Lingual kinematics and coarticulation for alveolopalatal and velar consonants in Catalan

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Vertical lingual movement data for the alveolopalatal consonants /ʃ/ and /ɲ/ and for the dorsovelar consonant /k/ in Catalan /aCa/ sequences produced by three speakers reveal that the tongue body travels a smaller distance at a slower speed and in a longer time during the lowering period extending from the consonant into the following vowel (CV) than during the rising period extending from the preceding vowel into the consonant (VC). For two speakers, two-phase trajectories characterized by two successive velocity peaks occur more frequently during the former period than during the latter, whether associated with tongue blade and dorsum (for alveolopalatals) or with the tongue dorsum articulator alone (for velars). Greater tongue dorsum involvement for /ɲ/ and /k/ than for /ʃ/ accounts for a different kinematic relationship between the four articulatory phases. The lingual gesture for alveolopalatals and, less so, that for velars may exert more prominent spatial and temporal effects on V2 than on V1 which is in agreement with the salience of the C-to-V carryover component associated with these consonants according to previous coarticulation studies. These kinematic and coarticulation data may be attributed to tongue dorsum biomechanics to a large extent. © *2010 Acoustical Society of America.* [DOI: 10.1121/1.3372631]

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I. INTRODUCTION

Articulatory data for different languages reveal that the so called "palatal" consonants /ʎ/, /ɲ/, /c/, /ɟ/, /ʃ/, /ç/, /ʝ/, and /j/ do not form a homogeneous articulatory class but may be subdivided into two place of articulation types, i.e., alveolopalatals and palatals proper. Alveolopalatals are produced simultaneously at the alveolar and palatal zones with the tongue blade and the tongue dorsum; palatals are dorsal consonants articulated at the palatal zone exclusively. Electropalatographic (EPG) data indicate that Catalan dialects may favor either one place of articulation or the other. Thus, while /ʎ/ is fixedly alveolopalatal in Eastern and Majorcan Catalan, the nasal stop is alveolopalatal in Eastern Catalan, and may be alveolopalatal or palatal in Majorcan Catalan where an oral stop [c] exhibiting both places of articulation is also present as an allophone of /k/. A similar scenario holds in other languages (see Recasens and Espinosa, 2006, pp. 296–297 for a review). In both Catalan dialects, the fricatives /ʃ/ and /ʒ/ (and the corresponding affricates /tʃ/ and /dʒ/) may be characterized as alveolopalatal instead of as postalveolar or palatoalveolar as in other languages, though they involve less dorsal rising than /ɲ/ in line with consonant-dependent differences in constriction degree associated with manner of articulation (Recasens and Espinosa, 2007). The present paper investigates the kinematic characteristics of alveolopalatal /ɲ/ and /ʃ/ in Eastern Catalan using electromagnetic midsagittal articulometry (EMA). Kinematic data for the dorsovelar stop /k/ will also be analyzed for comparison.

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Some information about linguopalatal contact changes over time for alveolopalatal consonants is available in the phonetics literature. According to EPG and x-ray data for /ɲ/, closure location for alveolopalatal stops is restricted to the postalveolar or the postalveolo-prepalatal zone at closure onset, and undergoes some expansion of the closure area as consonant midpoint is approached; the release takes place gradually from front to back such that the laminal contact is released before the dorsal contact which results into an /j/-like tongue body configuration at closure offset (Hungarian: Bolla, 1980; Eastern Catalan: Recasens *et al.*, 1995). However, neither the EPG nor the x-ray techniques provides detailed information about tongue kinematics which will be of concern in the present investigation. The present study investigates possible kinematic differences between the tongue body rising and lowering movements to and from the point of maximum displacement, which have been claimed to differ regarding control and muscle synergies (Gracco, 1988, 1994).

There are several reasons for carrying out this analysis, such as possible interactions between tongue body articulatory structures and kinematic differences among consonants. Another goal is to find out whether there is any relationship between the kinematic characteristics of the VC rising lingual trajectory (the trajectory extending from the preceding vowel into the consonant) and the CV lowering ligual trjectory (the trajectory extending from the consonant into the following vowel), and the relative prominence of the anticipatory and carryover components of C-to-V coarticulation in VCV sequences, mostly for alveolopalatal consonants but for velars as well. In contrast with more anterior dental and alveolar consonants, alveolopalatals and velars exert not only considerable anticipatory effects but also much carryover

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coarticulation and, consequently, may trigger regressive and progressive assimilatory processes on the preceding and following vowels (Geng, 2008; Recasens *et al.*, 1997). This coarticulatory behavior could result from the biomechanical properties of the tongue dorsum articulator which is actively involved in the production of lamino-dorsal and dorsal consonants. The expected trend is then for the CV lingual trajectories to reflect the tongue dorsum contribution to a similar or greater extent than the VC lingual trajectories.

In order to evaluate the kinematics of the rising and lowering tongue movements, research will be carried out on tongue displacement, velocity and duration, as well as on the possible presence of two inflection phases characterized by two velocity peaks. Sections I A through I D review these kinematic characteristics for consonants in general, and formulate several predictions about lingual movement behavior for alveolopalatals and velars.

A. Displacement

Lingual displacement for consonants in CV and VC sequences has been found to vary directly with the distance between the consonant and the vowel targets and, thus, e.g., to decrease in the progression /ka/ > /ku/ > /ki/ (Löfqvist and Gracco, 1995). Displacement degree is also conditioned by manner of articulation and voicing in the consonant: greater lingual displacement has been shown to occur for stops than for fricatives (for /t/ vs /z/; Fuchs *et al.*, 2006), and for voiced than for voiceless stops though this difference may be associated with the duration characteristics of the vowels flanking the consonant (for /g/ vs /k/ and for /d/ vs /t/; Löfqvist and Gracco, 1994, 1995; Ostry *et al.*, 1983; Parush *et al.*, 1983).

Kinematic data for different lingual consonants and articulators reveal the existence of larger vertical displacement for the VC transition than for the CV transition. This has been reported to be the case for the tongue tip in sequences such as /ada, aza/ where the offset of apical lowering occurs at a higher spatial location than the onset of apical rising (Kent and Moll, 1972), and for the tongue body in VCV sequences with the consonants /t, s, k/ but not in those with /l/ which exhibit the opposite pattern (Kuehn and Moll, 1976). According to the former study, however, this asymmetrical relationship may disappear at fast speaking rates, mostly so for apicals. Data on tongue dorsum displacement for three speakers reported by Parush *et al.* (1983) reveal that the asymmetrical pattern of interest may not occur in VCV sequences with /k/, i.e., it holds for all speakers in the case of the sequences /oko, uku/ but just for one speaker in the case of the sequence /aka/.

Regarding alveolopalatals, the fact that /ɲ/ shows considerable lamino-predorsal involvement during closure formation and a prominent /j/-like dorsopalatal configuration at closure offset suggests that the CV lowering movement should exhibit less extensive displacement than the VC rising movement, and that the tongue body position should be higher at the offset of the CV trajectory than at the onset of the VC trajectory. This expectation appears to be consistent with the physico-biomechanical characteristics of the tongue dorsum such as mass and inertia, and also with the prominence of the carryover effects exerted by these consonants on the following vowel.

