.90*	*5.83*	*3.76*	*11.58*	*0.17*	*1.33*	*0.55*	*0.00*	*0.33*	*0.00*
	/ɲ/	$\overline{X}$	36.50	48.00	26.83	86.00	3.17	14.83*	0.67	0.00	11.00	24.00
		se	*2.20*	*4.90*	*2.90*	*13.27*	*1.52*	*4.37*	*0.41*	*0.00*	*3.26*	*10.30*
	/k/	$\overline{X}$	23.00	26.00	32.84	68.00	20.00*	12.83	10.67	6.00	6.50	6.00
		se	*5.76*	*7.48*	*3.91*	*12.00*	*2.06*	*4.76*	*3.24*	*4.00*	*3.37*	*6.00*
*F*2	[p]	$\overline{X}$	−179.20	40.00	−137.00	46.00	⋯	⋯	151.20	78.00	81.40	18.00
		se	*27.67*	*4.47*	*34.00*	*15.68*			*29.81*	*15.94*	*18.62*	*8.00*
	[n]	$\overline{X}$	124.00	56.00	22.40	36.00	158.94*	172.91*	124.44	92.00	112.56	50.00
		se	*31.62*	*14.35*	*28.86*	*20.64*	*45.74*	*38.49*	*14.68*	*13.19*	*30.75*	*22.14*
	[ɫ]	$\overline{X}$	−187.00	52.00	−196.00	40.00	197.27*	90.92*	99.39	52.00	29.09	6.00
		se	*40.72*	*13.93*	*31.21*	*3.16*	*21.66*	*21.08*	*13.02*	*17.44*	*13.21*	*6.00*
	[s]	$\overline{X}$	198.40	58.00	14.40	2.00	83.50	123.30	58.40	2.00	67.20	66.00
		se	*59.82*	*12.81*	*23.45*	*2.00*	*28.84*	*49.23*	*21.45*	*2.00*	*23.10*	*29.26*
	[ʃ]	$\overline{X}$	364.80	94.00	151.20	44.00	114.80*	117.20	132.80	44.00	60.00	25.00
		se	*25.66*	*5.10*	*30.92*	*19.13*	*27.62*	*44.36*	*27.05*	*15.03*	*16.57*	*16.58*
	[ɲ]	$\overline{X}$	472.00	84.00	475.20	126.00	89.32	186.80*	76.00	24.00	131.20	22.00
		se	*29.31*	*5.10*	*115.89*	*18.06*	*43.83*	*34.53*	*43.89*	*17.49*	*40.86*	*7.35*
	[k]	$\overline{X}$	228.00	64.00	160.80	38.00	⋯	⋯	148.00	42.00	87.00	30.00
		se	*9.38*	*6.00*	*86.69*	*17.15*			*39.27*	*18.81*	*53.86*	*18.97*

ing variations in lip rounding to changes in constriction location. As expected (Sec. B 1), dark /l/ exerts moderate *F*2 effects on /a/ in spite of the consonant being highly constrained since the two phonetic segments are produced with comparable articulatory trajectories and small differences in tongue-dorsum position. Thus for consonants specified for DAC=3, C-to-V effects appear to be less prominent when the consonant and the vowel gestures are compatible (as for /la/) than when they are antagonistic (as for /ɲa/). Negative C-to-V effects in *F*2 for dark /l/ (Table II) are consistent with this consonant requiring active tongue-dorsum lowering.

Analogously to the /i/ condition, C-to-V size effects and C-to-V temporal effects, i.e., $CV_s \times CV_t$, are highly correlated in the /a/ condition (see Table III). High positive *r* values were obtained both for *Qp* (anticipatory effects) and

TABLE III. Correlations for C-to-V, V-to-C, and V-to-V effects in *Qp* and *F*2 across data for seven consonants and five speakers; lowercase *s* and *t* indicate size and temporal effects, respectively. *r* values at and above 0.70 are given independently for the anticipatory and carryover direction and for each fixed vowel condition. An asterisk indicates the presence of significant correlations ($p<0.05$).

	Vowel /i/				Vowel /a/			
	Qp		*F*2		*Qp*		*F*2	
	Anticipatory	Carryover	Anticipatory	Carryover	Anticipatory	Carryover	Anticipatory	Carryover
C effects								
$CV_s \times CV_t$	0.94*	0.79	0.84	0.73	0.81		0.84	0.94*
V effects								
$VC_s \times VV_s$		0.91*	0.99*	0.99*	0.82			1.00*
$VC_s \times VV_t$		0.87	0.95	0.96			0.72	
$VV_s \times VV_t$		0.94*	0.95*			0.91*	0.71	
C effects×V effects								
$CV_s \times VC_s$								
$CV_s \times VV_s$	0.71					0.71		
$CV_s \times VV_t$					−0.85			
$CV_t \times VV_t$		−0.70			−0.79			

for $F2$ (anticipatory and carryover effects). A close match between the C-to-V effects in size and temporal extent is apparent across consonants in the graphs of Fig. 3(b).

B. Vocalic coarticulatory effects

1. Fixed /i/

Figure 4(a) displays the size and the temporal extent of vocalic coarticulation in the sequence pairs /iCi/–/iCa/ (anticipatory) and /iCi/–/aCi/ (carryover), i.e., the size of the vocalic effects at the consonantal midpoint (V-to-C) and their size and temporal extent during the fixed vowel /i/ (V-to-V). Effects are always positive and occur when the Qp or $F2$ value for /i/ exceeds that for /a/.

The data in Fig. 4(a) show that vowel-dependent effects in Qp and/or $F2$ tend to be larger and longer for consonants specified for lower DAC values (bilabial /p/, alveolar /n/) than for consonants requiring more active tongue-dorsum control (dark /l/, fricative /s/, alveolopalatals, velars). This finding is in accordance with the degree of coarticulatory resistance varying directly with the DAC value for the consonant and with the DAC value for /s/ being higher (3) than that for /n/ (2). The size effects for /p/ and /n/ are significantly different from those for other consonants; moreover the Qp effects are significantly larger for /p/ vs /n/ which accords with DAC differences between the two consonants.

