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Voicing assimilation in Catalan three-consonant clusters

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ABSTRACT

Electroglottographic and acoustic data for Catalan three-consonant clusters composed of a word- and syllable-final C1C2 sequence and an underlyingly voiced C3 in word- and syllable-initial position were collected in order to verify whether a regressive voicing assimilation process operates on all obstruents placed at the C2 and C1 sites. Data reveal the presence of low percentages of vocal fold vibration during final stops and fricatives, C3-dependent regressive voicing effects occurring to some extent during C2 but not during C1, and a more robust voicing interaction involving C1 and C2 and thus consonants placed within the same syllable and the same word. Moreover, except for perceptually and/or aerodynamically conditioned cases, voicing effects were found to be triggered by sonorants rather than by obstruents and the trill /r/ in agreement with the predictions of the Degree of Articulatory Constraint (DAC) model of coarticulation. Acoustic data for three-consonant cluster pairs differing in the underlying C3 voicing status show that speakers may use C2 duration and intensity (but not C1 or preceding vowel duration) as voicing cues. Taken together these results suggest that voicing assimilation in Catalan three-consonant cluster cannot be modeled as a long-distance regressive process, and is strongly dependent on syllable/word affiliation and on the manner and place of articulation characteristics of the consonants in the cluster.

1. Introduction

While there is a considerable number of phonetic studies dealing with voicing assimilation in heterosyllabic two-consonant clusters (Dutch: Slis (1986); English: Docherty (1992), Jansen (2004); French: Snoeren, Hallé, and Seguí (2006); Hungarian, Dutch: Jansen (2004)), the phonetic implementation of voicing assimilation in heterosyllabic three-consonant sequences has been paid little attention in the literature. This paper deals with the latter research topic.

Languages where voiced stops exhibit voicing lead, e.g., French, Catalan and Northern Italian dialects, are known to have a regressive voicing assimilation rule through which a word final obstruent, i.e., a stop or a fricative, assimilates in voicing to a following voiced consonant placed at the beginning of the word. In Catalan, regressive voicing assimilation applies postlexically after a word final devoicing rule which renders obstruents voiceless if underlyingly voiced (Bonet & Lloret, 1998), e.g., [baz] in [ˈbazus] "glasses" alternates with [bas] "glass" and the [s] phonetic outcome becomes [z] when followed by word initial /b/ as in [bazˈβujt] "empty glass". Whenever underlyingly voiceless, the obstruent consonant stays voiceless word finally and assimilates in voicing to a following voiced consonant as well, e.g., /s/ in [gos] "dog" ([gos] "dog"—[ˈgosus] "dogs") becomes [z] in [goz ˈðols] "sweet dog". Regressive voicing assimilation may be said to also account for those cases where C2 is voiceless since a syllable final obstruent is always realized as voiceless in this case, e.g., [bas pəˈtit] vas petit "small glass", [gos pəˈtit] gos petit "small dog". Also word internally an obstruent agrees in voicing with the following heterosyllabic consonant ([əzɣuˈta] "to exhaust", [əspəˈra] "to wait for").

The same regressive assimilation rule is said to operate on obstruents in Catalan three-consonant clusters where C1 and C2 are word final and belong to the same syllable, and C3 is word initial and belongs to the following syllable (heterosyllabic three-consonant sequences occur rarely in word internal position in this language). Therefore, in Catalan three-consonant clusters, syllable affiliation (CC.C) coincides with word affiliation (CC#C). By virtue of this phonological rule, one or two final obstruents become voiced if C3 is voiced, as in the case of [talb ˈdu] talp dur "tough mole" where C2 is an obstruent but C1 is not, and [kazg ˈmɔʎ] casc moll "wet helmet" where both C1 and C2 are obstruent consonants. Moreover, as shown by the latter example, Catalan differs from other languages (for example, Russian, Dutch, Hungarian and Czech; Dvorak, 2010, Hayes, 1984, Jansen, 2004, Markó, Gráczi, & Bóna, 2010) in that voicing assimilation is triggered not only by obstruents but by sonorants as well, i.e., nasals, laterals, rhotics and approximants. Even though the present investigation deals exclusively with regressive voicing assimilation before a voiced C3, it should be noted that,

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Table 1
List of three-consonant combinations under analysis.

	C1	C2	C3
(*a*) *Clusters with a fricative C2*			
Obstruent + obstruent	p, t, k, f	s	b, d, g, m, n, l, ʎ, j
Obstruent + obstruent	t	ʃ	b, d, g, m, n, l, ʎ, j
Sonorant + obstruent	m, l, r	f, s	b, d, g, m, n, l, ʎ, j
(*b*) *Clusters with a stop C2*			
Obstruent + obstruent	s	p, k	b, d, g, m, n, l, z, r, ʎ, j
Sonorant + obstruent	l, r	p, k	b, d, g, m, n, l, z, r, ʎ, j

in parallel to two-consonant clusters, obstruents are realized as voiceless before a voiceless C3, e.g., [talp ˈtow] talp tou "soft mole", [kask ˈtipik] casc típic "typical helmet". Given that final devoicing operates prior to regressive voicing assimilation and the underlying voicing status of final obstruents is of no concern to the present investigation, those word final obstruents undergoing voicing assimilation in the three-consonant clusters under analysis in this paper will be always transcribed with the voiceless phonetic symbol independently of their underlying voicing status. Thus, for example, underlying /b/ will be represented as /p/ and, therefore, clusters such as /rbg, rbl/ (as in verb gal "French verb" and verb lògic "logical verb") will be transcribed as /rpg, rpl/.

It has been assumed that obstruent voicing in languages where underlying voiced stops exhibit voicing lead and thus a negative VOT is implemented primarily by the presence of vocal fold vibration (Kohler, 1979, 1984). Thus, as a general rule, utterance initial voiced stops show voicing all throughout, as well as voicing before closure onset, in languages such as Catalan, Spanish or French (Solé, 2011). Also, when one considers regressive voicing assimilation in these languages, the expected trend is for final obstruents to exhibit voicing during the entire consonant period or a significant portion of it as, for example, in Russian stop + fricative clusters (Burton & Robblee, 1997) and in French stop + consonant sequences (Snoeren et al., 2006). This scenario is in contrast with that for languages like German or English where voiced stops are regularly voiceless utterance initially (Jansen, 2004; Beckman et al., 2009), and segmental duration may be a more relevant voicing cue than vocal fold vibration for syllable final obstruents, i.e., C1 and vowel duration in English /zC/–/sC/ pairs (Smith, 1997).

A study of ours dealing with regressive voicing assimilation in Catalan two-consonant clusters composed of the word final obstruents /p, t, k, f, s, ʃ/ followed by the word initial voiced consonants /b, d, g, m, n, l, z, r, ʎ, j/ does not fully support this assumption, however, since highly variable percentages of vocal fold vibration were found to occur during C1 as a function of speaker and segmental composition of the cluster (Recasens & Mira, 2012). Thus, voicing percentages for C1 = /p, t, k/ and for C1 = /f, s, ʃ/ had a mean value of about 60% and 40% respectively, and the corresponding speaker-dependent ranges were 15–90% and 15–60%. These data lead us to conclude that, whenever vocal fold vibration is taken as the signaling voicing cue (see Section 1.2 regarding other phonetic characteristics that may cue the voicing distinction), regressive voicing seems to take place for some speakers but not for others, thus questionning the validity of the regressive assimilation rule. It has also been shown for French that regressive voicing in clusters is phonetically gradient (Hallé & Adda-Decker, 2007).

The voicing data for Catalan two-consonant clusters just referred to calls for a detailed analysis of the intersegmental voicing adaptation patterns in three-consonant clusters where syllable-final obstruents should be less likely to acquire voicing in view of the high intraoral pressure level involved in the production of sequences composed of a larger number of consonants (Westbury & Keating, 1986). A first goal of the present investigation is therefore to study the extent to which word final obstruents assimilate in voicing to the following word initial voiced consonant in Catalan three-consonant clusters. The Catalan CC#C combinations presented in Table 1 will be analyzed, where C2 is always an obstruent while C1 and C3 may be an obstruent or a sonorant, as in the examples talp dur and casc moll referred to above. In order to formulate the research hypotheses to be explored later on in this Introduction section, it must be noted that in the clusters of interest /r/ is realized as a trill in C3 position and as a more tap-like rhotic in C1 position, and that C3 = /b, d, g/ are expected to lenite to the approximant allophones [β, ð, ɣ] (these symbols will be used instead of [β̞, ð̞, ɣ̞] throughout the paper) after a fricative though a voiced stop realization may also occur (Recasens, 1993, 1996).

In view of the failure for a strong version of the regressive voicing assimilation rule to operate in two-consonant clusters (vocal fold vibration data only), another goal of the present study is to look into the voicing coarticulation effects occurring among consonants placed in different positions in the cluster so as to find out what the patterns of intersegmental voicing organization are. This investigation involves carrying out an analysis of not only the regressive voicing effects exerted by C3 onto the preceding obstruent(s) but also the progressive voicing effects from the C1C2 sequence onto C3, and the effects involving C1 and C2 exclusively (regressive: C2-to-C1; progressive: C1-to-C2).

The analysis of these voicing coarticulation relationships will allow investigating another research topic, i.e., whether syllable and word affiliation (which, as pointed out above, cannot be teased apart in our Catalan consonant cluster data) plays any role in the intersegmental voicing effects that we observe. If it does, voicing coarticulation could take place between consonants placed within the same syllable and the same word rather than across a syllable and a word boundary, and therefore between C1 and C2 rather than between these two consonants and C3. While this hypothesis has not been clearly supported by research on overlap of lingual gestures for consonants in CC clusters (Byrd, 1996), there is some evidence in the literature that the application of certain phonetic or phonological processes is conditioned by syllable affiliation. Thus, acoustic data for /ns/ in American English and Dutch indicate that stop insertion between C1 and C2 is more prone to apply whenever the two consonants are placed within the same syllable than when they are separated by a syllable boundary (Yoo & Blankenship, 2003; Warner & Weber, 2002).

1.1. *Voicing coarticulation and the DAC model*

This analysis of voicing coarticulation will be carried out within the framework of the Degree of Articulatory Constraint (DAC) model of coarticulation which was used for the investigation of voicing adaptation patterns in two-consonant sequences in our previous study. The model, which has been mainly applied to the study of lingual coarticulation (Recasens, Pallarès, & Fontdevila, 1997), is based on the principle that the extent to which consonants resist the coarticulatory effects of other phonetic segments (coarticulation resistance) and exert coarticulatory effects on these adjacent segments (coarticulation aggressiveness) ought to increase with the involvement of a given articulator in their production. Thus, for example, since the tongue dorsum is more actively involved in the production of (alveolo)palatal consonants than in that of labials and alveolars, the former consonants ought to be more resistant to tongue dorsum coarticulation effects from the adjacent vowels than the latter, while at the same time exerting more prominent coarticulatory effects on the vowels in question. The basic prediction of the model regarding voicing coarticulation is that there should be a positive relationship between: (a) the degree to which a given consonant allows voicing to occur as measured by the percentage of voicing during the consonant, and the degree of voicing resistance, i.e., the extent to which the consonant resists voicing effects from the contextual consonants; (b) those two properties and the degree of voicing coarticulation aggressiveness, i.e., the extent to which voicing is transmitted from one consonant to another. More specifically, consonants which because of their production requirements are prone to exhibit voicing all throughout ought to be most resistant to changes in voicing degree induced by the adjacent consonants and also most aggressive. Thus, for example, sonorants (nasals, laterals) are expected to exert more voicing coarticulation on preceding obstruents (stops, fricatives) than obstruents since they exhibit more voicing and are less prone to devoice across contextual conditions.

Voicing degree and thus voicing coarticulation resistance as a function of the contextual consonants is expected to depend on manner and place of articulation. In agreement with data reported in our previous study, higher degrees of voicing should occur for sonorants excluding the alveolar trill, namely, nasals, laterals and approximants (/j/ and the allophones [β, ð, ɣ] of C3 = /b, d, g/). Lower degrees of voicing should occur for obstruents, i.e., stops (including the allophones [b, d, g] of C3 = /b, d, g/) and fricatives, as well as for the alveolar trill. Voicing ought to be thus easier in nasals, laterals and approximants, which are produced with relatively unimpeded airflow. The production of the alveolar trill and stops requires a high intraoral pressure level, and that of fricatives a relatively open glottis (Westbury & Keating, 1986; Ohala & Solé, 2010). Both requirements conflict for voicing.

As for the effect of place of articulation, labial and dental stops are expected to stay voiced throughout to a larger extent than velar stops as the size of the back cavity and the associated degrees of compliance of the vocal tract surface walls increase with closure anteriority (Ohala & Riordan, 1979). In principle, a positive relationship between closure or constriction fronting and voicing degree ought to hold for fricatives as well. However, in contrast with languages where /f/ voices to a larger extent than /s, ʃ/ due to its being more anterior and exhibiting a shorter and weaker frication noise (English; Haggard, 1978), voicing degree was found to be less for C1 = /f/ than for C1 = /s, ʃ/ in our study on regressive voicing assimilation in Catalan two-consonant clusters. We hypothesize that this special voicing behavior may be due to a requirement to preserve the integrity of the labiodental fricative by enhancing its weak acoustic properties in the light of the scarce number of words ending in /f/ in Catalan (there are only about four genuine and widely used Catalan words showing this consonant in postvocalic word final position).

Regarding coarticulatory aggressiveness, voicing coarticulation patterns reported in our study on two-consonant clusters with C1 = /p, t, k, f, s, ʃ/ and C2 = /b, d, g, m, n, l, z, r, ʎ, j/ were in partial agreement with the DAC prediction that the extent to which consonants cause other adjacent consonants to acquire voicing should vary positively with voicing degree and voicing coarticulation resistance in the triggering consonant. In line with C2-dependent differences in voicing, /z/ and the approximant allophones of /b, d, g/ turned out to exert more regressive voicing than the trill /r/ and the stop allophones of /b, d, g/. Contrary to the initial expectation, however, syllable final fricatives and stops showed much less voicing than expected before the nasals and laterals /m, n, l, ʎ/ (above 80% voicing at C2, less than 45% voicing at C1), and voicing differences as a function of place of articulation for /b, d, g/ did not extend into C1. The presence of little voicing during obstruents followed by nasals and laterals is not in accordance with the regressive voicing assimilation rule. It appears to be due to the need to preserve the pressure difference across the oral constriction for intense turbulence and thus the integrity of the frication noise for fricatives, and to allow for a sufficient intraoral pressure build-up for the generation of a salient burst for stops, which could be impaired if regressive voicing occurred simultaneously with anticipatory nasalization for nasals and with anticipatory tongue front raising for laterals (see Ohala and Solé (2010) regarding this issue). In the light of these results, the present paper will verify whether patterns of voicing degree and aggressiveness in three-consonant clusters conform to those occurring in two-consonant clusters and, in particular, whether nasals and laterals induce less voicing on other consonants than expected.

Attention is to be drawn to the progressive voicing effects. In principle, our expectation is that progressive voicing should be more dependent on mechanical constraints and the on-line state of the articulators than regressive voicing since the latter involves phonemic planning while the former does not. Our previous study on voicing assimilation in Catalan two-consonant sequences reported some progressive voicing effects, i.e., less voicing for an underlying voiced C2 as a function of a preceding fricative than of a preceding stop, which were attributed to a larger amplitude of the devoicing gesture for the former vs latter class of obstruents (see Hoole, 1999). In any case, these progressive effects turned out to be less prominent than the regressive ones, which is consistent with the regressive nature of the voicing assimilation process in Catalan.

1.2. Other voicing cues

Another research goal of the present paper is to investigate whether other phonetic characteristics which are more closely related to oral pressure and airflow volume such as segmental duration and intensity may act as voicing cues. If so, it may be claimed that regressive voicing assimilation applies in Catalan though cued by more phonetic parameters than just vocal fold vibration.

While the traditional view is that vocal fold vibration should be the primary voicing cue for obstruents in languages with voicing lead like Catalan (see above), it has been proposed that segmental duration for the target consonant and the preceding vowel may also contribute to signaling the voicing distinction (Martínez Celdrán & Fernández Planas, 2007). In agreement with this possibility, data for two-consonant cluster pairs differing in the C2 voicing status, e.g., /sb/–/sp/, reported in our previous study revealed that regressive voicing assimilation and thus the C1 voicing contrast may be cued not only by vocal fold vibration but by segmental duration and intensity as well. In particular, while underlying voiceless obstruents were longer than their voiced counterparts in C2 position, C1 turned out to be longer before a voiceless C2 than before a voiced C2 in stop/fricative + stop sequences while the opposite trend was found to hold in stop + fricative sequences; moreover, the vowel preceding the cluster was longer in fricative + stop and stop + fricative clusters with a voiced C2 than in those with a voiceless C2. In addition, some speakers produced the C1 = /s/ frication noise in fricative + stop clusters more intensely when C2 was voiceless than when it was voiced. These findings are essentially in agreement with the expected outcome for obstruents to be shorter if phonetically voiced than voiceless, for vowels to be longer before a voiced obstruent than before a voiceless one (see Smith (1997) for English and Jansen (2004) for Hungarian), and for fricatives to exhibit a higher noise intensity level and for stops to show a longer burst if voiceless than if voiced (Balise & Diehl, 1994; Zue, 1980; Crystal & House, 1988).

An additional set of sentences including three-consonant cluster pairs differing in the underlying C3 voicing status, i.e., three stop + fricative + stop pairs and one sonorant + stop + fricative pair (see Section 2.1), will be used in the present study in order to investigate the extent to which other phonetic characteristics besides vocal fold vibration cue voicing in three-consonant clusters. The following predictions should hold true: whether underlyingly in C3 position or as a result of voicing assimilation in C1 or C2 position, obstruents ought to be shorter, and show a less prominent frication noise and a shorter burst, if voiced than voiceless; moreover, the vowel preceding the cluster ought to be longer in clusters where C3 is voiced than in those where it is voiceless.

1.3. Summary of research goals

The present paper seeks to investigate the phonetic implementation of the regressive voicing assimilation process in Catalan CC#C sequences by looking into the extent to which syllable final obstruents are affected by an underlyingly voiced C3 regarding vocal fold vibration and segmental duration and intensity. Other regressive and progressive voicing effects will also be subjected to analysis in order to find out whether a tighter voicing interaction occurs between C3 and the two preceding consonants (as predicted by the phonological regressive voicing rule), or else between C1 and C2 and thus between consonants placed within the same syllable. Electroglottographic and acoustic data will be recorded and analyzed for that purpose. The prediction of the DAC model will be tested that the degree to which consonants influence each other in voicing should depend on the extent to which voicing for the triggering consonant is kept high across contextual conditions. Therefore, voicing aggressiveness should be greater for sonorants than for obstruents and for anterior vs. posterior obstruents, though specific perceptual and/or aerodynamic requirements for stop, fricative+nasal, lateral sequences and for labiodental fricatives may prevent this from being the case. Progressive voicing related to glottal opening is expected to be favored by fricatives vs stops.

2. Method

2.1. Experimental paradigm

The CC#C sequences subjected to analysis are presented in Table 1. They have been split according to whether the obstruent C2 is a fricative (/f, s, ʃ/) or a stop (/p, k/). The consonant sequences were recorded and analyzed in the seven- to eight-syllable long meaningful sentences listed in Appendix 1. In all sentences, consonants are preceded and followed by a lexically stressed mid or low vowel, and sentence stress falls on the vowel following the cluster. Acoustic and electroglottographic data were recorded simultaneously using the multichannel Kay Pentax system. Electroglottography (EGG), a method which has been widely used for the study of voicing assimilation in the literature (Slis, 1981; Smith, 1997), provides information on vocal fold opening and closing by measuring the change in electrical impedance across the throat, and allows measuring the onset and offset of vocal fold vibration and thus the duration of a given voicing period on glottal waveforms (Rothenberg & Mahshie, 1988). The acoustic data were recorded with a Shure SM58-LCE microphone, and the EGG data with an EGG-2 glottograph from Glottal Enterprises by placing two surface electrodes onto the speaker's neck. Both signals were acquired at 22,050 Hz, and downsampled to 500 Hz for the EGG signal and to 11,025 Hz for the acoustic signal. The same eight native Catalan speakers who took part in the study on voicing assimilation in heterosyllabic CC combinations, i.e., five women (MA, EV, PE, LO, and VA) and three men (DR, MO, and SO) of about 25–55 years of age, read all sentences eight to ten times each at their normal speaking rate. These informants come from different areas of Catalonia: six of them speak the Eastern Catalan dialect and were born in urban Barcelona (SO, PE) and in other towns and villages (DR, Tarragona; MO, Banyoles; LO, Montblanc; VA, Cadaqués); the remaining two subjects speak Western Catalan and were born in the Baix Urgell region (MA, EV). All CCC productions were expected to conform to the regressive voicing assimilation rule independently of the speakers' dialectal origin. Seven repetitions of each cluster were chosen for analysis. The EGG signal was smoothed using three steps depending on the degree of noisiness of the glottal signal and analyzed using the MatLab script Peakdet 2 according to the criteria described in Section 2.2 (Abadal & Recasens, 2009).

In order to investigate the contribution of other phonetic characteristics besides vocal fold vibration to regressive voicing assimilation in Catalan, acoustic recordings were carried out of a second list of sentences (see Appendix 2), which exhibit the same lexical and prosodic characteristics as those appearing in Appendix 1. All clusters were preceded by a low vowel since this vowel duration was one of the potential voicing cues which was subjected to measurement. The sentence list was read by four out of the eight speakers who took part in the first recording session, i.e., DR, MO, SO and EV, several months after the first recording took place. Sentences include four pairs of three-consonant clusters with a final obstruent differing in underlying voicing, i.e., the stop+fricative+stop pairs /psb–psp/, /tsd–tst/ and /ksg–ksk/ and the sonorant+stop+fricative pair /lpz–lps/. Ten out of twelve repetitions of each cluster were chosen for analysis. This speech material was used for the analysis of C1, C2 and C3 and preceding vowel duration, the acoustic energy of the frication noise for C2 = /s/ and for C3 = /s, z/, and the duration of the C3 stop burst for the underlying voiceless stops and for their voiced counterparts whenever realized as stops instead of as approximants.

2.2. Measurement criteria

2.2.1. Segmentation

C1, C2 and C3 onsets and offsets were identified based on visual inspection of simultaneous spectrographic and waveform displays using CSL (Computerized Speech Lab) from Kay Pentax such as those displayed in Fig. 1. Phonetic segments were delimited by the edges of periods of high intensity formant structure in the case of the vowels preceding and following the three-consonant cluster, of low intensity formant structure for nasals, laterals and approximants, of acoustic closure with no available formants for stops, and of a high frequency frication noise for fricatives. Differences in noise frequency and intensity (both lower for /f/ than for /s/ as shown in Fig. 2) allowed determining the boundary between the two fricatives in the sequence /fs/ for all speakers except for speaker LO who therefore contributed no /fsC/ cluster data to the voicing database. The alveolar trill in C3 position was identified essentially by the presence of two short closures separated by a short opening phase, and could be realized much less often with one or three contacts, as an approximant or as a fricative; on the other hand, the preconsonantal rhotic had a single contact as a general rule, and could be realized as an approximant or as a fricative less often by some speakers. Bursts were considered not to be part of stop consonants and could be absent occasionally for a stop C2 followed by another stop; cluster tokens without a visible C2 burst were excluded from analysis since stop duration could not be measured in these circumstances. C2 = /b, d, g/ were classified as approximants or as stops depending on whether they exhibited weak formant structure with or without some frication noise overimposed or a closing phase and possibly a burst, respectively.

Based on visual inspection of spectrographic displays and on the first author's auditory impression, about 40% of repetitions of the clusters /spC, skC/ and 10% of tokens of /lpC, lkC, rpC, rkC/ had to be excluded from the analysis of the vocal fold vibration data. This happened to be the case whenever C1 was absent (just a few tokens), C2 was absent (38.4% of the time for /skC/, 8–8.5% for /rkC, spC/ and very seldom for /lpC, lkC, rpC/), and /p/ was replaced by /f/ or /s/ and /p/ blended into /f/ in the case of the /spC/ sequences (12.9% and 11.5% of the time, respectively). The frequency of application of these changes varied according to speaker, e.g., speakers MA and DR showed no instances of stop deletion.

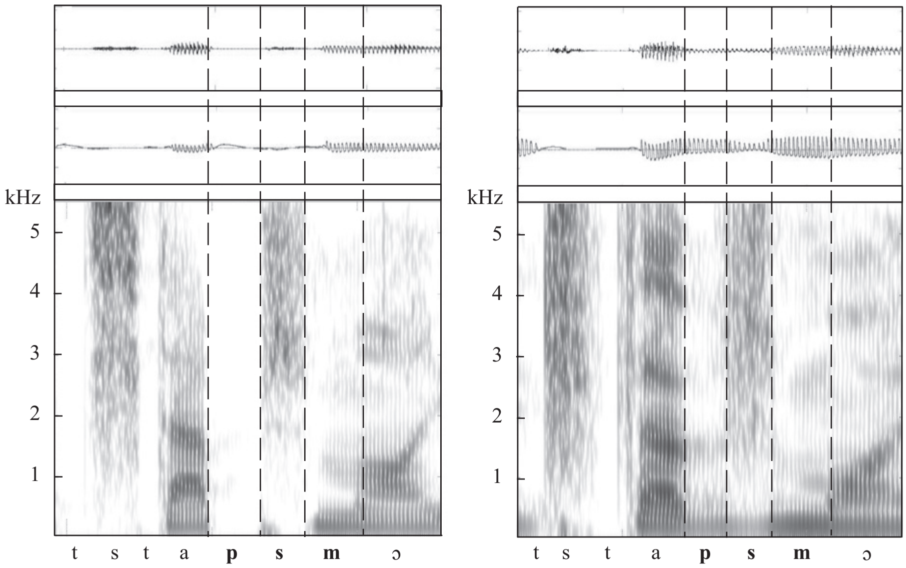

Fig. 1. Acoustic waveform (top), glottal waveform (middle) and spectrogram (bottom) for two realizations of the sequence /tstapsmɔ/ occurring in the sentence 'asseca'ls aquests taps molls' "dry these wet corks" according to speakers MA (left) and VA (right). Vertical lines have been inserted at the onset and offset of the phonetic segments of the cluster /psm/ (in boldface).

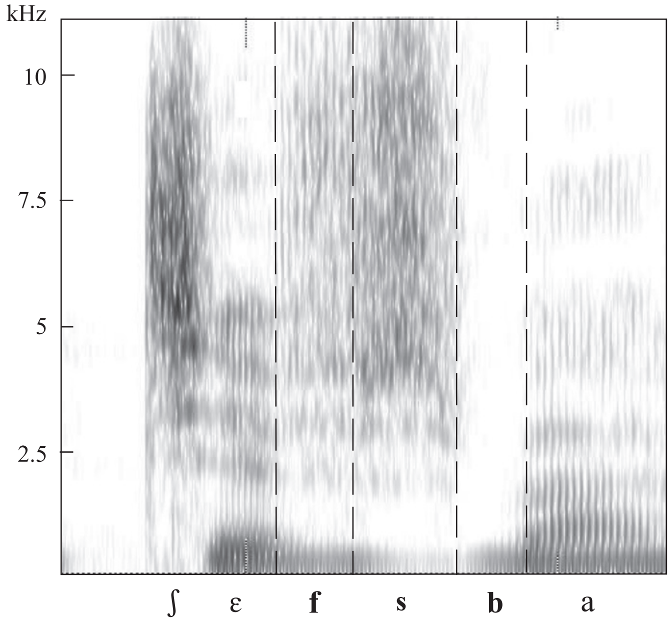

Fig. 2. Spectrogram for a realization of the sequence /ʃɛfsba/ occurring in the sentence 'a la cuina hi ha xefs bascos' "there are Basque chefs at the kitchen" according to speaker VA. Vertical lines have been inserted at the onset and offset of the phonetic segments of the cluster /fsb/ (in boldface).

A voiceless period devoid of formant structure occurred often at the boundary between a fricative or a stop C2 and a nasal C3 and, less often, between a fricative C2 and a lateral C3. As shown by the left spectrographic display for the sequence /psm/ in Fig. 1, this period was considered to be part of C3 (see also Docherty, 1992 for similar cases of voicing delay past C1 offset in English fricative + nasal clusters). Formant structure occurs all throughout the nasal in the right graph of the figure.

2.2.2. *Detection and analysis of voicing*

Peakdet 2 was used for identifying the onset and offset of vocal fold vibration. Voicing pitch pulses are identified by Peakdet 2 at each positive peak of the first derivative of the glottal waveform (DEGG), and inserted simultaneously at the glottal closing instant of the corresponding vibration period on the EGG waveform (see Fig. 3). As also shown in the figure, for periods of voicelessness between two periods of continuous voicing, labeling was carried out at the closing state of the last glottal pulse of a voicing period as determined by the last positive DEGG peak, and at the first glottal pulse of the voicing period following the period of voicelessness as determined by its first DEGG peak. This peak picking procedure was applied setting a threshold detection at 25% of the DEGG positive maximum which is slightly below other threshold values proposed in the literature (Rothenberg & Mahshie, 1988). In order to account for the presence of double DEGG peaks, the peak picking procedure was carried out using the barycentre method which weighs the two peaks and takes a temporal point close to the highest peak (Mazaudon & Michaud, 2008). Two or more

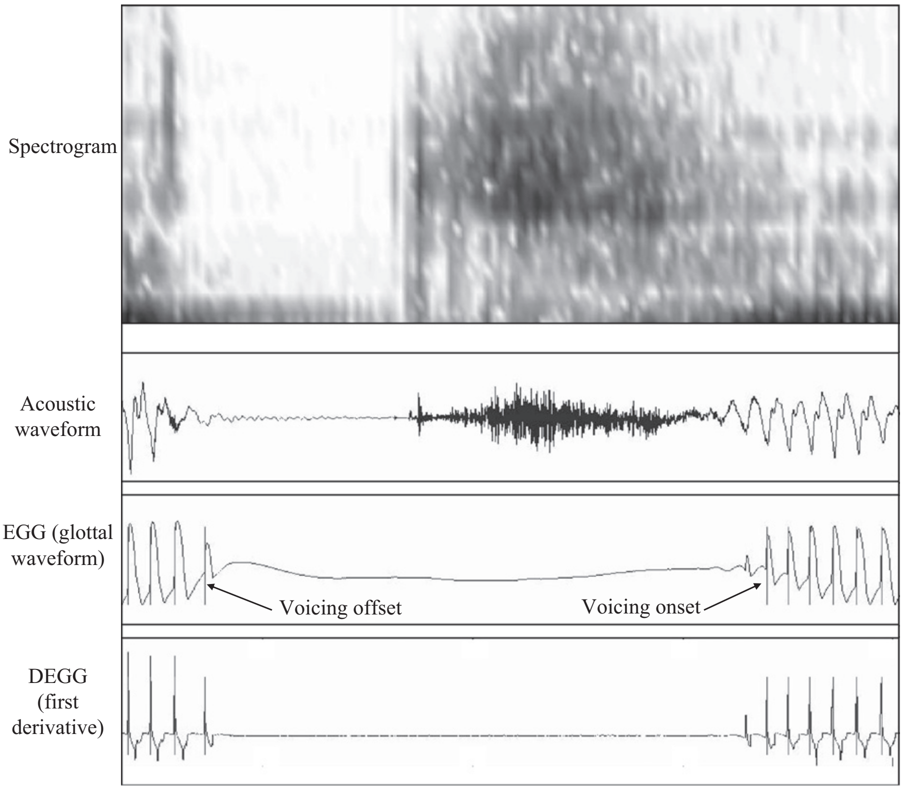

Fig. 3. Identification procedure of the voicing pitch pulses in the glottal waveform using Peakdet 2. Labels are inserted simultaneously at the DEGG positive peaks and the corresponding EGG temporal points. The graph illustrates how voicing offset and voicing onset were determined.

consecutive pulses had to be present for them to be attributed to a voicing period; therefore, isolated glottal pulses surrounded by periods of voicelessness were assigned to a voiceless period.

The present study establishes voicing degrees for each consonant based on the voicing percentages over consonant duration, which is a way to normalize the voicing data across variations in segmental duration which may arise from the presence of different speakers' speaking rates (see for the same procedure Haggard (1978), Docherty (1992), Smith (1997) and Snoeren et al. (2006)). Analogously to these other studies, voicing percentages were computed from the EGG data exclusively while consonant durations were determined acoustically applying the segmentation criteria described in Section 2.2.1.

2.2.3. *Energy*

The absolute energy level of the frication noise was measured at C2 midpoint in the stop +/s/+stop sequences appearing in Appendix 2, and at C3 midpoint in the /l/+stop+/s, z/ sequences. Energy values in dB are obtained by multiplying intensity by duration (Dorman, Studdert-Kennedy, & Raphael, 1977). They were taken with a frequency range 0–11,025 Hz on 15 ms window energy profiles using the energy display of the CSL system of Kay Pentax. In order to normalize the absolute energy differences across speakers and to make sure that the energy measures for the fricative were not influenced by differences in syllable prominence, relative energy values were also calculated for each sequence token by dividing the absolute energy value at the midpoint of the fricative by that at the midpoint of the preceding vowel (Cho, Jun, & Ladefoged, 2002).

2.2.4. *Voicing degree, and coarticulation resistance and aggressiveness*

Voicing degree for a given consonant has been taken to equal the voicing percentage for that consonant at its original location across contextual consonants. