A study of jaw coarticulatory resistance and aggressiveness for Catalan consonants and vowels

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The goal of this study is to investigate coarticulatory resistance and aggressiveness for the jaw in Catalan consonants and vowels and, more specifically, for the alveolopalatal nasal /ɲ/ and for dark /l/ for which there is little or no data on jaw position and coarticulation. Jaw movement data for symmetrical vowel-consonant-vowel sequences with the consonants /p, n, l, s, ʃ, ɲ, k/ and the vowels /i, a, u/ were recorded by three Catalan speakers with a midsagittal magnetometer. Data reveal that jaw height is greater for /s, ʃ/ than for /p, ɲ/, which is greater than for /n, l, k/ during the consonant, and for /i, u/ than for /a/ during the vowel. Differences in coarticulatory variability among consonants and vowels are inversely related to differences in jaw height, i.e., fricatives and high vowels are most resistant, and /n, l, k/ and the low vowel are least resistant. Moreover, coarticulation resistant phonetic segments exert more prominent effects and, thus, are more aggressive than segments specified for a lower degree of coarticulatory resistance. Data are discussed in the light of the degree of articulatory constraint model of coarticulation. © *2012 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4726048]

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I. INTRODUCTION

Previous studies on lingual coarticulation have shown that consonants and vowels differ regarding the degree of coarticulatory resistance, i.e., the extent to which they block coarticulatory effects from the contextual phonetic segments (Fowler and Brancazio, 2000; Iskarous *et al.*, 2010; Recasens, 1999; Recasens and Espinosa, 2009). According to the degree of articulatory constraint (DAC) model of coarticulation (Recasens *et al.*, 1997), coarticulatory resistance increases with the involvement of the tongue body in closure or constriction formation, e.g., the alveolopalatal nasal /ɲ/ is less sensitive to vowel coarticulation than /b/ or /n/ since the blade and the tongue dorsum are directly involved in closure formation for the former consonant, but not for the two latter ones. In order to ascertain whether the jaw is also subject to different degrees of contextual adaptation depending on the target phonetic segment, this paper investigates coarticulatory resistance in jaw position for several Catalan consonants and vowels in symmetrical vowel-consonant-vowel (VCV) sequences. The consonants are as follows: the bilabial /p/; the alveolars /n/ and /s/, which are articulated with tip, blade, or tip and blade; the alveolar /l/, which in Catalan is more or less dark and, therefore, involves some tongue predorsum lowering and tongue dorsum retraction in addition to a primary apicoalveolar central closure; the alveolopalatals /ʃ/ and /ɲ/, which are produced with the blade and the predorsum; the back dorsal velar /k/. As for vowels, high front /i/ may be laminodorsoalveolopalatal or dorsopalatal, low /a/ is produced at the lower pharynx with the tongue root, and high back /u/ is a postdorso-velar vowel involving lip rounding. Patterns of coarticulatory resistance will be related to specific vowel-to-consonant (V-to-C) and consonant-to-vowel (C-to-V) coarticulatory effects.

Another research goal of the present study is to ascertain whether in Catalan, as in other languages (German: Hoole *et al.*, 1990; Mooshammer *et al.*, 2007; English, Swedish: Keating *et al.*, 1994; Korean, Arabic, French: Lee, 1994), jaw coarticulatory variability is inversely related to jaw height. Moreover, the present investigation will look into the relationship between coarticulatory resistance and coarticulatory aggressiveness, i.e., the degree to which a given target phonetic segment affects the articulatory characteristics of the contextual phonetic segments; in line with findings for the tongue reported in Recasens and Espinosa (2009), the hypothesis will be tested that those phonetic segments that are more resistant ought to be more aggressive as well.

A comparison between trends in jaw and tongue coarticulation in Catalan is possible since the data for the jaw reported in this study were collected simultaneously with the lingual data presented in our previous paper (Recasens and Espinosa, 2009). A literature review provides the following scenario for vowels and consonants.

A. Articulatory position

Regarding vowels, jaw height is positively correlated with tongue dorsum height and oral closing, with height for /i, u/ being greater than for /a/ (to be indicated henceforth as /i, u/ > /a/) (Fletcher and Harrington, 1999). In parallel to data for several consonants presented below, maximal jaw height for high vowels may be largely attributed to front dorsum raising in the case of /i/ and to lip closing in the case of /u/.

Regarding consonants, differences in jaw height do not fully agree with differences in tongue body height. Data for Catalan indicate that tongue body height is greater for the laminodorsal and dorsal consonants /ʃ, ɲ, k/ than for /s/, and

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lowest for the bilabial /p/ and the non-fricative alveolars /n, l/ (to be indicated henceforth as /ʃ, ɲ, k/ > /s/ > /p, n, l/) (Recasens and Espinosa, 2009). Regarding the jaw, all studies referred to above report maximal height for the lingual fricatives /s, ʃ/ which has been attributed to the need to leave a small passage between the upper and lower incisors for the generation of high frequency frication noise (Shadle, 1985); in addition, /ʃ/ has often been found to be articulated with a higher jaw than /s/ (Hoole *et al.*, 1990; Mooshammer *et al.*, 2007) in line with differences in tongue dorsum height between the two consonants. As for oral stops, jaw height is less than for the two front lingual fricatives and has been reported to decrease with lingual closure retraction and predorsum lowering in the progression /t, d/ > /k, g/, the bilabials /p, b/ falling in between (Hoole *et al.*, 1990; Keating *et al.*, 1994; Lee, 1994). Differences in jaw height as a function of stop closure placement result from the rotational movement component of the jaw by which a higher jaw position occurs concomitantly with lip closing and tongue front raising rather than with tongue back dorsum raising. The consonant /l/ is found at the lower end of the jaw height scale, and at the same level as or below the labial and velar stops (Hoole *et al.*, 1990; Keating *et al.*, 1994; Mooshammer *et al.*, 2007). A low jaw position is related to laterality in this case, namely, to the need to lower the blade and the tongue predorsum for the passage of airflow through the sides of the oral cavity. Additional tongue dorsum lowering and postdorsum retraction for dark varieties of /l/ should result in even greater jaw lowering (Lindblad and Lindqvist, 2003). The alveolar nasal may be articulated with considerable or moderate jaw lowering (see Mooshammer *et al.*, 2007 and Keating *et al.*, 1994 for the two possibilities). The lowering of the jaw for /n/ co-occurs with a relatively low tongue body position and thus with an increase in the size of the cavity behind closure location (as in Catalan; Recasens *et al.*, 1997), and could be associated with the absence of a requirement toward an intraoral pressure buildup as air is vented continuously through the nasal cavity. More stringent manner of articulation demands for /l/ than for /n/ confirm the hypothesis put forth by Mooshammer *et al.* (2007) that jaw position is actively controlled for the lateral but not for the nasal. Finally, data on jaw position for /ɲ/ are not available in the phonetics literature though experimental evidence for the alveolopalatal oral stop /c/ in Arrernte (Tabain, 2009) indicates that the alveolopalatal nasal ought to be produced with a high jaw and tongue blade and predorsum position.