Correlation data for the /i/ context condition in Table III often reveal high positive r values between the size of the V-to-C effects, and the size and the temporal extent of the V-to-V effects (i.e., $VC_s \times VV_s$, $VC_s \times VV_t$), and between the two latter magnitudes (i.e., $VV_s \times VV_t$). This trend occurs for $F2$ both at the anticipatory and carryover levels, and for Qp at the carryover level. Figure 4(a) reveals that consonants allowing large vocalic size effects are the same ones allowing long vocalic effects in temporal extent (/p/, /n/), while vocalic effects are usually small and short for another set of consonants (dark /l/, /s/, alveolopalatals, velars).

Negative correlation values between the consonantal and the vocalic effects should be taken as evidence that the latter vary inversely with respect to the former (see Sec. I C). As shown in Table III, only one high negative correlation (i.e., $CV_t \times VV_t$) was obtained out of 16 possibilities. Low correlation values occur since the degree of vocalic coarticulation is inversely related to the degree of C-to-V coarticulation in some cases (/l/) but not in others (alveolopalatals, velars). Thus while dark /l/ exerts maximal C-to-V coarticulation and allows vowel-dependent effects of little prominence, alveolopalatals and velars exhibit little C-to-V and vocalic coarticulation.

2. Fixed /a/

Vocalic coarticulatory effects for fixed /a/ are displayed in Fig. 4(b). $F2$ effects in temporal extent reveal the expected trend for consonants specified for higher DAC values to allow lesser vocalic coarticulation than consonants with lower DAC values. Indeed, dorsal /l/, /ɲ/, /ʃ/, and /k/ and fricative /s/ (which appears to be specified for a high DAC value) allow shorter V-to-V anticipatory temporal effects in $F2$ frequency than consonants /p/ and /n/ requiring lesser tongue-dorsum activation.

V-to-C size effects in Qp are also most prominent for consonants /p/ and /n/ (for /p/>/n/) specified for low DAC values, as well as for /k/ which may be due to vowel-related changes in velar closure fronting; these effects for /p/ and /k/ (also V-to-V size effects in Qp for /k/) are significantly larger than those for other consonants. V-to-C size effects in $F2$ are small and show a less coherent picture, with anticipatory size effects decreasing in the progression /l/>/n/, /ʃ/>/s/, /ɲ/ for most speakers. V-to-V size effects in Qp and $F2$ and V-to-V temporal effects in Qp are very small and short.

Correlation data for the /a/ context condition in Table III yield similar results to those for the /i/ condition. High positive r values occur at least once for correlations involving vocalic effects exclusively, i.e., $VC_s \times VV_s$, $VC_s \times VV_t$, $VV_s \times VV_t$, meaning that there is a good correspondence between vowel-dependent size and temporal coarticulation. An inverse correlation between vocalic coarticulation and consonantal coarticulation was found to hold just for 2 out of 16 correlation pairs (i.e., $CV_s \times VV_t$, $CV_t \times VV_t$). The absence of high negative correlations between the consonant-dependent and vowel-dependent effects appears to be mostly related to the high variability in the coarticulatory effects across consonants (given the considerable number of consonants included in the correlation analyses) and to /a/ exhibiting little dorsopalatal contact (Qp correlations only).

3. Articulatory dimension of the V-to-C effects

Data on V-to-C coarticulation in Tables I and II and those for the individual speakers reveal a trend for the vowel-dependent effects during the consonantal period to favor the target articulatory position for the consonant.

A comparison between V-to-C effects in the two tables reveals that consonants /ɲ/ and /k/ requiring a high tongue-dorsum position allow larger effects in tongue-dorsum raising (exerted by /i/ in the fixed /a/ context) than in tongue-dorsum lowering (exerted by /a/ in the fixed /i/ context). This is so for the coarticulatory effects in Qp (/ɲ/, /k/) and in $F2$ (/ɲ/). Thus for example, the size of the anticipatory and carryover effects in $F2$ for /ɲ/ is 89.32 Hz and 186.8 Hz in the fixed /a/ context but only 22.4 Hz and 105.48 Hz in the fixed /i/ context. $F2$ and dorsopalatal contact (Qp) trajectories for /ɲ/ in Fig. 5 suggest that the raising movement for /aɲi/ occurs earlier (it begins during V1 and ends about closure offset) than the lowering movement for /iɲa/ (it begins during closure or somewhat later and ends during the V2 period). It thus appears that the tongue dorsum early achieves a high position when /ɲ/ follows /a/ and holds this position as long as possible when /ɲ/ follows /i/.

Dark /l/, on the other hand, allows effects in tongue-dorsum lowering exerted by /a/ in the fixed /i/ context over those exerted by /i/ in the fixed /a/ condition which accords with this consonant involving active tongue-dorsum lowering. This trend is at work for the Qp data but not so for the $F2$ data (see Tables I and II). Qp and $F2$ data in Fig. 5 reveal indeed that the lowering trajectories for /ila/ begin

