An articulatory investigation of lingual coarticulatory resistance and aggressiveness for consonants and vowels in Catalan

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Lingual movement data for Catalan vowel-consonant-vowel sequences reveal differences in contextual coarticulatory variability in tongue position at the middle of the consonant for /p/ > /n/ > dark /l/ > /s/ > /ʃ/ > /ɲ/ and at vowel midpoint for /u/ > /a/ > /i/. The velar stop /k/ exhibits a high degree of contextual variability in the horizontal dimension but not in the vertical dimension. These differences in coarticulatory sensitivity are attributed to differences in articulatory constraint, e.g., palatality and frication cause a higher degree of resistance in the consonant than laterality. A higher degree of contextual variability for dark /l/ than expected appears to be associated with speaker-dependent differences in darkness degree. Contextual variability is greater at regions not involved in closure or constriction formation, e.g., at the tongue dorsum than at the tongue front for alveolars. Coarticulatory resistance and coarticulatory aggressiveness are positively correlated: Phonetic segments, which are especially resistant to coarticulatory effects from the adjacent segments, exert maximal coarticulation on them. Consequently, highly constrained segments such as alveolopalatal consonants turn out to affect tongue position for less constrained segments such as back vowels rather than vice versa.
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I. INTRODUCTION

The concept of coarticulatory resistance in phonetic segments, i.e., the extent to which a phonetic segment blocks the coarticulatory influence of adjacent phonetic segments, has long attracted scholars in the field of speech production (Bladon and Al-Bamerni, 1976; Hardcastle and Hewlett, 1999). Coarticulatory resistance for a given consonant or vowel is a measure of its degree of articulatory variability as a function of phonetic context. According to the degree of articulatory constraint (DAC) model of coarticulation (Recasens *et al.*, 1997), coarticulatory resistance should increase with the degree of articulatory constraint, i.e., with the mechanico-inertial properties of the articulators and their involvement in the formation of a closure or constriction and with manner of articulation demands. Thus, for example, consonants produced at the alveolopalatal or palatal zone (e.g., /ɲ/) are expected to resist the coarticulatory influence of the adjacent vowels at the primary tongue dorsum (TD) articulator to a greater extent than alveolars (e.g., /n/) for the production of which this lingual region is not involved directly in closure formation. Moreover, the higher the degree of articulatory constraint, the greater the degree of coarticulatory aggressiveness, i.e., the strength of the coarticulatory effects exerted by the target segment on the neighboring phonetic segments (Farnetani, 1990; Fowler and Saltzman, 1993).

In view of literature accounts summarized below, this paper attempts to validate differences in coarticulatory resistance and aggressiveness for consonants and vowels with lingual movement data collected by means of electromagnetic midsagittal articulometry (EMA). Data will be reported for symmetrical vowel-consonant-vowel (VCV) sequences with the Catalan consonants /p, n, l, s, ʃ, ɲ, k/ and the vowels /i, a, u/. These seven consonants differ in place of articulation and in primary articulator: /p/ is bilabial; /n, l, s/ are alveolar and articulated with the tongue tip and/or the tongue blade; /ʃ, ɲ/ are usually produced at the alveolopalatal zone with the tongue blade and the tongue predorsum; and /k/ is dorsopalatovelar or dorsovelar depending on vowel context.

A. Coarticulatory resistance

1. Consonant- and vowel-dependent characteristics

The DAC model makes the following predictions regarding coarticulatory resistance for consonants and vowels.

(a) Lingual coarticulatory resistance is minimal for labials since the tongue does not intervene in the production of these consonants.
(b) Alveolopalatal stops produced with the tongue blade and dorsum (e.g., /ɲ/) are more constrained than alveolars articulated with the tip and/or blade (e.g., /n/). This ought to be so since the production of the former consonants involves a larger contact surface and a more sluggish articulator, i.e., the tongue dorsum, than the produc-

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tion of the latter, and fronting and raising the tongue dorsum blocks the coarticulatory activity of other tongue regions (Recasens, 1985).

(c) Manner requirements on the formation of a narrow central groove for the passage of airflow account for why lingual fricatives are highly constrained, and perhaps more so the alveolopalatal fricative /ʃ/ than the alveolar fricative /s/ for reasons mentioned in (b) (Tabain, 2001). The formation of lateral openings for the apicoalveolar lateral /l/ requires that the tongue predorsum occupies a relatively low position, thus rendering the tongue body configuration relatively constrained. Moreover, dark /l/ (which is the variety of /l/ typically found in Catalan) should be more constrained than clear /l/ since it involves additional predorsum lowering and postdorsum retraction (Recasens and Espinosa, 2005).

(d) Dorsovelars exhibit highly systematic differences in closure fronting as a function of front vs back vowels. In this case, vowel-consonant overlap yields a blended outcome showing distant closure location targets depending on the following vowel rather than a single place which adapts to vowel context to different degrees (Browman and Goldstein, 1989).

(e) The entire tongue body is highly constrained during the production of the palatal vowel /i/, much in the same way as for alveolopalatal consonants. Regarding back vowels, there may be a stronger linkage between the tongue predorsum and the primary articulator for lower pharyngeal /a/ (tongue root) than for velar /u/ (tongue postdorsum).

Vowel-dependent differences in degree of lingual coarticulation as a function of the contextual consonants are consistent with differences in articulatory constraint mentioned in (e), i.e., coarticulatory resistance varies for /i/ > /a/ > /u/ (Catalan: Recasens, 1985; German: Hoole and Kühnert, 1995; Scottish English: Zharkova, 2007). Moreover, in agreement with the consonant-dependent characteristics in degree of articulatory constraint indicated in (a)–(d), F2 data and tongue dorsum contact data for Catalan consonants obtained by means of electropalatography (EPG) reveal the existence of differences in degree of vowel coarticulation varying in the progression /p/ (minimal degree of articulatory constraint or DAC value)>/n/ (intermediate DAC value) >dark /l/, /s/, /ʃ/, and /ɲ/ (maximal DAC value), with /k/ showing more or less variability depending on fixed vowel context (Recasens *et al.*, 1997). Similar patterns of coarticulatory resistance to vowel-dependent effects have been reported for other languages. According to tongue front and back movement data for German consonants, vowel coarticulation is maximal for the labials /p, b, m, f, v/, minimal for the palatoalveolar /ʃ/, and intermediate for alveolars in the progression /d/, /n/, clear /l/ > /t/ > /s/, and for the velars /k, g/ (Hoole *et al.*, 1990). EMA data for American English /b, v, ð, d, z, ʒ, g/, show more variability in tongue body position for labials than for dentals and alveolars, least variability for palatoalveolars, and moderate or little variability for velars occurring mostly along the horizontal dimension (Fowler and Brancazio, 2000). Tongue body coarticulation for a subset of Scottish English consonants recorded with ultrasound indicate that coarticulatory variability is maximal for /p, f/, minimal for /k/, and intermediate for the alveolars /t, l, s, r/ with the rhotic being more variable than /t, l, s/ (Zharkova, 2007). Finally, F2 data for stops in Australian languages show differences in coarticulatory resistance for /c/ > /t/ > /p/, with /k/ exhibiting large degrees of vowel coarticulation (Butcher and Tabain, 2004). This cross-language scenario suggests that most consonants are specified for nearly invariant degrees of coarticulatory resistance (Fowler and Brancazio, 2000), and that this articulatory characteristic may account for spectral regularities across places of articulation such as locus equation slopes.