Consonants may also differ regarding jaw fronting which, according to previous studies (Farnetani and Faber, 1992; Hoole *et al.*, 1990; Mooshammer *et al.*, 2007), tends to be maximal for lingual fricatives (more for /ʃ/ than for /s/) and minimal for /l/, with that for stops falling in between.

B. Coarticulatory resistance

Differences between patterns of jaw and lingual coarticulation in several languages seem to be related to the fact that the former may depend on jaw height and not only on specific requirements on lingual movement and positioning. Moreover, a trend for phonetic segments articulated with a higher jaw to exhibit greater coarticulatory resistance than those articulated with a lower jaw (see data for vowels and consonants in this section) appears to be associated with the same factors which contribute to the raising of the jaw, i.e., manner constraints for fricatives, and the involvement in closure or constriction formation of the lips for labial consonants and vowels, and of the blade and predorsum or just the tongue dorsum for (alveolo)palatal phonetic segments.

Regarding vowels, the jaw but not the tongue body is similarly constrained for /i/ and /u/. Indeed, while the two high vowels are expected to show similar degrees of jaw coarticulatory resistance (since they are both produced with a high jaw position), /i/ has been consistently found to exhibit more tongue body resistance to consonantal effects than /u/ (see Recasens, 1999 for references). A motivation for this coarticulatory characteristic of /i/ may be sought in the achievement of a global tongue body stabilization when the anterior and posterior genioglossus are coactivated and the tongue sides are pressed against the palate surface (Buchaillard *et al.*, 2009).

A relevant theoretical issue is the extent to which consonant-dependent patterns of coarticulatory resistance for the jaw match differences in jaw height and in tongue body height and contextual variability (lingual coarticulatory resistance varies in the progression /ɲ/ > /ʃ/ > /s/ > /l, k/ > /n/ > /p/ in Catalan; Recasens and Espinosa, 2009). The lingual fricatives /s, ʃ/ are articulated with maximal jaw height and show least mandibular and lingual coarticulation (Lee, 1994; Mooshammer *et al.*, 2007), presumably in line with the strict manner of articulation demands on tongue positioning and shape involved in their production (Stone *et al.*, 1992); the extent to which jaw variability differences between /s/ and /ʃ/ conform to a higher tongue dorsum and jaw and less lingual variability for /ʃ/ than for /s/ deserves to be examined. Among stops, jaw coarticulatory resistance decreases with jaw height in the progression /t, d/ > /k, g/, the bilabials /p, b/ falling in between (Keating *et al.*, 1994); differences in jaw height may account for why the jaw is more constrained than the tongue dorsum in the case of bilabial stops and to some extent of dentoalveolar stops as well. A considerable degree of contextual variability for the jaw operates on /l/ (Keating *et al.*, 1994; Mooshammer *et al.*, 2007), which is produced with a low jaw and is expected to exhibit varying degrees of lingual and perhaps mandibular coarticulatory resistance depending on darkness degree, i.e., the higher the degree of darkness, the higher the degree of articulatory constraint and of coarticulatory resistance. On the other hand, the alveolar nasal may exhibit more or less jaw contextual variability depending presumably on whether it is articulated with considerable or moderate jaw lowering, respectively (compare Mooshammer *et al.*, 2007 and Keating *et al.*, 1994 for the two possibilities); in parallel to the tongue body, /n/ is expected to be highly sensitive to vowel-dependent jaw coarticulation perhaps since, differently from /l/, jaw position is not actively controlled for this consonant. Finally, if produced with a high jaw, the alveolopalatal nasal /ɲ/ should exhibit little jaw coarticulation and thus, a similar coarticulatory behavior to the tongue body which is also highly resistant to vowel effects in this case (see Recasens and Espinosa, 2009 for the tongue body data).

C. Coarticulatory aggressiveness

The present investigation will also test the hypothesis that consonants and vowels which are maximally resistant to jaw coarticulation are also more aggressive and thus, more prone to exert coarticulatory effects on the adjacent segments. For example, tongue body data for Catalan gathered at the vowel midpoint indicate that /i, a, u/ differ from each other to a greater extent in the context of the less resistant consonants /p, n/ than of the more resistant alveolopalatals /ʃ, ɲ/, which may be taken as evidence for greater aggressiveness for the latter than for the former (Recasens and Espinosa, 2009). Some jaw coarticulation data suggest that the relationship of interest also holds for the jaw. Thus, consonants involving a higher jaw and little vowel coarticulation such as /t, s/ were found to exert more jaw raising on the low vowel /a/ than consonants allowing larger vowel jaw height effects such as /b, l, k/ (Keating *et al.*, 1994). Also, V-to-C effects in jaw height on /b, k/ were reported to be greater for the more resistant high vowels /i, u/ than for the less resistant vowel /a/ (Lee, 1994).

D. Summary of research goals

The present study examines the hypothesis that jaw height and coarticulatory resistance and aggressiveness are positively related, mostly with respect to /s/ vs /ʃ/, to the nasal alveolar /n/ in comparison with /l/, and to the alveolopalatal /ɲ/ vis-à-vis the other consonants involving tongue dorsum activation /ʃ, k/ as well as the alveolars /n, l/. In order to obtain a more precise picture of the mutual influences occurring between vowels and consonants in VCV sequences, an analysis will be carried out of the V-to-C and C-to-V coarticulatory effects in jaw position.

II. METHOD

Details on data recording, segmentation, and analysis have been reported in Recasens and Espinosa (2009) and are summarized here. Three male speakers of Eastern Catalan of 40–50 years of age read symmetrical VCV sequences with /p, n, l, s, ʃ, ɲ, k/ and /i, a, u/ ten times. All VCV sequences were embedded in the meaningful sentence [ˈgraβə pVCVp əˈβans] ("He records pVCVp earlier") where [p] and [ə] are largely unspecified for tongue position. Speakers were instructed to produce the two vowels of the target VCV sequences with equal degrees of stress.

Articulatory movement data were collected by means of a Carstens articulograph system AG-100 (Carstens Medizinelektronik GmbH, Bovenden, Germany) composed of a head mount with three magnetic transmitter coils and several small transducer coils attached to the articulatory structures. Coils were placed on the tongue tip, blade, and dorsum and on the lips for recording of lingual and labial movement, on the lower incisors for recording of jaw movement, and on the bridge of the nose and upper incisors for head movement correction. Movement and acoustic data were digitized at a sampling rate of 250 Hz for movement and 10 kHz for the acoustic signal. 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.

