Articulatory reduction and coarticulation in Catalan three-consonant sequences

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Electropalatographic and acoustic data on Catalan /Ck#C/ sequences where # is a word boundary and /k/ is preceded by /l, s, r/ and followed by /b, m, d, l, n, z, r, ʎ/ were collected in order to test the hypothesis that the velar stop is most prone to be reduced and deleted next to consonants involving high articulatory and aerodynamic demands. Analysis results reveal the absence of a velar stop closure in about half of the sequence tokens, mostly so when /k/ occurs after /s/ and before an oral stop presumably due to the high manner of articulation requirements involved. On the other hand, /Ck#C/ sequences where a /k/ closure period is available show a prominent realization of the velar stop mostly next to /s, z/. This scenario points to two different production mechanisms for three-consonant sequences with contextual obstruents: articulatory reduction and elision, and a slowing down and an increase in articulatory salience, of the velar stop. /Ck#C/ sequences lacking an acoustic closure for /k/ were found to show a residual velar stop articulation which was implemented through an increase in cluster duration and in dorsopalatal contact at the approximate /k/ location in comparison to identical /C#C/ sequences with no /k/. © *2015 Acoustical Society of America*.
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I. INTRODUCTION

Phonetic research on consonant clusters has dealt primarily with the articulatory adaptation mechanisms occurring between two consonants placed in adjacent syllables, namely, mutual coarticulatory effects, assimilation of one consonant to another, or blending of the two consonant gestures into an intermediate articulation (Ellis and Hardcastle, 2002; Kochetov and Colantoni, 2011; Recasens and Pallarès, 2001). Differences in temporal coordination of articulatory gestures for two tautosyllabic consonants have also been looked into (Bombien *et al.*, 2010; Marin and Pouplier, 2010). Little attention has been paid to the production characteristics of three-consonant clusters (see, however, Zharkova *et al.*, 2009). The present study contributes to fill this gap through an electropalatographic (EPG) and acoustic investigation of the phonetic characteristics of heterosyllabic /Ck#C/ sequences in Catalan, where # is a word boundary, C1 may be /l, s, r/, and C3 is one of the voiced consonants /b, m, d, l, n, z, r, ʎ/ (e.g., /sk#d/ and /lk#m/ in [kazg'du] casc dur "tough helmet" and [mɔlg'maltə] molc malta "I grind malt").

In contrast with two-consonant sequences, the present investigation tests the general hypothesis that, in /Ck#C/ sequences, an increase in the articulatory and aerodynamic demands involved in the production of the consonant cluster is likely to cause the velar stop to undergo articulatory reduction and even to be deleted. Descriptive studies on Catalan phonetics and phonology indicate indeed that /k/ may be hardly perceptible and even inaudible in the clusters of interest (Recasens, 1996, p. 199; Wheeler, 2005, p. 237). Along these lines, the goal of the present study is to explore two main research topics identified in Secs. I A and I B below: the contextual effects on the degree of articulatory prominence of the velar stop, as characterized by measures of degree of linguopalatal contact and duration; and whether /k/ is deleted or leaves a gestural residue in productions of /Ck#C/ sequences, where /k/ shows no velar closure, either acoustically or in terms of tongue-palate contact, and is thus inaudible or very hard to perceive.

In order to formulate a set of testing hypotheses, several aspects about the Catalan sequences under investigation need to be mentioned. On the one hand, /k/ does not agree in place of articulation with any of the contextual consonants in the /Ck#C/ sequences under analysis since /b, m/ are bilabial, /d/ is dental, /l, n/ are front alveolar, /s, z, r/ are centroalveolar or postalveolar, and /ʎ/ is alveolopalatal. Except for labials, consonants appearing in the C1 and C3 positions will often be referred to as "front lingual" throughout the paper, where the term "front" implies that they may be articulated with the tongue tip, blade, and/or predorsum. Other relevant phonetic characteristics of these contextual Catalan consonants need to be pointed out (Recasens, 1996): /l/ is darker when occurring as C1 syllable-finally than as C3 syllable-initially, as revealed by the fact that F2 is about 1000 Hz in the case of the former allophone and 1000–1500 Hz in the case of the latter; the rhotic /r/ is realized as a trill both syllable-initially and syllable-finally, but may also have a reduced tap-like realization in syllable-final position showing at the same time a single apicoalveolar contact (as for the tap) and a relatively lowered and retracted tongue body (as for the trill). Regarding the stop or approximant realization of C3 = /b, d/, see Sec. I B.

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A. Contextual effects

There are several reasons why extreme degrees of articulatory reduction can occur for C2 = /k/ in the clusters under investigation. It has been pointed out that consonants are more unstable in syllable-final than in syllable-initial clusters since they participate in less coupling relations in the former than in the latter, i.e., while syllable-initial consonants are all coupled to the following vowel, syllable-final ones overlap with each other to a larger extent and are coupled sequentially (Marin and Pouplier, 2010). This means essentially that, compared to its timing as a singleton, the consonant adjacent to the vowel shifts toward the vowel in syllable-initial clusters but not in coda clusters. A more specific reason is the difficult task involved in changing place of articulation and thus, in repositioning the tongue body twice during the same three-consonant cluster: from alveolar C1 to velar C2 and from velar C2 to dental, alveolar or alveolopalatal C3 (Chitoran *et al.*, 2003). As for clusters where /k/ is followed by a labial consonant, we speculate that articulatory reduction could cooccur with gestural overlap whenever the lip closing gesture is anticipated in time, though as pointed out in Sec. I B, this instance of overlap is less likely to occur than in dental, alveolar + labial clusters such as /tp, np/.

