An EMA study of VCV coarticulatory direction

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(Received 27 November 2000; revised 25 October 2001; accepted 6 March 2002)

This study addresses three issues that are relevant to coarticulation theory in speech production: whether the degree of articulatory constraint model (DAC model) accounts for patterns of the directionality of tongue dorsum coarticulatory influences; the extent to which those patterns in tongue dorsum coarticulatory direction are similar to those for the tongue tip; and whether speech motor control and phonemic planning use a fixed or a context-dependent temporal window. Tongue dorsum and tongue tip movement data on vowel-to-vowel coarticulation are reported for Catalan VCV sequences with vowels /i/, /a/, and /u/, and consonants /p/, /n/, dark /l/, /s/, /ʃ/, alveolopalatal /ɲ/ and /k/. Electromidsagittal articulometry recordings were carried out for three speakers using the Carstens articulograph. Trajectory data are presented for the vertical dimension for the tongue dorsum, and for the horizontal dimension for tongue dorsum and tip. In agreement with predictions of the DAC model, results show that directionality patterns of tongue dorsum coarticulation can be accounted for to a large extent based on the articulatory requirements on consonantal production. While dorsals exhibit analogous trends in coarticulatory direction for all articulators and articulatory dimensions, this is mostly so for the tongue dorsum and tip along the horizontal dimension in the case of lingual fricatives and apicolaminal consonants. This finding results from different articulatory strategies: while dorsal consonants are implemented through homogeneous tongue body activation, the tongue tip and tongue dorsum act more independently for more anterior consonantal productions. Discontinuous coarticulatory effects reported in the present investigation suggest that phonemic planning is adaptative rather than context independent. [DOI: 10.1121/1.1479146]

PACS numbers: 43.70.Aj, 43.70.Bk [AL]

I. INTRODUCTION

A. The DAC model

A goal of this investigation is to verify the validity of the degree of articulatory constraint model (DAC model) for predicting patterns of coarticulatory direction in speech production. Data on dorsopalatal contact and F2 frequency presented in Recasens *et al.* (1997) suggest that this model may account satisfactorily for trends in coarticulation extent and direction in VCV sequences.

Within the framework of the coproduction theory of coarticulation (Fowler, 1977, 1980), the DAC model is based on the assumption that articulatory gestures associated with consecutive segments are coproduced and overlap to different degrees depending on their spatiotemporal properties as well as on prosodic factors and speech rate. According to this model, coarticulatory sensitivity for consonants to the influence of the adjacent vowels in VCV sequences (V-to-C effects) varies inversely with the strength of the consonantal effects (C-to-V effects) and with the degree of articulatory constraint for the intervocalic consonant. Regarding the dorsum of the tongue (which is the articulator about which the model can make theoretical predictions so far), consonants differ in DAC value according to the following order: dorsals (alveolopalatals, palatals, velars), lingual fricatives (/s/, /ʃ/), dark /l/, which can be assigned a maximum DAC value (DAC=3); dentals and alveolars such as /n/ and clear /l/ (DAC=2); and bilabials, with the lowest DAC value (DAC=1). Strictly speaking, /ʃ/ is both a lingual fricative and a dorsal consonant to the extent that it involves tongue dorsum activation.

Consonants are specified for a maximal DAC value based on demands on place and manner of articulation. It is hypothesized that dorsal consonants are highly constrained based on the observation that their primary contact or constriction location stays relatively fixed in line with the large contact size involved and perhaps the sluggishness of the tongue dorsum. The same observation may even apply to velars provided that at least two targets in front and back vowel contexts are accounted for. Maximal tongue body constraint is also associated with tongue dorsum grooving for lingual fricatives and with the formation of a secondary postdorsal constriction at the upper pharynx for dark /l/. Among the remaining consonants specified for a lower degree of tongue dorsum constraint, a higher DAC value for dentals and alveolars (2) than for bilabials (1) is related to coupling effects between the tongue dorsum and the primary tongue front articulator for the former consonantal group and to the absence of tongue body activation for the latter. Among the vowels, /i/ should be essentially more constrained (DAC =3) than /a/ and /u/ (DAC=2) at the tongue predorsum given the fact that this tongue region is actively raised for front vowels while staying low and inactive for back vowels. The lowest DAC value (1) corresponds to /ə/ which does not involve any obvious tongue body target configuration (see however Browman and Goldstein, 1992).

In our previous paper, the size and temporal extent of

 0001-4966/2002/111(6)/2828/14/$19.00

the C-to-V coarticulatory effects were found to depend not only on the articulatory characteristics of the consonant but on those of the vowel as well. Thus, as expected, C-to-V effects happen to be particularly salient as the DAC value for the consonant increases with respect to that for the vowel, e.g., effects from /ɲ/ (DAC=3) on /a/ (DAC=2). More interestingly, maximal consonantal effects on vowels are also obtained when the lingual gestures for the two consecutive segments are at the same time highly constrained and antagonistic, e.g., effects from dark /l/ on /i/ which are both specified for DAC=3 and are produced with tongue body lowering and retraction (dark /l/) and tongue dorsum raising and fronting (/i/).

Within this theoretical framework, patterns of C-to-V coarticulatory direction were characterized as anticipatory or carryover according to the requirements on consonantal production. Consonants with a maximal DAC value (3) favor a specific direction for the consonantal effects on vowels: on the one hand, dark /l/ favors C-to-V1 anticipation given that tongue dorsum lowering and retraction often start before tongue tip raising for the implementation of this consonantal realization; on the other hand, consonants produced with tongue dorsum raising such as alveolopalatals, palatals, and velars favor C-to-V2 carryover effects in line with the slow lowering motion of the primary dorsal articulator at consonantal release which may be due to inertia. Two basic C-to-V patterns are found for consonants produced with the tongue front and involving little tongue dorsum activation (DAC =2), e.g., dentals and alveolars (but for dark /l/): consonantal effects on /a/ happen to be more prominent at the anticipatory level presumably since this vowel permits free apical anticipation; effects on /i/, on the other hand, are especially salient at the carryover level for analogous reasons to (alveolo) palatals.

A major prediction of the DAC model is that these patterns of C-to-V coarticulatory direction in VCV sequences should account for the direction of the vocalic effects. According to the model, vocalic anticipation (i.e., V2-to-C and V2-to-V1 effects) ought to vary inversely with the prominence of the C-to-V2 carryover effects while vowel-dependent carryover effects (i.e., V1-to-C and V1-to-V2) are expected to decrease with the strength of the C-to-V1 anticipatory component. These inverse relationships occur because carryover effects associated with the vowel conflict with anticipatory effects associated with the consonant while vocalic anticipatory effects conflict with consonantal carryover effects. In agreement with this prediction our previous papers report robust patterns of V-to-C and V-to-V coarticulatory direction in VCV sequences with clear patterns of C-to-V direction: sequences with dark /l/ allow more vocalic anticipation than vocalic carryover while vocalic carryover exceeds vocalic anticipation in sequences with /ɲ/.

Patterns of vowel-dependent coarticulatory direction in other VCV cases were found to be less consistent, though in general agreement with our initial predictions. A specific situation applies to VCV sequences with velars: vocalic effects from /i/ versus /a/ show the expected carryover direction when the transconsonantal vowel is /i/ (i.e., in the sequence pair /aki/-/iki/), but not so in the transconsonantal /a/ condition where extensive vocalic anticipation appears to be facilitated by forward tongue dorsum motion during the velar closure period (i.e., sequence pair /aki/-/aka/). Regarding dentoalveolars and labials, vocalic effects appear to favor the carryover component when transconsonantal /i/ contributes to tongue dorsum raising during the consonant and thus causes much C-to-V2 carryover coarticulation to occur (e.g., /ati/-/iti/); on the other hand, the absence of substantial tongue dorsum raising for those consonants in the context of /a/ may explain why the anticipatory direction prevails (e.g., /ati/-/ata/).

The present study seeks to improve our understanding of the directionality patterns for the vocalic effects in VCV sequences using articulatory movement data collected with electromagnetic articulometry (EMA) instead of linguopalatal contact or acoustic data. In comparison to Recasens *et al.* (1997), more natural experimental conditions will be used. Temporal patterns of V-to-V coarticulation will be analyzed for the same consonants and vowels in long real sentences (instead of in isolated VCVs). Stress will be placed on V2 (instead of on V1), and the Catalan phonological rule reducing unstressed /a/ to [ə] will be avoided so that the sequences /aˈCa/ become fully symmetrical at the phonetic level. The same analysis method will be used: anticipatory V2-to-V1 effects associated with two different V2 will be measured during the consonant and preceding V1 (e.g., effects from /i/ versus /a/ on /ɲ/ and preceding /i/ in the pair /iɲa/-/iɲi/) and carryover effects for V1 pairs will be analyzed during the consonant and following V2 (e.g., effects in the pair /aɲi/-/iɲi/).

Within the DAC model framework, the present paper also investigates the extent to which V-to-V effects at the tongue tip conform to patterns of tongue dorsum coarticulatory direction. In a previous EMA study of V-to-C lingual coarticulation in German symmetrical VCV sequences, Hoole *et al.* (1990) found somewhat larger vocalic effects at the tongue front than at the tongue back, perhaps because the tongue tip has less inertia. VCVs with alveolars and velars yielded more carryover than anticipatory effects at the tongue front and dorsum while VCV sequences with bilabials happened to favor the opposite trend at the two lingual regions; also, anticipatory effects were greater than carryover effects at the tongue front in sequence pairs starting with /uk/. As expected, V-to-V coarticulation was blocked to a larger extent by /i/ than by /a/.