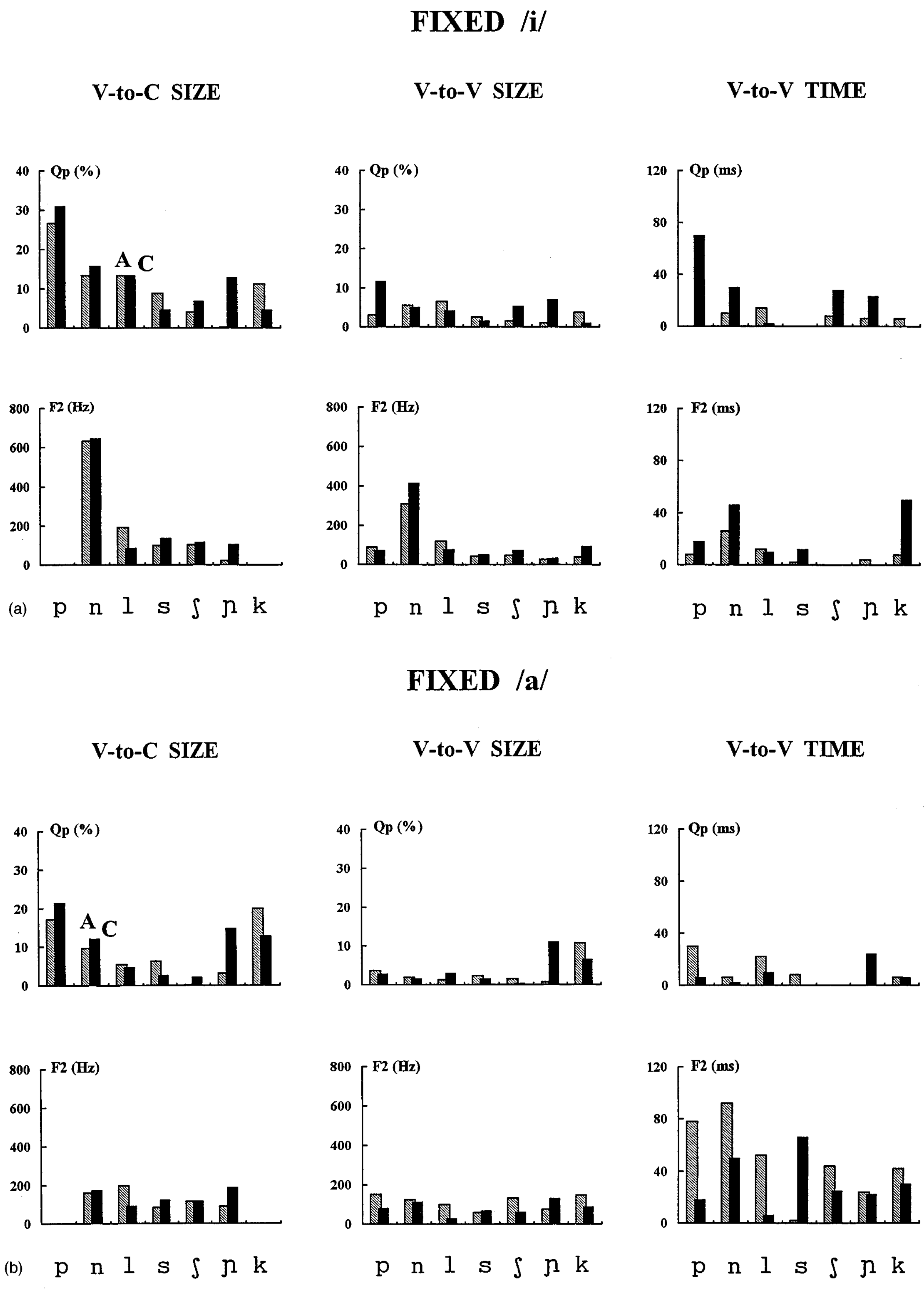

FIG. 4. (a) Mean V-to-C and V-to-V effects across repetitions and speakers for each consonant when the fixed vowel is /i/. Size effects in % of electrode activation and in Hz (left: V-to-C, middle: V-to-V) and temporal effects in ms (right: V-to-V) are plotted separately for Qp (above) and $F2$ (below), and for each coarticulatory direction, i.e., anticipatory (dotted bars) and carryover (black bars). (b) Same representation as in (a) when the fixed vowel is /a/.