In the light of this literature survey, the present study will try to substantiate some relevant findings on coarticulatory resistance reported earlier and will address several new issues on the subject. Recasens *et al.* (1997) did not report any obvious differences in coarticulatory sensitivity among dark /l/, /s/, /ʃ/, and /ɲ/ presumably since the EPG technique provides little information about tongue dorsum position for consonants such as dark /l/ and /s/, which are produced with more or less tongue lowering. The research goal is then to investigate by means of EMA whether differences in manner of articulation for highly constrained consonants sharing the same place of articulation (i.e., between /s/ and dark /l/ and between /ʃ/ and /ɲ/) affect degree of coarticulatory resistance. Special attention will be paid to variability patterns in articulatory displacement for /ɲ/, which have not been explored in detail so far; indeed, studies that have used EMA data for uncovering information on coarticulatory resistance do not have the alveolopalatal nasal in their consonant inventories (English: Fowler and Brancazio, 2000; German; Hoole *et al.*, 1990).

Data reported in literature summarized above indicate that velars may be more or less sensitive to vowel coarticulatory effects at the tongue dorsum and, therefore, could be specified for higher or lower degree of articulatory constraint. Another research topic of the present study is to investigate tongue dorsum contextual variability for velars and whether coarticulation for these consonants occurs along the horizontal rather than the vertical dimension (Fowler and Brancazio, 2000).

2. Tongue regions and articulatory dimensions

While differences in coarticulatory resistance among vowels and consonants have been much explored, articulator-dependent differences in coarticulation have been neglected to a large extent. Regarding vowels, earlier work indicates more sensitivity at tongue regions not involved directly in constriction formation, namely, at the postdorsum than at the blade and mediodorsum for /i/ and at more anterior tongue regions than at the tongue back for /a, u/ (Perkell and Nelson, 1985; Kiritani *et al.*, 1977). As for consonants, Hoole *et al.* (1990) found vowel coarticulation for consonants to increase at lingual regions not involved in closure or constriction formation, i.e., at the tongue back for alveolars and at the tongue front for velars.

Information on the specific articulatory dimensions along which coarticulatory effects occur has been gathered with EPG and EMA for vowels, but mostly with linguopalatal contact data, less so with articulatory movement data, in the case of consonants. As for vowels, coarticulatory effects on /i/ are mostly associated with consonants produced with a low tongue dorsum position, i.e., dark /l/ and to some extent /s/. Variability at the tongue dorsum surface occurs mostly vertically for /a/ presumably since this pharyngeal vowel allows for little room for backward tongue body movement, and antero-posteriorly for /u/, which has been attributed to contraction of the posterior genioglossus muscle (Perkell, 1990). Coarticulatory effects involve tongue front raising and stretching as a function of dentoalveolars and alveolopalatals for /a/ and /u/, and tongue dorsum raising as a function of velars in the case of the vowel /a/. Regarding consonants (Recasens, 1999), tongue dorsum contact effects occur mostly in vowel height and fronting (/i/ > /u/ > /a/) and, less so, in vowel fronting (/i/ > /a,u/) for dentals and alveolars, and, when available, in vowel height (/i,u/ > /a/) for (alveolo)palatals. On the other hand, tongue dorsum fronting for /k/ decreases in the progression /i/ > /a/ > /u/, thus suggesting that place of articulation for velars adapts continuously to vowel context. Alveolar and velar consonants may also exhibit differences in tongue tip and blade fronting for /i/ > /a/ > /u/ or /i/ > /a,u/, with much backing for /u/ occurring perhaps in order to assist in lip rounding during the consonant so that the acoustic effect induced by front cavity enlargement is enhanced.

The present study will try to replicate earlier findings on lingual coarticulation at the tongue front and tongue dorsum for vowels and consonants using lingual movement data. Special attention will be paid to tongue articulator-dependent differences in coarticulation for alveolopalatals. In principle, alveolopalatals should exhibit an analogous behavior to velars though, in this particular case, the fact that maximal articulatory constraint takes place at a more anterior portion of the primary dorsal articulator is prone to cause little coarticulation at most or all lingual regions.

B. Coarticulatory aggressiveness

This investigation will also explore whether there is a direct relationship between coarticulatory resistance and coarticulatory aggressiveness, i.e., whether those sounds that are most resistant should be most aggressive and those that are least resistant should barely influence the adjacent phonetic segments. Systematic surveys of this relationship have not been carried out so far with articulatory movement data. Regarding V-to-C coarticulation, the expected trend is for coarticulatory aggressiveness to be greater for /i/ than for /a, u/. On the other hand, C-to-V coarticulatory effects ought to increase with the degree of coarticulatory resistance and, therefore, with the degree of articulatory constraint for the consonant in the progression alveolopalatals > alveolars > labials, with consonants of different manners of articulation within each place category exerting different degrees of coarticulation as well.

The coarticulatory outcome is especially relevant in strings of consonants and vowels involving antagonistic articulatory configurations. In sequences of phonetic segments specified for different degree of articulatory constraint, highly constrained consonants involving a high and front tongue body position (alveolopalatals) should affect vowels leaving a low tongue front relatively free to coarticulate (/a, u/), while the opposite, i.e., tongue dorsum lowering from back vowels on alveolopalatal consonants, ought to be less prone to occur. In sequences composed of highly constrained segments, stricter requirements on consonants than on vowels to achieve a closure or constriction ought to result into more prominent C-to-V than V-to-C effects. Therefore, the prediction is for consonants that are articulated with a relatively low tongue dorsum position such as dark /l/ and /s/ to exert tongue dorsum lowering effects on /i/, rather than /i/ to exert tongue dorsum raising effects on dark /l/ and /s/.

II. METHOD

Three male speakers of Eastern Catalan of 40–50 years of age (D. Recasens, J. Pi, and J. Cererols) read symmetrical VCV combinations with the consonants /p, n, l, s, ʃ, ɲ, k/ and the vowels /i, a, u/. As pointed out in the Introduction, /l/ is generally dark, and /ɲ/ is alveolopalatal, in this Catalan dialect. All VCV sequences were embedded in the meaningful sentence [ˈgraβə pVCVp əˈβans] ("He records pVCVp earlier") and, therefore, were preceded and followed by the phonetic segments [p] and [ə], which are largely unspecified for tongue position. Speakers were instructed to pronounce all target [pVCVp] sequences ten times each with a similar degree of prominence on the first and second syllables. The same or a similar speech material produced by the same speakers was used in previous EMA and EPG investigations (Recasens, 2002; Recasens *et al.*, 1997).

Articulatory movement data were collected by means of a Carstens articulograph system AG-100. The system is composed of a head mount with three magnetic transmitter coils and several small transducer coils attached to the articulatory structures. In the present experiment, coils were placed at roughly equidistant positions on the tongue tip (TT), tongue blade (TL), and tongue dorsum (TD), as well as on the lower incisors (jaw) and on the upper lip and lower lip. The TT coil was placed about 1 cm from the apex of the tongue, and cross-speaker distance ranges between coils were 1.5–2.3 cm (TL-TT) and 1.4–1.9 cm (TD-TL). Palate traces were recorded for each speaker. Coils were also attached to the bridge of the nose and upper incisors for head movement correction. Figure 1 presents sensor locations relative to the hard palate for each speaker.

Movement and acoustic data were digitized at a sampling rate of 250 Hz for movement and at 10 kHz for speech. The kinematic data were corrected for head movement, rotated to the corresponding occlusal plane, extracted into X and Y articulatory channels, and smoothed by a finite impulse response low pass filter using a Kaiser window with a cut-off frequency of 25 Hz.