B. Velocity

Peak velocity appears to be strongly correlated with articulatory displacement for limb movements (Cooke, 1980) as well as for speech related articulatory movements mostly as a function of stress (Munhall *et al.*, 1985; Ostry *et al.*, 1983) but also of speech rate (Ostry and Munhall, 1985) and phonetic segment. Regarding the latter factor, which is of special interest in the present research, the tongue has been reported to travel faster for stops than for fricatives, i.e., for /t, d/ than for /s, z/ (Fuchs *et al.*, 2006; Kent and Moll, 1972; Kuehn and Moll, 1976), and more slowly for the dorsal stop /k/ than for the non-dorsal stop /t/ (Kuehn and Moll, 1976). Löfqvist and Gracco (2002) found, however, no clear differences in articulatory velocity between the tongue tip and the tongue dorsum in VCV sequences. Lingual movement may also proceed at a faster speed for voiced consonants than for their voiceless cognates, as shown by the VC lingual trajectories for the velars /k, g/ and, less clearly so, for the alveolars /t, d/, though, as pointed out above, this difference may be associated with the duration characteristics of the adjacent vowel (Kent and Moll, 1969; Löfqvist and Gracco, 1994, 1995; Parush *et al.*, 1983).

Since articulatory displacement is often greater during the VC closing vs CV opening movements, velocity should also be higher for the former than for the latter. This has been found to occur for the tongue body movement trajectories for /d, z, j/ (Kent and Moll, 1972), and for those for /t, k/ but not for those for /l/ (Kuehn and Moll, 1976), in VCV sequences with a low vowel. A faster (and perhaps more controlled) closing vs opening movement is in agreement with the association of the closing period with the formation of an occlusion or a constriction and of the opening period with vowel sounds (Gracco, 1994).

C. Duration

The relationship between movement duration, and movement displacement or peak velocity, is less straightforward and often negative (see Cooke, 1980 for non-speech movements). In comparison to the lingual constriction gesture for fricatives, the tongue closing gesture for stops travels a larger distance at a faster speed in less time (Fuchs *et al.*, 2006; Kuehn and Moll, 1976). Regarding dorsovelars, some studies report greater VC displacement, velocity, and duration values for /g/ than for /k/ (Löfqvist and Gracco, 1994, 1995), while others report no correlation between displacement or velocity, on the one hand, and duration, on the other hand (Parush *et al.*, 1983).

In line with the salience of the carryover C-to-V effects for alveolopalatals and velars, the CV lowering movement is expected to last longer than the VC rising movement in VCV sequences with these consonants. This expected trend is in agreement with the principle that an increase in curvature, which may be associated with physical and biomechanical sources and with muscle force directions (see Sec. I D),

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should be accompanied by a slowing of the articulatory movement and, thus, a longer time to travel the same distance (Perrier and Fuchs, 2008; Tasko and Westbury, 2004).

D. VC and CV movement phases

VC and CV lingual trajectories follow curved paths and loops may occur during the closure period for dorsal consonants (Mooshammer *et al.*, 1995). It has been suggested that these curved paths are strongly influenced by tongue biomechanics, including passive tongue elasticity, muscular anatomy, and force generation mechanisms (see data for /kak/ in Munhall *et al.*, 1991, and for /VkV/ sequences with /i, a, u/ in Perrier *et al.*, 2003).

VCV curved trajectories may give rise to two or more successive velocity peaks during the closing and/or opening periods. Evidence for an increase in the number of velocity peaks in speech production has been reported to occur at slower rates (tongue tip: Adams *et al.*, 1993; jaw: Wieneke *et al.*, 1987), with an increase in segmental duration for tense vs lax vowels (Kroos *et al.*, 1997), and, both for real and modeled data, in a /y/-/u/ movement (Payan and Perrier, 1997). It remains unclear whether the presence of multiple peaks in single articulatory movements results from an active control mechanism ensuring spatial and temporal adjustments though a sequence of submovements, or else should be attributed to muscular and biomechanical factors (see Fuchs and Perrier, 2005, for a review of these two theoretical approaches). As for the latter possibility and crucially for the consonants under investigation in this paper, the presence of multiple peaks in tongue movements could be due to the co-contraction of antagonistic muscles such as the posterior genioglossus driving the tongue forward and upward and the anterior genioglossus forming the midline groove and pulling the dorsum down for alveolopalatals, and the genioglossus and styloglossus for velars (Fujimura and Kakita, 1979; Perrier *et al.*, 2003; Takano and Honda, 2006). Other potential multiple peak triggers are as follows: passive tongue elasticity; tongue-palate collision, such that velocity changes may occur as the tongue approaches and is released from the palate; the influence of jaw and labial activity on tongue movement; and the successive activation of different muscle structures for the realization of consecutive phonetic segments, e.g., the genioglossus for alveolopalatals, the styloglossus for velars, and the hyoglossus and the pharyngeal constrictors for /a/.

In line with data on linguopalatal contact changes over time described in Sec. I, VC closing and CV opening paths for alveolopalatal consonants are expected to exhibit two phases associated with the laminal or lamino-predorsal and with the dorsal activity: an initial dorsal phase (I) before a laminal phase (II) during the VC rising trajectory, and a termination dorsal phase (IV) following a laminal phase (III) during the CV lowering trajectory. The four phases will be also referred to as peripheral (I and IV) and central (II and III) throughout the paper. Moreover, since the /j/-like component is supposed to be especially salient at closure release, the initial expectation is for two phases to be available during the CV trajectory rather than during the VC trajectory. This expectation is consistent with a trend for double peaks to occur in longer vs shorter movements. Regarding velars, the presence of two-phase VC and CV trajectories should result from the intrinsic characteristics of the tongue dorsum motion alone since the tongue blade does not intervene actively in the production of these consonants.

Little is known about differences in displacement, velocity, and duration between the two-phase components that may occur during the VC rising and CV lowering articulatory trajectories. As for alveolopalatals, we expect phases I and IV, which should be associated with tongue dorsum activity, to exhibit less displacement, proceed more slowly and last longer than the two tongue blade dependent phases II and III. In addition, if the dorsal component is more clearly defined during phase IV than during phase I, the former phase ought to travel a smaller distance more slowly and last longer than the latter. As for velars, two-phase components resembling those for alveolopalatals could occur if the tongue dorsum travels most slowly at onset and offset of the VCV trajectory.

E. Summary of research goals and hypotheses

The testing hypotheses of our investigation may be summarized as follows. The VCV kinematic and coarticulatory characteristics for alveolopalatals and velars ought to vary with rising vs lowering trajectory, consonant, and phase. In comparison to the CV trajectory, the VC trajectory should travel a larger distance at a faster rate and in less time; moreover, the tongue body could occupy a higher position at CV offset than at VC onset. As for consonant-dependent differences, displacement and velocity could vary with tongue dorsum involvement for /k/ > /ɲ/ > /ʃ/ or else with manner requirements for /ɲ, k/ > /ʃ/, while duration ought to decrease in the progression /ʃ/ > /ɲ, k/. Double phases should occur more frequently at the CV trajectory than at the VC trajectory; moreover, lesser displacement, a lower velocity, and a longer duration should hold for the two peripheral phases I and IV than for the central phases II and III, and for the CV termination phase (IV) than for the VC initiation phase (I).