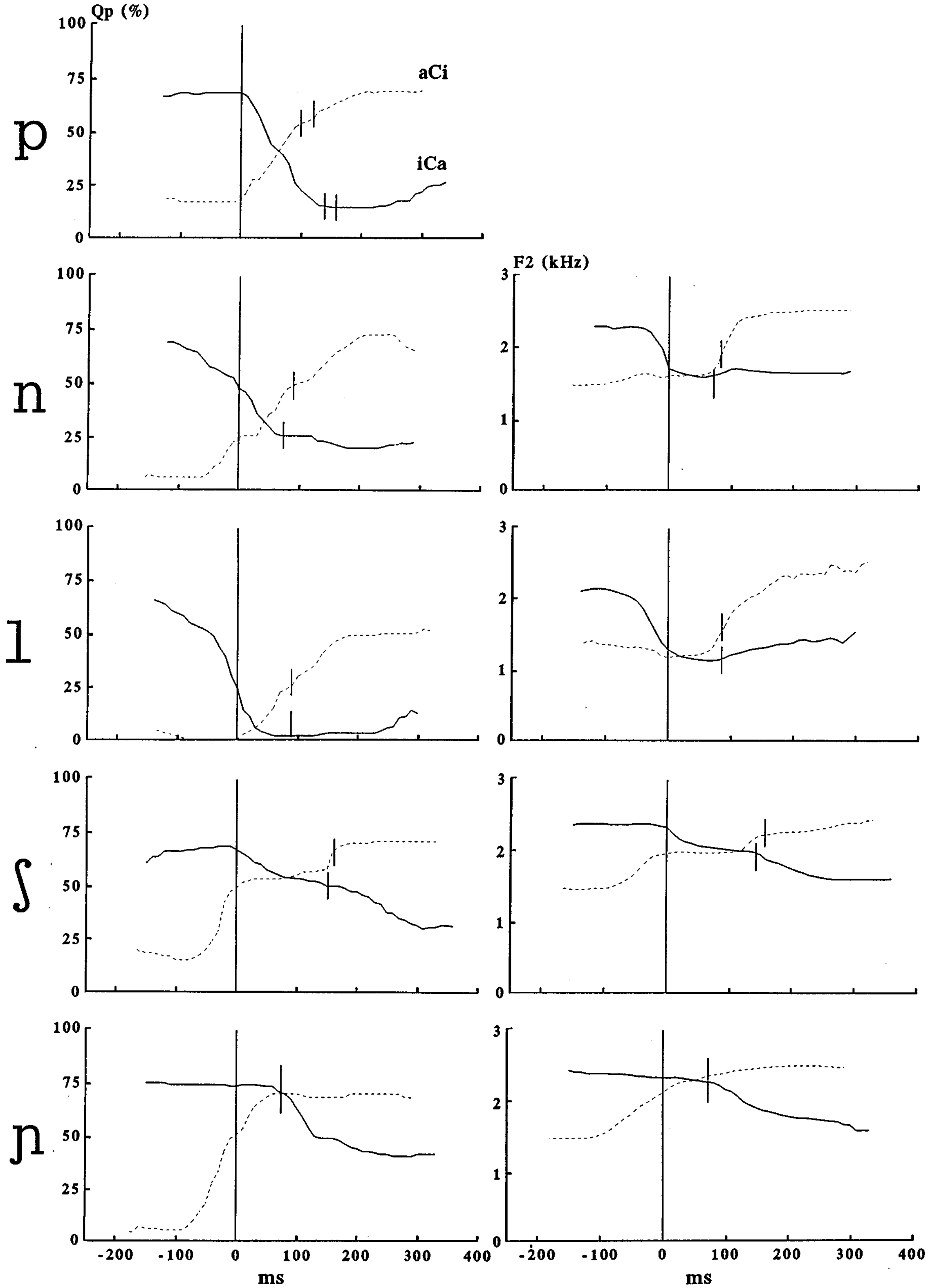

FIG. 5. Qp trajectories (left) and $F2$ trajectories (right) for the sequences /aCi/ (dashed lines) and /iCa/ (solid lines) lined up at the onset of the consonantal period (0-ms value along the temporal axis). Short vertical marks crossing the $F2$ and Qp trajectories have been inserted at the offset of the consonantal period. Data correspond to a single speaker, i.e., JP (/l/, /n/, /ɲ/) and DR (/ʃ/, /p/).Trajectories for /p/ have been displayed for Qp only (no formant structure is available during the closure period for this consonant); vertical marks have been indicated at closure offset and at burst offset in this case.

earlier (during V1) and achieve an earlier endpoint (during closure) than the raising trajectories for /ali/ (in this case raising onset occurs toward the end of V1 or during the central closure period and a raising maximum is not achieved until the V2 period). It is thus apparent that the tongue reaches and maintains a low target position for the production of dark /l/ which is more compatible with that for a low vowel than with that for a high vowel.

According to data in Tables I and II, bilabial /p/ (Qp) and dentoalveolar /n/ (Qp, $F2$) also allow more prominent effects from /a/ in the fixed /i/ condition than effects from /i/ in the fixed /a/ condition. Qp trajectories for bilabial /p/ in Fig. 5 show indeed that, although the increase in lingual contact for /api/ and the contact decrease for /ipa/ begin more or less at the same time (at V1 offset), the latter ends earlier (at closure offset) than the former (during V2). This finding suggests that bilabial /p/ is more sensitive to tongue-dorsum lowering effects than to tongue-dorsum raising effects, which is consistent with this lingual region exhibiting a low position at rest. Trajectories for /n/ in the figure show that, analogously to dark /l/, $F2$ lowering onset for /ina/ occurs earlier (during V1) than $F2$ raising onset for/ani/ (at the end of the closure period); the offset of these $F2$ trajectories also takes place much earlier after /i/ (at closure onset) than after /a/ (during V2). As for the Qp data, the lowering trajectory for /ina/ and the raising trajectory for /ani/ start more or less simultaneously during V1 while their endpoint is achieved earlier for the former (at closure offset) than for the latter (during V2). Predominance of the vowel-related lowering effects for /n/ is a quite unexpected outcome since the tongue dorsum should exhibit a high position during the production of this consonant if subject to coupling effects with the primary tongue tip articulator. This finding suggests that /n/ and perhaps other dentoalveolar consonants may differ with respect to tongue-dorsum height across languages (i.e., /n/ would be specified for a rather low tongue-dorsum position in Catalan) and that articulatory regions which are not involved in the closure or constriction making process may be actively controlled.

Data in Tables I and II reveal that fricatives /s/ and /ʃ/ also favor slightly the effects from /a/ over those from /i/ (for Qp and $F2$ in the case of /s/, and for Qp in the case of /ʃ/). The situation for fricatives is exemplified by the Qp and $F2$ trajectories for /ʃ/ in Fig. 5 (the /s/ trajectories show an analogous behavior to those for /ʃ/ in the figure). Table II indicates a slight predominance of the vowel-dependent lowering vs raising effects for these consonants (thus, for example, V-to-C effects for /s/ amount to 99.2 Hz and 137.4 Hz in the fixed /i/ context, and to 83.5 Hz and 123.3 Hz in the fixed /a/ context). These V-to-C data are not in agreement with the onset times of trajectory movement in Fig. 5 (since raising onset for /aʃi/ occurs earlier than lowering onset for /iʃa/) and may be related to Qp and $F2$ raising trajectories achieving a plateau while the corresponding lowering trajectories exhibit continuous motion.

C. Coarticulatory direction

In order to evaluate the relative salience of the two coarticulatory directions, values for the size and the temporal extent of the anticipatory component have been subtracted from those of the carryover component (see Tables I and II) and the resulting differences have been displayed in Fig. 6(a) and (b) (consonant-dependent effects) and in Fig. 7(a) and (b) (vowel-dependent effects). Differences in sign have not been taken into account in the subtraction procedure. Negative values in the figures indicate that anticipation prevails over carryover; positive values indicate the opposite relationship.