Keeping these aspects in mind, several predictions may be made regarding the effect of the contextual consonants on the realization of /k/ in three-consonant clusters. On the one hand, the likelihood that /k/ is severely reduced is expected to increase with the manner of articulation requirements for contextual obstruents, i.e., stops and fricatives, and the alveolar rhotic mostly if realized as a trill (/b, d, s, z, r/), as opposed to contextual sonorants, i.e., nasals and laterals (/m, n, l, ʎ/). The rationale behind this contextual difference for most clusters under investigation is that the stricter the C1 and C3 manner demands, the harder it should be for the articulators to travel from the articulatory position for a front lingual C1 to that for the back dorsal C2 and back to a front lingual C3 again. Strict production demands for obstruents are related to the formation of a complete closure and the generation of an audible burst for stops, and to the passage of a high velocity air jet through a narrow central lingual slit for the generation of turbulent noise for fricatives, and to the intraoral pressure rise associated with all these articulatory maneuvers (Ohala and Solé, 2010). The alveolar trill should also be highly constrained due to the fine tuning between tongue tip tension, articulatory configuration, and translingual airflow involved in the execution of one or several fast alveolar contacts (Solé, 2002). On the other hand, the production of sonorants, i.e., nasals and laterals, ought to be less demanding than that of obstruents and the trill since they allow continuous airflow and exhibit a lower oral pressure level; moreover, a nasal consonant could contribute to the maintenance of the dorsal closure for preceding /k/ in order to facilitate the production of the stop burst by preventing nasal venting during the oral stop (Bombien *et al.*, 2013).

Other articulatory characteristics for the contextual consonants should also have an effect on /k/ articulation and thus ought to play an active role in the prominence of the velar dorsal gesture. In principle, considerable lingual contact at the palatal zone for the velar stop is expected to occur next to consonants which are produced with a relatively large dorsopalatal contact area such as the alveolopalatal /ʎ/ and, to a lesser extent, /s, z/. Other contextual consonants should contribute to preserve the dorsovelar closure for /k/ while causing the consonant to exhibit a lowered tongue predorsum position and thus little dorsopalatal contact. This should be so for labials since these consonants involve no tongue body activity, and for dark /l/ and perhaps the trill /r/, which are produced with some predorsum lowering and postdorsum retraction and possibly a secondary postdorsal constriction at the pharynx (/l, r/) or the velar region (/l/) (Proctor, 2011; Browman and Goldstein, 1995). A similar articulatory outcome is predicted to take place next to other front lingual consonants articulated with more or less front dorsum lowering, i.e., /d/ due to its dental place of articulation and the alveolar nasal /n/ presumably since it requires a low intraoral pressure level and no prominent burst (Dart, 1991; Recasens, 2012).

In sum, a joint consideration of the manner and place requirements for the contextual consonants in /Ck#C/ sequences allows predicting that /k/ should undergo more articulatory reduction, i.e., it ought to show less tongue dorsum contact, be shorter and drop more often, next to oral stops than to nasals and laterals. The role of /s, z/ and /r/ is less clear than that of the other contextual consonants since two opposite outcomes for /k/ may be predicted to occur in this case: While articulatory reduction should be favored by manner demands on frication and trilling, /s, z/ could trigger an increase in dorsal contact at the palatal zone and /r/ the preservation of the dorsovelar closure.

B. Gestural residue

Data from the literature reveal a trend for articulatory reduction and gestural overlap to affect apical and labial stops rather than dorsal stops (Hardcastle and Roach, 1979; Byrd, 1996). The high articulatory complexity involved in the production of three consecutive consonants may account for why syllable-final velars may undergo considerable gestural reduction in three-consonant clusters. This scenario allows investigating whether a consonant which leaves no obvious acoustic trace and is hardly perceived (i.e., /k/ in our study) may still be realized phonetically and thus may show a gestural residue in the articulatory signal. Instances of perceptually assimilated but nevertheless present articulatory gestures have been identified in the literature, as for the alveolar nasal stop closure being overlapped by the lip closing gesture for the following labial stop in the cluster /np/ (seven plus; Browman and Goldstein, 1991), and the alveolar stop showing some incomplete central alveolar closure and/or some tongue contact fronting at the sides of the alveolar and palatal zones in the cluster /dg/ (did gardens; Künhert and Hoole, 2004).

Along these lines, the paper makes a crucial distinction between "/Ck#C/ sequences with [k]" and "/Ck#C/ sequences with no [k]" depending on whether a /k/-related closure event occurs in the acoustic signal or not, respectively. Traces of the dorsal gesture for /k/ will be looked for by

comparing /Ck#C/ sequences with no [k] with control /C#C/ sequences where C1 and C2 are identical to C1 and C3 of the three-consonant sequence, as for example /lk#d/ in molc dàtils "I grind dates" and /l#d/ in vol dàtils "he/she wants dates." In comparison to the two-consonant control sequences, the /k/ gestural residue is expected to be signaled by several articulatory and acoustic events: greater dorsal contact at the hard palate mostly so in consonant contexts other than /l, r/ (see Sec. I A) since, even if lacking a full closure, the velar stop ought to involve some tongue dorsum raising; a longer cluster duration since speakers plan for three phonemes in /Ck#C/ sequences as opposed to two in /C#C/ control sequences.

Another phonetic characteristic in support of the presence of a gestural residue for /k/ will be sought in the manner of articulation of C3 = /b, d/, which should be realized as approximants in /Ck#C/ sequences with no [k] if a trace of the dorsal gesture is not available but as stops when such a trace is present. This ought to be the case since, in Catalan, voiced stops are produced as stops after stops, and essentially as approximants after fricatives, nasals, laterals, and approximants except when the two consecutive consonants are homorganic and share the same closure location (Recasens, 1996). This instance of contextual adaptation may be viewed as a progressive manner assimilation process through which /b, d, g/ acquire the close or open vocal tract configuration of the preceding consonant. Thus, for example, /lk#b/ in a sequence like calc bo "good tracing paper" is expected to be implemented as [lgb] if the velar stop is realized phonetically and as [lß] if the velar stop has been deleted and in the control sequence /l#b/. In the sequence /lk#d/ (e.g., molc dàtils "I grind dates"), however, dental /d/ should be realized as the dental stop [d] not only when [k] is present but also when it is absent, since /l/ assimilates to following /d/ which results in the two consonants being articulated with the tongue front at the dentoalveolar zone. Moreover, the stop realization of C3 = /b, d/ is expected to be maintained in CC#C sequences with [k] since, unlike the velar stop, the two voiced stop phonemes occur in the syllable-initial prevocalic position.

C. Summary of research goals

The primary goal of the present study is to determine the contextual influences on the frequency of occurrence and degree of prominence of the velar stop in Catalan /Ck#C/ sequences, and whether the stop leaves an articulatory trace in /Ck#C/ productions where it shows no major acoustic cues. The presence of the dorsovelar stop should be favored by sonorants as opposed to obstruents, by consonants produced with considerable dorsopalatal contact and by those exhibiting some degree of homorganicity with /k/ at the velar or upper pharyngeal place of articulation. Evidence for a residual articulation will be sought through a comparison between /Ck#C/ sequences with no [k] and the corresponding control /C#C/ sequences using measures of dorsopalatal contact, cluster duration, and manner of articulation for C3 = /b, d/.

EPG and acoustics have been used simultaneously for the study of velar stops in other studies (Byrd, 1996; Bombien *et al.*, 2010; Fougeron and Ridouane, 2008; Celata *et al.*, 2013). The acoustic record should provide a good indication about the presence of a velar stop closure which may also be detected on the EPG record if occurring at the back hard palate. Whenever taking place behind the hard palate, the velar stop closure will be inferred from the acoustic signal alone since EPG does not provide information about dorsovelar contact. In comparison with EPG, other techniques, i.e., electromagnetic midsagittal articulometry (EMA), ultrasound, and magnetic resonance imaging (MRI) provide more direct information about lingual activity but may be problematic with respect to temporal resolution (MRI) and to capturing dorsovelar closure location and extent for velars (EMA, ultrasound).

II. METHOD

A. Recording and segmentation

Three-consonant sequences composed of all /Ck#C/ combinations of C1 = /l, s, r/, C2 = /k/, and C3 = /b, m, d, l, n, z, r, ʎ/ were recorded in seven or eight syllable long sentences with the main sentence stress falling on the syllable containing C3 (e.g., /lk#b/ in necessito aquest calc bo "I need this good tracing paper," where sentence stress falls on the syllable bo). This particular set of consonant combinations was selected in order to test the effect of contextual consonants of different place and manner of articulation on the presence and degree of prominence of C2 = /k/, and represent all possible /Ck#C/ sequences in Catalan regarding C1 and to a large extent C3 as well (a few other consonants may appear in C3 position such as /j/, e.g., molc iuca "I grind yuca"). The clusters under analysis were preceded and followed by low or mid back rounded vowels which show practically no dorsopalatal contact and therefore should not interfere with the degree of linguopalatal contact for the consonants in the cluster. Two-consonant sequences sharing the same C1 and C3 as these /Ck#C/ sequences, which will be referred to as "C#C control sequences" throughout the paper, were also recorded in comparable sentences both regarding contextual vowels, number of syllables and sentence stress (e.g., /l#b/ in em va dir que no cal bosses "he/she told me that bags are not needed," where sentence stress falls on the syllable bo).

Three Eastern Catalan speakers (DR, the paper's first author; JP, JC) recorded seven times EPG and acoustic data of the sentence material in a reading task with a 1.5 mm thick wedge-shaped artificial palate equipped with 62 electrodes. Naturalness in the speakers' productions was sought by having the three subjects read in random order as naturally as possible and at their normal speech rate a long sentence list including the sentences of interest and an additional series of Catalan sentences containing phonetic material for another analysis study. Linguopalatal contact configurations were obtained with the WinEPG system of Articulate Instruments every 10 ms (Hardcastle *et al.*, 1989). As shown by the top left-most EPG contact pattern displayed in Fig. 3, electrodes on the artificial palate were distributed in eight rows (from back-most row 8 to anterio-most row 1)

and in four columns at each half of the artificial palate (from central-most column 4 to lateral-most column 1); they were also grouped into two articulatory zones such that the four front rows were assigned to the alveolar zone and the four back rows to the palatal zone. The acoustic signal was acquired at 22 050 Hz and downsampled to 11 025 Hz for analysis using the Computerized Speech Lab (CSL) analysis system of Kay Elemetrics. The EPG data were converted into CSL format for simultaneous visual inspection of the waveform, the spectrographic display and the linguopalatal contact patterns. Spectrograms were displayed using 100 sample points per frame, a Hamming window and a preemphasis factor of 0.8. Recorded files included no more than five sentence tokens each so as to avoid problems with the temporal alignment between the EPG and audio signals which could arise in longer files. For all recorded sentences, we verified that there were no temporal misaligments by focusing on events where temporal matching between the articulatory and acoustic signals could be easily determined such as closure onset and offset for stops.

EPG printouts of all linguopalatal contact patterns were made for all 1008 sequence tokens, i.e., 504 /Ck#C/ tokens and 504 /C#C/ control sequences (48 sequences $\times$ 3 speakers $\times$ 7 tokens). The presence or absence of /k/ was determined based on the presence or absence of a closure period devoid of formant structure on the spectrographic displays. The velar stop closure could be followed by a weak and hardly perceptible burst which was not taken to be part of the consonant (see also Henderson and Repp, 1982). As revealed by a token-to-token and speaker-by-speaker analysis of the EPG data, this period of acoustic closure could correspond to a sequence of EPG contact patterns exhibiting full electrode activation at the back-most row 8 of the artificial palate (actual closure at the postpalatal or palatovelar zone), or else no linguopalatal closure and variable degrees of lateral contact at the four back rows of the palatal zone, which did not show up in the corresponding /C#C/ controls (actual closure at the velar zone, or no velar closure and gestural residue). Thus, even in those cases where a period of acoustic closure did not cooccur with a visible tongue closure on the EPG record because the closure for /k/ was formed behind the hard palate (more often for speakers DR and JP than for speaker JC), there was enough electrode activation at the palatal zone to ascertain that a velar stop realization was present.

The onset and offset of the other consonants in the consonant sequences under analysis were identified through simultaneous inspection of the EPG contact patterns and the spectrographic displays. Regarding those measures which depended on the alignment between the two signals, we included as part of a specific phonetic segment a given 10 ms EPG frame if it took place five or more milliseconds later than the acoustic onset of the segment in question. Stop realizations of C3 = /b, d, g/ were taken to occur whenever there was a period of acoustic closure devoid of formant structure starting at the offset of the preceding consonant (often at the /k/ burst whenever the velar stop was present) and ending at the voiced stop burst, which in the case of C3 = /d/ was matched by a complete dentoalveolar closure on the EPG record. The edges of laterals and nasals, and of approximant realizations of C3 = /b, d, g/, were identified with the onset and offset of a period of low intensity formant structure, and with the onset and offset of an alveolar closure for /n/ and of tongue contact occurring at least at the two and four central alveolar columns in the case of /l/ and /ʎ/, respectively (i.e., at columns 4-4 and 3-4-4-3 in Fig. 3, top left EPG contact configuration). The segmental boundaries for /s, z/ were placed at the onset and offset of a period of high frequency frication noise delimited by the vowel edges. The segmentation criteria for /r/ were conditioned by manner of articulation: whenever realized as a trill in C3 position, the rhotic exhibited generally two or more alveolar contacts separated by opening periods for speaker DR, or was realized with a single contact or as a fricative or an approximant for speakers JP and JC (the approximant or fricative realization of the trill occurred fairly often after /s/ for all speakers); in C1 position, /r/ was realized with a single contact or most of the time as an approximant with low intensity formants whose edges were identified as the onset and offset of the consonant.