For each speaker, a measure of jaw coarticulatory resistance was calculated at the consonant (C) midpoint for consonants and at the two vowels' midpoints (V1, V2) for vowels, as identified on the acoustic waveform with the help of spectrographic displays. Coarticulatory resistance for a given vowel or consonant was obtained by computing the centroid or grand mean across all contextual segments (i.e., all seven consonants for the analysis of coarticulatory resistance for vowels, all three vowels for the analysis of coarticulatory resistance for consonants), and then averaging the Euclidean distances between the (x, y) position values for each contextual segment and the centroid. Thus, for example, the degree of coarticulatory resistance for /p/ at C midpoint equaled the average of three values obtained by computing the square root of the expressions $[(Xp_i\text{-}Xp_{iau})^2 + (Yp_i\text{-}Yp_{iau})^2]$, $[(Xp_a\text{-}Xp_{iau})^2 + (Yp_a\text{-}Yp_{iau})^2]$ and $[(Xp_u\text{-}Xp_{iau})^2 + (Yp_u\text{-}Yp_{iau})^2]$, where Xp_i, Yp_i, Xp_a, Yp_a, Xp_u, and Yp_u are the X and Y values for /p/ next to /i/, /a/, and /u/, and Xp_{iau} and Yp_{iau} are the X and Y values for /p/ averaged across all three vowels. In both vowel and consonant cases, the higher the degree of coarticulatory resistance, the smaller the contextual dispersion from the centroid. In order to determine the separate contribution of the X and Y dimensions to the overall pattern of contextual variability as determined using the Euclidean distance measure, the size of the contextual ranges in X and Y articulatory position was also calculated for each consonant at C midpoint and for each vowel at the midpoint of V1 and V2. In spite of the rotational nature of jaw movement, the two dimensions may contribute different amounts to jaw movement (Edwards and Harris, 1990), and consequently to differences in overall jaw position variability among consonants or vowels.

A measure of coarticulatory aggressiveness was also calculated for each consonant at the V1 and V2 midpoints, and for each vowel at the C midpoint, using the same Euclidean distance method described above. Also here, the higher the degree of coarticulatory aggressiveness associated with a given phonetic segment, the smaller the amount of dispersion among the contextual segments. Thus, the more aggressive the consonant, the less different the vowels will be from one another at the midpoint of the vowel period. Likewise, the more aggressive the vowel, the closer the jaw position values for different contextual consonants will be at the midpoint of the consonant period.

Jaw position data were subjected to a speaker normalization procedure in order to render them comparable across speakers. For that purpose, the minimum and maximum X and Y values were selected for each speaker, and the absolute X and Y values for all tokens were converted to percentage point values relative to the minimum and maximum X and Y values (see Cho, 2001, 2004). The minimum and maximum values in question coincided essentially with those appearing in Fig. 1, e.g., the maximal Y value was the Y value for /s/ or

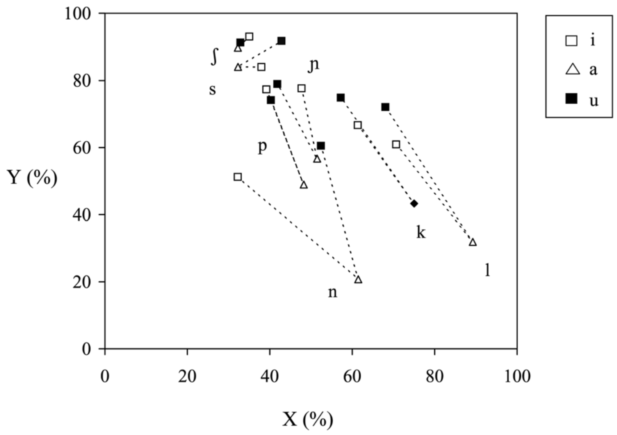

FIG. 1. Jaw position for the consonants /p, n, l, s, ʃ, ɲ, k/ in the vowel contexts /i, a, u/ measured at C midpoint. Data correspond to averages across tokens and speakers. For each target consonant, the three contextual vowels are connected by a dotted line. The front of the vocal tract is on the left and the back is on the right.

/ʃ/ in a high vowel context and the minimal *Y* value was the *Y* value for /n/ or /l/ next to /a/. Data were normalized for the graphic displays appearing in Figs. 1–5 but not for the statistical analyses where "speaker" was included as a random effect in order to account for the intrasubject correlation in each of the measurements.

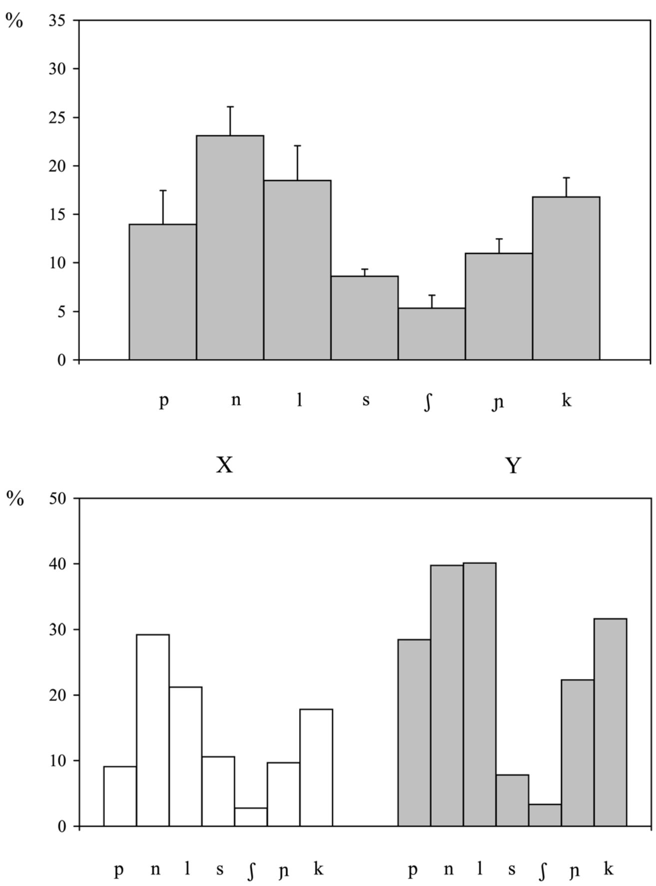

FIG. 2. (Top) Mean Euclidean distances in jaw position for /p, n, l, s, ʃ, ɲ, k/ across the vowel contexts /i, a, u/ measured at C midpoint. Data correspond to averages across tokens and speakers. Error bars correspond to one standard deviation. (Bottom) Jaw position ranges along the *X* (unfilled bars) and *Y* (filled bars) dimensions.