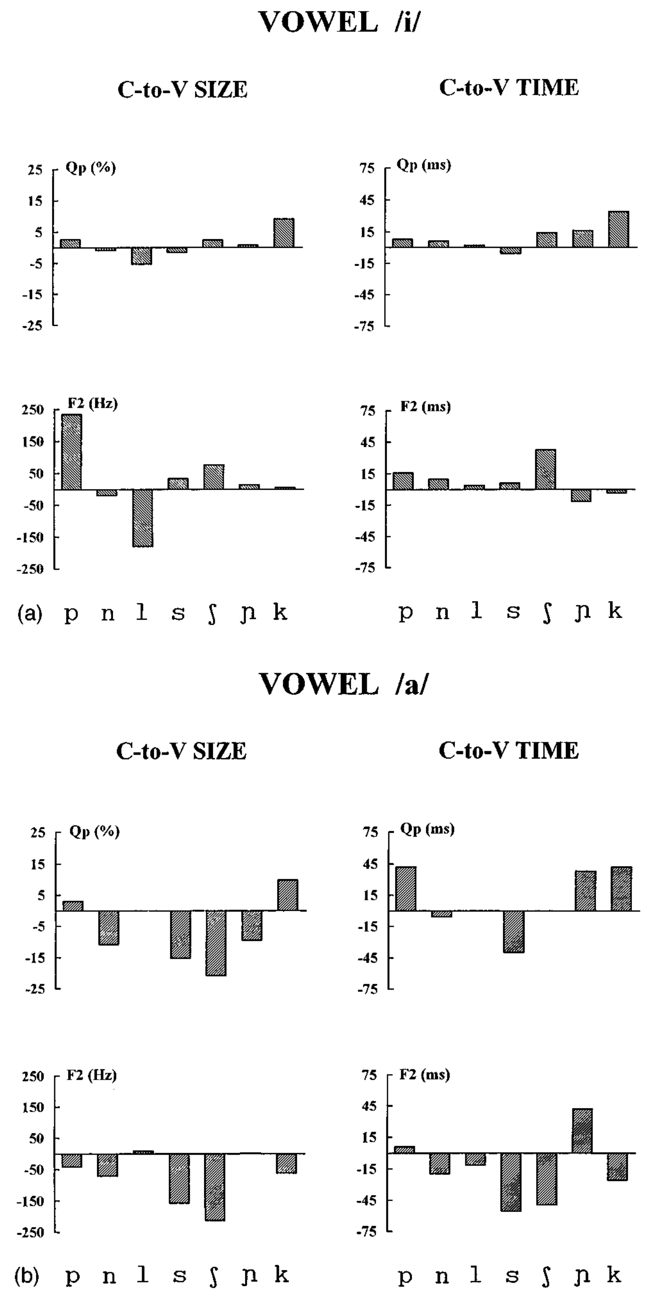

FIG. 6. (a) Differences in coarticulatory direction for the C-to-V effects for each consonant across repetitions and speakers when the contextual vowel is /i/. Predominance of the anticipatory component yields a negative value (below the 0 line); predominance of the carryover component yields a positive value (above the 0 line). Size effects in % of electrode activation and in Hz (left) and temporal effects in ms (right) are plotted separately for Qp (above) and $F2$ (below). (b) Same representation as in (a) when the fixed vowel is /a/.

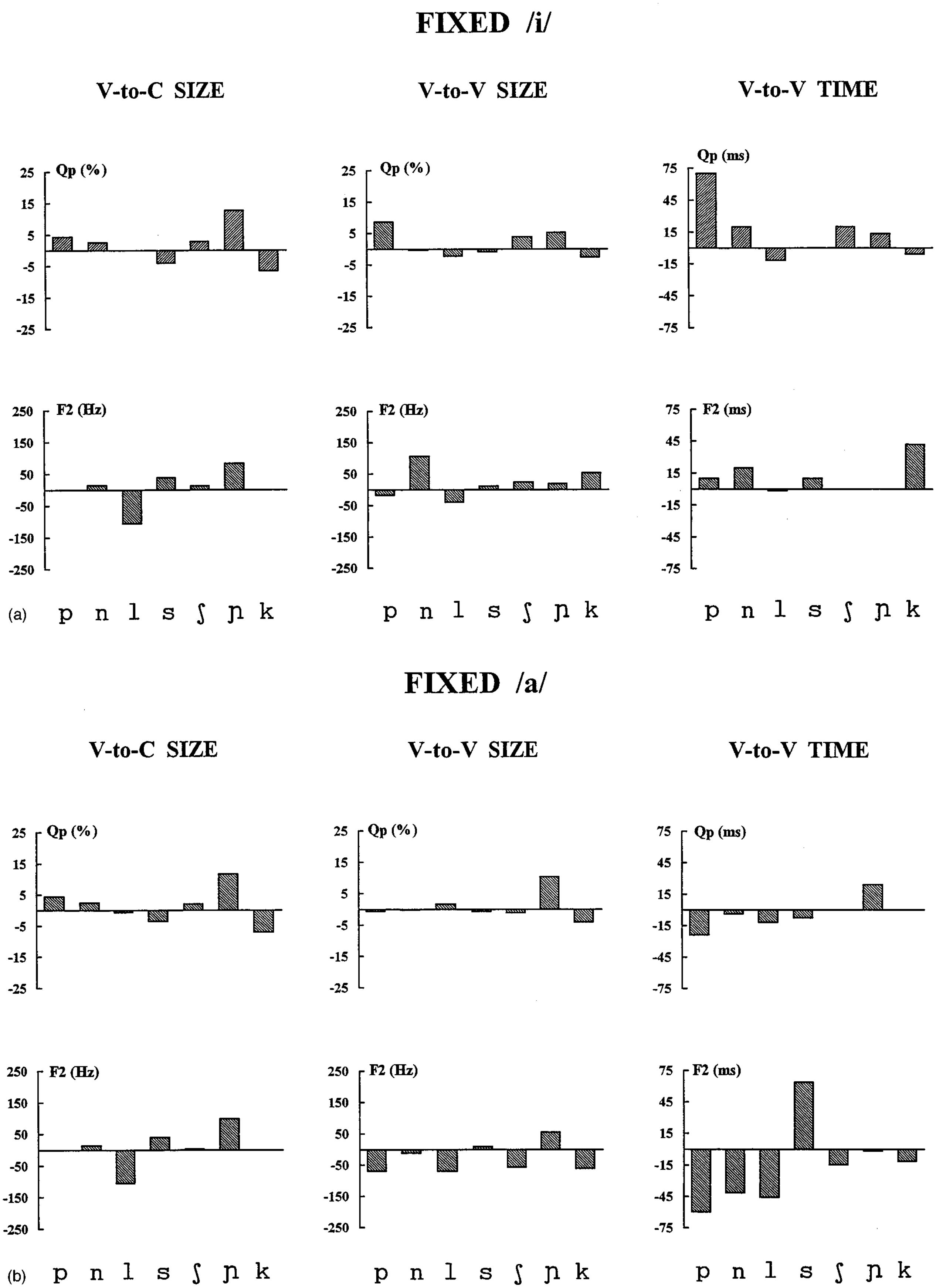

FIG. 7. (a) Differences in coarticulatory direction for the V-to-C and V-to-V effects for each consonant across repetitions and speakers when the fixed vowel is /i/. Predominance of the anticipatory component yields a negative value (below the 0 line); predominance of the carryover component yields a positive value (above the 0 line). Size effects in % of electrode activation and in Hz (left: V-to-C, middle: V-to-V) and temporal effects in ms (right: V-to-V) are plotted separately for Qp (above) and $F2$ (below). (b) Same representation as in (a) when the fixed vowel is /a/.