Segmentation of the VCV sequences involved identifying five temporal points on the acoustic waveform with the help of spectrographic displays, namely, V1 onset, C onset, closure offset (just for the two stops /p/ and /k/), V2 onset, and V2 offset. V1 onset was taken to occur at the onset of the

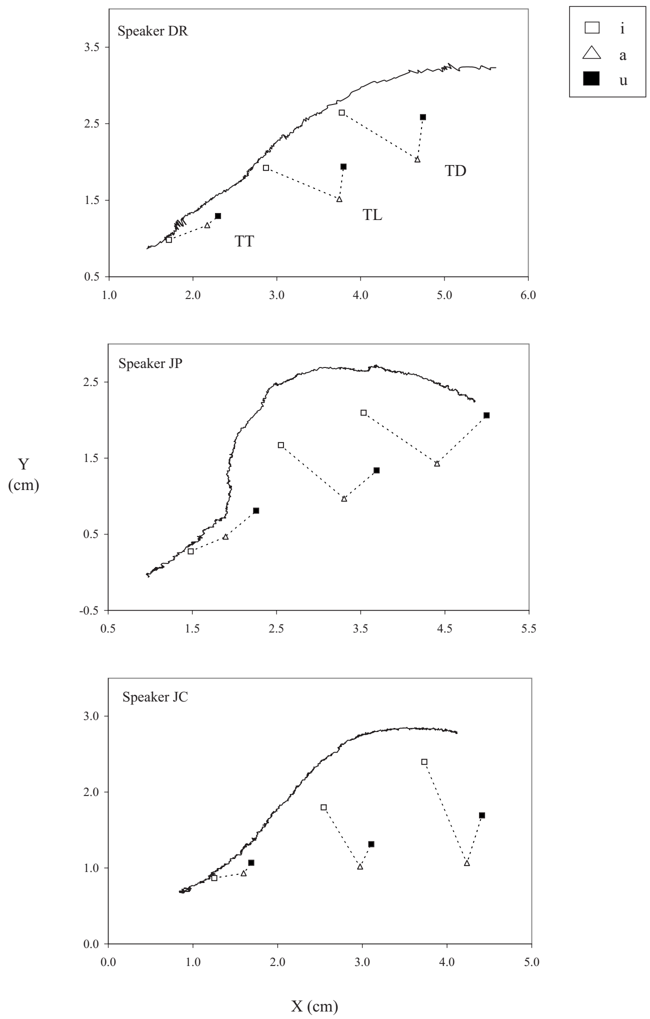

FIG. 1. TT, TL, and TD positions at consonant midpoint for /ini, ana, unu/ with palate trace. Data correspond to the speakers: D. Recasens (DR), J. Pi (JP), and J. Cererols (JC).

first pitch pulse following the burst for the first /p/, and V2 acoustic offset at the offset of vowel formant structure before closure onset for the second /p/. The onset of the intervocalic consonant occurred at the end of the V1 formant structure, which coincides with the onset of the acoustic closure for /p, k/, the frication noise for /s, ʃ/, and the low intensity formants for /n, l, ɲ/. Closure offset for /p, k/ takes place at the onset of the stop burst frication noise. V2 onset was set at the first vowel pitch pulse after the burst of a stop, the frication noise of a fricative, and the low intensity formant period of a nasal or a lateral.

Measurement points were selected according to an acoustic criterion rather than to an articulatory one since articulatory displacement maxima for the consonant and the two vowels were hard or impossible to detect in VCV sequences involving little movement (e.g., /iʃi/ and /iɲi/). Coarticulation was analyzed at two temporal points, i.e., at consonant midpoint for measuring V-to-C coarticulation and at vowel midpoint for measuring C-to-V coarticulation. Consonant midpoint was taken to occur at the midpoint of the period between C onset and closure offset for the stops /p, k/ and between C onset and V2 onset for the other consonants. Vowel midpoint was halfway between the onset and offset of voicing for the vowel. In order to render the vowel measures comparable across sequences with consonants of different manners of articulation, the 10–40 ms stop burst for unaspirated stops were not considered part of the vowel (see also Peterson and Lehiste, 1960 and Stevens, 1998, p. 258). Movement data for consonants and vowels were processed separately for each pellet and for the X and Y dimensions of articulatory displacement at the temporal points just mentioned.

A measure of coarticulatory resistance was calculated for each consonant and vowel, and for each speaker. Coarticulatory resistance for consonants was obtained at C midpoint by computing the centroid or grand mean across all three vowel contexts, and then averaging the Euclidean distances between the (x,y) position values for each vowel context and the centroid. Coarticulatory resistance for vowels was obtained at the midpoints of V1 and V2 by calculating the centroid or grand mean across all seven consonant contexts, and averaging the Euclidean distances between the (x,y) position values for each consonant context and the centroid. In both cases, the higher the degree of coarticulatory resistance, the smaller the contextual dispersion from the centroid. Data on coarticulatory resistance for vowels will be provided mostly for V1 since differences in coarticulatory resistance among vowels were found to be better defined at V1 midpoint than at V2 midpoint.

In order to find out whether variability was greater along the X or Y dimension, we also calculated the size of the contextual ranges in X and Y articulatory positions for each consonant and vowel, and for each speaker. Contextual ranges for each consonant were calculated at C midpoint by subtracting the minimal from the maximal mean contextual values across tokens for the three sequences /iCi/, /aCa/, and /uCu/ (e.g., /ipi, apa, upu/ for /p/). Ranges for each vowel at V1 location were derived by applying the same procedure to all seven VCV sequences exhibiting the same vowel (e.g., /ipi, ini, ili, isi, iʃi, iɲi, iki/ for /i/). Two other variability measures, i.e., standard deviation and coefficient of variation, were also computed but will not be reported because they yielded essentially the same differences among consonants and vowels as the contextual ranges.

A measure of coarticulatory aggressiveness was calculated for each consonant at V1 midpoint, and for each vowel at C midpoint, on the data for each speaker using the same Euclidean distance method described above. Coarticulatory aggressiveness for consonants was determined by averaging the Euclidean distances between the (x,y) position values for each consonant in the three vowel contexts and the centroid. Coarticulatory aggressiveness for vowels was computed by averaging the Euclidean distances between the (x,y) position values for each vowel in the seven consonant contexts and the centroid. In both cases, the higher the degree of coarticulatory aggressiveness, the smaller the contextual dispersion from the centroid.

Differences in coarticulatory resistance and aggressiveness were evaluated statistically by running analyses of variance (ANOVAs) with repeated measures on the Euclidean distances with consonant as a factor (resistance and aggressiveness for consonants) and with vowel as a factor (resis-