Differences in coarticulatory resistance and aggressiveness were evaluated statistically by running a linear mixed model (LMM) procedure for repeated measures data applying the maximum likelihood estimate of parameters and using values for all sequence tokens. Analyses were performed on the Euclidean distances with "subject" as a random factor, and with "consonant" or "vowel" as within-subject factors for testing coarticulatory resistance and aggressiveness for consonants and vowels, respectively. Additional statistical tests using the same procedure were run separately on the *X* and *Y* jaw position values for vowels at the C midpoint and for consonants at the V1 and V2 midpoints so as to explore the prominence of the V-to-C and C-to-V coarticulatory effects. The levels of the "vowel" factor were "i," "a," and "u," and the levels of the "consonant" factor were "p," "n," "l," "s," "ʃ," "ɲ," and "k." Pairwise comparisons between levels of a given factor were carried out using Bonferroni *post hoc* tests for the *X* and *Y* jaw position data, and Fischer LSD (least significant difference) *post hoc* tests for the Euclidean distances in view of the small amount of data subject to analysis in the latter case. In order to interpret the significant "consonant" × "vowel" interactions, LMM analyses were performed on all levels of a given factor while keeping the other factor constant. The degree of significance was set at $p < 0.05$ in all statistical tests.

III. RESULTS

A. Coarticulatory resistance

1. Consonants

According to the jaw position values across speakers shown in Fig. 1, the jaw is highest for the two fricatives (and higher for /ʃ/ than for /s/) followed, in that order, by the alveolopalatal /ɲ/, the bilabial /p/, the velar /k/, and the apicoalveolars /n, l/ (and higher for /l/ than for /n/). As for the horizontal dimension, /s, ʃ/ are most anterior and /l, k/ most posterior.

Mean Euclidean distances for consonants at C midpoint plotted in Fig. 2 (top graph) reveal that jaw contextual resistance is positively related to jaw height and thus, decreases in the progression /ʃ/ > /s/ > /ɲ/ > /p/ > /k/ > /l/ > /n/. As indicated in Table I (top), a statistically significant "consonant" effect [$F(6, 18) = 14.04$, $p < 0.001$] was associated with differences between the consonants exhibiting maximal and minimal variability (i.e., /n/ and /ʃ/, respectively) and the remaining consonants, as well as between /s, ɲ/ (less variable) and /l, k/ (more variable). A Pearson correlation analysis conducted on data for all seven consonants and all speakers yielded a high correlation value between jaw height and the Euclidean distances [$r(21) = 0.838$, $p < 0.001$]. Moreover, the *X* and *Y* contextual ranges displayed in Fig. 2 (bottom graph) reveal that the consonant-dependent variability differences just described hold along the two dimensions, and that most consonants, i.e., /p, n, l, ɲ, k/, and even /ʃ/, are more variable along the *Y* dimension than along the *X* dimension. Jaw height and the *Y* contextual ranges turned out to be moderately correlated [$r(21) = 0.615$, $p < 0.001$] while jaw fronting and the *X* ranges were not.

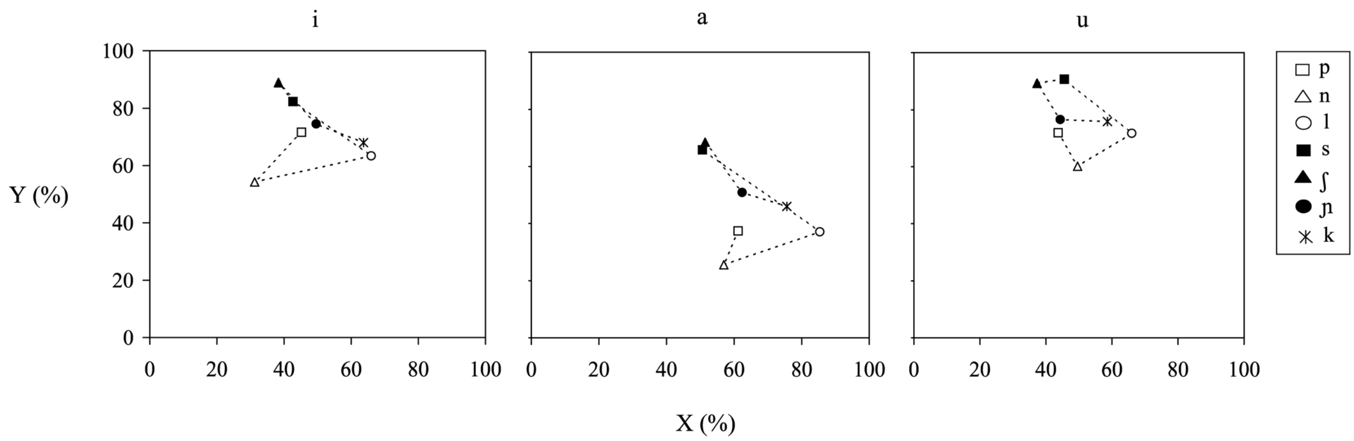

FIG. 3. Jaw position values for the vowels /i, a, u/ in all seven consonant contexts taken at V1 midpoint. Data correspond to averages across tokens and speakers. For each target vowel, the seven contextual consonants are connected by a dotted line. The front of the vocal tract is on the left and the back is on the right.

V-to-C effects in jaw fronting (X) and height (Y) measured at the midpoint of the consonant were consistent with the variability measures reported in Fig. 2. Statistical tests yielded a main vowel effect [$F(2,623.9) = 209.86$, $p < 0.001$] and a significant consonant × vowel interaction [$F(12,623.9) = 12.2$, $p < 0.001$], which, as shown in Fig. 1, turned out to be associated with higher X and Y values for high vs low vowels (/i, u/ > /a/ along the X dimension,