1. C-dependent coarticulation

a. /i/ context. According to Fig. 6(a), C-to-V effects in Qp and $F2$ show some noticeable trends in coarticulatory direction. On the one hand, alveolopalatals and velars tend to favor carryover over anticipatory coarticulation in size and temporal extent; the absence of much C-to-V anticipation in a sequence made of two comparable highly constrained phonetic segments (such as /ʃ/, /ɲ/, or /k/ and the vowel /i/) may lead to the prevalence of the carryover component associated with the mechanico-inertial properties of the tongue-dorsum raising gesture. On the other hand, dark /l/ exerts larger (but not longer) anticipatory than carryover effects; the salience of the C-to-V anticipatory effects in this case appears to be linked to the performance of the highly constrained lingual gesture for the consonant when preceded by the antagonistic vowel /i/.

Speaker-dependent Qp and $F2$ data reveal no clear coarticulatory direction pattern for the alveolars /s/ and /n/ although most speakers favor the carryover direction in some instances. Size and temporal effects for the bilabial /p/ also show predominance of the carryover component which may be related to the influence of the bilabial release and, as for the other nondorsal consonants /n/ and /s/, to the inertial requirements associated with the raising of the tongue dorsum induced by the vowel /i/.

b. /a/ context. Qp and $F2$ data in Fig. 6(b) show that fricatives resemble other constrained consonants in exerting strong gestural anticipation: Size and temporal data reveal that /s/ and /ʃ/ often favor the C-to-V anticipatory component. To a lesser extent, predominance of anticipation over carryover is also at work for the alveolars /n/ (size and temporal coarticulation in Qp and $F2$) and /l/ (coarticulation in $F2$ temporal extent for four speakers). Overall, alveolars may give preference to the anticipatory component in line with the tongue dorsum being ruled by apical activity and not being subject to strong mechanico-inertial constraints during their production in the /a/ context; consonants subject to important manner requirements, i.e., fricatives, give particular emphasis to the anticipatory direction.

More retracted dorsal consonants exhibit a different behavior. Alveolopalatal /ɲ/ favors anticipatory size effects in Qp and also in $F2$ [for four speakers in spite of Fig. 6(b) not showing so since one speaker exhibits very large carryover effects], presumably because the articulatory manifestation of the dorsal gesture is more /j/-like at consonantal release than at consonantal formation; temporal effects in Qp and $F2$ for /ɲ/ are however longer at the carryover versus anticipatory level. Regarding velar /k/, C-to-V effects are larger and longer for the carryover vs anticipatory direction (Qp) and for the anticipatory versus carryover direction ($F2$). The finding of more prominent carryover than anticipatory effects for dorsals vs alveolars is in accordance with the mechanico-inertial properties associated with the tongue-dorsum raising gesture for the former consonantal class.

No clear coarticulatory direction holds for bilabial /p/ which favors anticipation in $F2$ size and perhaps carryover in Qp size (longer carryover vs anticipatory effects in Qp for this consonant are associated with two speakers only).

2. V-dependent coarticulation

a. Fixed /i/. According to Fig. 7(a) highly constrained dark /l/, which favors consonant-dependent anticipation, often gives priority to the anticipatory direction for the vocalic effects in size and temporal extent. On the other hand, consonants assigning more weight to carryover over anticipation for the C-to-V effects also allow more prominent vowel-dependent carryover than anticipation, i.e., /ɲ/ and /ʃ/ (in Qp and $F2$) and /k/ (in $F2$).

Consonants giving much less clear priority to a specific direction in consonant-dependent coarticulation favor no obvious direction when the vowel-dependent effects are taken into consideration. This is so for most speakers in the case of /p/ (which shows prevalence of the carryover direction in Qp and of the anticipatory direction in $F2$ size for four speakers) and of /s/ (which favors the anticipatory component for the Qp size effects and the carryover component for the $F2$ effects). While exhibiting a similar behavior to /p/ and /s/ in C-to-V directionality, alveolar /n/ gives some more weight to the carryover over the anticipatory component component for the vocalic effects.

b. Fixed /a/. Qp and $F2$ data in Fig. 7(b) reveal the existence of maximal vocalic anticipation for consonants (/p/, /n/, /l/) giving preference to no clear C-to-V coarticulatory direction (/p/) or to C-to-V anticipation (/n/, /l/). There is a trend to favor more prominent vocalic effects in $F2$ size and temporal extent and in Qp temporal extent at the anticipatory vs carryover level for /p/, /l/, and /n/; somehow V-to-C trends in Qp for /p/ and /n/ are larger at the carryover level. Velar /k/ also tends to favor the anticipatory component for the vocalic effects whether related to a more salient consonant-dependent carryover component (for Qp) or anticipatory component (for $F2$); preference for vocalic anticipation for /k/ in the fixed /a/ context condition follows from specific constraints in the production of velars (see Sec. III). Alveolopalatal /ɲ/, which exerts longer C-to-V effects at the carryover level than at the anticipatory level, is the only consonant clearly allowing more prominent vowel-dependent carryover vs anticipatory coarticulation. Fricatives, which clearly exert more prominent anticipatory versus carryover effects, may give more weight to either the vowel-dependent anticipatory or the carryover component: There is a trend for /s/ to favor Qp anticipation and $F2$ carryover; as for /ʃ/, vocalic size effects are quite small for Qp and may give priority to the anticipatory direction for $F2$.

III. GENERAL SUMMARY AND DISCUSSION

Data reported in Sec. II confirm the validity of the DAC model of coarticulation in many respects. Consonants and vowels were assigned different DAC values depending on the degree of tongue-dorsum constraint during their production, i.e., 3 to alveolopalatals, palatals, velars, and dark /l/, 1 to bilabials and the schwa, and 2 to those consonants and vowels the production of which involves some uncontrolled tongue-dorsum activity (/n/, /a/). It was also suggested that manner requirements could raise the DAC value (e.g., from 2 to 3 for /s/). As shown next, this DAC scale accounts to a large extent for the C-to-V, V-to-C, and V-to-V effects reported in the present study.