II. METHOD

A. Data recording procedure

EMA recordings were carried out for ten tokens of symmetrical /aCa/ sequences with the consonants /ʃ, ɲ, k/ uttered by the three Eastern Catalan speakers DR, JP, and JC. The vowel /a/ was chosen since it involves a low tongue predorsum position and, thus, allows a full implementation of the lingual gesture for the consonants under analysis. The /aCa/ sequences were preceded and followed by /p/ and embedded in the Catalan sentences [ˌɡɾaβə_əˈβans] "He records_earlier." The inclusion of a labial consonant and /ə/ immediately before and after the target sequence ensured that the lingual activity for the contextual segments would not interfere with that for the alveolopalatal and velar consonants of interest. Speakers were instructed to read the /aCa/ sequences with a

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similar degree of stress on the vowels preceding and following the target consonant so as to eliminate possible prosodically induced articulatory and acoustic differences between the two vowels. This task was possible since VCV sequences with two lexically stressed vowels are allowed in Catalan provided that a word boundary occurs between the consonant and V1 or V2, and also because the sentence stress did not fall on any of the adjacent vowels but on the last word of the carrier sentence [əˈβans].

Articulatory movement data were collected by means of a Carstens Articulograph AG-100. This system is composed of a head mount with three magnetic transmitter coils and several small transducer coils attached to the articulatory structures. Movement of the transducer coils induce a signal which results in a set of voltages which are converted to distance. 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 and on the upper and lower lip. Coils were also attached to the bridge of the nose and upper incisors for head movement correction. More details on these recordings may be found in Recasens, 2002. Movement and acoustic data were digitized at a sampling rate of 250 Hz for movement and at 10 kHz for the acoustic signal. The time resolution of the EMA data was 4 ms. 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 (FIR) low pass filter using a Kaiser window with a cut-off frequency of 25 Hz. The first and second derivatives of the position signal, i.e., velocity and acceleration, were computed by central differentiation, and smoothed using the same filtering procedure as above. Differentiation and smoothing were performed using a MATLAB script.

B. Analysis of articulatory trajectories

1. VC and CV movement

The TL and TD data were processed for the vertical dimension. For each /aCa/ sequence token, the onset of VC rising movement, the articulatory displacement maximum and the offset of CV lowering movement were defined algorithmically at zero crossings in the *Y* velocity signal (see Fig. 1). We did not take displacement measurements integrating the *X* and *Y* dimensions based on landmarks occurring in the tangential velocity curve for several reasons. First, the fact that the contextual vowel is low often renders the tongue body rising/lowering component for /ʃ, ɲ, k/ especially salient, as for the trajectories for all consonants for speaker JC and for /ɲ, k/ for speaker JP in Fig. 2. More importantly, even in cases where tongue body fronting and rising occurs simultaneously or articulatory movement is greater horizontally than vertically, the inflection time between two phases during the VC and CV trajectories was not the same in the *X* and *Y* directions but took place earlier vertically than horizontally most of the time as indicated by the dashed circles in Fig. 2. Other scholars have also used the vertical displacement signal as representative of lingual gestures for dorsal consonants, and the zero crossings of the vertical velocity signal for determining the corresponding onset and offset times of articulatory displacement (see Parush *et al.*, 1983).

No special threshold criterion was applied for identifying the onset and offset times of the tongue blade and tongue dorsum gestures since we were especially interested in determining as precisely as possible the temporal boundaries of the lingual rising and lowering movements and of the slow moving dorsal phases I and IV. Measures include duration and peak velocity values, and differences in spatial displacement between onsets and offsets, both for the VC and CV trajectories. Average velocities were also calculated by dividing the total displacement by the time required to accomplish the movement.

2. Trajectory phases

It was often apparent that the VC rising and CV lowering trajectories did not proceed continuously but could be split into two phases of articulatory movement exhibiting different velocities. Thus, the tongue dorsum could travel more slowly at the beginning and move faster later on during the VC rising trajectory, while the reverse could happen during the CV lowering trajectory. Following Perkell and Matthies (1992) and as exemplified in Fig. 1, those two displacement phases were divided from each other based on acceleration maxima flanked by two zero crossings defined algorithmically in the acceleration signal. This could result into the four phases I, II, III, and IV.

For each phase, measurements were taken of the duration, peak velocity, and spatial displacement between onset and offset.

3. Coarticulation

The degree of C-to-V coarticulation was also quantified. In order to take coarticulation measures, we first identified the V1, C, and V2 segmental boundaries in the /aCa/ sequences of interest on the acoustic waveform with the help of spectrograms. V1 onset was taken to occur at the onset of the first pitch pulse following the burst for the first /p/, and V2 offset at the offset of vowel formant structure before closure onset for the second /p/. V1 offset (and C onset) was set at the end of the V1 formant structure which coincides with the onset of the frication noise for /ʃ/, the low intensity formants for /ɲ/, and the acoustic closure for /k/. C offset (and V2 onset) were set at the first vowel pitch pulse after the frication noise for /ʃ/ and after the low intensity formant period of /ɲ/. As for the sequences with /k/, C offset was set at the end of the acoustic closure period and V2 onset at the first vowel pitch pulse (consequently, the 30–40 ms burst for the unaspirated velar stop was excluded both from the consonant and from the vowel).

In order to find out whether the CV lowering movement of the /aCa/ trajectories with /ʃ, ɲ, k/ occurred to a larger extent during or after the consonant, we computed the percentages of this movement over the acoustic period for the consonant both for the TL and the TD data. Moreover, in order to evaluate the relative prominence of the C-to-V anticipatory and carryover coarticulation effects in space and over time, the following comparisons were carried out: be-

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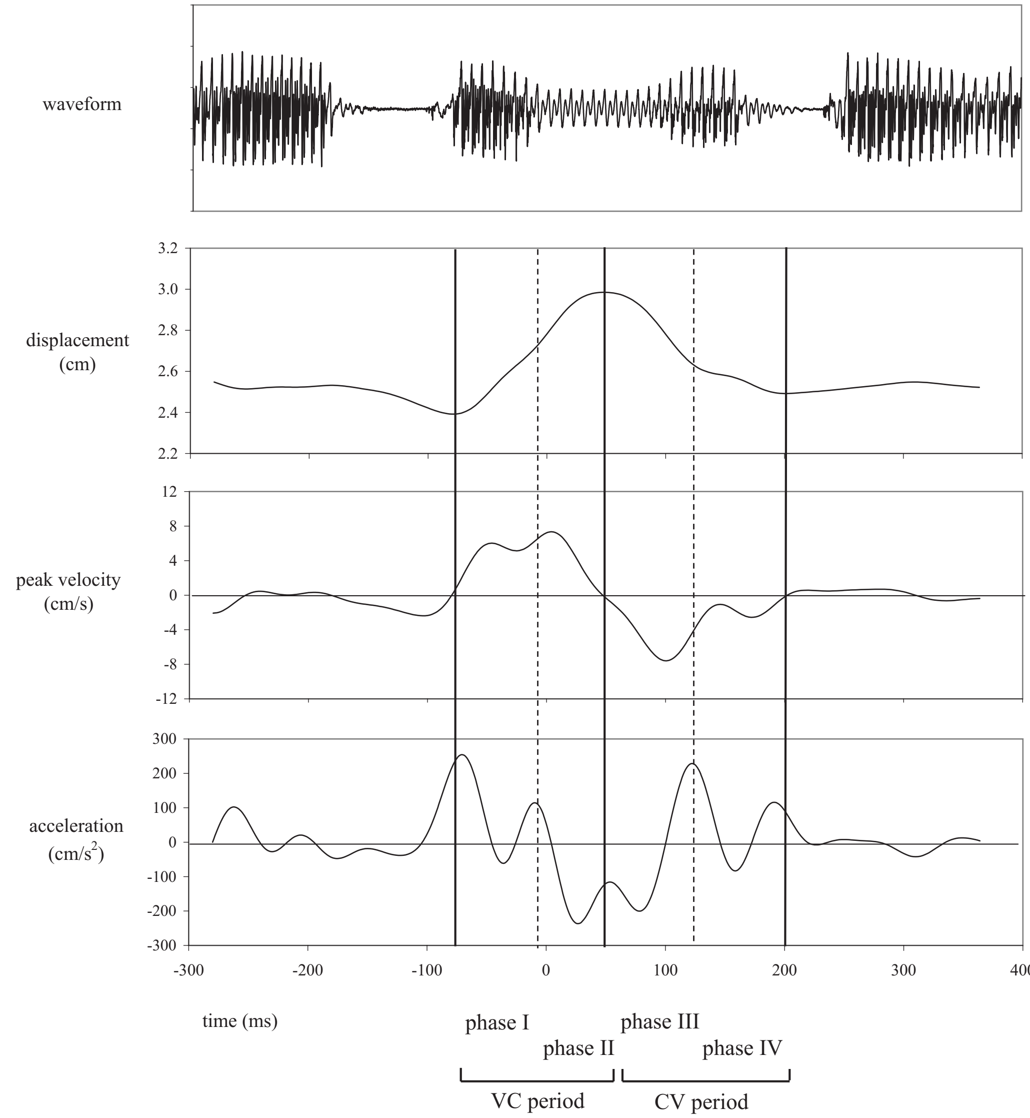