B. Data analysis

The frequency of occurrence of the stop consonant in the /Ck#C/ sequences of interest was computed as a function of C1 and C3 through visual inspection of the spectrographic and EPG displays using the criteria for velar stop identification described in Sec. II A. Moreover, in order to find out whether speaker-dependent differences in the frequency of occurrence of the velar stop were conditioned by speech rate, a measure of global speech rate was obtained for each speaker by dividing sentence duration by the total number of phonological units occurring in the sentence (Pfitzinger, 1996). A subset of eight sentences selected at random from the sentence database was used for that purpose.

Articulatory prominence for the velar stop in /Ck#C/ sequences with [k] was based on measures of closure duration and dorsopalatal contact size. Regarding the latter measure and as specified by the contact index of EPG data reduction method (Fontdevila *et al.*, 1994), Qp or palatal contact index values were obtained by averaging the number of "on" electrodes at the palatal zone over the total number of 32 electrodes at this zone (see Fougeron and Ridouane, 2008 and Celata *et al.*, 2013 regarding similar index measures for quantifying dorsopalatal contact for velar stops). Coarticulatory effects in Qp were analyzed at the midpoint of the velar stop closure period.

The presence of a gestural residue in /Ck#C/ sequences with no [k] was investigated by comparing several measures for the sequences in question and the corresponding control /C#C/ sequences: Qp values at the onset of the last cluster consonant and at 10 ms before this point which is where the gesture for /k/ was expected to occur; overall cluster duration, as determined from the same signals which were used for segmentation (see Sec. II A); the frequency of occurrence of stop and approximant realizations of C3 = /b, d/.

C. Statistics

In order to evaluate the effect of C1 and C3 on the frequency of occurrence of the velar stop, a logistic regression

analysis was performed on the /k/ percentages of occurrence for /Ck#C/ sequences using a Generalized Linear Mixed model (GENLINMIXED) with "C1" and "C3" as fixed factors and "speaker" as a random factor. The test was run on 496 out of 504 recorded sequence tokens (8 tokens were discarded due to lack of clarity in the acoustic signal or to problems with the speakers' productions). Contextual effects on the Qp values at /k/ midpoint and on /k/ duration in /Ck#C/ sequences with /k/ were analyzed by means of a repeated measures GENLINMIXED test with C1 and C3 as fixed factors and speaker and "repetition" as random factors. In order to ascertain statistically the possible implementation of /k/ in /Ck#C/ sequences with no [k], another repeated measures GENLINMIXED test was run on the Qp values at C3 onset and at −10 ms before this temporal point, and on cluster durations, for /Ck#C/ sequences and their /C#C/ controls, with C1, C3, and "cluster type" (levels /Ck#C/ and /C#C/) as fixed factors and speaker and repetition as random factors. The statistical model included all main effects and interactions between fixed factors in all tests with the exception of the logistic regression test, where the factor interaction could not be analyzed due to the high number of minimal (0) and maximal (7) data counts. Moreover, the interpretation of factor interactions in the two remaining tests should be taken with caution in view of the uneven number of tokens for the /Ck#C/ combinations with and without /k/ (overall there were 274 tokens with /k/ and 222 with no /k/; see Sec. III A). Whenever applicable, Bonferroni's *post hoc* comparisons were performed on pairs of three or more levels of an independent variable yielding a main effect. The significance level was established at $p < 0.05$. All analyses were performed on the IBM SPSS Statistics 20 package.

III. RESULTS

A. Frequency of occurrence

According to the combined acoustic/EPG inspection method described in Sec. II A, the velar stop occurred in 274 out of 496 cases (55.2%) and its presence turned out to be conditioned by C1 and, to a lesser extent, by C3 as well. Results from the logistic regression yielded a main C1 effect [$F(2, 62) = 40.94$, $p < 0.001$], which was associated with the frequency of occurrence of the velar stop varying with the preceding consonant in the progression /l/ > /r/ > /s/ and thus being higher next to a sonorant than to an obstruent (see Fig. 1, left graph). Speakers generally agreed in showing more deletions after /s/ than after /l, r/ and less deletions after /l/ than after /s, r/; in particular, the C1-dependent percentages of occurrence for /k/ amounted to 60.7% (/l/), 17.9% (/s/), and 71.4% (/r/) for speaker DR, 75%, 0%, and 12.5% for speaker JP, and 100%, 78.6%, and 73.2% for speaker JC. The main effect of C3 [$F(7, 62) = 6.73$, $p < 0.001$] was related to significant differences for /m, l, n, ʎ/ (least deletions) > /b, d/ (most deletions) and, therefore, to a more frequent presence of the velar stop when C3 was a sonorant than when it was an obstruent (see Fig. 1, right graph).

There was no straightforward relationship between number of elisions and speech rate. Thus, while speaker DR spoke faster than speakers JP and JC (average segment duration was 63.50 ms, s.d. = 3.36 for the former subject, and 78.61 ms, s.d. = 3.1 and 77.36 ms, s.d. = 3.62 for the two latter ones), the frequency of occurrence of the velar stop varied in the progression JC > DR > JP.