An important finding was that the prominence of the C-to-V effects depends both on the relative DAC specification for the two adjacent phonetic segments as well as on their articulatory trajectories being compatible or antagonistic. When the consonant and the vowel are specified for the same DAC value, C-to-V effects are negligible in a situation of gestural compatibility (e.g., /ɲi/) and become more prominent as the degree of gestural antagonism increases (e.g., for /li/ vs /na/, /sa/). When the consonant is specified for a higher DAC value than the vowel, C-to-V effects increase with the degree of gestural antagonism involved (e.g., for /ɲa/ vs /la/). Negligible C-to-V coarticulation occurs when the DAC value for the vowel exceeds that for the consonant (e.g., for /pi/, /pa/). More prominent C-to-V effects in tongue-dorsum lowering than expected for /si/ indicate that manner of articulation may modify the basic DAC value (from 2 to 3 in this case). It thus appears that gestural antagonism does not only prevent coarticulatory effects from occurring (as postulated by several coarticulation theories: Henke, 1966; Bell-Berti and Harris, 1981) but, on the contrary, may cause C-to-V coarticulation to increase. Our finding is consistent with differences in the production mechanisms of consonants and vowels: The formation of a closure or constriction requires consonants to be actualized during the adjacent vowel and such production requirements become especially relevant with the difficulty involved in the making of the vowel-to-consonant transition. It can be claimed that maximal antagonism results in maximal C-to-V coarticulation so as to ensure that the consonantal gesture is successfully realized and that, for a given DAC value, consonants are more constrained than vowels.

V-to-C coarticulation data reported in Sec. II are consistent with the notion that V-to-C sensitivity should vary inversely with the DAC value for the consonant, i.e., in the progression bilabials>dentoalveolars>alveolopalatals, velars, dark /l/, /s/ (which is in support of /s/ being specified for DAC=3). This progression was found to hold in both fixed vowel conditions in spite of the initial expectation that it should be at work when the fixed vowel is /a/ but not necessarily so when it is /i/ since a highly constrained fixed vowel could prevent much V-to-V coarticulation from occurring. However, there were very few high negative correlations between the vocalic effects and the consonantal effects in both vowel conditions, and thus no inverse relationship between the strength of the two coarticulatory types. This finding has been attributed to several factors often acting concomitantly such as the high number of consonants submitted to analysis or the coexistence of little consonantal and vocalic coarticulation in some scenarios (e.g., in sequences with alveolopalatal consonants and the vowel /i/).

High correlations were obtained between C-to-V effects in size and temporal extent meaning that larger effects are usually longer (e.g., for /li/, /ɲa/) while smaller effects are often shorter (e.g., for /p/, /n/, /l/, and /s/ with adjacent /a/). A similar relationship appears to hold for the vocalic effects, more so when the fixed vowel is /i/ than when it is /a/ (e.g., effects in the former vowel context are larger and longer for /p/ and /n/ and smaller and shorter for /s/ and dorsals including dark /l/). It thus appears that the extent of the consonant- and vowel-dependent effects along the time domain is related to their magnitude (see also Farnetani and Recasens, 1993).

The notion that the articulatory dimension of the C-to-V effects should depend on the target articulatory position for the consonant was also confirmed. Articulatory activity associated with the target tongue position often begins earlier and is held for a longer period than that for other tongue positions. Thus consonants requiring tongue-dorsum raising (alveolopalatals, velars) are more sensitive to effects from /i/ vs /a/ while those involving tongue-dorsum lowering favor effects from /a/ vs /i/ (bilabial /p/, alveolar /n/, dark /l/). Some justification for /p/ and /n/ involving tongue-dorsum lowering is needed: Tongue-dorsum relaxation for /p/ may occur concomitantly with lip closing (see Engstrand, 1988), while tongue-dorsum lowering for /n/ is possibly a language-specific characteristic (see Footnote 8 for other possible explanations). Fricatives /s/ and /ʃ/ were found not to clearly favor either tongue-dorsum raising effects or tongue-dorsum lowering effects associated with the adjacent vowel; this particular behavior may be related to fricatives requiring the formation of a precise medial groove which causes the tongue-dorsum surface to occupy an intermediate position between that for high and low consonantal articulations.

An important goal of this study was to test the implications of the DAC model with respect to coarticulatory directionality. C-to-V data presented in the paper confirm that, among consonants specified for a high DAC value, some favor the anticipatory component while others favor the carryover component. Prevalence of the anticipatory component for dark /l/ follows from this consonant involving the formation of two lingual constrictions; such anticipatory effects are especially salient when tongue-dorsum lowering and retraction for dark /l/ needs to be made during the preceeding antagonistic vowel /i/. Consonants produced with active tongue-dorsum raising, i.e., the alveolopalatal /ɲ/ and the velar /k/, favor the carryover over the anticipatory component due to the tongue dorsum being lowered more slowly at consonantal release than raised at consonantal onset, and thus in line with the tongue dorsum mechanico-inertial requirements for the consonant; moreover, this asymmetrical relationship becomes more obvious as the articulatory distance between the vowel and the consonant increases, i.e., for /ɲ/ and /k/ with adjacent /a/ vs /i/. Coarticulatory directionality for other consonants appears to depend on whether the vowel causes the tongue dorsum to be raised or not during the consonant. Prevalence of the anticipatory direction occurs in the context of /a/ when tongue-dorsum raising is absent, presumably in line with the flexibility of the apical articulator (for the alveolar /n/) and with lingual grooving associated with manner of articulation demands (for the fricatives /s/ and /ʃ/); tongue-dorsum raising for /n/, /s/, /ʃ/, and /p/ with adjacent /i/ contributes to an increase in the mechanico-inertial requirements which results in a more prominent dorsal release and a more salient carryover vs anticipatory component.