FIG. 1. Acoustic waveform and tongue dorsum vertical displacement, velocity, and acceleration signals for one token of the sequence /aɲa/ (speaker DR). Continuous lines identify onsets and offsets of the VC rising and CV lowering trajectories as determined by zeros in the velocity signal, and discontinuous lines phases I–IV as determined by acceleration maxima. The 0 ms line up point has been set at acoustic closure onset.

tween the TL and TD articulatory position values at VC trajectory onset and at CV trajectory offset (spatial effects), and between the duration of the VC and CV trajectory portions occurring before and after the consonant, respectively (temporal effects).

C. Statistical analysis

Two-way analyses of variance with repeated measures (RM ANOVAs) were run on the displacement, velocity, and duration data for each articulator and each speaker with "trajectory period" (VC and CV) and "consonant" (/ʃ, ɲ, k/) as factors. Bonferroni *post-hoc* tests were applied to the main effects. One-way RM ANOVAs with trajectory period (VC and CV) as factor were also carried out for the interpretation of the significant interactions. The degree of significance was set at $p < 0.05$. Huynh–Feldt corrected degrees of freedom were applied in order to account for violations of the sphericity assumption.

In order to investigate the relative prominence of the anticipatory and carryover C-to-V effects, additional statistical comparisons between the articulatory position values at VC trajectory onset and CV trajectory offset, and between the durations of the articulatory trajectories for the consonant before its onset and after its offset, were performed in the same way as for the kinematic data. They consisted of two-way RM ANOVAs for each articulator and speaker with trajectory period and consonant as factors, and of one-way RM ANOVAs on data for each consonant, articulator, and speaker with trajectory period as factor.

One-way RM ANOVAs were also run on displacement, velocity, and duration values for phases III and IV for speakers DR and JC but not for JP due to the scarce instances of double phases for this speaker. Other statistical comparisons among phases could not be carried out in view of the small number of tokens exhibiting double phases during the VC period for all speakers.

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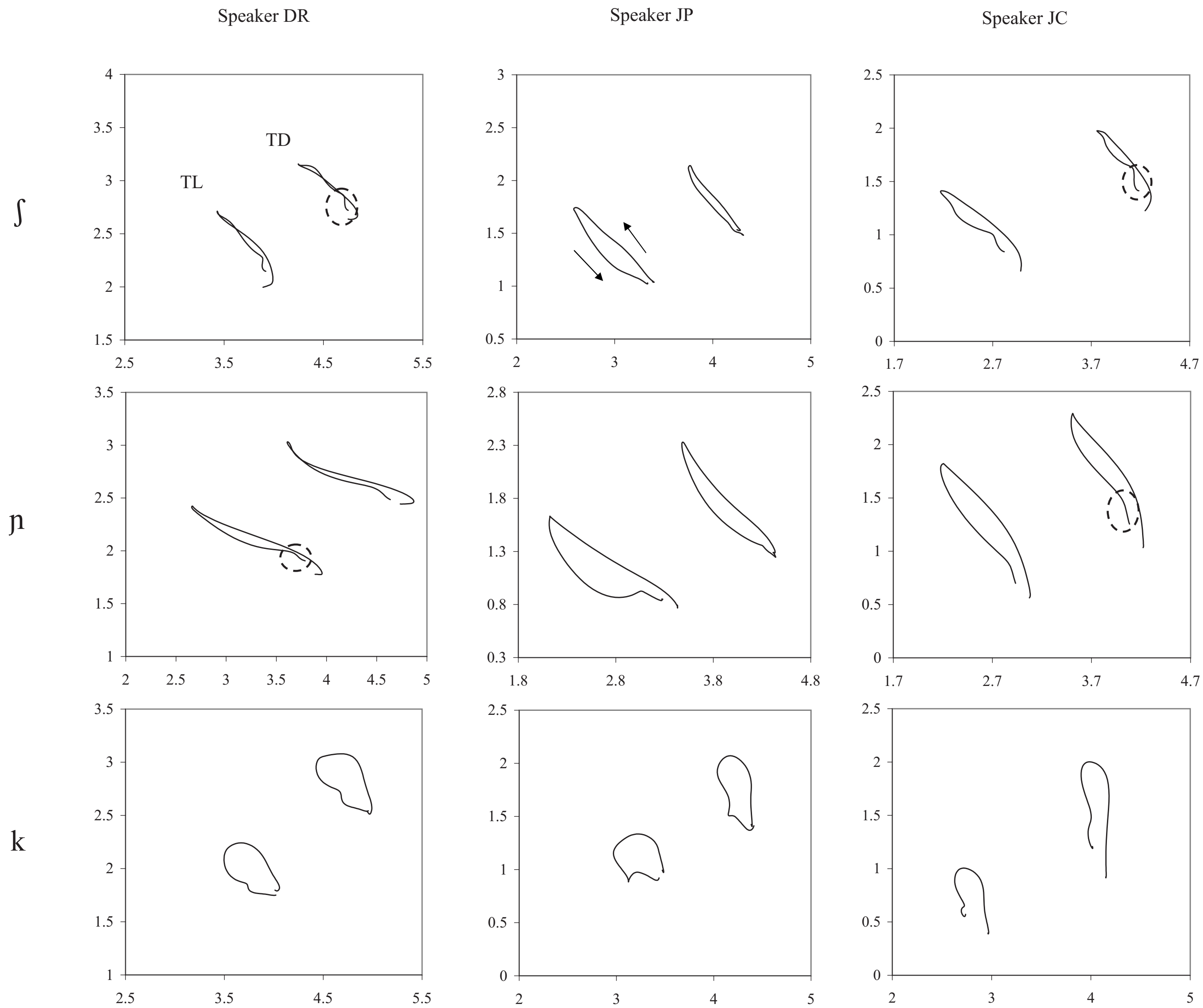

FIG. 2. *X-Y* tongue blade and tongue dorsum trajectories for individual tokens of /aʃa, aɲa, aka/ (all speakers). Trajectory direction is signaled by the arrows in the middle upper graph. Dashed circles have been appended to several trajectory portions exhibiting a vertically oriented CV termination phase.