B. Temporal window and discontinuous coarticulatory effects

An interesting research topic regarding temporal coarticulation is the extent to which coarticulatory effects provide information about the execution of phonemes and may reflect phonemic planning as well. Differences in the temporal extent of coarticulation could be assigned two different interpretations, i.e., phonemes are executed at different times depending on the articulatory properties of the preceding contextual segments or else, while they are required to begin at a given time, their surface manifestation may vary according to the degree of coarticulation resistance for the contextual segmental units (Fowler, 1993; Fowler and Brancazio, 2000). According to Fowler and Saltzman (1993), the onset of anticipatory coarticulation for a given lingual, labial, or velar gesture is essentially fixed, and occurs about 200–250 ms before the target phoneme; moreover, the actual phonetic implementation of a given anticipatory effect may be discontinuous and thus momentarily interrupted by the ongoing requirements on segmental production. This view is consistent with the time-locked model of temporal coarticulation proposed by Bell-Berti and Harris (1981) in that the period of anticipation associated with the target phoneme is independent of preceding phone length; contrary to the model by Bell-Bert and Harris, it assumes that articulatory conflict does not delay anticipatory coarticulation. Discontinuities in vocalic coarticulation during a noncontiguous segment such as those referred to are not equivalent to troughs, namely, interruptions in the articulatory manifestation of a vocalic gesture in symmetrical VCV sequences caused by the intervocalic consonant (e.g., the trough associated with active lip retraction for /t/ in the sequence /utu/; Perkell, 1986).

In the present paper we will test the validity of Fowler and Saltzman's (1993) approach through an analysis of the temporal location, duration, and frequency of occurrence of discontinuous V-to-V effects in the VCV sequences under study. If their approach is correct, the onset of V2-dependent anticipatory activity should not vary much with changes in V1 and in the intervocalic consonant independently of whether those vocalic anticipatory effects are continuous or discontinuous. The opposite finding could be taken in support of the notion that phonemic planning is adaptative rather than context independent, i.e., phonemes are planned at different times depending on the articulatory requirements for the consonant and/or for the transconsonantal vowel.

This paper also explores the possibility that discontinuous anticipatory effects differ essentially from discontinuous carryover effects. While discontinuous anticipatory effects may reflect the implementation of an early planning strategy, momentary interruptions in long-lasting effects occurring after the target segment are probably related to other factors. A possible origin for discontinuous carryover effects is articulatory overshoot in strings of consecutive highly constrained segments sharing a specific articulatory property; thus, for example, differences in tongue height in V2 in the sequence pair /aʃi/-/iʃi/ could be associated with an intensification of the tongue dorsum raising gesture for /ʃ/ when the consonant is preceded by V1=/i/ rather than with tongue dorsum lowering for V1=/a/.

Even if the onset of V2-dependent anticipation turns out to be contextually conditioned rather than invariant, the present research allows testing whether the temporal span of the anticipatory effects is less variable than that of the carryover effects. This is the expected outcome if phonemic anticipation reflects preprogramming and carryover effects do not, while being strongly determined by inertia and by the gestural requirements for the contextual phonetic segments (Gay, 1977; Recasens, 1989).

II. METHOD

A. Recording procedure

Three Catalan speakers (DR, JP, JC) who also acted as subjects in Recasens *et al.* (1997) uttered all possible VCV combinations with the consonants /p,n,l,s,ʃ,ɲ,k/ and the vowels /i,a,u/. Those VCV sequences were repeated ten times before and after other phonetic segments unspecified for lingual activity ([p], [ə], [β]) in the Catalan sentence [ˈɡɾaβəpVˈCVpəˈβans] (''He records pVCVp earlier''); the inclusion of contextual labial consonants and a schwa ensured that the temporal extent of tongue dorsum coarticulation could be expanded sufficiently along the time domain.

Articulatory movement and acoustic data were collected simultaneously using electromagnetic articulometry by means of a Carstens articulograph system AG-100. This system consists of a head mount with three magnetic transmitters that generate a magnetic field, and a set of small transducer coils that can be attached to different articulatory structures in the midsagittal plane. As the articulators move inside the vocal tract, the transducer coils induce a signal that is inversely proportional to the cube of the distance between transmitter and transducer. The output signal results in a set of voltages which can be converted to distance. In the present experiment coils were placed on the tongue tip (TT), tongue blade (TL), tongue dorsum (TD), incisors of the lower jaw (J), upper lip (UL), and lower lip (LL), as well as on the bridge of the nose and upper incisors for head movement correction. The three coils attached on the tongue surface were roughly equidistant both for TL-TT (DR =1.5 cm; JP=2.3 cm; JC=1.8 cm) and for TD-TL (DR =1.9 cm; JP=1.4 cm; JC=1.6 cm). Estimates for the subjects' occlusal planes were obtained as anatomical references to which the data could be rotated (correction angles in degrees were 0.8 for DR, 0.7 for JP and 0.4 for JC), as well as traces of their palates.

Movement and acoustic data were digitized using a real-time input system at a sampling rate of 250 Hz for movement and 10 kHz for speech; the time resolution of the EMA data was 4 ms. The kinematic data were converted from voltage to distance, corrected for head movement, rotated to the occlusal plane, and extracted into X and Y articulatory channels.

B. Data analysis

The temporal extent of V-to-V coarticulatory effects was analyzed from $[\beta]_1$ onset to $[\beta]_2$ offset in the sequence [βə##pVCVp##əβ]. For each VCV repetition, the onset and offset of the intervocalic consonant were identified from visual inspection of spectrographic and waveform displays. Consonantal boundaries were placed at closure onset and at V2 voicing onset following the stop burst for stops (/p/,/k/), and at the onset and offset of frication for the lingual fricatives (/s/,/ʃ/). The segmental boundaries for /l/, /n/, and /ɲ/ were located at the onset and offset times of the low-intensity formants for the two nasals and for the lateral, and often coincided with the endpoints of the vowel transitions. Occasionally these segmental boundaries could not be clearly detected on the spectrographic displays because of the low intensity level of the acoustic signal; in this case consonantal onsets were identified with the onset of maximal TT displacement for /n/, /l/, and /s/, maximal TL displacement for /ʃ/ and /ɲ/, and maximal TD displacement for /k/.

Vocalic temporal effects were considered to occur as long as a significant vowel-dependent difference (referred to as ''changing'' vowel in this paper) extends into the consonant and the transconsonantal vowel (also ''fixed'' vowel from here forward). The changing vowel is V2 and the fixed vowel is V1 when measuring V-to-V anticipation, while V1 is the changing vowel and V2 is the fixed vowel when V-to-V carryover effects are analyzed. In order to single out these effects, significant differences in articulatory displacement were calculated as a function of each changing vowel condition (/i/ versus /a/, /i/ versus /u/, /a/ versus /u/) for each consonant and fixed vowel condition (/i/, /a/, /u/). X and Y movement data were analyzed for all six articulatory regions TT, TL, TD, J, UL, and LL though results will only be presented for TDX, TDY, and TTX.

Statistical evaluation was applied to differences in articulatory position associated with a given pair of vowels in the consonant and the transconsonantal vowel, e.g., effects from V2=/i/ on /ɲ/ and transconsonantal V1=/a/ were measured through a statistical comparison between mean articulatory trajectories across repetitions for /aɲi/ with those for /aɲa/. It was thus assumed that vowels affect each other in asymmetrical sequences and that the degree of vocalic coarticulation may be obtained when data for a given asymmetrical sequence are compared with those in symmetrical sequences composed of the same consonant and the same fixed transconsonantal vowel. There were 1134 sequence pairs submitted to statistical analysis, i.e., 3 changing vowel conditions×3 fixed vowels×7 consonants×3 trajectory types (TDX,TDY,TTX)×2 directions (anticipatory, carryover)×3 speakers. One-way ANOVAs Scheffé ($p < 0.05$, df=1) were applied every 4 ms starting at consonantal offset back to $[\beta]_1$ onset in order to determine the extent of vocalic anticipation and from consonantal onset until $[\beta]_2$ offset in order to estimate the extent of vocalic carryover. $[\beta]_1$ onset and $[\beta]_2$ offset were identified with the shortest temporal values for a given pair of symmetrical and asymmetrical VCV sequences across repetitions. The last significant difference counting backwards during fixed V1 was taken to be the onset of a V2-dependent anticipatory effect and the last significant difference counting forwards during fixed V2 was taken to be the offset of a V1-dependent carryover effect. The following expected differences in amplitude of articulatory movement were submitted to statistical analysis: TDY differences in vowel height for /i/>/a/, /i/>/u/, and /u/>/a/; TTX and TDX differences in vowel fronting for /i/>/a/, /i/>/u/, and /a/>/u/.

Discontinuous effects, i.e., coarticulatory effects which cancel out and reappear earlier or later in time, were identified and the onset and offset times of the (nonsignificant) interruption periods associated with them were measured. These measurements were taken for TDX and TDY but not so for TTX since more than one interruption was found to hold for a considerable number of TTX coarticulatory comparisons. With regard to the tongue dorsum trajectories, two successive interruptions occurred only in five coarticulatory comparisons and were unified as a single discontinuity.