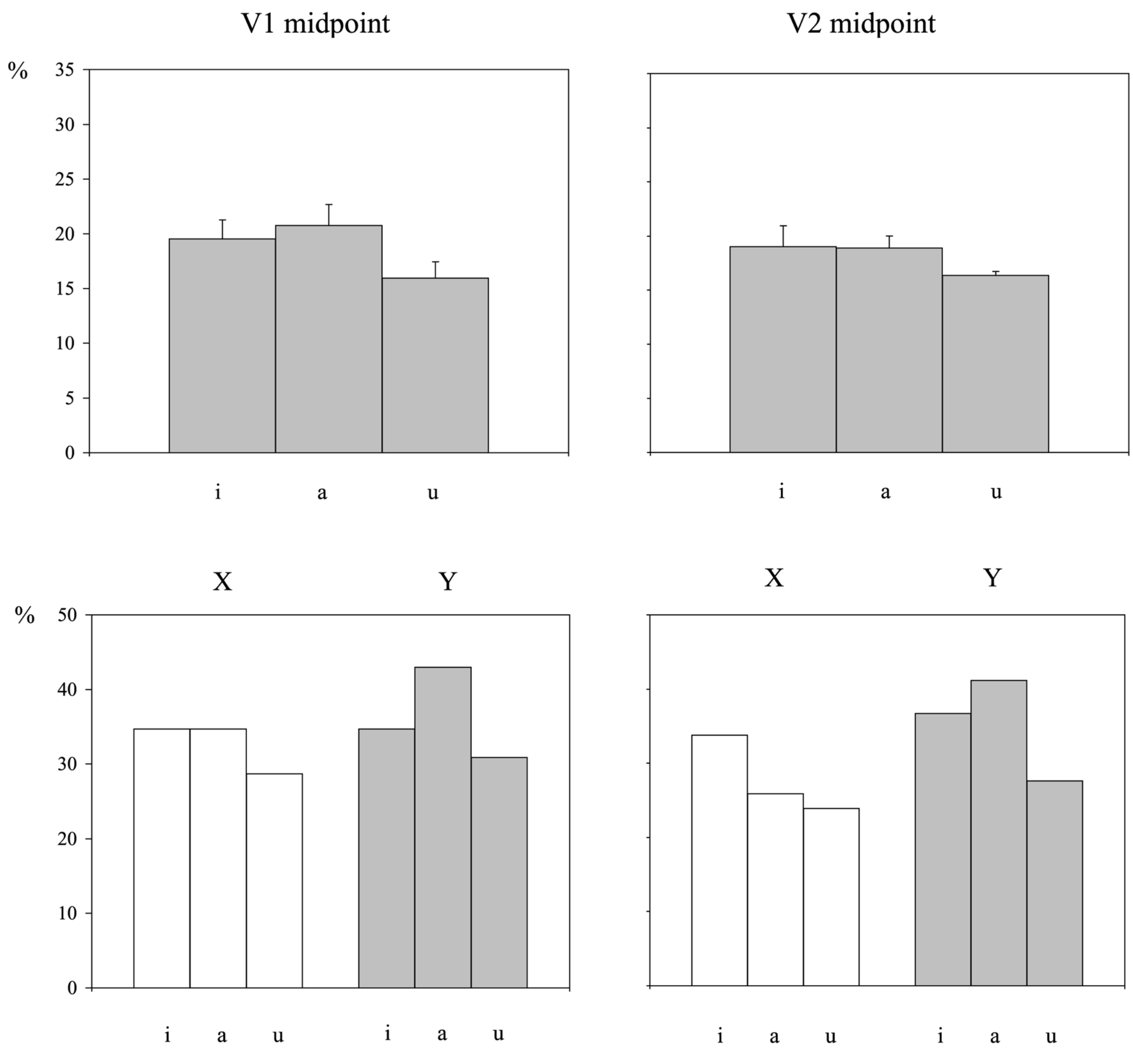

FIG. 4. (Top) Mean Euclidean distances in jaw position for /i, a, u/ across the contextual consonants /p, n, l, s, ʃ, ɲ, k/ measured at the V1 and V2 midpoints. Data correspond to averages across tokens and speakers. Error bars correspond to one standard deviation. (Bottom) Jaw position ranges along the X (unfilled bars) and Y (filled bars) dimensions.

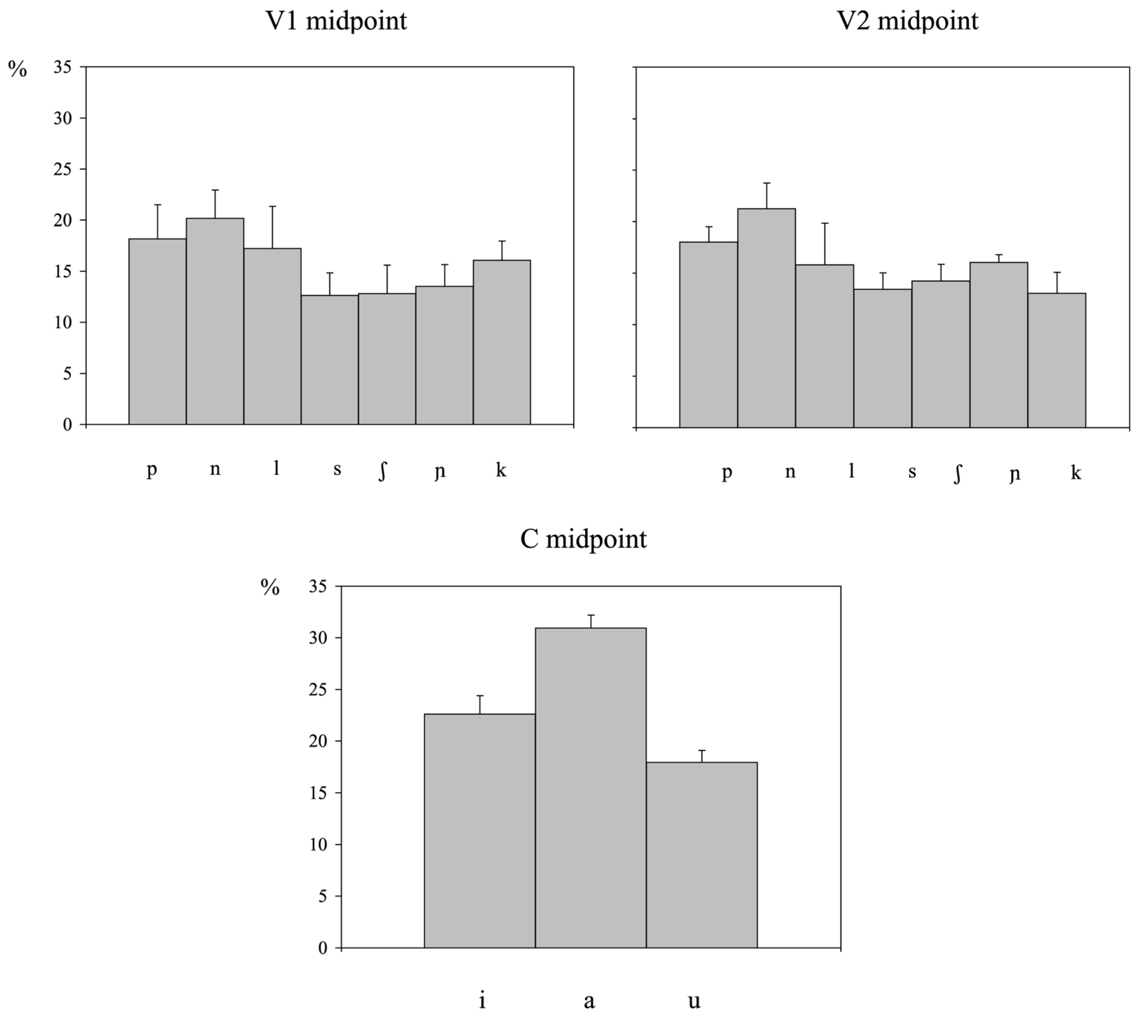

FIG. 5. Mean Euclidean distances in jaw position for consonants at the V1 and V2 midpoints (top) and for vowels at C midpoint (bottom). Data correspond to averages across tokens and speakers. Error bars correspond to one standard deviation.

/u/ $\geq$ /i/ $>$ /a/ along the *Y* dimension) for all consonants except for /ʃ/ and /s/.

2. Vowels

Jaw data for vowels measured at the vowels' midpoints reveal the presence of a higher jaw position for /i, u/ than for /a/ and a more retracted jaw position for /a/ than for /i, u/ (Fig. 3). The figure also shows a slightly higher jaw position for /u/ than for /i/ among high vowels.

Mean Euclidean distances were greater, but not significantly so, for /i, a/ than for /u/ (see the two top graphs of Fig. 4), and not significantly correlated with jaw height. As shown in the bottom graphs of the figure, failure for these vowel-dependent differences in coarticulatory variability to reach significance follows from the different contribution of the *X* and *Y* components, i.e., coarticulatory variability decreases in the progression /i/ $\geq$ /a/ $>$ /u/ along the *X* dimension and /a/ $>$ /i/ $>$ /u/ along the *Y* dimension.

Data on the C-to-V coarticulatory effects were consistent with the variability patterns just described. Statistical tests run on the jaw fronting (*X*) and height (*Y*) values at V1 and V2 yielded a main effect of consonant [V1, *X*: $F(6{,}624) = 72.44$, $p < 0.001$; V2, *X*: $F(6{,}624) = 43.11$, $p < 0.001$; V1, *Y*: $F(6{,}624) = 103.57$, $p < 0.001$; V2, *Y*: $F(6{,}624) = 91.47$, $p < 0.001$), and a significant consonant $\times$ vowel interaction (V1, *X*: $F(12{,}624) = 3.33$, $p < 0.001$; V2, *X*: $F(12{,}624) = 2.75$, $p < 0.01$; V1, *Y*: $F(12{,}624) = 2.96$, $p < 0.001$; V2, *Y*: $F(12{,}624) = 3.87$, $p < 0.001$). C-to-V effects on each vowel may be traced in Fig. 3. Statistical analyses run separately on the data for /i/, /a/, and /u/ revealed that C-to-V effects along the *Y* dimension occur between the fricatives /s, ʃ/ and the laminodorsals and dorsals /ɲ, k/ (which cause the vowels to exhibit the highest jaw position), and the labial /p/ and the non-fricative alveolars /n, l/ (which trigger minimal jaw height during the vowels); moreover, in agreement with vowel-dependent differences in coarticulatory variability along the *Y* dimension (see above), these effects are more numerous for /a/ than for /i, u/ (according to the *post hoc* tests, the number of significant comparisons between consonant pairs was 35 for /a/, 25 for /i/, and 26 for /u/). As for the *X* dimension, vowels exhibit a more retracted jaw position when occurring next to consonants involving a back constriction (/l, k/) than to more anterior consonants (/p, n, s, ʃ, ɲ/); C-to-V effects in horizontal jaw position are more frequent for the target vowel /i/ than for /a, u/ (these vowels exhibited 26, 20, and 21 significant pairwise comparisons, respectively), which is in line with vowel-dependent

TABLE I. Significant consonant-dependent differences at C midpoint and at the V1 and V2 midpoints according to Bonferroni *post hoc* tests (*, $p < 0.05$, **, $p < 0.01$, ***, $p < 0.001$).

		p	n	l	s	ʃ	ɲ	k
C midpoint	p		***			***		
	n			*	***	***	***	**
	l				**	***	*	
	s					*		*
	ʃ						**	***
	ɲ							*
	k							
V1 midpoint	p				*	**	*	
	n			*	***	***	***	**
	l					*		
	s							
	ʃ							
	ɲ							
	k							
V2 midpoint	p					*		*
	n			**	**	***	*	***
	l							
	s							
	ʃ							
	ɲ							*
	k							

differences in coarticulatory variability along the *X* dimension (see above).

B. Coarticulatory aggressiveness

A comparison between the top graphs of Figs. 2 and 5 reveals that the Euclidean distances computed at V1 and V2 midpoints for each of the seven consonants (consonant aggressiveness; Fig. 5) exhibit roughly the same hierarchy as those measured at consonant midpoint (consonant resistance; Fig. 2). The two sets of values were highly correlated, i.e., $r(21) = 0.793$, $p < 0.001$ (V1), $r(21) = 0.703$, $p < 0.001$ (V2). Likewise, as revealed by a comparison between the bottom graph of Fig. 5 and the top graphs in Fig. 4, the Euclidean distances measured at the consonant midpoint for vowels (vowel aggressiveness; Fig. 5) were also positively, though more weakly, correlated with those measured at the vowels' midpoints (vowel resistance, Fig. 4), i.e., $r(9) = 0.613$, $p < 0.05$ (V1), $r(9) = 0.612$, $p < 0.05$ (V2). The fact that phonetic segments exhibit a comparable degree of coarticulation during both the consonantal and vocalic periods means that there is a close correspondence between coarticulatory resistance and coarticulatory aggressiveness. Thus, for example, vowels show less variability when adjacent to the consonants that vary less with vocalic context; those more resistant consonants thus may be said to exert more prominent effects on surrounding vowels. Details on differences in coarticulatory aggressiveness for consonants and vowels follow.

As shown in Fig. 5 (top graphs), Euclidean distance values for consonants at the vowels' midpoint are smaller for fricatives and laminodorsals and dorsals than for bilabials and non-fricative alveolars which should be taken as evidence that the former consonants exert greater C-to-V effects and are thus more aggressive than the latter. Statistical analyses run on these values yielded a main consonant effect [V1: $F(6, 18) = 5.93$, $p < 0.001$; V2: $F(6, 18) = 4.82$, $p < 0.01$) which, as revealed by results from *post hoc* tests performed on data at the two vowels' midpoints (see Table I, middle and bottom), turned out to be related to differences between the most variable consonants /n/ and to a lesser extent /p/, on the one hand, and consonants exhibiting intermediate and minimal degrees of variability (/l, s, ʃ, ɲ, k/), on the other hand. Other significant differences involved /ʃ/ (more resistant) and /l/ (less resistant) at V1, and /k/ (more resistant) and /ɲ/ (less resistant) at V2.

As for coarticulatory aggressiveness from vowels on consonants, Euclidean distances at C midpoint were larger for the low vowel /a/ than for the high vowels /i, u/ (Fig. 5, bottom graph). An LMM analysis yielded a main vowel effect [$F(2, 6) = 24.66$, $p < 0.001$] which turned out to be associated with more variability for /a/ than for /i/ ($p < 0.01$) and /u/ ($p < 0.001$), thus meaning that the high vowels are more aggressive than the low vowel.