III. RESULTS

A. Articulator trajectories

1. VC and CV trajectory periods

Figure 3 shows that mean displacement and peak and average velocity values are generally higher for the VC trajectory than for the CV trajectory in the case of the TL and TD articulators. According to Table I, these differences are generally significant for displacement in the case of speakers DR and JC, and for velocity in the case of all speakers. Significant trajectory period × consonant interactions for speaker JP [TL, $F(1.3,\ 12.2)=21.76$, $p=0.000$; TD, $F(1.5,\ 13.5)=4.30$, $p=0.045$] turned out to be associated with a significantly higher displacement for the VC vs CV trajectory period in the case of /ɲ/ but less so or not at all in the case of /ʃ, k/.

Duration turned out to be consistently greater for the CV trajectory than for the VC trajectory for all articulators and speakers.

2. Consonant

According to Fig. 3, the displacement and peak and average velocity values vary basically in the progression /ɲ/ > /ʃ/ ≥ /k/ for the TL movement trajectories and /ɲ/ ≥ /k/ > /ʃ/ for the TD trajectories. Consonant-dependent differences reached significance especially when the speakers taken into consideration were JP and JC (see Table I). These results indicate the existence of faster and more extensive lingual movements for the nasal than for the two other consonants (lower values for /k/ than expected may be due partly to the fact that the TL coil and presumably the TD coil were attached in front of the actual closure location). Moreover, while the nasal stop shows maximal displacement and velocity at both articulators, there is a trend for /k/ to exhibit more displacement and a higher velocity at the tongue dorsum than at the tongue blade, and the reverse for /ʃ/.

Mean values in Fig. 3 also show consonant-dependent differences in duration varying in the progression /ʃ/ > /ɲ/ ≥ /k/ which turned out to be significant for all articulators

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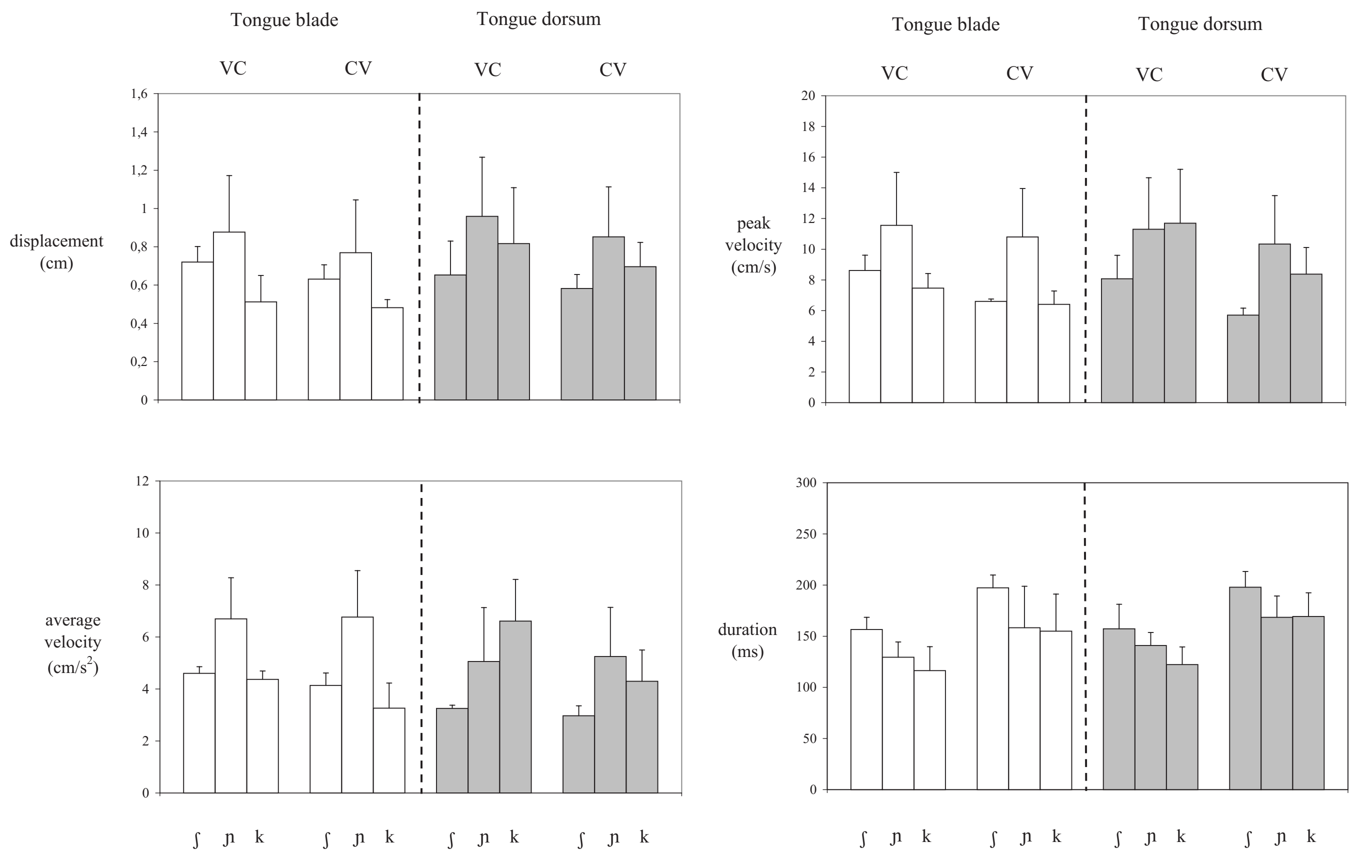

FIG. 3. Mean tongue blade and tongue dorsum displacement, peak and average velocity, and duration values for /ʃ, ɲ, k/ across speakers. Error bars correspond to one standard deviation.

and speakers (Table I). It is thus the case that the VC rising and CV lowering trajectories are longer for the fricative than for the two stops.

B. C-to-V coarticulation

The consonant gesture was found to extend into the stop /p/ preceding V1 at onset and following V2 at offset. Indeed, according to data across speakers, the VC movement trajectory started 98–136 ms before the target consonant and the CV movement trajectory ended 81–125 ms after the target consonant, while V1 and V2 duration ranges were 63–70 and 61–88 ms, respectively.

Consonants differed regarding the portion of the CV lowering trajectory occurring during the acoustic periods of the target consonant and the following sequence /Vp/. For all three speakers, the portion of the lowering movement occurring during the target consonant turned out to be greater for /ʃ, k/ (40%–70%) than for /ɲ/ (30%–45%). Therefore, the portion of the movement trajectory taking place during the sequence /Vp/ was greater for the nasal (55%–70%) than for the other two consonants (30%–60%).

With a few exceptions, the offset of the CV trajectory occurred at a higher articulatory position than the onset of the VC movement trajectory independently of consonant, articulator and speaker (see cross-speaker values in Fig. 4, left graph) which means that the C-to-V spatial effects are greater at the carryover vs anticipatory level. These differences parallel those for articulatory displacement reported in Sec. III A 1, and reached significance for both articulators and speakers DR and JC (Table I). Again there was a significant trajectory period × consonant interaction for speaker JP due to the presence of a higher TL and TD position at CV trajectory offset than at VC trajectory onset for /ɲ/ and, less so or not at all, for /ʃ, k/. There was also a main effect of consonant for all articulators and speakers according to which tongue blade and dorsum are generally located at a higher position at the onset and offset of the lingual gesture for /ʃ/ than for /ɲ, k/ (see Table I).