Figure 1 illustrates the analysis procedure for measuring V-to-V coarticulation. Movement data in the figure correspond to TTX, TLX, and TDX trajectories (top) and to TTY, TLY, and TDY trajectories (bottom) for the sequence pair /aɲa/-/iɲa/ (speaker JP). According to the top graph, the TTX, TLX, and TDX signals show a lower value for V1 =/i/ versus V1=/a/ before the 0 line up point at /ɲ/ closure onset which means that the tongue surface is positioned at a fronter location for the former vowel than for the latter; according to the bottom graph, /i/ exhibits higher TTY, TLY, and TDY values than /a/ during V1 meaning that the tongue body occupies a higher position for /i/ versus /a/. Carryover coarticulatory effects in the figure are judged to occur when the same X and Y differences, i.e., /a/>/i/ for X and /i/ >/a/ for Y, reach significance during the consonant (the acoustic period allocated to /ɲ/ closure ends up at +92 ms for /iɲa/ and at +63 ms for /aɲa), the fixed transconsonantal V2, and the following segments [p], [ə], and $[\beta]_2$ of the carrier sentence. Significant coarticulatory periods after the 0 line up point are indicated with horizontal bars at the base of each panel. Thus, small V1-dependent carryover effects for X last until $[\beta]_2$ offset for TTX and TLX, and end at +164 ms about V2 offset for TDX; on the other hand, Y effects end at +248 ms for TDY, at +144 ms for TLY, and presumably at $[\beta]_2$ offset (+364 ms) for TTY.

While we measured the longest possible extent of V-to-V coarticulation, coarticulatory effects could be discontinuous and, thus, cancel out and reappear. In Fig. 1, coarticulatory interruptions occur during the consonantal period for TLX (from closure onset until +68 ms), TDX (0/+84 ms), and TLY (0/+20 ms), or else after this period for TTX (between +164 ms and +200 ms) and TTY (+152/+200 ms and +264/+324 ms).

Significant coarticulation times obtained according to the procedure just described are shown in Tables I and II across speakers. Those values were submitted to further statistical analysis in view of the large speaker-dependent variability involved (see standard deviations in the tables). Repeated measures ANOVAs and *post-hoc* tests (Scheffé) were performed for TDX, TDY, and TTX with speaker as a factor and coarticulation time as the dependent variable ($p < 0.05$, 2 df between groups). While only results with a probability of having been obtained by chance of 0.05 or less are reported, precise probabilities are provided. Two analyses were carried out. In test 1, main effects and interactions were computed for the independent variables ''direction'' (anticipatory, carryover), ''changing vowel'' (/i/ versus /a/, /i/ versus /u/, /a/ versus /u/ for TTX, TDX, and TDY) and ''consonant'' (/p, n, l, s, ʃ, ɲ, k/). In order to evaluate the role of the fixed vowel in the duration of the coarticulatory effects, test 2 was run for the variables ''direction,'' ''consonant,'' and ''fixed vowel'' separately for changing front /i/ versus back /a/, /u/ (thus pooling together the coarticulation times for the two back vowels) (test 2a) and for changing low back /a/ versus high back /u/ (test 2b). Significant effects for the mean values of interest are presented in Table III.

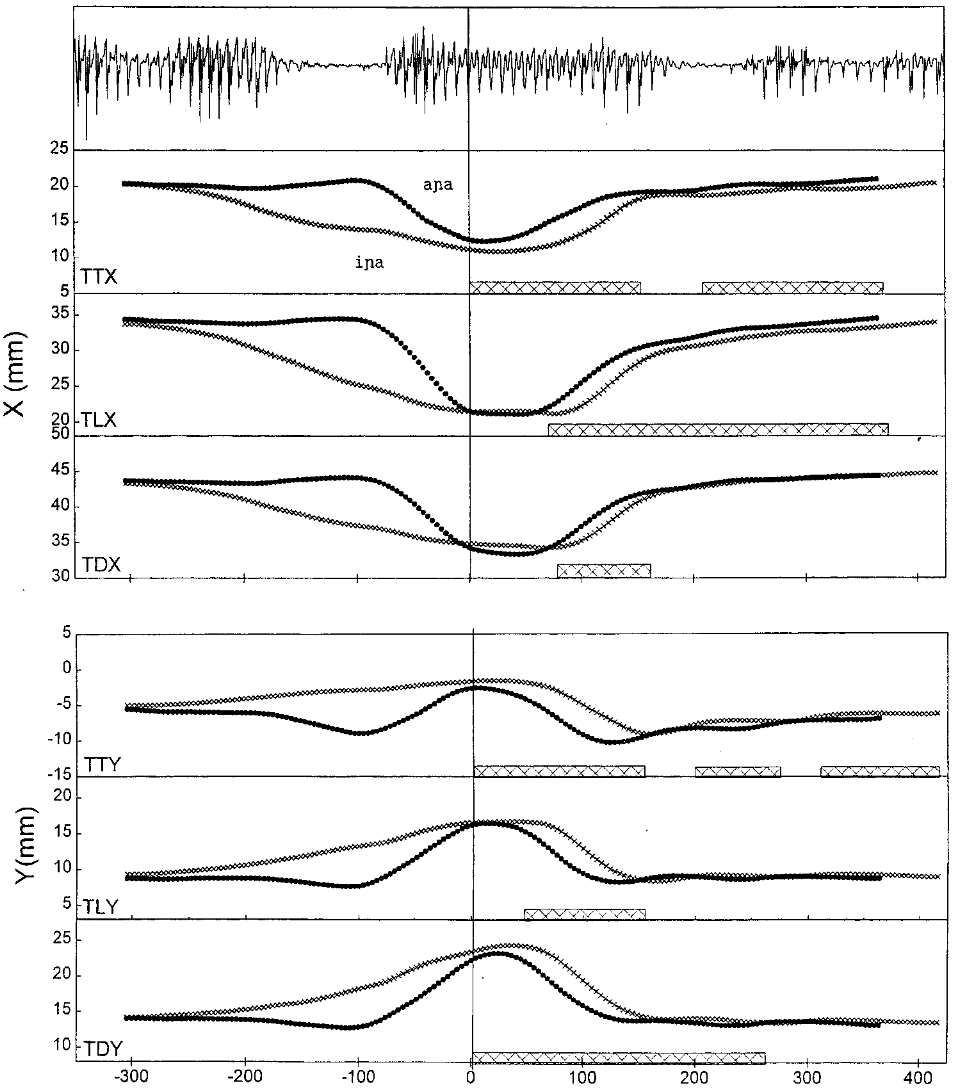

FIG. 1. Mean trajectories across repetitions for TTX, TLX, and TDX (top) and for TTY, TLY, and TDY (bottom) for the sequences /iɲa/ and /aɲa/ (speaker JP). Trajectories have been lined up at closure onset for /ɲ/ so as to measure carryover effects from changing V1 during the consonant, fixed V2 = /a/, and the following segments of the carrier sentence. Periods with significant differences after the 0 line up point are indicated with horizontal bars above the baseline. The acoustic waveform corresponds to one repetition of the symmetrical sequence /aɲa/ preceded and followed by the segments [βəp] and [pəβ] of the carrier sentence.

III. RESULTS

A. Tongue dorsum

1. Coarticulatory durations

Coarticulatory durations for TDX were significantly longer for the carryover direction than for the anticipatory direction according to results from test 1 [anticipation = 147 ms, carryover = 191 ms; $F(2,24) = 5.837$, $p < 0.020$] and from test 2a [anticipation = 147 ms, carryover = 208 ms; $F(2,2) = 19.838$, $p < 0.000$]. The latter test yielded a significant consonant × direction interaction [$F(2,12) = 8.806$, $p < 0.000$] which was associated with differences in the duration of the carryover effects for /n/, /ɲ/ > /ʃ/ (see Table III, top central panel). The top panels in the table also reveal the existence of very short TDX anticipatory effects and very long TDX carryover effects for /n/, /l/, and /ɲ/ in the /i/ versus /a/, /u/ condition and for the two lingual fricatives /s/ and /ʃ/ in the /a/ versus /u/ condition.

TDY data also yielded a significant interaction consonant × direction both according to test 1 [$F(2,12) = 4.291$, $p < 0.002$] and to test 2a [$F(2,12) = 9.035$, $p < 0.000$]. Those interactions were related to differences in carryover coarticulation for /ɲ/ > /l/, /k/ (test 1) and for /s/, /ɲ/ > /l/ (test 2a). Data in Table III (top left and central panels) indicate the existence of an important difference between TDY anticipatory and carryover durations for dark /l/ and /k/ (long anticipation, short carryover) and those for alveolo-palatal /ɲ/ (short anticipation, long carryover). On the other hand, the two fricatives resemble each other in exhibiting much TDY anticipation when the changing vowel condition is /a/ versus /u/, and differ from each other in that /s/ allows longer TDY carryover effects than /ʃ/ when the changing vowel is /i/ versus /a/, /u/.