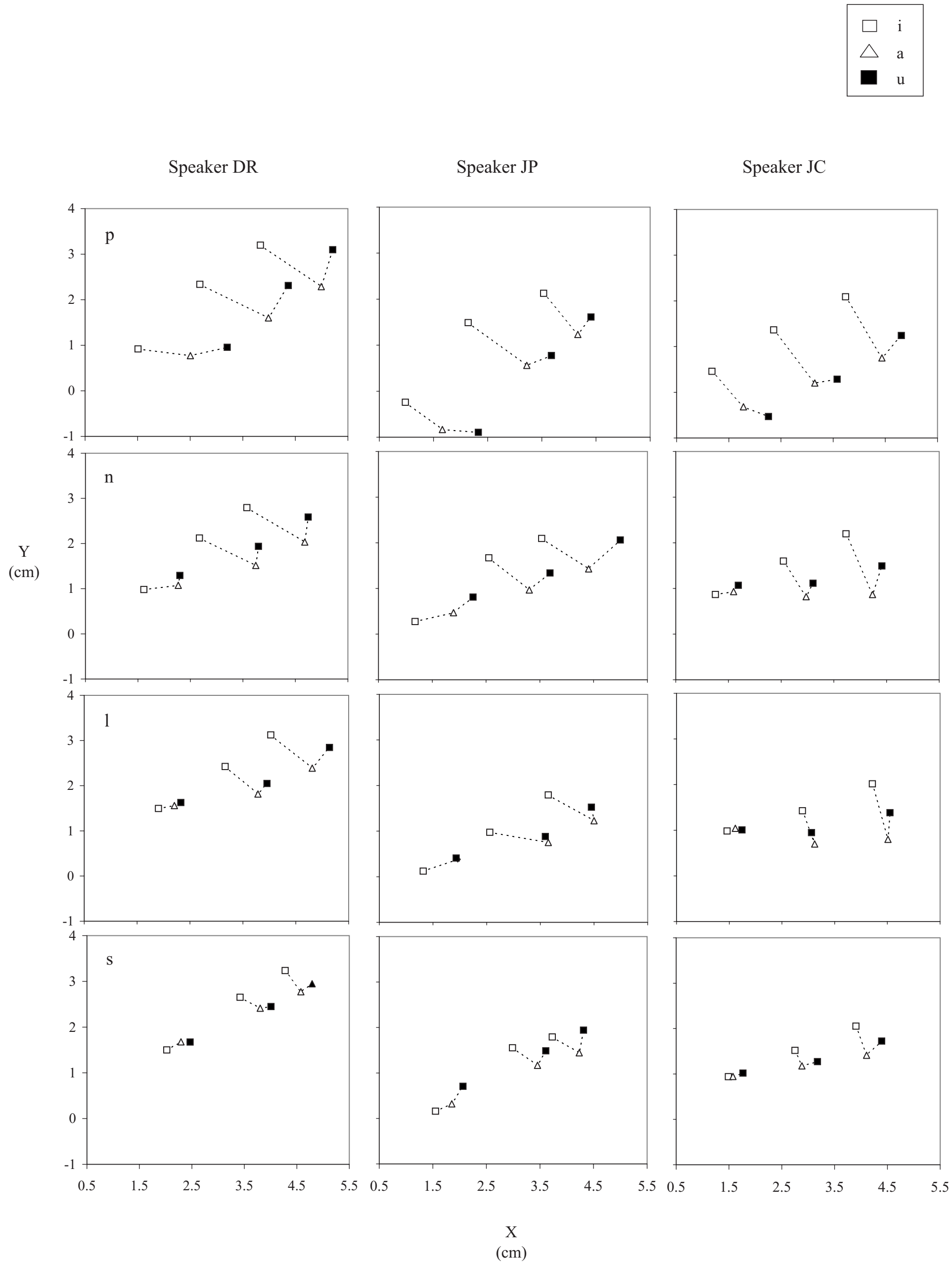

FIG. 2. (a) TT, TL, and TD positions for /p, n, l, s/ measured at consonant midpoint in the vowel contexts /i, a, u/. Data are given for all three speakers: D. Recasens (DR), J. Pi (JP), and J. Cererols (JC).

tance and aggressiveness for vowels). In order to elicit statistical differences in the V-to-C and C-to-V coarticulatory effects in articulatory position, ANOVAs with repeated measures were run separately on the *X* and *Y* lingual position values with vowel as a factor (V-to-C effects) and with consonant as a factor (C-to-V effects). Results for the significant C-to-V effects will be provided both at V1 and at V2 so as to achieve a more accurate description of the extent to which a given vowel is affected by different consonants. Levels of the vowel factor were i, a, and u and levels of the consonant factor were p, n, l, s, ʃ, ɲ, and k. Each speaker contributed one averaged score per condition. Huynh–Feldt corrected degrees of freedom were performed on the main effects. Given the small number of data entered in the ANOVAs, pairwise comparisons between levels of a given factor were carried out using Fischer least significant difference *post-hoc* tests. The degree of significance was set at $p < 0.05$.

III. RESULTS

A. Coarticulatory resistance

1. Consonants

According to Fig. 2, tongue tip position at closure or constriction location is highest for the alveolars /n, l, s/, and somewhat more retracted for /s/ than for the two other consonants; tongue blade and tongue dorsum position turns out to be higher for /s/ than for /n, l/. Bilabials, alveolopalatals, and velars are produced with the tongue tip down. Place of articulation for /ʃ/ and /ɲ/ occurs at the tongue blade and perhaps at the tongue dorsum, as indicated by the fact that

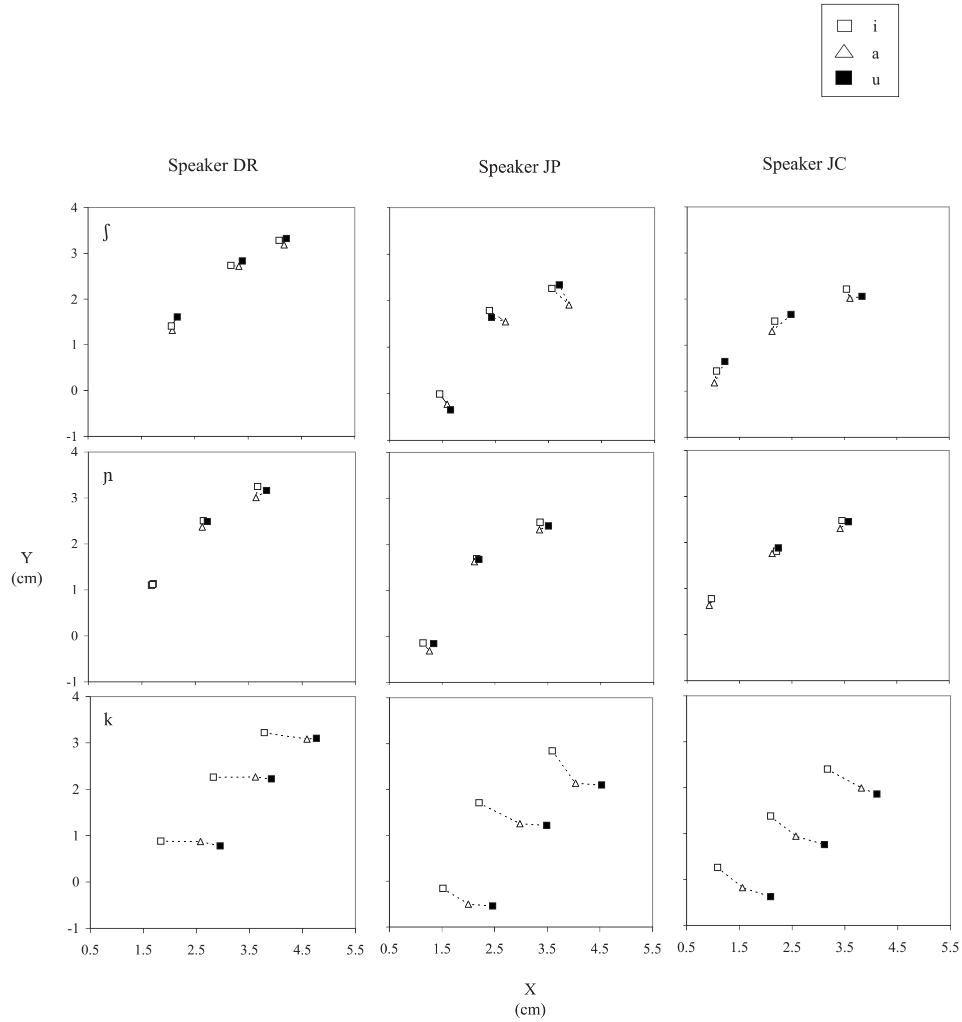

FIG. 2. (b) TT, TL, and TD positions for /ʃ, ɲ, k/ measured at consonant midpoint in the vowel contexts /i, a, u/. Data are given for all three speakers: D. Recasens (DR), J. Pi (JP), and J. Cererols (JC).

both articulators occupy the highest and anteriormost position in this case. The highest tongue position for /k/ is at the dorsal articulator.