Differences between the temporal extent of anticipatory and carryover C-to-V coarticulation did not conform to the same pattern across speakers (see Fig. 4, right graph, and Table I). Thus, the portion of articulatory movement occurring during the sequence /Vp/ turned out to be significantly longer than that occurring during the sequence /pV/ (thus, meaning that C-to-V temporal effects are greater at the carryover vs anticipatory level) for speaker DR, but the reverse for speakers JP and JC. The temporal extent of coarticulation appears to be less for /k/ than for the other two consonants in the case of speakers JP and JC.

C. Two-phase movements

The frequency of occurrence of two phases during the VC and CV trajectories, i.e., I and II during the VC rising trajectory and III and IV during the CV lowering trajectory, depends mostly on trajectory period, consonant, and speaker. According to percentages computed over data across conso-

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TABLE I. Significant effects of trajectory period and consonant for trajectory displacement, peak and average velocity and duration, for articulatory position at VC trajectory onset and at CV trajectory offset, and for trajectory duration during the /pV/ and /Vp/ sequences. Data are plotted as a function of articulator (TL and TD) and speaker (DR, JP, and JC). Significance levels are $p<0.05$ (*), $p<0.01$ (**), and $p<0.001$ (***). Non-significant effects are left blank.

			Trajectory period			Consonant		
Displacement	DR	TL	VC>CV	***	29.48(1,9)	ʃ>ɲ,k	***	24.92(1.7,15,1)
		TD	VC>CV	**	22.89(1,9)			
	JP	TL				ɲ>ʃ>k	***	166.01(1.9,17.7)
		TD				ɲ>k>ʃ	***	108.48(1.9,17,8)
	JC	TL	VC>CV	***	89.39(1,9)	ɲ>ʃ>k	***	137.47(1.9,17.5)
		TD	VC>CV	***	977.60(1,9)	ɲ>k>ʃ	***	57.37(2,18)
Peak velocity	DR	TL	VC>CV	***	117.77(1,9)			
		TD	VC>CV	***	105.75(1,9)	k>ʃ	*	5.05(1.9,17.9)
	JP	TL	VC>CV	**	14.61(1,9)	ɲ>ʃ,k	***	105.73(2,18)
		TD				ɲ>k>ʃ	***	110.55(1.7,15.8)
	JC	TL	VC>CV	***	173.44(1,9)	ɲ>ʃ,k	***	151.16(2,18)
		TD	VC>CV	***	556.73(1,9)	ɲ,k>ʃ	***	74.51(1.3,11.8)
Average velocity	DR	TL	VC>CV	***	286.93(1,9)			
		TD	VC>CV	**	9.25(1,9)	ɲ,k>ʃ	**	9.25(2,18)
	JP	TL	VC>CV	**	11.01(1,9)	ɲ>ʃ,k	***	149.21(2,18)
		TD	VC>CV	***	39.13(1,9)	ɲ>k>ʃ	***	82.70(1.5,13.7)
	JC	TL	VC>CV	***	460.73(1,9)	ɲ>ʃ>k	***	206.51(2,18)
		TD	VC>CV	***	450.52(1,9)	ɲ,k>ʃ	***	119.53(2,18)
Duration	DR	TL	CV>VC	***	97.07(1,9)	ʃ>ɲ,k	***	45.69(1.2,11.3)
		TD	CV>VC	***	673.02(1,9)	ʃ>ɲ,k	***	14.25(1.9,16.8)
	JP	TL	CV>VC	**	11.14(1,9)	ʃ>ɲ>k	***	41.42(1.1,9.5)
		TD	CV>VC	**	26.58(1,9)	ʃ>ɲ,k	***	25.58(2,18)
	JC	TL	CV>VC	***	95.08(1,9)	ʃ>ɲ>k	***	38.10(2,18)
		TD	CV>VC	***	38.91(1,9)	ʃ>ɲ>k	***	55.15(2,18)
Position at onset/offset	DR	TL	CV>VC	***	29.48(1,9)	ʃ>ɲ>k	***	242.09(1.7,15.5)
		TD	CV>VC	**	22.88(1,9)	ʃ>k>ɲ	***	206.00(2,18)
	JP	TL				ʃ>ɲ,k	***	49.49(1.1,9.5)
		TD				ʃ>ɲ,k	***	41.19(1.7,15.1)
	JC	TL	CV>VC	***	89.39(1,9)	ɲ>ʃ>k	***	23.91(1.4,12.9)
		TD	CV>VC	***	977.60(1,9)	ʃ>ɲ>k	***	50.27(2,18)
Temporal extent during /pV/ and /Vp/	DR	TL	CV>VC	*	10.49(1,9)	ʃ>ɲ,k	*	6.21(1.2,11.2)
		TD	CV>VC	***	196.20(1,9)			
	JP	TL	VC>CV	**	14.25(1,9)	ʃ>ɲ>k	***	44.10(1.1,10.2)
		TD				ʃ,ɲ>k	***	17.16(2,18)
	JC	TL	VC>CV	***	31.16(1,9)	ʃ,ɲ>k	***	18.43(2,18)
		TD	VC>CV	**	12.75(1,9)	ʃ,ɲ>k	***	28.19(2,18)

nants and tokens, i.e., 30 tokens overall, two-phase TL and TD movements occur more often during the CV trajectory than during the VC trajectory for speakers DR and JC but not for speaker JP (se Fig. 5). Percentages for the individual consonants reveal a trend for two-phase movements to take place somewhat more frequently for /ʃ, k/ than for /ɲ/.

As shown by Table II, there is a robust trend for phase IV to exhibit less articulatory displacement and a lower velocity than phase III for all consonants and speakers DR and JC. Duration was not a good phase predictor, however. Illustrative displacement, velocity, and duration values for the two phases may be found in Fig. 6 (see also Fig. 1).

Inspection of those tokens exhibiting all four phases I–IV reveal some other interesting characteristics (see Fig. 6). According to data for the fricative /ʃ/ (left graphs), phase II and less so phase III show a greater displacement, velocity, and duration than the two peripheral phases. As for the two stops /ɲ, k/ (middle and right graphs), displacement and/or velocity often vary in the progression phase III>phases I, II>phase IV, and phases III and IV happen to be longer than phases I and II. A comparison between the tongue dorsum related phases I and IV among all consonants reveals that, in comparison to the fricative, the two stops exhibit higher displacement and velocity values and similar durations in the case of phase I, and similar displacement and velocity values and longer durations in the case of phase IV.

IV. SUMMARY AND DISCUSSION

Data reported in Sec. III for /aCa/ sequences with /ʃ, ɲ, k/ reveal, as predicted, the existence of greater displacement