A main significant effect of fixed vowel was obtained for TDY which was associated with longer coarticulation times for fixed back /a/, /u/ (207 ms) than for fixed front /i/ (154 ms) [test 2a; $F(2,2) = 13.743$, $p < 0.001$]. As shown in Table III (bottom left panel), this difference applies to six consonants taken independently in the case of the TDY coarticulation times, and to five consonants when the TDX coarticulatory durations are taken into consideration. Regarding the changing /a/ versus /u/ condition (Table III, bottom right panel), tongue dorsum coarticulatory durations for most consonants are longer in sequences with fixed /a/ than in those with fixed /u/ (TDY = 187 versus 130 ms and TDX = 175 versus 131 ms across consonants). In summary, V-to-V ef-

TABLE I. Temporal extent of significant V-to-V anticipatory and carryover effects at the tongue dorsum across speakers. Data (in ms) are listed as a function of consonant, and changing and fixed vowel condition, for the X dimension (a) and for the Y dimension (b). Each cell shows the mean value at the top and the standard deviation at the bottom.

	i̲ vs a̲ (*fixed i̲*)	i̲ vs u̲ (*fixed i̲*)	i̲ vs a̲ (*fixed a̲*)	i̲ vs u̲ (*fixed u̲*)	a̲ vs u̲ (*fixed a̲*)	a̲ vs u̲ (*fixed u̲*)
(a)						
p *(Ant-X)*	**150**	**171**	**299**	**188**	**49**	**231**
	134	*126*	*92*	*142*	*13*	*124*
p *(Car-X)*	**104**	**84**	**237**	**189**	**128**	**207**
	71	*31*	*152*	*104*	*34*	*76*
n *(Ant-X)*	**184**	**65**	**75**	**155**	**255**	**164**
	136	*20*	*20*	*112*	*131*	*148*
n *(Car-X)*	**263**	**268**	**321**	**337**	**231**	**23**
	131	*114*	*6*	*2*	*155*	*22*
l *(Ant-X)*	**120**	**71**	**156**	**79**	**112**	**116**
	139	*48*	*170*	*46*	*194*	*166*
l *(Car-X)*	**189**	**295**	**333**	**191**	**137**	**76**
	132	*65*	*13*	*142*	*173*	*72*
s *(Ant-X)*	**143**	**144**	**188**	**152**	**85**	**95**
	140	*100*	*138*	*53*	*51*	*82*
s *(Car-X)*	**60**	**129**	**260**	**219**	**175**	**209**
	7	*74*	*92*	*147*	*137*	*167*
ʃ *(Ant-X)*	**264**	**225**	**107**	**48**	**76**	**119**
	187	*184*	*98*	*46*	*132*	*206*
ʃ *(Car-X)*	**43**	**203**	**59**	**104**	**356**	**131**
	26	*152*	*53*	*100*	*8*	*199*
ɲ *(Ant-X)*	**8**	**8**	**171**	**137**	**116**	**225**
	11	*14*	*174*	*238*	*104*	*134*
ɲ *(Car-X)*	**264**	**307**	**220**	**292**	**245**	**45**
	37	*66*	*122*	*139*	*143*	*79*
k *(Ant-X)*	**248**	**237**	**204**	**125**	**309**	**120**
	146	*92*	*122*	*5*	*51*	*106*
k *(Car-X)*	**316**	**252**	**195**	**89**	**177**	**67**
	62	*177*	*149*	*18*	*12*	*36*
(b)						
p *(Ant-Y)*	**168**	**193**	**228**	**127**	**275**	**37**
	118	*110*	*108*	*67*	*134*	*36*
p *(Car-Y)*	**135**	**184**	**280**	**180**	**356**	**65**
	90	*135*	*116*	*135*	*17*	*25*
n *(Ant-Y)*	**215**	**104**	**239**	**177**	**228**	**127**
	141	*124*	*135*	*141*	*166*	*174*
n *(Car-Y)*	**120**	**149**	**239**	**145**	**220**	**153**
	110	*171*	*137*	*173*	*191*	*159*
l *(Ant-Y)*	**219**	**197**	**237**	**261**	**175**	**77**
	107	*122*	*131*	*52*	*140*	*45*
l *(Car-Y)*	**40**	**69**	**147**	**67**	**141**	**115**
	16	*110*	*154*	*34*	*139*	*98*
s *(Ant-Y)*	**149**	**88**	**160**	**208**	**87**	**368**
	120	*22*	*118*	*79*	*13*	*11*
s *(Car-Y)*	**204**	**312**	**196**	**331**	**75**	**164**
	152	*62*	*143*	*34*	*86*	*114*
ʃ *(Ant-Y)*	**84**	**29**	**203**	**293**	**233**	**203**
	14	*41*	*137*	*186*	*173*	*168*
ʃ *(Car-Y)*	**81**	**161**	**155**	**236**	**216**	**83**
	72	*175*	*99*	*204*	*172*	*45*
ɲ *(Ant-Y)*	**19**	**108**	**100**	**212**	**135**	**32**
	6	*187*	*94*	*206*	*206*	*14*
ɲ *(Car-Y)*	**317**	**311**	**321**	**248**	**227**	**163**
	64	*94*	*64*	*215*	*132*	*169*
k *(Ant-Y)*	**221**	**213**	**291**	**196**	**160**	**232**
	107	*82*	*96*	*167*	*153*	*198*
k *(Car-Y)*	**145**	**76**	**201**	**129**	**85**	**0**
	114	*52*	*147*	*129*	*74*	*0*

TABLE II. Temporal extent of significant V-to-V anticipatory and carryover effects at the tongue tip along the X dimension across speakers. See Table I for details.

	i̲ vs a̲ (*fixed i̲*)	i̲ vs u̲ (*fixed i̲*)	i̲ vs a̲ (*fixed a̲*)	i̲ vs u̲ (*fixed u̲*)	a̲ vs u̲ (*fixed a̲*)	a̲ vs u̲ (*fixed u̲*)
p *(Ant-X)*	**227**	**192**	**269**	**279**	**211**	**260**
	90	*108*	*143*	*149*	*115*	*146*
p *(Car-X)*	**217**	**264**	**181**	**197**	**275**	**228**
	136	*142*	*176*	*96*	*158*	*113*
n *(Ant-X)*	**179**	**65**	**75**	**255**	**275**	**131**
	145	*10*	*6*	*93*	*96*	*171*
n *(Car-X)*	**209**	**329**	**237**	**337**	**300**	**39**
	149	*8*	*140*	*2*	*35*	*33*
l *(Ant-X)*	**136**	**139**	**52**	**148**	**115**	**0**
	151	*158*	*28*	*110*	*113*	*0*
l *(Car-X)*	**237**	**327**	**244**	**191**	**219**	**52**
	161	*12*	*142*	*144*	*189*	*90*
s *(Ant-X)*	**240**	**112**	**247**	**239**	**159**	**41**
	161	*26*	*115*	*95*	*158*	*42*
s *(Car-X)*	**56**	**88**	**52**	**176**	**353**	**177**
	14	*33*	*52*	*107*	*20*	*108*
ʃ *(Ant-X)*	**253**	**83**	**139**	**40**	**71**	**119**
	188	*81*	*151*	*14*	*122*	*206*
ʃ *(Car-X)*	**131**	**276**	**149**	**207**	**316**	**367**
	213	*146*	*185*	*126*	*97*	*23*
ɲ *(Ant-X)*	**136**	**20**	**157**	**199**	**236**	**81**
	208	*18*	*164*	*198*	*123*	*70*
ɲ *(Car-X)*	**273**	**219**	**324**	**227**	**117**	**131**
	76	*192*	*66*	*138*	*203*	*159*
k *(Ant-X)*	**257**	**235**	**224**	**132**	**256**	**137**
	122	*56*	*149*	*11*	*156*	*115*
k *(Car-X)*	**271**	**281**	**259**	**96**	**292**	**93**
	141	*126*	*146*	*28*	*104*	*49*

fects are blocked to a larger extent by front /i/ than by back /a/ and /u/ and, less clearly so, by high /u/ than by /a/ among back vowels.

Consonant×fixed vowel interactions reached significance for TDX according to test 2a [$F(2,12)=5.656$, $p<0.001$] and for TDY according to test 2b [$F(2,12)=3.258$, $p<0.032$]. *Post-hoc* tests revealed that the former interaction is related to the difference /k/>/s/ when the fixed vowel is /i/, while the latter depends on /p/>/s/,/k/ when the fixed vowel is /a/. As shown in Table III, the former interaction reflects the existence of a more general trend towards long TDX effects in VCV sequences with dorsal consonants and fixed /i/ and in those with labial and dentoalveolar consonants and fixed /a/, /u/.

2. Coarticulatory direction

In order to estimate trends in coarticulatory direction, the vowel-dependent carryover effects (C) were subtracted from the vowel-dependent anticipatory effects (A) for each consonant and all pairs of changing vowels in each fixed vowel context condition. Bars in Fig. 2 show C-A differences in temporal extent of V-to-V tongue dorsum coarticulation across speakers for the X dimension (top) and for the Y dimension (bottom). For each consonant, bars plot C-A values for /i/ versus /a/ and for /i/ versus /u/ in the fixed /i/ condition (two black bars; left), for /i/ versus /a/ in sequences with fixed /a/ and for /i/ versus /u/ in sequences with fixed

TABLE III. Mean values across speakers (in ms) and significant effects (indicated by brackets) for V-to-V coarticulation times. Data for the consonant x direction condition (top) are plotted as a function of changing vowel and articulatory dimension (columns) and consonant and direction (rows). Data for the consonant x fixed vowel condition (bottom) are presented as a function of changing vowel and articulatory dimension (columns) and consonant and fixed vowel (rows).