B. Clusters with [k]

According to results from the repeated measures GENLINMIXED test run on the Qp values at closure midpoint, data for /Ck#C/ sequences with [k] yielded a main effect of C1 [$F(2, 251) = 96.23$, $p < 0.001$] and C3 [$F(7, 251) = 12.61$, $p < 0.001$], and a significant C1*C3 interaction [$F(13, 251) = 6.08$, $p < 0.001$]. *Post hoc* tests and data for the individual subjects revealed that dorsopalatal contact for /k/ varies as a function of C1 in the progression /s/ > /r/ > /l/, and as a function of C3 in the progression /z, ʎ/ > /b, m, d, l, n, r/ (see Fig. 2, left and right graphs). EPG contact patterns plotted in Fig. 3 show that, in agreement with the predictions made in Sec. I A, these C1- and C3-dependent differences are related to the presence of more dorsal contact at the

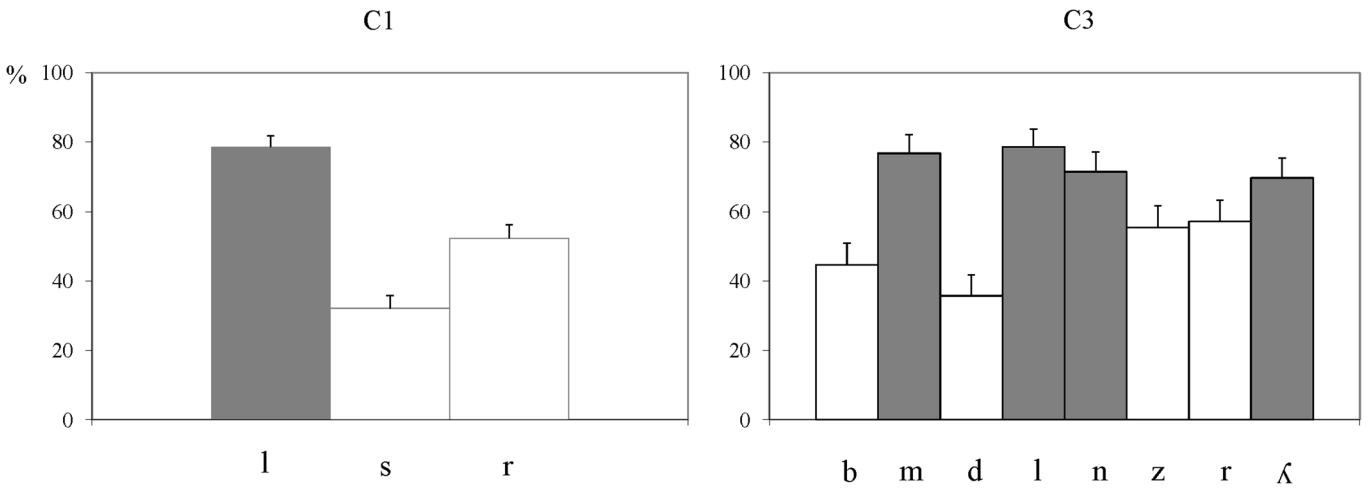

FIG. 1. Frequency of occurrence of the velar stop in /Ck#C/ sequences with [k] plotted as a function of C1 (left graph) and C3 (right graph). Filled bars correspond to sonorants (nasal, laterals), and unfilled bars to obstruents (stops, fricatives) and the alveolar trill. Error bars correspond to the standard error of a proportion.

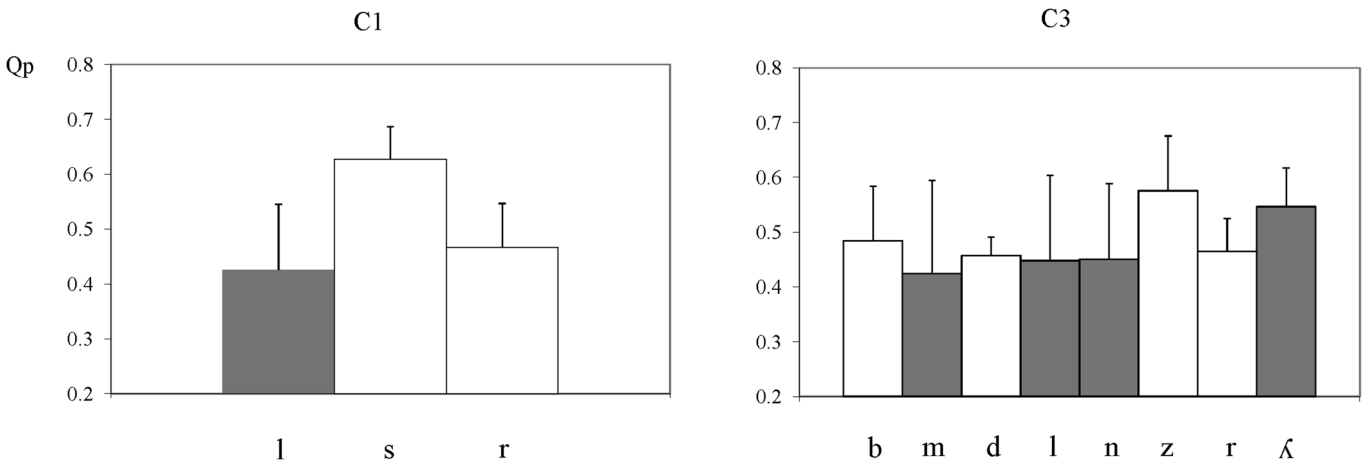

FIG. 2. Qp values for the velar stop in /Ck#C/ sequences with [k] plotted as a function of C1 (left graph) and C3 (right graph). Filled bars correspond to sonorants (nasal, laterals), and unfilled bars to obstruents (stops, fricatives) and the alveolar trill. Error bars correspond to one standard deviation.

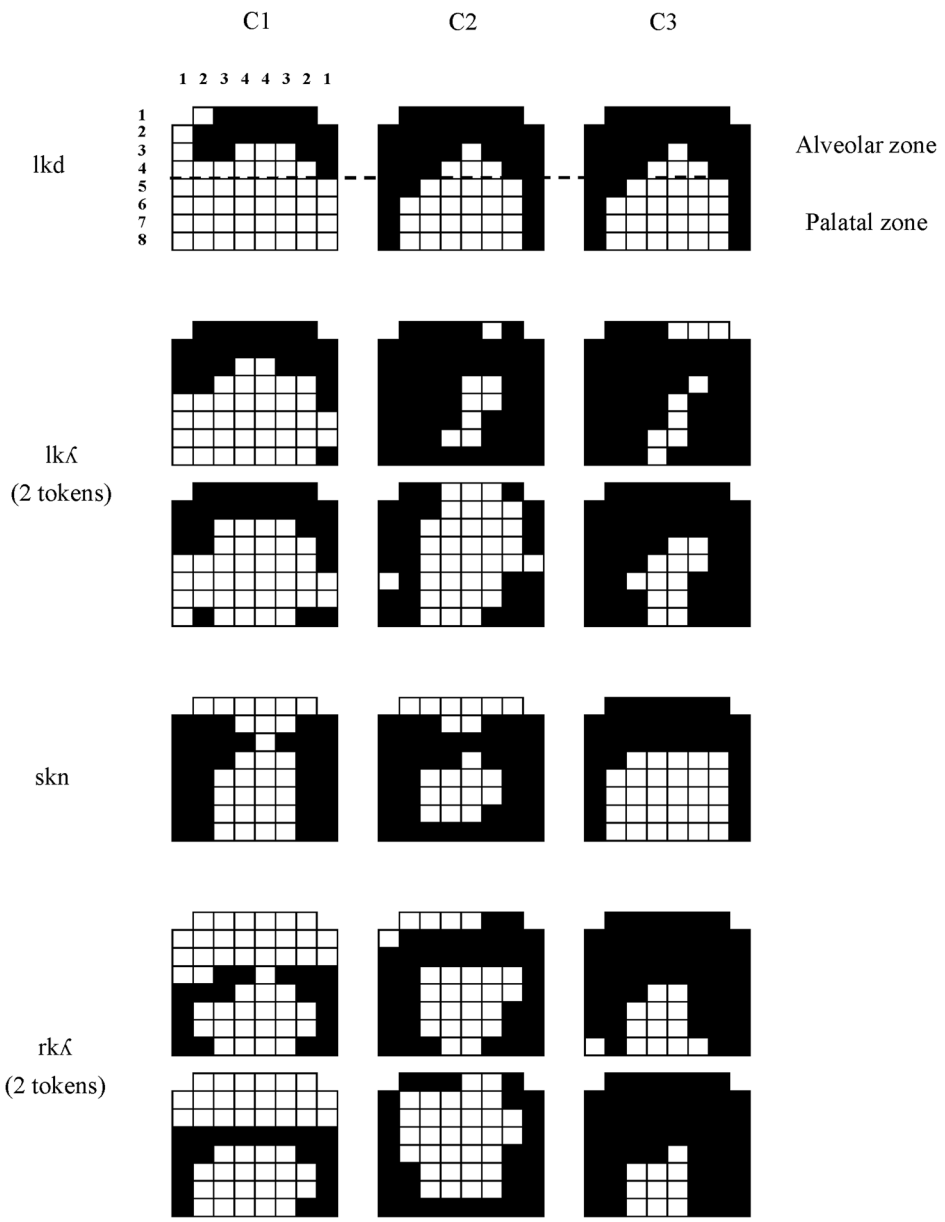

FIG. 3. Linguopalatal contact configurations at the midpoint of C1, C2, and C3 for selected cluster tokens. Data for /lk#d/ correspond to speaker JP, those for /lk#ʎ/ to speaker DR, and those for /sk#n/ and /rk#ʎ/ to speaker JC. Electrodes are filled if contacted by the tongue and unfilled otherwise. The top left EPG contact pattern shows the numbering of rows and columns on the artificial palate.

palatal zone for contextual /s, ʎ/ (see C1 pattern for the sequence /sk#n/ and C3 patterns for /lk#ʎ, rk#ʎ/) than for contextual /d, l, n, r/ (C1 patterns for /lk#d, lk#ʎ, rk#ʎ/ and C3 patterns for /lk#d, sk#n/). Data for /lk#ʎ, sk#n, rk#ʎ/ in the figure also reveal that C2 = /k/ may show central alveolar contact with the tongue front next to two flanking consonants articulated with an alveolar closure or constriction. The significant C1*C3 interaction turned out to be associated with smaller Qp differences among consonants whenever C2 = /k/ is flanked by an obstruent and a rhotic than by a nasal or lateral sonorant, which suggests that the two former manner classes constrain the tongue dorsum for /k/ to a larger extent than the two latter ones. Thus, for example, the maximal Qp difference for /k/ among all eight consonants appearing in C2 position was less when the velar was preceded by /s, r/ (0.081, 0.103) than when it occurred after /l/ (0.261).

The repeated measures GENLIMIXED test run on the /k/ duration values yielded a main effect of C1 [$F(2, 251) = 4.03$, $p < 0.05$] and C3 [$F(7, 251) = 7.53$, $p < 0.001$], and a significant C1*C3 interaction [$F(13, 251) = 3.93$, $p < 0.001$]. As shown by Fig. 4, C1-dependent differences in /k/ duration are small and turned out to be significant for /r/ > /s/ only. As for the effect of C3, the dorsovelar closure period turned out to be significantly longer before /z, r/ than before /m, n, ʎ/ (and also before /d, l/ than before /m/). Analogously to the Qp scenario, the significant C1*C3 interaction was related to a higher number of significant effects among contextual consonants and thus greater /k/ duration variability when the consonant flanking /k/ was a sonorant, often including /r/, than when it was an obstruent. Thus, for example, the maximal /k/ duration difference among all eight consonants appearing in C2 position was less when C1 = /s, r/ (32.6 ms, 25.6 ms) than when C1 = /l/ (37.1 ms).

The linguopalatal contact and duration data just presented reveal that, contrary to the frequency of occurrence scenario (Sec. III A), the velar stop in the context of alveolar fricatives is not especially reduced: it may be articulated with more dorsopalatal contact (both after /s/ and before /z/) and exhibits a longer duration (at least before /z/) than in the context of the other dental and alveolar consonants.

C. Clusters with no [k]

1. Qp and duration

According to results from the repeated measures GENLINMIXED test and as shown in Table I, most /Ck#C/ sequences with no [k] had significantly more dorsopalatal contact and were significantly longer than the corresponding control /C#C/ sequences which may be taken in support of a trend for three-consonant sequences to exhibit a trace of the dorsovelar stop gesture.

Qp values at C3 onset yielded a main effect of cluster type, C1 and C3 [$F(1, 486) = 49.09$, $p < 0.001$; $F(2, 486) = 95.38$, $p < 0.001$; $F(7, 486) = 169.35$, $p < 0.001$], and the significant interactions C1*C3 and cluster type*C3 [$F(11, 486) = 48.59$, $p < 0.001$; $F(7, 486) = 4.3$, $p < 0.001$]. These significant effects were associated with more dorsopalatal contact for /Ck#C/ sequences with no [k] than for the /C#C/ controls in all C1 conditions (and more so after C1 = /l/ than after C1 = /s, r/) and before most C3 (all but /ʎ/). Statistical results at 10 ms before C3 onset were highly similar to those obtained at C3 onset.

The cluster duration values also yielded a main effect of cluster type, C1 and C3 [$F(1, 486) = 93.52$, $p < 0.001$; $F(2, 486) = 27.81$, $p < 0.001$; $F(7, 486) = 11.83$, $p < 0.001$], and the significant interactions C1*C3 and cluster type*C1 [$F(11, 486) = 10.51$, $p < 0.001$; $F(2, 486) = 6.87$, $p < 0.001$]. These significant differences were related to longer /Ck#C/ sequences with no [k] than the /C#C/ controls in practically all the C1 and C3 contextual scenarios (for C1 = /l/ rather than C1 = /s, r/ and for all C3 but /d/).

2. Stop vs approximant realization

As shown in Table II, the frequency of occurrence of the stop and approximant realizations of /b, d/ in clusters with C1 = /l, s, r/ varied a great deal depending on whether /Ck#C/ sequences with no [k] or the corresponding /C#C/ control sequences were taken into consideration. Overall, voiced stops were realized much more often as stops than as approximants in the /Ck#C/ sequences with no [k] (63 vs 18 out of 81 cases and thus, 77.8% vs 22.2%), while the

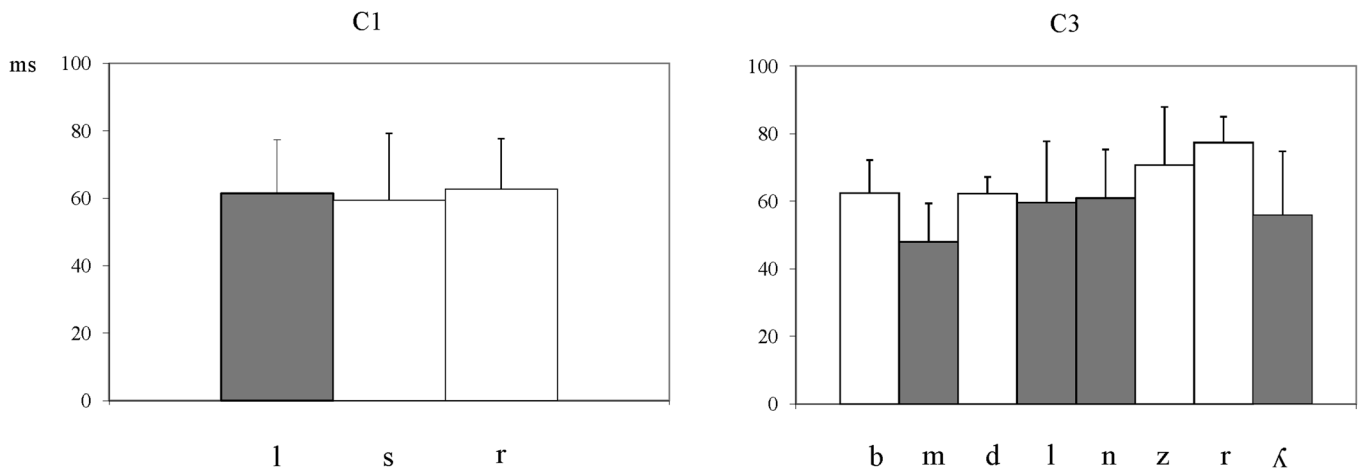

FIG. 4. Closure duration for C2 = /k/ in /Ck#C/ sequences with [k] plotted as a function of C1 (left graph) and C3 (right graph). Filled bars correspond to sonorants (nasal, laterals), and unfilled bars to obstruents (stops, fricatives) and the alveolar trill. Error bars correspond to one standard deviation.

TABLE I. Cross-speaker Qp values at C3 onset (left), and cluster durations in ms (right), for /Ck#C/ sequences with no [k] and the corresponding /C#C/ controls. Data are presented as a function of C1 = /l, s, r/ averaged across C3 conditions (top) and as a function of C3 = /b, m, d, l, n, z, r, ʎ/ averaged across C1 conditions (bottom). Standard deviations are given in italics.

	Qp at C3 onset		Cluster duration	
	Ck#C	C#C	Ck#C	C#C
l	0.2475	0.1812	147.82	131.14
	0.094	*0.095*	*7.53*	*27.88*
s	0.4031	0.3533	174.07	161.63
	0.008	*0.013*	*28.65*	*16.09*
r	0.3518	0.3176	170.20	160.21
	0.059	*0.072*	*14.44*	*22.21*
b	0.2912	0.2321	177.62	159.21
	0.019	*0.059*	*29.19*	*17.59*
m	0.3658	0.3225	160.00	157.86
	0.004	*0.055*	*21.21*	*26.26*
d	0.3450	0.2783	168.25	152.30
	0.024	*0.030*	*30.84*	*32.95*
l	0.2526	0.2418	160.36	148.93
	0.004	*0.075*	*6.57*	*7.58*
n	0.2850	0.2429	150.60	146.90
	0.026	*0.070*	*6.23*	*16.50*
z	0.4445	0.4055	177.00	172.62
	0.043	*0.056*	*14.72*	*30.48*
r	0.3358	0.3090	171.43	153.73
	0.081	*0.093*	*1.56*	*19.17*
ʎ	0.5376	0.5089	160.01	157.44
	0.026	*0.080*	*40.50*	*21.01*

percentage of stop realizations was slightly lower than that of approximant realizations in the control /C#C/ sequences (58 vs 67 out of 125 cases and thus, 46.4% vs 53.6%). The difference in stop realization percentages between the two sequence types was highly significant [$\chi^2(1) = 19.96$, $p < 0.001$]. Differences were even higher after excluding the data for /lkd/ and /ld/ since, as shown in the table and as pointed out in Sec. I B, /d/ is realized invariably as a stop after homorganic /l/: indeed, when /lk#d, l#d/ were excluded, stop realization percentages decreased down to 35.6% for the controls while staying much the same for the /Ck#C/ sequences with no [k] (75.7%). These data on the manner of articulation for /b, d/ agree with the Qp and duration data referred to in Sec. III C 1 in pointing to the presence of a dorsovelar stop gesture in /Ck#C/ sequences with no [k].

TABLE II. Cross-speaker percentages of occurrence for stop and approximant realizations of /b, d/ in pairs of /Ck#C/ sequences with no [k] and the corresponding /C#C/ controls.