ANOVAs on mean Euclidean distances yielded a significant effect of consonant for all articulators TT $[F(2.9,5.9) = 21.39,\ p = 0.001]$, TL $[F(6,12) = 46.00,\ p = 0.000]$, and TD $[F(1.9,3.9) = 30.09,\ p = 0.004]$. Consonant-dependent differences in coarticulatory sensitivity presented in Fig. 3 (top) turned out to be in accordance with data for Catalan reported in earlier EPG and acoustic studies. According to results from *post-hoc* tests, those differences vary in the progression /p/ > /n/ > /l, k/ > /s/ > /ʃ, ɲ/ especially for the TL and/or TD movement data. These consonant-dependent differences in coarticulatory sensitivity become apparent when the contextual position values for each consonant in Fig. 2 are taken into consideration: /p/ is most variable, /ʃ, ɲ/ are least variable, and, among alveolars, variability is maximal for /n/ and minimal for /s/. Considerable variability for /l/ appears to be related to speaker-dependent differences in tongue blade and dorsum positions mostly in the context of /i/ and, presumably, in darkness degree: Thus, the tongue body for the alveolar lateral occupies a higher position next to /i/ than to /a, u/ for some speakers (D. Recasens and J. Cererols) but less so or not at all for others (J. Pi); therefore, the consonant is less resistant to tongue dorsum raising effects induced by the high front vowel and thus, presumably clearer, for the two former speakers than for the latter. Speaker-dependent contextual differences for /l/ also occur along the *X* dimension.

Figure 3 (bottom) shows that the consonant-dependent differences in coarticulatory variability just referred to hold both along the *X* and *Y* dimensions. The only clear exception is /k/, which favors more *X* than *Y* movement and, therefore, is highly variable along the *X* dimension (as for /n/) and highly resistant along the *Y* dimension (as for /s/) (see also Fig. 2). The labial /p/ and the alveolars /n, l, s/ also exhibit a slightly greater degree of variability in the horizontal dimension than in the vertical dimension at the tongue tip and blade. Both dimensions of articulatory displacement show similar degrees of variability at all lingual regions for the alveolopalatals /ʃ, ɲ/.

Figure 3 (bottom) also reveals a decrease in contextual variability for TD > TL > TT in the case of the consonants /p, n, l, s/ along the *Y* dimension, and of /n, l/ and, to some extent, /s/ along the *X* dimension. It thus appears that the degree of coarticulation for front lingual consonants increases the more we depart from the primary articulator. The

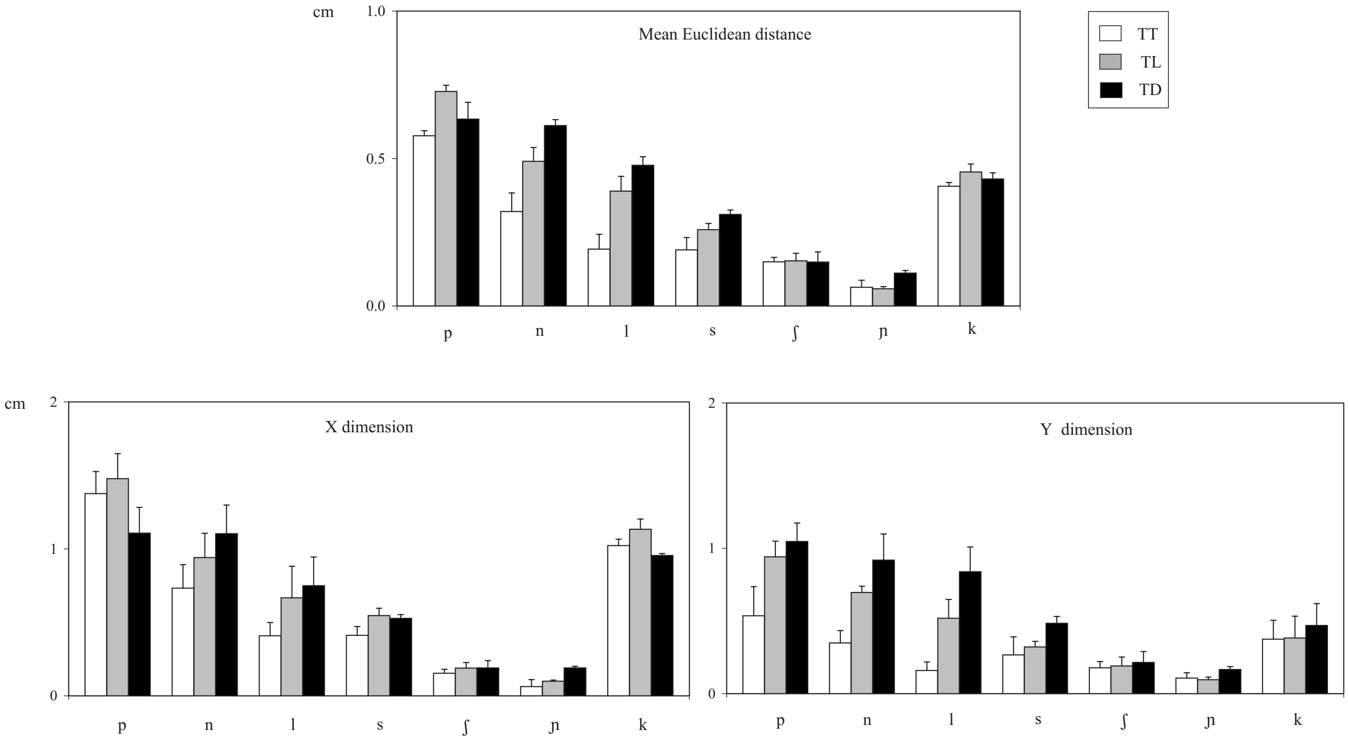

FIG. 3. Mean Euclidean distances in TT, TL, and TD positions (top), and ranges of tongue position values along the *X* and *Y* dimensions (bottom), for /p, n, l, s, ʃ, ɲ, k/ across vowel contexts measured at consonant midpoint. Data correspond to means and standard deviations across speakers.

lamino-predorsal and dorsal consonants /ʃ, ɲ, k/ exhibit no clear variability differences among lingual articulators (though they may also show a trend for the *X* and *Y* ranges for the tongue dorsum to exceed those for the tongue tip and blade).

According to Table I (see also Fig. 2), labials (/p/) and velars (/k/) allow significant vowel effects in horizontal displacement for /i/ > /a/ > /u/ at all or most pellets, which in the case of /k/ could be associated with three instead of two places of articulation. Moreover, labials also show significant tongue dorsum effects in vertical displacement as a function of high versus low vowels. *X* and *Y* vowel effects on the alveolopalatal consonants /ʃ, ɲ/ are negligible. As for alveolars, tongue fronting decreases in the progression /i/ > /a, u/ (/n/) and /i, a/ > /u/ (/s/), and tongue dorsum height in the progression /i, u/ > /a/ (/n, l/) and /i/ > /a/ (/s/). In a few cases, vowel-dependent differences in articulatory position for a given alveolar consonant fail to achieve significance because they may show up to different degrees or fail to occur depending on speaker, e.g., /i/ > /a, u/ for /p/ (TT*Y* and TL*Y*) and for /l/ (TL*Y*) (see Fig. 2).

TABLE I. Significant main vowel-dependent effects and *post-hoc* pairwise comparisons for /p, n, l, s, ʃ, ɲ, k/ as a function of tongue articulator and articulatory dimension (*, $p<0.05$; **, $p<0.01$; ***, $p<0.001$). *X* differences among contextual vowels proceed from most anterior to most posterior, and *Y* differences from highest to lowest.