Our model predicts that the direction of the vocalic effects should conform to the directionality trends for consonantal coarticulation. Predominance of the V2-dependent anticipatory effects for /l/ occurs presumably since vowel anticipation is not much affected by the carryover component for this consonant; on the other hand, the salience of the vowel-dependent carryover effects in the case of /ɲ/ accords with the mechanico-inertial constraints associated with the tongue-dorsum raising gesture preventing much vowel-related anticipation from occurring. Vocalic anticipation is also blocked when fixed /i/ contributes to the raising of the tongue dorsum during the consonant; this would explain why consonantal and vocalic effects for /n/, /ʃ/, and perhaps /p/ are more prominent at the carryover level when adjacent to /i/ and at the anticipatory level when adjacent to /a/. The absence of a clear directionality pattern for the vocalic effects for /s/ in the two fixed vowel contexts may be attributed to the strong manner requirements for this consonant and perhaps to the mechanico-inertial requirements on the tongue dorsum in the /i/ context. Analogously to dorsal /ɲ/, dorsal /k/ favors the carryover component for the consonantal and vocalic effects in the /i/ condition; prevalence of vocalic anticipation in the /a/ context condition appears to be related to how the tongue dorsum is being controlled during velar closure.[12]

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[1]The term ''tongue dorsum'' is preferred to the term ''tongue body'' and refers to the upper surface of the tongue in front of the hard and soft palate where palatal and velar sounds are articulated (Catford, 1988).

[2]In a previous paper (Recasens *et al.*, 1995), the degree of dorsopalatal contact was correlated with $F2$ at the consonantal midpoint in the sequences /iCi/ and /aCa/ for the same consonants analyzed in the present study. High positive correlations were found across consonants and speakers as well as across consonants for a given speaker. This finding is consistent with data collected with vocal tract analogues indicating an increase in $F2$ frequency with a decrease in dorsopalatal constriction width (Stevens and House, 1955; Fant, 1960; Gay *et al.*, 1991).

[3]The DAC scale is not to be identified with the CR (coarticulatory resistance) scale proposed elsewhere (Bladon and Al-Bamerni, 1976). The CR scale assigns different values to phonetic segments depending on the degree of coarticulation allowed. The following CR values correspond to different allophones of English /l/: 1 to the least resistant allophone, i.e., clear /l/ in *leaf*; 2 to an allophone specified for an intermediate CR degree, i.e., dark /l/ in *feel*; 3 to the most resistant allophone, i.e., syllabic /l/ (*fiddle*). The DAC scale characterizes phonetic segments according to the types of articulatory constraints involved in their production and can be used as a predictor of coarticulatory resistance (see Sec. B 2).

[4]The term ''fixed vowel'' is applied to VCV pairs used to investigate vowel-dependent coarticulation. It refers to the vowel which is kept constant in a given VCV pair, e.g., V1=/a/ in the sequence pair /api/-/apa/ which allows studying right-to-left effects associated with V2=/i/ vs /a/ in this particular V1 condition.

[5]$F3$ and $F1$ coarticulatory effects were also measured for the same speech material. Results for $F3$ were highly similar to those for $F2$ which is in accordance with both formants being related to dorsopalatal constriction location and narrowing (Fant, 1960); they will be reported occasionally when deviating from those for $F2$ in some interesting way. $F1$ coarticulatory effects will not be commented in this paper since they differ from those for $F2$ in many respects presumably because of reflecting jaw opening variations in addition to changes in dorsopalatal constriction width.

[6]The following piece of evidence suggests that differences in phonetic realization between V1 and V2 in the /aCa/ sequences (i.e., V1 was realized as stressed [a] and V2 as unstressed [ə]) did not affect the analysis results significantly. Had this been the case, V-to-V carryover effects would have exceeded the corresponding anticipatory effects in /VpV/ sequences (where /p/ is specified for a minimal DAC value) since there are reasons to expect stressed vowels to exert more coarticulation than unstressed ones and non-reduced vowels to allow less coarticulation than reduced ones. V-to-V coarticulation data across /p/ on fixed /a/ reported in Sec. II reveal that the opposite in fact happened, i.e., anticipatory size and temporal effects were found to be more prominent than carryover effects. More carryover than anticipatory V-to-V coarticulation across /p/ in the fixed /i/ context is probably independent of the stress pattern since stressed and unstressed /i/ differ very slightly in Catalan.

[7]The exclusion of that row from the calculation of the Qp index for the latter four consonants is also advisable when their place of articulation is more front than usual since the dorsal contact at the front palatal zone in this case is presumably related to interarticulatory coupling effects with the tongue front rather than to tongue-dorsum activation.

[8]In a few instances, reinforcement of the tongue-dorsum raising gesture by the action of successive dorsopalatal V1 and C in the sequences /iɲV/ and /iʃV/ may cause articulatory overshoot, i.e., more dorsopalatal contact and frequency displacement than usual for a long period of time during V2. Carryover effects extending until vowel offset in these circumstances have been excluded from analysis.

[9]In this paper, a given coarticulatory effect will be often characterized in comparison to other effects as ''large'' or ''small'' (size) and ''long'' or ''short'' (temporal extent).

[10]C-to-V effects in $F3$ for dorsal /ɲ/ and /k/ are somewhat larger and longer than $F2$ effects. This finding is consistent with information provided by nomograms (Fant, 1960) showing that a considerable reduction of the constriction area for alveolopalatals causes more $F3$ than $F2$ raising as the constriction location moves forward from the mediopalate to the prepalate. It also accords with negative $F3$ effects if, as indicated by electropalatographic data (Recasens, 1991a), some constriction retraction for /i/ in this specific consonantal environment is accompanied by a decrease in lingual contact at the prepalate.

[11]Other explanations could account for the Qp and $F2$ lowering for /n/ and /s/. Apical consonants have been reported to be articulated with a somewhat concave tongue surface behind closure location and some postdorsum retraction resulting into a narrower pharyngeal passage than that exhibited by laminoalveolar articulations (Dart, 1991). Some tongue-dorsum relaxation could also be related to nasality and the resulting lack of pressure containment associated with it (Perkell, 1969).

[12]The salience of the anticipatory component for the vocalic effects is consistent with ultrasound data showing an early onset of V2 related tongue-dorsum movement during V1 (Parush *et al.*, 1983), and with electromagnetic midsagittal articulometry data showing V2 anticipation in /akV/ sequences during closure mostly for V2=/i/ but also for V2=/a/ (Mooshammer *et al.*, 1995). Our EPG data generally show more dorsopalatal contact during V1 for /aki/ than for /ika/ which is consistent with a strong V2-dependent forward movement in the former sequence already during V1. It is agreed that these anticipatory effects reflect passive forward tongue-dorsum movement associated with the large mass of the tongue body being controlled in a continuous fashion (Perkell, 1969). This forward movement does not occur to the same extent when V1=/i/ since the tongue dorsum is already located at a front location at closure onset in this case.

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