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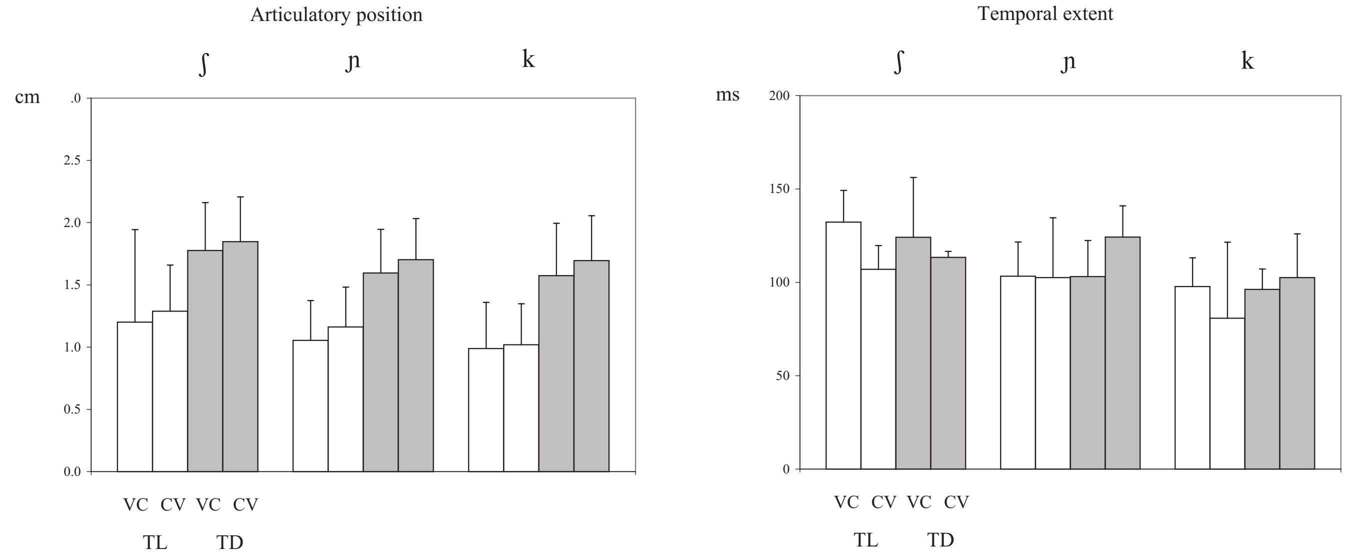

FIG. 4. Tongue blade and tongue dorsum position values at VC trajectory onset and CV trajectory offset (left), and VC and CV trajectory durations during the sequences /pV/ and /Vp/, respectively (right). Data correspond to mean values for /ʃ, ɲ, k/ across speakers. Error bars correspond to one standard deviation.

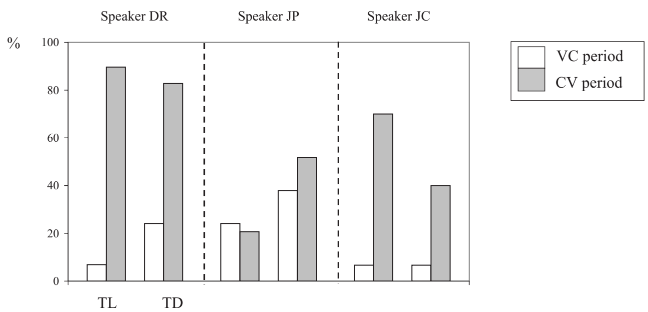

FIG. 5. Frequency of occurrence of two-phase VC and CV trajectories across /ʃ, ɲ, k/ plotted as a function of articulator (TL and TD) and speaker.

and velocity values for the VC vs CV lingual movements (mostly for speakers DR and JC), and loger durations for the CV vs VC ones (all speakers). It is then the case that, in comparison to the rising lingual trajectories, the lowering lingual trajectories for alveolopalatal and velar consonants travel a somewhat smaller distance at a slower speed and in a longer time. In agreement with previous studies (see Introduction), trajectory durations are longer for the fricative /ʃ/ than for the stops /ɲ, k/, while the production of the two stops requires a larger displacement and a higher velocity than the production of the fricative at least at the tongue dorsum. The two articulators TL and TD were found to behave in a highly similar way regarding all kinematic proper-

TABLE II. Significant effects of phase III vs phase IV for trajectory displacement, peak velocity, and duration as a function of articulator (TL and TD) and speaker (DR and JC). Significance levels are $p<0.05$ (*), $p<0.01$ (**), and $p<0.001$ (***). Non-significant effects are left blank. Statistical tests were not run on data for /ɲ/ for speaker JC because of insufficient data values.

			Speaker DR			Speaker JC		
Displacement	TL	ʃ	III>IV	***	47.40(1,9)	III>IV	*	5.56(1,7)
		ɲ	III>IV	***	59.42(1,5)	III>IV	*	22.77(1,3)
		k	III>IV	***	126.47(1,9)	III>IV	***	55.99(1,8)
	TD	ʃ	III>IV	**	22.25(1,8)	III>IV	*	8.93(1,5)
		ɲ	III>IV	***	35.79(1,6)			
		k	III>IV	***	28.22(1,7)	III>IV	*	17.01(1,3)
Peak velocity	TL	ʃ	III>IV	***	174.87(1,9)	III>IV	*	9.55(1,7)
		ɲ	III>IV	***	399.77(1,5)	III>IV	***	175.92(1,3)
		k	III>IV	***	919.53(1,9)	III>IV	***	101.51(1,8)
	TD	ʃ	III>IV	***	32.77(1,8)	III>IV	*	15.43(1,5)
		ɲ	III>IV	***	131.39(1,6)			
		k	III>IV	***	396.20(1,7)	III>IV	**	80.67(1,3)
Duration	TL	ʃ						
		ɲ						
		k						
	TD	ʃ	IV>III	*	6.42(1,8)	III>IV	*	9.26(1,5)
		ɲ						
		k						

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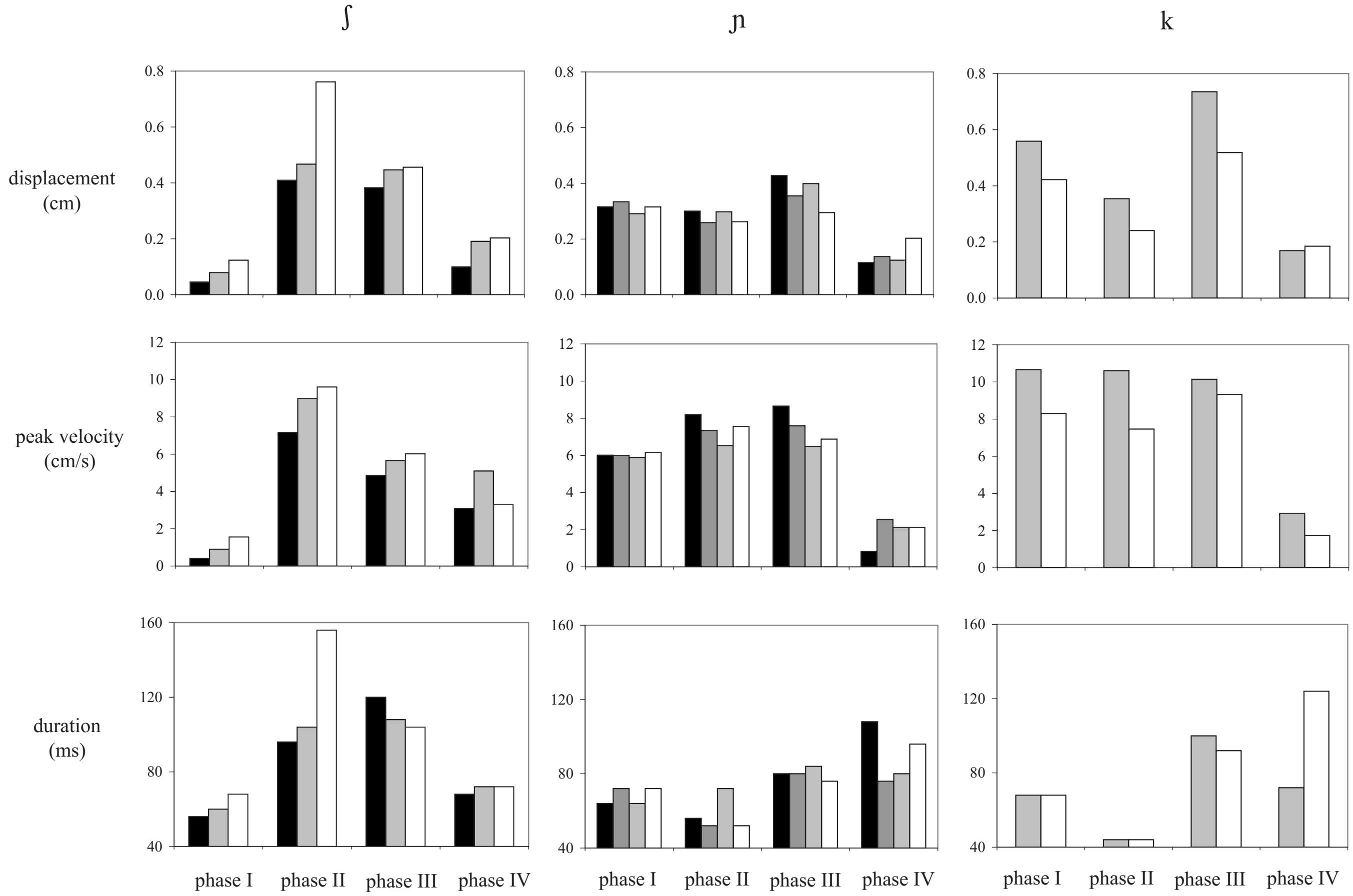

FIG. 6. Tongue dorsum displacement (top), peak velocity (middle), and duration (bottom) values for phases I–IV. Data correspond to tokens exhibiting all four phases, i.e., three tokens for /ʃ/ (two for speaker DR and one for speaker JC), four tokens for /ɲ/ (speaker DR), and two tokens for /k/ (speaker JC).

ties. In comparison to the consonant productions of speakers DR and JC, those of speaker JP failed to exhibit some of the expected kinematic characteristics presumably because they were uttered at a faster rate; indeed, VC and CV trajectories were found to be shorter for the latter vs two former speakers in 9 our of 12 cases (3 consonants $\times$ 2 periods $\times$ 2 articulators).

In line with these kinematic findings, coarticulation data reported in this paper speak in support of the prominence of the carryover coarticulatory effects exerted by alveolopalatal and velar consonants, mostly /ɲ/, on vowels. Thus, the offset of CV lowering movement was found to occur at a higher articulatory position than the onset of the VC rising movement for most consonants and speakers (DR and JC). Directionality patterns in the temporal extent of coarticulation are less clear.

The kinematic and coarticulatory evidence just reviewed may be accounted for to a large extent assuming that tongue dorsum involvement is greater during the often more curved CV lowering trajectories than during the more straight VC raising ones (see Fig. 2). This finding could be attributed to the sequential organization of tongue blade and tongue dorsum activity during the production of alveolopalatals (i.e., the tongue dorsum activity precedes the activity of the tongue blade during the VC rising trajectory and the reverse occurs during the CV lowering movement), and to the tongue dorsum motion properties for velars. As suggested in the Introduction, several factors may play a role in this articulatory and coarticulatory outcome, i.e., tongue dorsum mass, inertia and elasticity, and antagonistic muscle force directions.

The presence of double velocity peaks is also consistent with this interpretation. Two-phase movements were found to occur more often during the CV trajectory than during the VC trajectory for speakers DR and JC. Moreover, a prominent dorsal component at CV trajectory offset accounts for why the tongue body may travel a shorter distance more slowly and in more time during phase IV than during the other phases including phase I. This kinematic pattern was found to hold to a larger extent for /ɲ, k/ than for /ʃ/, presumably in line with differences in tongue dorsum involvement in consonant production, i.e., higher for /k/ than for /ʃ/ because the tongue dorsum is the primary articulator for velars, and for /ɲ/ than for /ʃ/ due to a higher degree of interarticulatory coupling between the laminal or laminopredorsal primary articulator and the tongue dorsum for the former consonant.

In the light of data from the literature (see Introduction), it seems likely that a more active participation of the tongue body in the production of alveolopalatals and velars vs apical and laminal consonants could contribute to more robust differences between the VC and CV trajectories as well as to more frequent double velocity peaks. These kinematic differences are matched by differences in the frequency extent and

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the acoustic duration of the CV vowel transitions and in the prominence of the C-to-V carryover effects between the two sets of consonants. In support of this possibility, asymmetrical displacement and velocity patterns, and double velocity peaks, were obtained for dorsal consonants in our study but not for apicals produced at fast rates in previous studies even though our VCV sequences were uttered at even faster rates, e.g., VCV duration ranges across speakers were 200–250 ms in our study and 375–390 ms in Kent and Moll, 1972. Moreover, a robust trend for the CV period to be longer than the VC period has not been reported for apicals. Also, the apicoalveolar lateral /l/, a consonant which favors typically anticipation vs carryover in coarticulation studies, has been found to exhibit lower, not higher displacement and velocity values at the VC vs CV period.

As suggested for voiced vs voiceless stops by Löfqvist and Gracco (2002), it could be that kinematic differences between the VC and CV periods are due to differences in duration between the two adjacent vowels rather than to the consonant gesture itself. However, this possibility cannot easily account for trajectory duration running opposite to trajectory displacement and velocity (i.e., CV > VC for the former and VC > CV for the latter), and is not consistent with different vowel duration patterns for speakers DR and JP (V2 was longer than V1 for both speakers) and for speaker JC (V1 was longer than V2 in this case).

The role of other additional factors in the presence of double velocity peaks has also been explored. First, tongue-palate contact does not seem to be involved since the frequency of occurrence of the two-phase periods was not less for the fricative /ʃ/ than for the stops /ɲ, k/ but rather the other way around. In the second place, a comparison between the onset time of phase IV for the *X* and *Y* signals allows concluding that the presence of double peaks in the vertical signal is not triggered by the horizontal movement. Indeed, the phase of interest was found to start often about 10–20 ms earlier, not later, vertically than horizontally (in the case of /ɲ/ for all speakers, of /ʃ/ for speaker JC, and of /k/ for speaker DR) or else about the same time in the two directions (in the case of /ʃ/ for DR and JP, and of /k/ for JC). Third, joint inspection of the jaw and tongue vertical movement trajectories suggests that the V2 = /a/-to-/p/ jaw closing movement could contribute to the formation of double phases during the tongue body lowering trajectory in specific circumstances. Indeed, the jaw extremum before closing was found to occur earlier than the onset of phase IV most of the time (in the case of all consonants for speakers DR and JP, and of /k/ for speaker JC), and those two temporal points turned to be highly correlated ($\underline{r}$ exceeded 0.6 in 11 out of 18 possible cases, i.e., 3 consonants × 2 articulators × 3 speakers). Moreover, the fact that jaw closing from V1 = /a/ to the target consonant preceded phase II suggests that jaw movement may also contribute to the formation of a double phase during the tongue body rising trajectory. However, the jaw cannot possibly account for the presence of double velocity peaks in VCV sequences with /ʃ/ produced by speaker JC since in this particular case there was very little jaw movement and the V2 = /a/-to-/p/ jaw closing motion was delayed with respect to the onset of phase IV.

Even though this investigation deals with VCV sequences with a single vowel, our prediction is that the C-to-V coarticulatory effects reported in this investigation could extend to other vowel context conditions (even though other factors such as overshoot could also be involved in the kinematics of sequences such as /iɲi/). Moreover, the fact that the articulatory characteristics for alveolopalatals and velars, as well as their VCV coarticulatory patterns, have been found to hold in other languages besides Catalan speak in favor of the cross-linguistic nature of the kinematic characteristics reported in this paper.

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