	TT*X*	TL*X*	TD*X*	TT*Y*	TL*Y*	TD*Y*
p	** i>a>u	** i>a>u	** i>a>u			** i, u>a
n	* i>a, u	** i>a, u	** i>a, u		* i, u>a	* i, u>a
l	*		*			* i, u>a
s	* i, a>u	* i, a>u	* i>u		* i>a	* i>a
ʃ	* i>u					
ɲ		** i, a>u			* u>a	
k	** i>a>u	*** i>a>u	* i>a, u			

2. Vowels

Tongue tip, blade, and dorsum position at V1 midpoint conform to the expected differences in anteriority for /i/ > /a/ > /u/ and in height for /i/ > /u/ > /a/. Thus, as shown in Fig. 4, the tongue dorsum is located between 3.5 and 4 cm behind the origin of the coordinate space at the upper incisors for /i/, between 4 and 4.5 cm for /a/, and between 4 and 5 cm for /u/. Moreover, according to the same figure, tongue dorsum height is about 2.5 cm for /i/, between 2 and 2.5 cm for /u/, and between 1.5 and 2 cm for /a/.

According to statistical tests run at V1 midpoint, differences in degree of consonant-dependent variability for vowels were highly significant at TT $[F(1.1,2.3)=34.03$, $p=0.021]$ and TL $[F(1,2)=39.55$, $p=0.024]$, and barely significant at TD $[F(1,2)=13.42$, $p=0.067]$. *Post-hoc* tests reveal that those differences decrease in the progression /u/ > /a/ > /i/ at the tongue tip and blade and /u/ > /i/ at the tongue dorsum (see Fig. 5, top). Figure 4 shows indeed much less dispersion among consonant contexts for the high front vowel than for the two back vowels. All articulators exhibit similar degrees of contextual variability along the *X* and *Y*

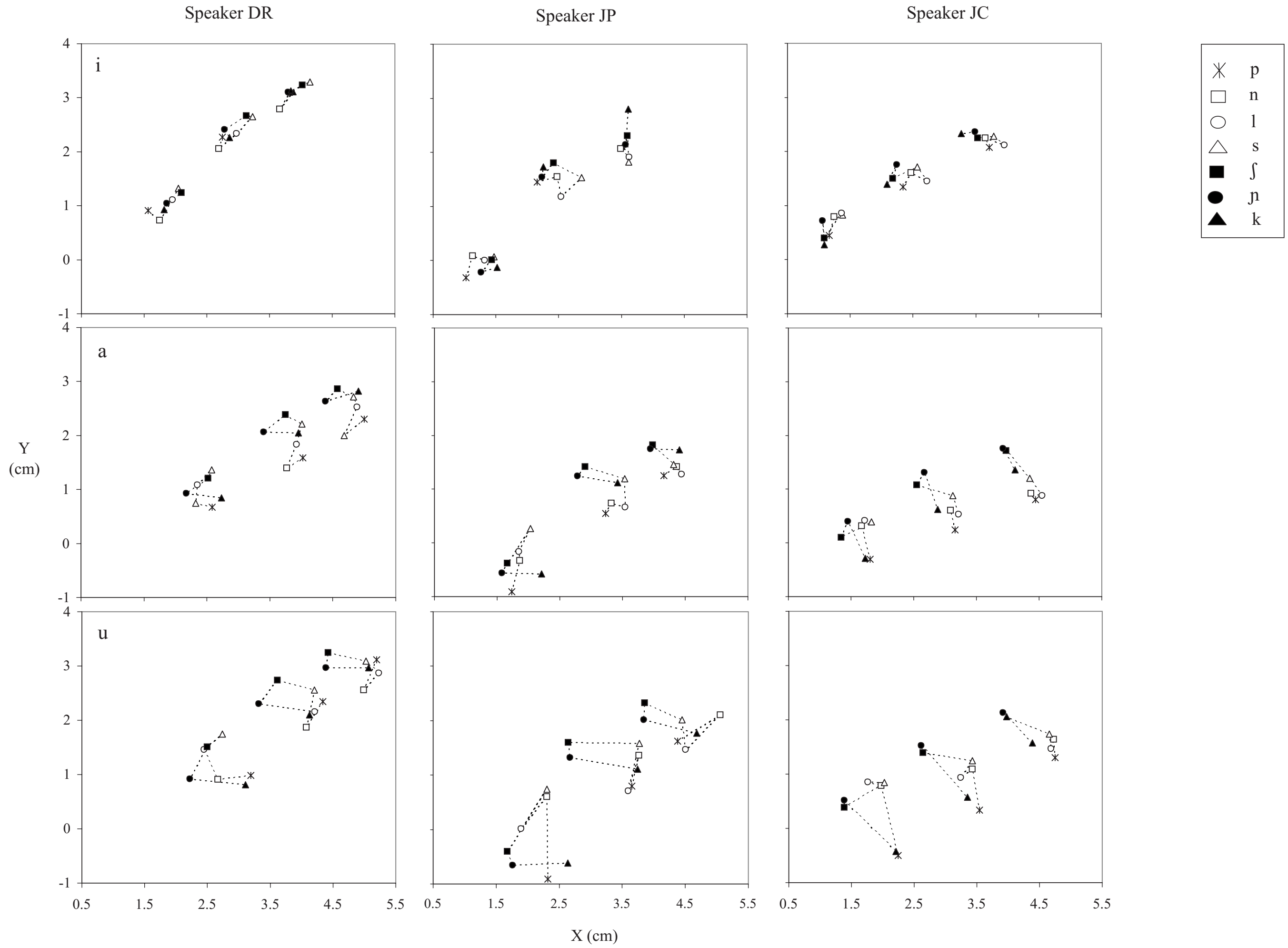

FIG. 4. TT, TL, and TD positions for /i, a, u/ measured at V1 midpoint as a function of contextual consonants of different place of articulation. Data are given for all three speakers: D. Recasens, J. Pi, and J. Cererols.

dimensions in the case of /i/ and some more variability in the *Y* dimension than in the *X* dimension for /a/ (Fig. 5, bottom). As for /u/, coarticulatory variability is especially large at the tongue tip along the *Y* dimension and slightly greater horizontally than vertically at the tongue blade and dorsum.

Table II provides information about the significant consonant effects at the two vowels' midpoint (see also Fig. 4). As indicated in the table caption, *X* and *Y* values for a given consonant appearing outside the panel always exceed those for the consonants that are paired with it and appear inside the panel. Consequently, for a given consonant pair, the consonant outside the panel may be considered to be responsible for significant C-to-V effects in the /a, u/ condition (since these effects involve tongue body raising and fronting), and the consonant inside the panel for significant C-to-V effects in the /i/ condition (since these effects involve tongue body lowering and backing). Effects on /i/ involve mostly tongue blade retraction as a function of /l, s/ (TL*X*) and tongue blade lowering as a function of /l/ (TL*Y*). Back vowels allow more considerable consonantal effects. Effects along the horizontal dimension occur on /u/ and, less so, on /a/, and involve fronting at the tongue blade and dorsum and, less so, at the tongue tip in the context of /ʃ, ɲ/, and at the tongue tip in the context of alveolars, mostly /l/. Effects along the vertical dimension are slightly larger on /a/ than on /u/, and involve raising at the tongue tip in the context of /l/, at the tongue blade next to /ɲ/, at the tongue blade and dorsum next to /k/, and at all articulators in the context of /s, ʃ/ (more so at tongue tip and blade in the case of /s/ and at tongue blade and dorsum in the case of /ʃ/).