IV. DISCUSSION

Data on jaw position reported in the present investigation suggest that the role of the jaw is not simply to assist the tongue in achieving a specific consonant place of articulation (see Browman and Goldstein, 1990 for this view). Indeed, consonant-dependent differences in jaw height (/ʃ/ > /s/ > /ɲ/ > /p/ > /k/ > /l/ > /n/) were found not to be completely in agreement with consonant-dependent differences in tongue body height for the same Catalan speakers reported in previous studies (/ʃ, ɲ, k/ > /s/> /p, n, l/; Recasens and Espinosa, 2009). A comparison between the two scales indicates that jaw height and tongue dorsum height keep a closer relationship for some consonants (/n, l, ʃ/) than for others (/p, s, ɲ, k/). As in other languages, /l/ has been found to exhibit maximal jaw and tongue dorsum lowering due to several production characteristics such as, laterality, apicality, and darkness degree. Of particular interest is the finding that /n/ is produced with a similar low jaw position to /l/; maximal jaw lowering for /n/ agrees with data reported for German (Mooshammer *et al.*, 2007) but not with those for English and Swedish (Keating *et al.*, 1994), and matches the presence of a low tongue dorsum position for the consonant in Catalan. Frication requirements, i.e., the formation of a narrow interdental passage (Shadle, 1985), cause the alveolar /s/ to appear at the top of the jaw height scale but not of the tongue body height scale, while /ʃ/ shows up at the top of both scales presumably since its production involves frication as well as tongue blade and tongue predorsum activation. While being articulated with maximal tongue dorsum height, the alveolopalatal /ɲ/ and the velar /k/ differ regarding jaw height (/ɲ/ > /k/) since the jaw lowers progressively as dorsal closure location becomes more posterior; there is then a closer relationship between jaw and tongue dorsum height for the alveolopalatal than for the velar. As for bilabials, while the tongue plays essentially no role, a relatively high jaw position serves to assist the bilabial closure formation. Regarding vowels, jaw height matches tongue height (/i, u/ > /a/), and the jaw may be argued to assist the tongue for front dorsal /i/ and the lips for /u/.

In agreement with data reported in previous studies, variability in jaw position was found to occur mostly along the vertical dimension, and to be inversely related to jaw height, thus confirming the notion that phonetic segments involving a higher jaw are more constrained and thus, less prone to vary with changes in segmental context than those produced with a lower jaw. As for consonants, lingual fricatives and alveolopalatals are most constrained while velars, /l/ and /n/ are least constrained, with labials lying in between; regarding vowels, /a/ is less constrained than high /i, u/, with /i/ being somewhat more variable than /u/. As outlined in the Introduction, there appear to be several reasons for differences in degree of jaw constraint which will be discussed next in the light of data on lingual coarticulatory resistance for consonants and vowels in Catalan reported in Recasens and Espinosa (2009).

(i) As for front lingual fricatives, a high degree of jaw constraint may be sought in the formation of an interdental passage for noise generation. In addition, /s, ʃ/ are also highly resistant at the tongue body which suggests that the precise shaping of the lingual medial groove for the passage of airflow plays a role in maximal jaw height for the two fricatives. Interestingly enough, both for the tongue and the jaw, the alveolopalatal /ʃ/ was found to be more resistant than the alveolar /s/ in line with differences in the tongue articulator which participates in the formation of the constriction, i.e., blade and predorsum for /ʃ/, tongue tip and/or tongue blade for /s/. It has been argued that tongue position is more prone to adapt to context-dependent on-line perturbations in the case of the alveolar vs alveolopalatal fricative since the articulatory space for /s/ functions as a quantal region and the alveolar fricative exhibits a somato-sensory target involving tongue contact at the lower incisors: /s/ would allow for relatively large changes in constriction size and location since these changes do not affect much the volume of a small and stable sublingual cavity and consequently the spectral characteristics of the frication noise (Ghosh *et al.*, 2010; Perkell *et al.*, 2004).

(ii) For most phonetic segments, a positive relationship between degree of coarticulation and constriction fronting can be largely attributed to the rotational movement of the jaw, i.e., the passive effect of the jaw on the active articulator increases with the distance between the articulator and the condyle (see also Mooshammer *et al.*, 2007). This may account for why the labials /p, u/ and the (alveolo)palatals /ɲ, i/ exhibit less jaw variability than the velar /k/ and the pharyngeal vowel /a/. This scenario matches the patterns of tongue dorsum coarticulation for (lamino)-dorsal /ɲ, i/ (less vowel coarticulation) and for back /k, a/ (more vowel coarticulation), but not for labials which are free to vary in tongue position but are produced with a high and relatively resistant jaw position. In any case, the scenario for velars is special in that these consonants exhibit large differences in dorsal closure location as a function of vowel context, thus becoming palatovelar before front vowels and purely velar before back rounded vowels. Much jaw position variability for /k/ could reflect these differences in closure location to a greater or lesser extent.

(iii) Differences in jaw and tongue coarticulatory resistance among front lingual consonants need to be addressed. Compared to the laminodorsal consonant /ɲ/ (also /i/), the apicals /n, ɫ/ exhibit a lower tongue dorsum and jaw position and are less coarticulation resistant. The reason why laminodorsals are more resistant to vowel coarticulatory effects in jaw height appears to lie in lingual stability induced by the active involvement of the tongue blade and dorsum in closure formation and the implementation of a large tongue-to-palate contact size at closure location and at the sides of the palate surface. Other possible explanations such that considerable jaw height and little contextual jaw variability may be associated with the requirement to produce a prominent burst could apply to the oral stops /t/ (Mooshammer *et al.*, 2007) and /c/, but not to /ɲ/ since nasal consonants exhibit bursts of little acoustic prominence.
More jaw coarticulatory sensitivity than expected for /l/ appears to be partly related to the fact that, as revealed by data on tongue dorsum position reported in Recasens and Espinosa (2009), the alveolar lateral was moderately dark rather than strongly dark in the case of the speakers subject to analysis in the present investigation. Darker realizations impose more severe constraints on tongue predorsum configuration and postdorsum constriction location at the upper pharynx, and should render the jaw more coarticulation resistant. The alveolar nasal /n/ turned out to allow much coarticulation at the two articulatory structures, presumably for the aerodynamic reason pointed out in Sec. I A, namely, the absence of a stringent requirement towards an intraoral pressure rise, and in line with the hypothesis of Mooshammer *et al.* that jaw position for /n/ may not be actively controlled.

(iv) As argued in (ii) above, differences in jaw height and coarticulation between high and low vowels can be attributed to differences in degree of involvement of the front dorsum (for /i/) and lips (for /u/) in constriction formation. On the other hand, more coarticulatory variability for /i/ than for /u/ is in accordance with differences in jaw height for /u/ > /i/ (see Sec. III A 2), and has been attributed to the need for the high front vowel to make room for the bunching of the tongue (Gay, 1974).

Analogously to lingual data reported in previous studies, most vowels and consonants exhibit a positive relationship between jaw coarticulatory resistance and coarticulatory aggressiveness; also for the jaw, phonetic segments happen to be more aggressive the more resistant they are to effects exerted by the contextual segments. In close agreement with the coarticulatory resistance scale, the coarticulatory aggressiveness scale decreases in the progression lingual fricatives, alveolopalatals, velars > labials and /n/ and, to a lesser extent, /l/ for consonants, and high /i, u/ > low /a/ for vowels. This match is, however, less successful than the one between coarticulatory resistance and jaw height presumably since consonant-dependent differences are less prominent at the adjacent vowels than at the target consonant location.

Data reported in this paper are relevant for speech production theories and models of coarticulation. Regarding the former, it has been shown that not only manner of articulation demands for fricatives, but also large degrees of tongue-palate contact for (alveolo)palatal consonants and vowels account for why these phonetic segments are articulated with a high jaw position and are specified for high degrees of jaw coarticulatory resistance. Jaw coarticulation data may be formulated according to several principles of the DAC model of coarticulation. A key concept appears to be jaw height, i.e., degree of constraint increases with jaw height whether jaw raising is induced by the generation of frication or by the involvement of the lips and of a front lingual articulator involving sufficient palate contact. In light of the results provided in this paper, a jaw resistance scale may be proposed which varies in the progression front lingual fricatives > (alveolo)palatals > labials > apicals /n, l/, velars. It would be worth investigating whether the degree of coarticulatory resistance increases for strongly vs moderately dark varieties of /l/, and is invariably high for the apicoalveolar trill in line with the precise articulatory and aerodynamic demands involved in the performance of trilling (McGowan, 1992).

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Browman, C. P., and Goldstein, L. (**1990**). “Tiers in articulatory phonology, with some implications for casual speech,” in *Papers in Laboratory Phonology I: Between the Grammar and Physics of Speech*, edited by M. Beckman and J. Kingston (Cambridge University Press, Cambridge), pp. 341–376.

Buchaillard, S., Perrier, P., and Payan, Y. (**2009**). “A biomechanical model of cardinal vowel production: Muscle activations and the impact of gravity on tongue positioning,” J. Acoust. Soc. Am. **126**, 2033–2051.

Cho, T. (**2001**). “Effects of prosody on articulation in English,” in *UCLA Dissertations in Linguistics* (University of California, Los Angeles), Vol. 22.

Cho, T. (**2004**). “Prosodically-conditioned strengthening and vowel-to-vowel coarticulation in English,” J. Phonetics **32**, 141–176.

Edwards, J., and Harris, K. S. (**1990**). “Rotation and translation of the jaw during speech,” J. Speech Hear. Res. **33**, 550–562.

Farnetani, E., and Faber, A. (**1992**). “Tongue-jaw coordination in vowel production: Isolated words versus connected speech,” Speech Commun. **11**, 401–410.

Fletcher, J., and Harrington, J. (**1999**). “Lip and jaw coarticulation,” in *Coarticulation: Theory, Data and Techniques*, edited by W. J. Hardcastle and N. Hewlett (Cambridge University Press, Cambridge), pp. 164–179.

Fowler, C. A., and Brancazio, L. (**2000**). “Coarticulatory resistance of American English consonants and its effects on transconsonantal vowel-to-vowel coarticulation,” Lang. Speech **43**, 1–41.

Gay, T. (**1974**). “A cinefluorographic study of vowel production,” J. Phonetics **2**, 255–266.

Ghosh, S. S., Matthies, M. L., Maas, E., Hanson, A., Tiede M., Ménard, L., Guenther, F. H., Lane, H., and Perkell, J. S. (**2010**). “An investigation of the relation between sibilant production and somatosensory and auditory acuity,” J. Acoust. Soc. Am. **128**, 3079–3087.

Hoole, P., Gfroerer, S., and Tillmann, H. G. (**1990**). “Electromagnetic articulography as a tool in the study of lingual coarticulation,” Forschungsberichte des Instituts für Phonetik und Sprachliche Kommunikation der Universität München **28**, 107–122.

Iskarous, K., Fowler, C. A., and Whalen, D. H. (**2010**). “Locus equations as an acoustic expression of articulator synergy,” J. Acoust. Soc. Am. **128**, 2021–2032.

Keating, P., Lindblom, B., Lubker, J., and Kreiman, J. (**1994**). “Variability in jaw height for segments in English and Swedish VCV sequences,” J. Phonetics **22**, 407–422.

Lee, S.-H. (**1994**). “Orals, gutturals, and the jaw,” in *Phonology and Phonetic Evidence: Papers in Laboratory Phonology IV*, edited by B. Connell and A. Arvaniti (Cambridge University Press, Cambridge), pp. 343–360.

Lindblad, P., and Lindqvist, S. (**2003**). “[l] tends to be velarised, apical as opposed to laminal, and produced with a low jaw, and these features are connected,” in *Proceedings of the 15th International Congress of Phonetic Sciences*, edited by M. J. Solé, D. Recasens, and J. Romero (Causal Productions, Barcelona), pp. 1899–1902.

McGowan, R. S. (**1992**). “Tongue-tip trills and vocal-tract wall compliance,” J. Acoust. Soc. Am. **91**, pp. 2903–2910.

Mooshammer, C., Hoole, P., and Geumann, A. (**2007**). “Jaw and order,” Lang. Speech **50**, 145–176.

Perkell, J. S., Matthies, M. L., Tiede, M., Lane, H., Zandipour, M., Marrone, N., Stockmann, E., and Guenther, F. H. (**2004**). “The distinctness of speakers’ /s/-/ʃ/ contrast is related to their auditory discrimination and use of an articulatory saturation effect,” J. Speech Lang. Hear. Res. **47**, 1259–1269.

Recasens, D. (**1999**). “Lingual coarticulation,” in *Coarticulation: Theory, Data and Techniques*, edited by W. J. Hardcastle and N. Hewlett (Cambridge University Press, Cambridge), pp. 80–104.

Recasens, D., and Espinosa, A. (**2009**). “An articulatory investigation of lingual coarticulatory resistance and aggressiveness for consonants and vowels in Catalan,” J. Acoust. Soc. Am. **125**, 2288–2298.

Recasens, D., Pallarès, M. D., and Fontdevila, J. (**1997**). “A model of lingual coarticulation based on articulatory constraints,” J. Acoust. Soc. Am. **102**, 544–561.

Shadle, C. (**1985**). “The acoustics of fricative consonants,” Ph.D. thesis, MIT.

Stone, M., Faber, A., Raphael, L. J., and Shawker, T. H. (**1992**). “Cross-sectional tongue and linguopalatal contact patterns in [s], [ʃ] and [l],” J. Phonetics **20**, 253–270.

Tabain, M. (**2009**). “A preliminary study of jaw movement in Arrernte consonant production,” J. Int. Phonetic Assoc. **39**, 33–51.