Consonant x direction

	(i vs a; i vs u; a vs u)			(i vs a, u)			(a vs u)		
	TDX	TDY	TTX	TDX	TDY	TTX	TDX	TDY	TTX
p *(Ant)*	181	171	240	202	179	242	140	156	235
p *(Car)*	158	200	227	154	195	215	167	211	251
n *(Ant)*	150	182	163	120	184	144	209	177	203
n *(Car)*	240	171	242	297	163	278	127	187	169
ɫ *(Ant)*	109	194	98	106	229	119	114	126	57
ɫ *(Car)*	204	96	212	252	81	250	107	128	135
s *(Ant)*	134	177	173	157	151	209	90	227	100
s *(Car)*	175	214	150	167	261	93	192	119	265
ʃ *(Ant)*	140	174	117	161	152	129	97	218	95
ʃ *(Car)*	149	155	241	102	158	191	243	149	341
ɲ *(Ant)*	111	101	138	81	110	128	171	83	159
ɲ *(Car)*	229	264	215	271	299	261	145	195	124
k *(Ant)*	207	219	207	204	230	212	215	196	197
k *(Car)*	183	106	215	213	138	227	122	43	193

C x fixed V

	(i vs a, u)		
	TDX	TDY	TTX
p *(fixed i)*	127	170	225
p *(fixed a u)*	228	204	232
n *(fixed i)*	195	147	196
n *(fixed a u)*	222	200	226
ɫ *(fixed i)*	169	131	210
ɫ *(fixed a u)*	190	178	159
s *(fixed i)*	119	188	124
s *(fixed a u)*	205	224	178
ʃ *(fixed i)*	184	89	186
ʃ *(fixed a u)*	79	222	134
ɲ *(fixed i)*	147	189	162
ɲ *(fixed a u)*	205	220	227
k *(fixed i)*	263	204	261
k *(fixed a u)*	153	164	178

C x fixed V

	(a vs u)		
	TDX	TDY	TTX
p *(fixed a)*	89	315	243
p *(fixed u)*	219	51	244
n *(fixed a)*	243	224	287
n *(fixed u)*	93	140	85
ɫ *(fixed a)*	125	158	167
ɫ *(fixed u)*	96	96	26
s *(fixed a)*	130	81	256
s *(fixed u)*	152	266	109
ʃ *(fixed a)*	216	225	193
ʃ *(fixed u)*	125	143	243
ɲ *(fixed a)*	181	181	177
ɲ *(fixed u)*	135	97	106
k *(fixed a)*	243	123	274
k *(fixed u)*	93	116	115

/u/ (two hatched bars; middle), and for /a/ versus /u/ in the fixed /a/ and fixed /u/ conditions (two white bars; right).

X and Y effects for the alveolopalatal /ɲ/ favor the carryover over the anticipatory component mostly so in VCV sequences with fixed /i/. Vocalic anticipation overrides vocalic carryover in one case only, i.e., in /VɲV/ sequences with changing /a/ versus /u/ and fixed /u/ along the X dimension.

The velar /k/ favors the anticipatory direction for the TDY effects in all VCV pairs under analysis. Regarding the TDX effects, V-to-V anticipation exceeds V-to-V carryover in sequences without /i/. Sequences with changing or fixed /i/ exhibit smaller C-A differences and may assign more weight to the carryover direction. Overall, the strength of the anticipatory component increases as we proceed from VCV pairs with /i/ towards those without /i/.

Dark /l/ usually favors the carryover component along the X dimension and the anticipatory component along the Y dimension, mostly so in VCV pairs with /i/. Coarticulatory durations in VCV sequences made exclusively of back vowels exhibit unclear directionality patterns.

Regarding lingual fricatives, VCV pairs with fixed /i/ (black bars) favor the anticipatory direction along the X dimension and the carryover direction along the Y dimension. Sequences without fixed /i/ (hatched and white bars) often exhibit prevalent TDX carryover effects, and prevalent TDY anticipatory effects except for those /VsV/ sequences with /i/ and fixed /a/ and /u/ (hatched bars).

Analogously to the TDX data for /l/, VCV sequences with /n/ favor the carryover direction along the X dimension but for VCV pairs without /i/ where vocalic anticipation may prevail upon vocalic carryover. Regarding the TDY data, differences between the carryover and the anticipatory direction are small and show no clear pattern of coarticulatory direction.

The bilabial consonant /p/ also exhibits small temporal differences between the carryover and the anticipatory com-

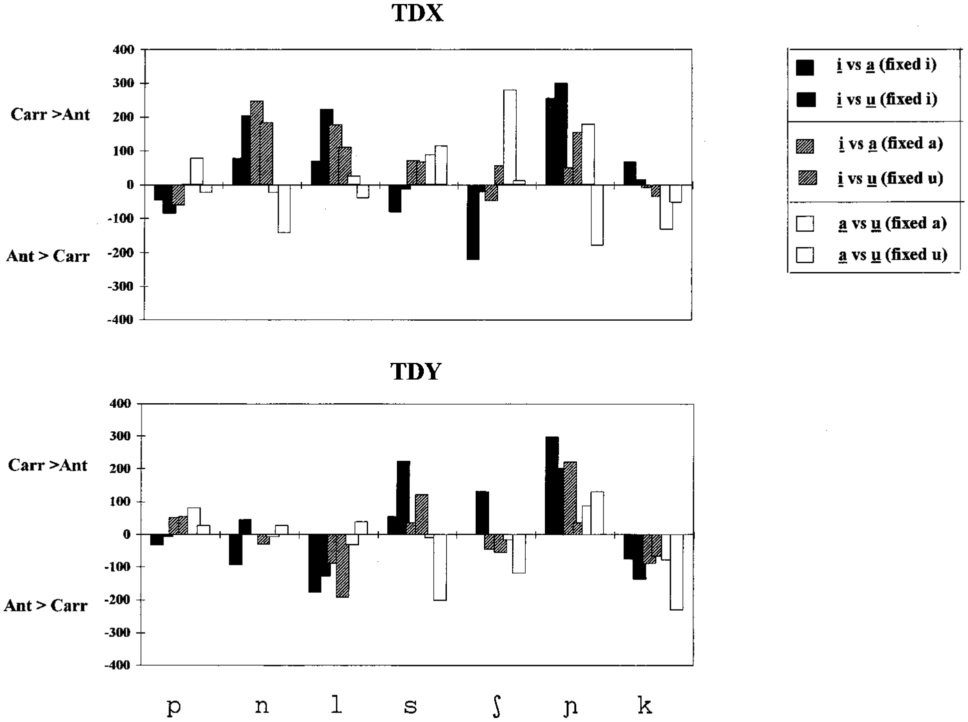

FIG. 2. C-A differences in temporal extent of V-to-V coarticulation for TDX (top) and TDY (bottom) across speakers. Data are displayed for all changing and fixed vowel conditions. Positive values indicate prevalence of the carryover over the anticipatory direction, and negative values the opposite relationship.

ponents. There appears to be a tendency to favor the anticipatory direction in sequences with fixed /i/ mostly along the X dimension, and the carryover direction in sequences with a fixed back vowel mostly along the Y dimension.

B. Tongue tip

1. Coarticulatory durations

Correlation analyses between TTX and TDX effects across changing vowel conditions yielded high r values for nonfricative alveolars (/n/ 0.87; /l/ 0.70), lower r values for dorsals (/ʃ/ 0.57; /ɲ/ 0.52; /k/ 0.40) and very low ones for /p/ and /s/.

TTX coarticulatory durations yielded a significant effect of direction according to tests 1 [$F(2,2)=10.148$, $p<0.003$] and 2a [$F(2,2)=6.979$, $p<0.013$], which reflects the existence of longer carryover than anticipatory coarticulation times (215, 216 ms versus 162, 169 ms). Test 1 also yielded a significant interaction changing vowel×consonant ×direction [$F(2,12)=2.165$, $p<0.033$], which turned out to be related to differences in carryover coarticulation for /p, n, l, ɲ, k/ (199, 223, 241, 299, and 265 ms)>/s/ (54 ms), /l,ɲ,k/>/ʃ/ (140 ms), and /ɲ/>/p/ in the changing /i/ versus /a/ condition. These consonant-dependent differences hold to a large extent for changing /i/ versus /a/, /u/ as well, as revealed by a consonant×direction interaction associated with /n/>/s/ in test 2a [$F(2,12)=4.094$, $p<0.005$] and by the existence of short carryover effects for the two lingual fricatives (see Table III, top central panel).

The TTX data resemble the TDX data in many respects. Regarding the changing /i/ versus /a/, /u/ condition, the two articulatory dimensions exhibit short anticipatory effects and long carryover effects for /n/, /l/, and /ɲ/, and short carryover effects for /s/ and /ʃ/. TTX and TDX coarticulation times for changing /a/ versus /u/ are short in the case of /l/, and short at the anticipatory level and long at the carryover level in the case of /s/ and /ʃ/.

TTX coarticulatory durations were also significantly longer for fixed /a/ (228 ms) versus fixed /u/ (133 ms) according to test 2b [$F(2,2)=7.928$, $p<0.014$]. As shown in Table III (bottom right panel), five consonants allow much longer coarticulation times in the former versus latter fixed vowel condition.

2. Coarticulatory direction

Differences in coarticulatory direction for TTX in Fig. 3 are similar to those for TDX in a good number of instances. Analogously to TDX, TTX shows more carryover than anticipation for /ɲ/ in most vocalic conditions, for /k/ in the context of fixed /i/, for /n/ and dark /l/ in VCV sequences with /i/, and for lingual fricatives and /p/ mostly in sequences without /i/. TTX and TDX effects also agree to a large extent in favoring the anticipatory direction for fricatives in sequences with fixed /i/, for /p/ in sequences with /i/, and for /n/ and /k/ in sequences without /i/.

In other cases, TTX and TDX exhibit different directionality patterns. Thus, vocalic carryover overrides vocalic anticipation for TTX but not so for TDX in several VCV pairs with /p/, /l/, /ʃ/, and /k/.

C. Discontinuous effects

Figures 4 and 5 display data on discontinuous V-to-V effects for the tongue dorsum. As pointed out in the Introduction, a discontinuous effect may be characterized as a long coarticulatory effect which becomes nonsignificant during a given temporal period.

For all the discontinuous effects in our coarticulation data, Fig. 4 plots differences between the onset time of each

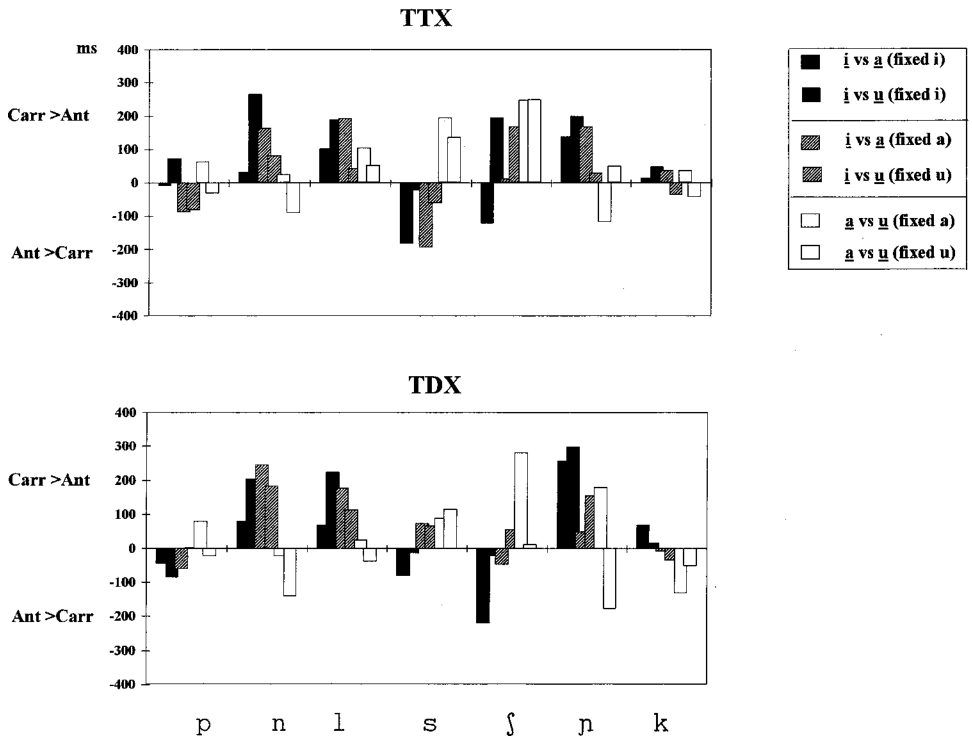

FIG. 3. C-A differences in temporal extent of V-to-V coarticulation for TTX (top) and TDX (bottom). See Fig. 2 for details.

interruption period and consonantal onset or consonantal offset depending on whether the coarticulatory interruptions occur during V1 or V2, respectively. In a few cases (nine) discontinuities did not extend beyond the closure period and, thus, started and ended during the consonant. These differences are given for each consonant and changing vowel condition, i.e., /i/ versus /a/ (upper graph), /i/ versus /u/ (middle graph), and /a/ versus /u/ (bottom graph); they are plotted separately for speakers DR, JP, and JC, the anticipatory and carryover directions, fixed /i/, /a/ and /u/, and the X and Y dimensions. Negative values indicate that a given interruption begins during the consonant (i.e., after consonantal onset for the anticipatory direction and before consonantal offset for the carryover direction) and positive values that it begins during V1 or V2. Figure 5 reports the absolute durations of all interruption periods.

Let us take, for example, the leftmost bottom panel in Fig. 4 which is displayed by itself in Fig. 4(a). The two unfilled triangles below the 0 baseline indicate two discontinuities in anticipatory coarticulation for /upa/ versus /upu/ starting 40 and 100 ms after /p/ closure onset and thus occurring during consonantal closure. (In the former case, i.e., TDX data for speaker JP, the interruption started about closure midpoint since closure was 88 ms long; in the latter, i.e., TDX data for speaker DR, the interruption lasted throughout the entire 100 ms closure period.) The filled triangle below the baseline corresponds to an interruption in carryover coarticulation for the sequence pair /apu/ versus /upu/ for speaker DR starting shortly (8 ms) before closure offset. The two symbols above the baseline refer to discontinuities starting during the vowel period for speaker JP, i.e., an interruption in the anticipatory effects for /apu/ versus /apa/ starting 85 ms before closure onset during V1 (unfilled square), and another interruption in the carryover effects for /upa/ versus /apa/ beginning 45 ms after closure offset during V2 (filled square).

A count of the number of interruptions for each consonant across all other factors yields a higher figure for /ɲ/ (26) than for all other consonants (12–18), and the lowest figure for the alveolar fricative /s/ (5). Figure 4 shows that these interruption events are often negative and therefore begin during the consonant in VCV sequences with dorsal /ʃ/, /ɲ/, and /k/. Moreover, they are usually positive and thus occur during the transconsonantal vowel in VCV sequences with alveolars and /p/. This scenario is most evident for changing /i/ versus /a/ in the upper graph.

The quality of the fixed vowel also plays a role in allowing more or less interruptions. Data for the VCV pairs with changing /i/ versus /a/ (top graph) reveal the existence of more interruptions during fixed /i/ (squares) than during fixed /a/ (triangles), and a trend for coarticulatory interruptions to occur mostly for the carryover effects in sequences with dorsal consonants (filled symbols) and for the anticipatory effects in sequences with alveolars (empty symbols). According to data for changing /i/ versus /u/ (middle graph), interruptions occur mostly at the carryover level during fixed /i/ in VCV pairs with /l/ and /ɲ/. Data for changing /a/ versus /u/ (bottom graph) show anticipatory interruptions during fixed /u/ and, less so, during fixed /a/, and many more carryover interruptions during fixed /a/ than during fixed /u/.

According to Fig. 5, coarticulatory interruptions tend to be longer in VCV sequences with dorsal consonants than in those with alveolar and labial consonants, clearly so when the fixed vowel is /i/ (top graph and, less so, middle graph). The same trend is also available in the fixed /a/ and /u/ conditions on the bottom graph.

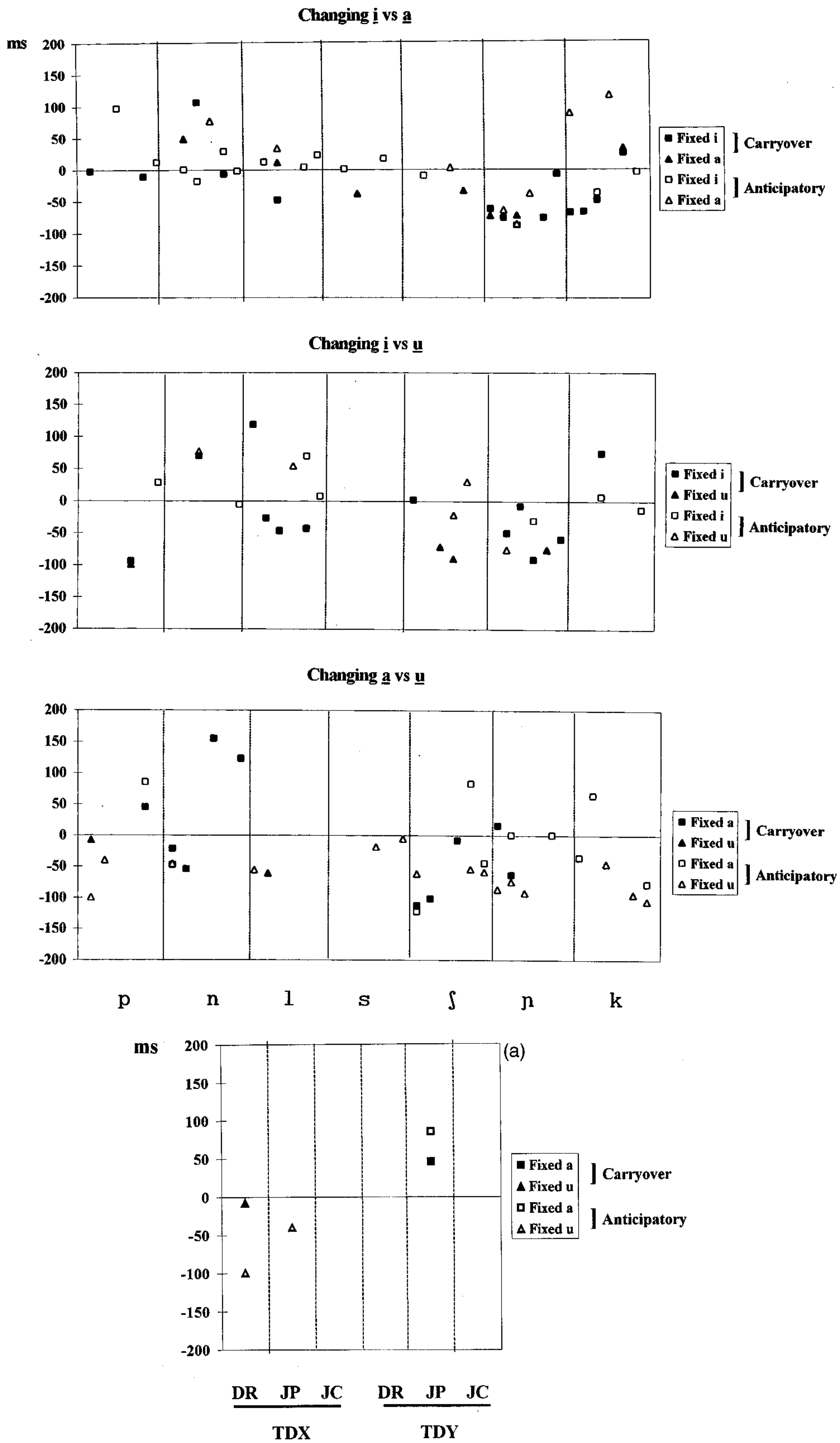

FIG. 4. Temporal differences between the onset time of all discontinuities in tongue dorsum coarticulation and the constriction onset or offset time for the intervocalic consonant. Negative values indicate that the interruption period begins during the consonant and positive values that it starts during the transconsonantal vowel. Data have been plotted as a function of consonant and changing vowel condition; values within each panel correspond to discontinuous effects for the two coarticulatory directions (carryover, anticipatory) and the three fixed vowel conditions (/i/, /a/, /u/); columns within each panel display data for a given articulatory dimension (TDX on the 3 left columns, TDY on the 3 right columns) and a given speaker (DR, JP, JC on columns 1, 2, and 3 for the TDX and TDY data sets). (a) Leftmost bottom panel of Fig. 5.

IV. DISCUSSION

A. General findings

In agreement with predictions from the DAC model, a major finding of this investigation is that V-to-V directionality patterns depend on specific articulatory requirements for the production of consonants (see following sections). The fact that all consonant×direction interactions reported in Sec. III occur for the carryover effects indicates that, as a general rule, the duration of these effects is far more variable

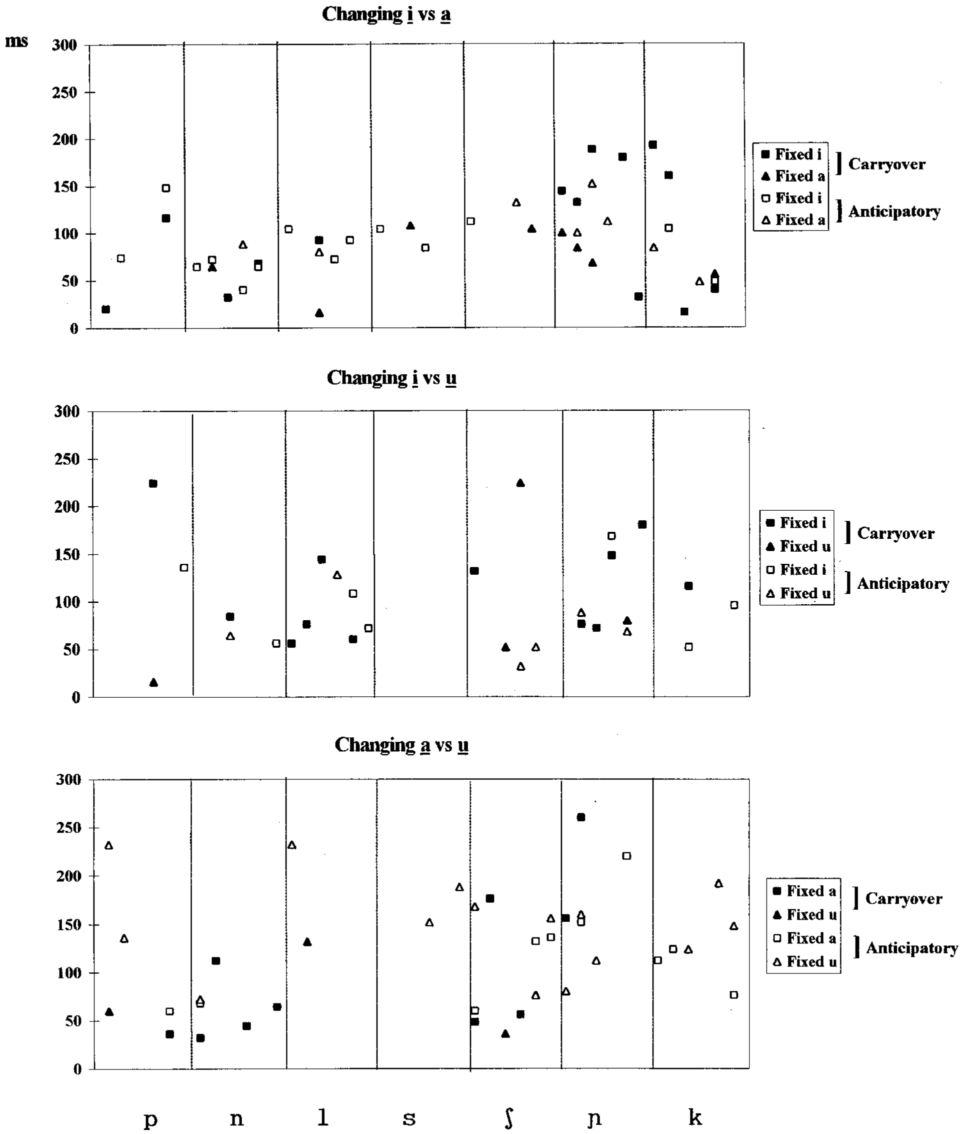

FIG. 5. Durations of the interruption periods for the discontinuous coarticulatory effects reported in Fig. 4.

than the temporal extent of the anticipatory effects. This finding confirms the hypothesis that, while anticipatory coar ticulation is associated with phonemic planning, carryover coarticulation is strongly dependent on the ongoing articulatory requirements for the production of the contextual segments (see the Introduction).

DAC specification for fixed vowels also plays a relevant role on the extent of V-to-V coarticulation. Vocalic effects were found to be generally longer in the context of fixed back /a/, /u/ versus front /i/ (TDX, TDY) and of fixed high back /u/ versus low back /a/ (TDX, TDY, TTX). However, dorsal consonants may cause long tongue dorsum effects to occur during fixed /i/ along the horizontal dimension.

B. Patterns of coarticulation

(a) The DAC model has been found to account satisfactorily for patterns of TDY coarticulatory direction in the case of VCV sequences with highly constrained consonants exerting either maximal C-to-V anticipation (dark /l/) or maximal C-to-V carryover (alveolopalatal/ɲ/). The C-to-V component blocks vowel-dependent effects along the crucial dimension (i.e., anticipation for /ɲ/ and carryover for /l/), which is why V-to-V coarticulation favors the opposite direction in each case (i.e., carryover across /ɲ/ and anticipation across dark-/l/). Accordingly, V-to-V effects for TDY were found to be quite short at the carryover level in /VlV/ sequences and at the anticipatory level in /VɲV/ sequences.

These two patterns of coarticulatory direction become most obvious in sequences with /i/. Prevalence of V-to-V anticipation for /l/ in the fixed /i/ condition is in agreement with a situation of gestural antagonism, i.e., C-to-V anticipation becomes especially prominent in this case so as to make sure that the velarization or pharyngealization gesture for the consonant will be successfully performed during a preceding antagonistic vowel which is also highly constrained. Vocalic carryover effects in VCV sequences with /ɲ/ and fixed /i/ appear to be caused by articulatory overshoot since they last until V2 offset most of the time.

(b) TDY data on vocalic coarticulation in VCV sequences with unconstrained /p/ and /n/ and the vowel /i/ presented in this paper were found to favor the carryover component to a lesser degree than dorsopalatal contact and acoustic data in Recasens *et al.* (1997). The fact that the present investigation deals with long sentences and more natural speech conditions than our previous study could account for the finding that carryover effects exerted by /i/ do not play a very important role. Additional evidence is needed in order to validate this hypothesis as well as the possibility that VCV sequences with consonants which are specified for an unconstrained tongue dorsum favor vocalic carryover or vocalic anticipation depending on the presence of fixed /i/ or fixed /a/, respectively (see the introduction).

(c) Similar trends in coarticulatory direction were reported for TDX and TTX in VCV sequences with the alveolars /n/ and /l/ and the alveolopalatal /ɲ/, mostly so in the context of /i/. In these circumstances, a given direction may prevail depending on the consonant taken into account, e.g., carryover (for /ɲ/, and for /n/ and /l/ in sequences with /i/) or anticipatory (for /n/ in sequences without /i/). TDX and TTX coarticulatory durations were in agreement with these directionality trends to a large extent, i.e., short at the anticipatory level and long at the carryover level for /ɲ/, /n/, and /l/ in sequences with /i/.

Regarding dorsal consonants for the production of which the tongue tip is down, these data suggest that TTX coarticulatory activity may reflect TDX coarticulatory activity. Indeed, the finding that data for TDX, TDY, and TTX are highly correlated and favor the same V-to-V coarticulatory direction in /VɲV/ sequences may be related to the possibility that tongue dorsum raising and tongue dorsum fronting start being implemented simultaneously for alveolopalatal production. Moreover, coarticulatory effects at the tongue dorsum are essentially the same as those at the less active tongue front since the entire tongue body moves in a homogeneous fashion for the implementation of /ɲ/. In agreement with this finding, vertical and horizontal lingual movements for front vowels have been found to start simultaneously at /p/ closure onset in English /əpV/ sequences (Alfonso and Baer, 1982).

TDX and TTX temporal effects for apical consonants (/n/, /l/) yielded high correlation coefficient values which may be taken to show that the tongue tip and the tongue dorsum do not move independently of each other along the horizontal dimension and TTX activity governs TDX activity for the production of these alveolar consonants. Moreover, the tongue tip articulator (and the tongue dorsum) was subjected to a major carryover action from dorsal vowels along the horizontal dimension. This finding is compatible with the DAC model if we assume that the two alveolars exert little C-to-V apical anticipation under the present experimental conditions, thus allowing extensive V-to-V carryover effects to occur. Prominent V-to-C carryover effects at alveolar closure location have also been reported for /i/ > /a/,/u/ in /VɾV/ sequences (Recasens, 1991).

(d) Patterns of V-to-V coarticulatory direction in VCV sequences with /k/ may also be related to patterns of C-to-V coarticulatory direction. In agreement with F2 data in Recasens *et al.* (1997), vocalic anticipation has been found to prevail upon vocalic carryover both for TDX and TDY in /VkV/ sequences with fixed /a/ and /u/. This trend may be related to continuous fronting of the entire tongue body during closure (Perkell, 1969; Mooshamer *et al.*, 1995). On the other hand, TTX anticipatory effects may be more salient than TTX carryover effects in sequences without /i/ presumably since the tongue tip for velars is left quite free to coarticulate with the surrounding vowels.

Regarding coarticulatory trends in /VkV/ sequences with fixed /i/, TDX and TTX data in the present study are also in agreement with Recasens *et al.* (1997) in assigning more weight to the carryover over the anticipatory component both for the consonantal and for the vocalic effects. This finding may be accounted for assuming that now the tongue body is not being pushed forward during closure and TTX coarticulatory activity conforms to TDX coarticulation. Contrary to previous results, TDY in this fixed /i/ condition has been found to favor the anticipatory over the carryover direction.

(e) Remarkable similarities in TDX and TTX coarticulatory direction for /s/ and /ʃ/ could be attributed to manner requirements and are in support of the notion that dorsal activity conforms to apicolaminal activity along the horizontal dimension during lingual fricative production. Regarding sequences with /i/, vocalic effects favor the anticipatory component for TTX and TDX in VCV pairs with fixed /i/ and for TTX in those with fixed /a/ presumably since these consonants need to be executed quite early, mostly so if preceded by an antagonistic high front vowel; accordingly, carryover effects were found to be short for TDX and TTX in the VCV sequences of interest. On the other hand, the existence of long carryover and short anticipatory effects for TDX and TTX in /VsV/ and /VʃV/ sequences without /i/ may be explained assuming that there is less need to anticipate the lingual gesture for the fricative consonant after an unconstrained vowel and perhaps that fricatives exert some blocking action on anticipatory lip protusion for /u/.

Regarding coarticulation along the Y dimension (TDY), carryover effects were found to exceed anticipatory effects in sequences with /i/ possibly because tongue dorsum raising for the fricative facilitates the carryover action associated with a preceding high front vowel. This finding is in agreement with coarticulation data for /VsV/ and /VʃV/ sequences with /i/ in the literature (Farnetani and Faber, 1991; Hoole *et al.*, 1993). TDY effects in VCV sequences with /i/ and a fixed back vowel exhibit this same pattern of coarticulatory direction for /s/ (also Recasens *et al.*, 1997) but not for /ʃ/, perhaps in view of the fact that the latter consonant exerts a particularly prominent anticipatory action at the predorsal constriction location. Moreover, TDY anticipation prevails upon TDY carryover in the absence of /i/ (long anticipatory effects occur in this case), presumably since the tongue dorsum does not have to be raised much for fricative production in this contextual condition.

C. Discontinuous coarticulatory effects

Coarticulation data in the present paper reveal that V-to-V effects may be interrupted during a consonant or vowel involving the tongue dorsum and reappear later or earlier on. Therefore, failure to find evidence for much tongue dorsum coarticulation during a dorsal segment in previous studies does not imply necessarily that coarticulatory effects were completely absent. As discussed by Fowler and Saltzman, if occurring at the anticipatory level, those interruption events could be taken in support of the existence of a fixed, long-term planning strategy of the upcoming V2 in a VCV string.

It should be pointed out, however, that such interruption periods occur mostly at one of both sides of the consonant (i.e., during V1 or during V2) depending on the VCV sequence. On the one hand, anticipatory interruptions show up mostly in VCV sequences made of an alveolar consonant preceded by /i/, and in VCV sequences with a dorsal consonant preceded by fixed /u/ in the V2=/a/ versus /u/ changing condition. On the other hand, discontinuous effects also occur at the carryover level in VCV sequences with dorsal consonants and fixed /i/, namely, in a contextual situation yielding articulatory overshoot. These carryover effects (and the interruption periods associated with them) were found to last for a very long time and could thus be attributed to some reinforcement of the dorsal gesture.

Our data do not confirm a strong version of Fowler and Saltzman's (1993) hypothesis but are rather consistent with the coarticulation model proposed by Bell-Berti and Harris (1981) (see the Introduction). Thus, e.g., the absence of discontinuous anticipatory effects in the /iɲV/ sequences and their presence in the /uɲV/ sequences suggests that speakers accommodate the occurrence of coarticulation to context and thus plan the upcoming phonemes according to the articulatory requirements for the ongoing phonetic segments. On the other hand, discontinuous effects during V2 cannot be related to phonemic anticipation but are caused by articulatory overshoot (e.g., only few effects occur in /VCi/ sequences with an alveolar consonant) and thus cannot reflect a phoneme-independent production mechanism.

Another piece of evidence for this accommodating strategy is provided by the existence of early anticipatory effects in the sequence pairs /uCa/-/uCu/. Prominent TDX anticipatory effects in these VCV pairs were found to hold for several consonants in our study, e.g., /n/, /l/, /ɲ/, /k/. An early onset of tongue dorsum activity for V2=/a/ in these circumstances may be explained assuming that the tongue predorsum for V1=/u/ stays inactive and allows substantial contextual modifications [also Hoole *et al.* (1990) for /ukV/; see the Introduction].

V. CONCLUSIONS

EMA data on temporal coarticulation of tongue dorsum vertical movement presented here are in accordance with several predictions formulated by the DAC model regarding highly constrained consonants, i.e., preference for anticipatory (for /l/) or carryover (for /ɲ/) V-to-V coarticulation, mostly so in situations of gestural antagonism, and long carryover effects in strings of dorsal segments due to articulatory overshoot. Other trends in vocalic coarticulatory direction have been attributed to the dynamical properties of the consonantal gesture, e.g., much vocalic anticipation through the frontwards sliding dorsal gesture for velars. In comparison to previous studies the present paper reports more vocalic anticipation relative to vocalic carryover in other cases (i.e., TDY data for /k/, /n/, and /p/ in VCV sequences with /i/) which could be related to differences in sentence length and stress placement. Our initial prediction on V-to-V coarticulation for front consonants and labials was found to be at work for the TDY data in VCV sequences with fricatives: indeed, /s/ and /ʃ/ turned out to allow more vocalic carryover in the context of /i/ and more vocalic anticipation in the absence of this vowel.

This study reports analogous patterns of coarticulatory direction for TDX, TDY, and TTX for /ɲ/ and /k/ in line with the fact that their production involves a homogeneous tongue body activity. Fronter lingual consonants exhibit analogous directionality trends for TDX and TTX (but not so TDY), i.e., vocalic carryover prevails upon vocalic anticipation presumably since apical anticipation is not too prominent; this finding is in support of the possibility that TTX activity governs TDX activity and that X and Y movements are relatively independent of each other in this case. Fricatives are exceptional in allowing much TDX and TTX anticipation on fixed /i/ in line with the manner constraints involved.

Overall, vowel coarticulation mechanisms have been found to be much the same at different articulatory structures in VCV sequences with /ɲ/ and /k/ (TDX, TDY, TTX). Coarticulatory interactions happen to be less robust for fricatives and even less so for other apical consonants, i.e., these consonants exhibit analogous TDX and TTX effects but different degrees of TDX-TDY coarticulatory coordination.

Our data also suggest that phonemic planning adapts to context or at least that context affects crucially the onset and offset times of gestural anticipation. This conclusion is supported by the absence of tongue dorsum discontinuous effects during V1 in /iɲV/ sequences vis-à-vis their presence in /uɲV/ sequences, and from an early onset of TDX activity for V2=/a/ during a preceding /uC/ string.

ACKNOWLEDGMENTS

This work was supported by Project Nos. DGES PB96-0103 and BFF2000-0075-C02-01 of the Ministry of Education and Science of Spain and by research group 1997SGR 00290 of the Government of Catalonia. I would like to thank Anders Löfqvist, Jonathan Harrington, and an anonymous reviewer for comments, and Maria Dolors Pallarès for help with the statistical analysis.

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