B. Coarticulatory aggressiveness

ANOVAs on mean Euclidean distances yielded a significant consonant effect at V1 midpoint for all articulators TT [$F(1.6,3.3)=16.24$, $p=0.020$], TL [$F(6,12)=49.76$, $p=0.000$], and TD [$F(2.8,5.6)=20.75$, $p=0.002$]. Significant differences in coarticulatory variability take place for /p/ > /n/ > /l, s/ > /ʃ, ɲ/, with /k/ not differing significantly from /p, l, s/, and therefore resemble those reported at C midpoint (see Fig. 6, top). Indeed, consonants such as /p/ and /n/ exhibit larger differences in articulatory position across vowel contexts than consonants such as /ʃ/ and /ɲ/ and, therefore, the former can be considered to be less aggressive than the latter. A correlation analysis between mean Euclidean distances for consonants at V1 midpoint and at C midpoint yielded a high r value between the two measures (0.931),

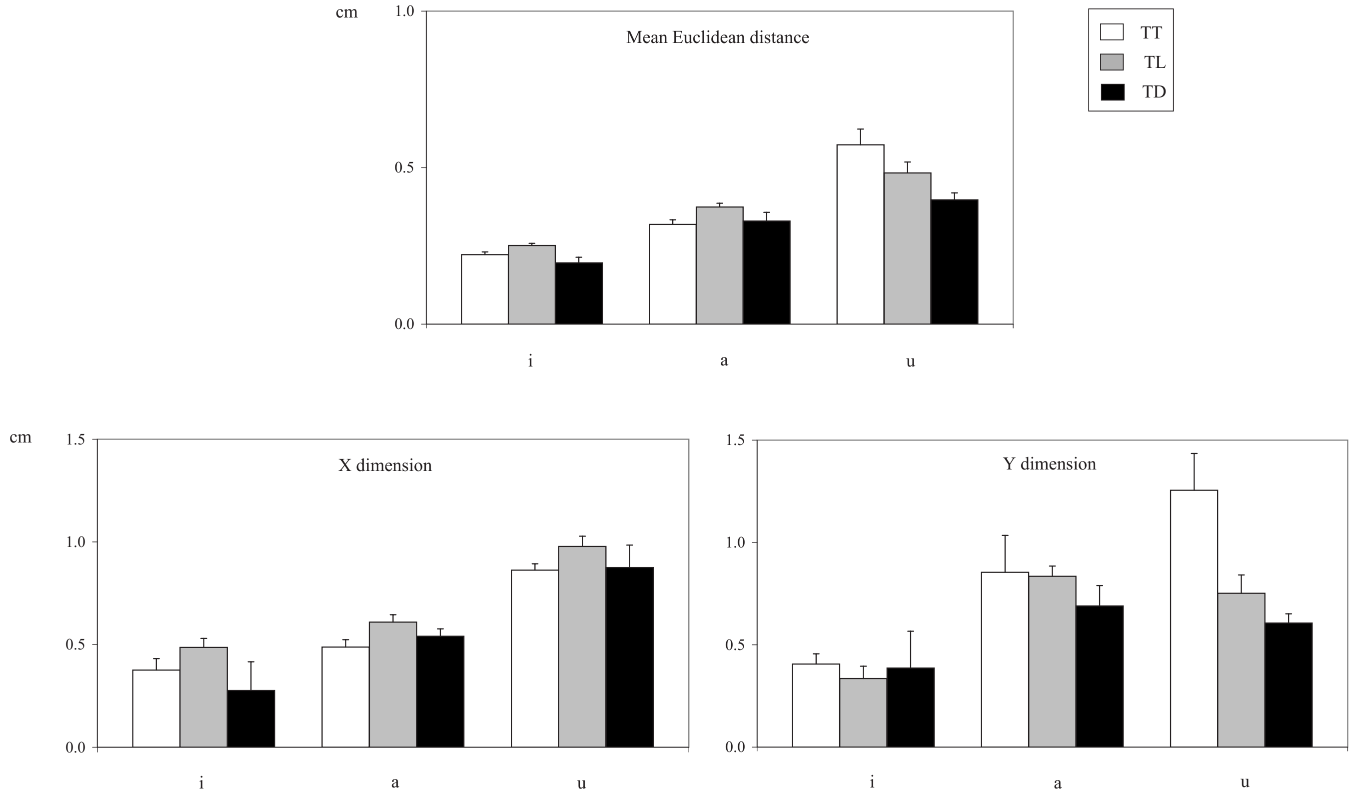

FIG. 5. Mean Euclidean distances in TT, TL, and TD positions (top), and ranges of tongue position values along the *X* and *Y* dimensions (bottom), for /i, a, u/ across consonant contexts measured at V1 midpoint. Data correspond to means and standard deviations across speakers.

thus proving that coarticulatory aggressiveness for consonants varies directly with coarticulatory resistance to vowel effects.

A similar scenario holds between coarticulatory aggressiveness and coarticulatory resistance for vowels. According to statistical tests run at C midpoint, the vowel factor turned out to be significant for TT [$F(1.8,3.6)=21.90$, $p=0.010$] and TL [$F(1.9,3.8)=38.60$, $p=0.003$], and barely significant for TD [$F(1,2)=21.48$, $p=0.043$]. *Post-hoc* tests reveal the existence of significant differences in coarticulatory variability for /a,u/ > /i/ at TL and TD (see Fig. 6, bottom). Given that /i/ exhibits less considerable consonant-dependent differences in articulatory position than /a, u/, it may be ascertained that the former vowel exerts greater V-to-C effects than the two latter ones. A correlation analysis between mean Euclidean distances for the three vowels at C midpoint and at V1 midpoint yields a high r value (0.873), meaning that coarticulatory aggressiveness and coarticulatory resistance for vowels are closely related.

The relative strength of the C-to-V and V-to-C effects in sequences of consonant and vowel segments produced with antagonistic articulatory actions depends on degree of articulatory constraint. Thus, as predicted, C-to-V effects from alveolopalatals on /a, u/ (Table II) are more prominent than V-to-C effects from /a, u/ on alveolopalatals (Table I). The coarticulation scenario in sequences of highly constrained segments conforms to some extent to our initial prediction that C-to-V effects should prevail onto V-to-C effects. Indeed, data show some tongue dorsum lowering and retraction effects from dark /l/ and /s/ on /i/ (Table II), and tongue dorsum raising and fronting effects from /i/ on /s/ but much less so on /l/ (Table I).

IV. DISCUSSION AND CONCLUSIONS

Patterns of contextual variability in tongue position for consonants and vowels (as well as individual V-to-C and C-to-V effects) reported in the present study confirm what appears to be a general principle of coarticulatory behavior, namely, that coarticulatory resistance and aggressiveness are indicative of degree of articulatory constraint and depend on the degree of involvement of a given articulatory region in closure and constriction formation and on manner requirements.

Differences in lingual variability for /p/ > /n/ > /l,k/ > /s/ > /ʃ,ɲ/ and /u/ > /a/ > /i/ are in agreement with the scale of degree of articulatory constraint proposed by the DAC model. They confirm previous accounts in that coarticulatory resistance decreases for alveolopalatals > alveolars > labials both along the horizontal and vertical directions of articulatory displacement (see below regarding the status of velars). In contrast with EPG data adduced by Recasens *et al.* (1997), a higher degree of coarticulatory resistance for alveolopalatals than for alveolars has been found to hold among the highly constrained consonants dark /l/, /s/, /ʃ/, and /ɲ/. These differences in coarticulatory sensitivity indicate that frication contributes more than laterality and possibly darkness to an increase in degree of articulatory constraint. Similar findings have been reported in studies measuring lingual coarticulatory resistance and variations in jaw-tongue tip cohesion induced by changes in vocal effort for German consonants, i.e., in this case variability was

TABLE II. Significant consonant-dependent effects and *post-hoc* comparisons for /i, a, u/ as a function of tongue articulator and articulatory dimension. (Top of each panel) Main effects at V1 and V2 (*, $p<0.05$; **; $p<0.01$; ***, $p<0.001$). (Bottom of each panel) Consonant pairs yielding a significant effect at either V1 or V2 (in regular typeface) or at both V1 and V2 (in boldface). The consonants appearing outside the panel exhibit a more anterior (X) or higher (Y) position value than the ones placed on the same row inside the panel.