Sequence pair	/b, d/ realization	Ck#C	C#C
lkb-lb	stop	92.9	4.8
	approximant	7.1	95.2
lkd-ld	stop	100.0	100.0
	approximant	0.0	0.0
skb-sb	stop	46.7	28.6
	approximant	53.3	71.4
skd-sd	stop	66.7	52.4
	approximant	33.3	47.6
rkb-rb	stop	88.9	9.5
	approximant	11.1	90.5
rkd-rd	stop	93.3	85.0
	approximant	6.7	15.0

The table also shows that, in disagreement with descriptive accounts (Sec. I B), /sd/ and /rd/ did not yield more approximant than stop C2 realizations. This was so presumably since, while C1 and C2 are not articulated at the same location in this case (the front lingual constriction occurs at the alveolar zone for C1 and at the dental zone for C2), they nevertheless share the same front lingual articulator (as for /ld/). Moreover, demanding manner requirements for C1 = /s, r/ may also contribute to the presence of (relatively) high stop or stop-like percentages for C2 = /d/ in these circumstances.

IV. DISCUSSION

The first goal of this investigation was to determine the contextual conditions which cause C2 = /k/ to stay or drop in three-consonant clusters. Data on the frequency of occurrence of the velar stop in Catalan /Ck#C/ sequences as determined by inspection of the acoustic and EPG record reveal that the stop closure was often absent or greatly reduced in about half of the sequences under analysis. This outcome, which may seem surprising given the fact that dorsal consonants are resistant to elision and gestural overlap (Byrd, 1996), may be accounted for by the high articulatory demands involved in the production of heterosyllabic three-consonant clusters. Moreover, the frequency of occurrence of the velar stop closure turned out to be affected by context, i.e., its presence varied mostly with C1 in the progression /l/ > /r/ > /s/ and, less so, with C3 in the progression sonorants > stops with /z, r/ falling in between. These data confirm the initial hypothesis that the chances that the velar stop is severely reduced should increase with the severity of the manner of articulation demands for contextual obstruents > contextual sonorants. Those requirements need to be sought in the performance of specific mechanisms for the generation of a burst for stops and of the frication noise for fricatives (Ohala and Solé, 2010). Thus, for example, the formation of the dorsal closure for /k/ becomes quite difficult after or before the generation of the long and audible turbulent noise for /s/ in sequences involving the production of another front lingual consonant. As expected, trilling for C2 = /r/ also resembles obstruents in causing /k/ to reduce to a larger extent than contextual nasals and laterals. Among consonants occupying the C1 position, differences in articulatory constraint between /s/, on the one hand, and /l/ and /r/, on the other hand, may also be related to the fact that Eastern Catalan /l/ is not strongly dark but may vary in darkness degree, and that syllable-final /r/ is often not realized as a pure trill but as a tap-like trill (see Sec. I).

In the so called /Ck#C/ sequences with [k], the articulatory prominence of the velar stop gesture as derived from a measure of linguopalatal contact degree was not found to decrease in the context of /s, z/. Indeed, visual inspection of tongue contact size at the back palate for /k/ in this context condition was comparable to or greater than in the context of the alveolopalatal /ʎ/ and the dentoalveolars /d, n/, and

exceeded clearly that occurring next to /l, r/ where little dorsopalatal contact for /k/ could result from the stop closure being formed far back into the velar zone. The velar stop closure duration was also maximal before /z/ (and /r/).

The data summarized so far reveal that, in comparison with other contextual consonants, a contextual alveolar fricative may cause at the same time a higher number of apparent /k/ elisions and yet more dorsopalatal contact and a longer closure during the stop. This double outcome does not appear to be in line with the principle that segmental elision should be preceded by large degrees of articulatory reduction and shortening in the target segment as found for voiceless stop lenition (Torreira and Ernestus, 2011), and may be resolved by calling for two different production strategies in three-consonant clusters that impose strict articulatory demands on the part of the speaker. The first strategy involves the extreme reduction of the /k/ dorsal gesture. The second strategy seeks to articulate all three consonants by slowing down their production and by causing a high degree of dorsopalatal contact to occur during the velar stop in the appropriate contextual conditions. This velar stop lengthening effect also occurs in /Ck#C/ sequences where C3 is an alveolar trill. Data for the individual speakers (Sec. III A) show that speaker JP chooses the former option while speaker JC prefers the latter, speaker DR lying somewhere in between. Syllable affiliation, i.e., the fact that C1 and C2 belong to the same syllable while C2 and C3 do not, could perhaps account for why the degree of articulatory prominence for /k/ in Catalan /Ck#C/ clusters is affected by the preceding consonant more than by the following one (see statistical results for the C1 and C2 effects on Qp for /k/ in Sec. III B). Other production events are prone to apply intrasyllabically rather than across a word boundary such as oral stop epenthesis in the sequence /ns/ (Warner and Weber, 2002).

Another goal of this study was to determine whether /Ck#C/ sequences where the velar stop was apparently absent in the articulatory and acoustic signals (/Ck#C/ sequences with no [k]) differed significantly from the corresponding control /C#C/ sequences and thus could be said to exhibit a trace of the original dorsal gesture. Results show robust differences between the two sequence types: In comparison with the controls, the /Ck#C/ clusters of interest were often longer, showed more dorsopalatal contact, and caused following /b, d/ to be realized as stops rather than as approximants. This finding implies that a trace of the dorsovelar stop gesture is often present in the phonetic signal when no acoustic closure is available and suggests that listeners might use this information for recovering the stop consonant in perception. This scenario resembles that of partial assimilations in heterosyllabic two-consonant sequences where, while not showing a full closure, an alveolar nasal or an oral stop may exhibit a gestural residue when occurring before a labial or a velar stop (Künhert and Hoole, 2004; Wright and Kerswill, 1989).

The present investigation reveals that heterosyllabic three-consonant clusters with C2 = /k/ are ruled by production mechanisms which could facilitate the realization of the consonantal sequence either by decreasing or increasing the prominence of the articulatory gesture for the stop consonant. Data reported in this study also indicate that manner of articulation demands for the contextual consonants (e.g., C1 = /s/) may yield severe gestural reduction of /k/ in /Ck#C/ sequences involving a double change in place of articulation. This production mechanism is in contrast with the phonetic implementation of heterosyllabic two consonant clusters such as /s#k, k#s/ where gestural superposition yielding eventually coarticulation, blending, or assimilation appears to be the preferred strategy (see Sec. I).

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