		TTX	TLX	TDX	TTY	TLY	TDY
	V1	NO	*	NO	NO	NO	NO
	V2	NO	*	NO	NO	NO	NO
i	p		**l**				
	n						
	l						
	s					l	
	ʃ						
	ɲ		**l s**			p l k	
	k		**s**				
	V1	**	***	***	**	**	**
	V2	NO	**	**	**	***	***
a	p						
	n	s	l				
	l	s			p		
	s				**p** ʃ ɲ **k**	**p l**	p l
	ʃ		s	l s	p k	**p** n **l** s **k**	**p** n
	ɲ	n l s k	**p n l** s	n **l s**		p **n**	
	k		s			**p** l	**p** l
	V1	***	***	**	**	*	*
	V2	***	***	***	**	***	*
u	p						
	n	**k**					
	l	p n s **k**	s k		ɲ k		
	s	**k**			p n l **k**	n l **k**	l
	ʃ	**p k**	**p** n l **s k**	p **n l** s k	p	**l k**	**l** s **k**
	ɲ	p n **s k**	**p n l s ʃ k**	**p n l s ʃ k**		l	
	k						s

found to be less for /s/ than for /l/ though the same for /l/ and /n/ perhaps since /l/ is clear in this language (Hoole *et al.*, 1990; Mooshammer *et al.*, 2006). In Scottish English, however, no differences in lingual coarticulatory resistance were found to occur between /l/ and /s/ (Zharkova, 2007).

The consonant /l/ turned out to be more variable than expected in the present study presumably in line with speaker-dependent differences in darkness degree. This appears to be in agreement with EPG and acoustic data reported in earlier studies for dark /l/ in Eastern Catalan (Recasens *et al.*, 1995) showing a high degree of speaker-dependent variability in the sequence /ili/ both regarding dorsopalatal contact size (between 10% and 35% of contact activation over the total amount of electrodes at the palatal zone) and F2 (between about 1250 and 1450 Hz). This finding suggests that certain articulatory properties are allowed to vary more than others, e.g., laterality and darkness than frication.

The special status of velars has been confirmed by the present investigation. Data from previous studies show that this consonant may be more or less variable depending on factors such as articulatory direction (Fowler and Brancazio, 2000), the transconsonantal vowel in asymmetrical VCV sequences (Recasens *et al.*, 1997), and language (Butcher and Tabain, 2004). In agreement with Fowler and Brancazio (2000), much contextual variability for velars has been found to take place along the horizontal dimension for /i/ > /a/ > /u/, which is in support of the notion that these consonants blend with the adjacent vowels. A high degree of coarticulatory resistance along the Y dimension is in accordance with minimal V-to-C coarticulatory effects on /k/ reported elsewhere (Zharkova, 2007).

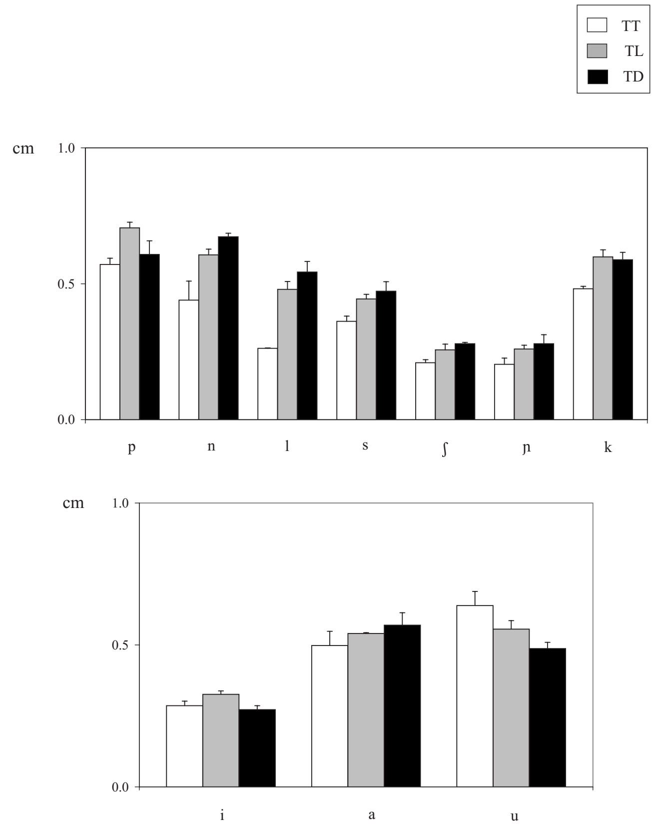

FIG. 6. Mean Euclidean distances in TT, TL, and TD positions for consonants across vowel contexts measured at V1 midpoint (top) and for vowels across consonant contexts measured at consonant midpoint (bottom). Data correspond to means and standard deviations across speakers.

As for vowels, fronting and raising the tongue body for /i/ appears to constrain all tongue regions to a large extent thus rendering this vowel more coarticulation resistant than back vowels. In agreement with previous studies, differences in coarticulatory resistance also hold for /a/ > /u/.

Whenever available, coarticulatory effects occur mostly at regions not participating in closure or constriction formation. Indeed, variability for /n, l, s/ was greater at the tongue dorsum where X and Y effects may take place as a function of front versus back and high versus low vowels, respectively, than at the tongue tip and blade where effects occur generally along the X dimension as a function of front versus back vowels. Regarding vowels, consonantal effects on /a, u/ take place mostly at the tongue tip and blade as a function of alveolopalatals and alveolars through variations in tongue height for /a/ and in tongue fronting for /u/, which is in accordance with a muscle-based account of variability for vowels (Perkell, 1990).

Trends in coarticulatory aggressiveness were found to be also consistent with the DAC model of coarticulation. Both for consonants and vowels, phonetic segments which were more resistant turned out to be more aggressive as well. Specific coarticulatory effects between segments involving antagonistic articulatory positions were in agreement with this general principle: More constrained alveolopalatals resist the lowering and backing influence of less constrained /a, u/ while exerting maximal coarticulation on these vowels. In consonant-vowel sequences composed of two highly constrained and antagonistic segments, e.g., dark /l/ or /s/ and /i/, the consonant appears to prevail onto the vowel rather than the other way around, which is in line with the articulatory demands for the two sound classes. In any case, the degree of V-to-C coarticulation exerted from /i/ on the consonant appears to be hard to evaluate since it depends heavily on the exact degree of darkness (for /l/) and frication (for /s/), which may vary according to speaker and other factors.

In summary, consonants and vowels may be differentiated quite successfully in terms of coarticulatory resistance, which falls naturally from the production demands involved. Moreover, a direct relationship appears to hold between coarticulatory resistance and coarticulatory aggressiveness. This scenario suggests that the coarticulatory resistance scale is a valid criterion of consonant and vowel classification and provides valuable information about the planning mechanisms used by speakers in speech production.

The present research points to several issues for further analysis. It remains unclear why phonetic segments in VCV sequences are more variable if produced with a low tongue dorsum than with a high dorsum. This finding suggests that production requirements for these sequences differ from those for consonant clusters where manner demands for low tongue dorsum consonants overcome consonants articulated with a high tongue dorsum position (Recasens and Pallarès, 2001). It may be that articulatory control on certain production mechanisms is greater in consonant clusters than in CV and VC sequences because consonants are required to configure the articulatory structures more precisely than vowels for the implementation of specific manners of articulation. In consonant clusters, the integrity of the consonant appears to be affected to a larger extent by deviations in tongue dorsum position induced in dark /l/, the apical trill /r/, and /s/ than in alveolopalatals even though the tongue dorsum is the primary articulator of the latter but not of the former group of consonants.

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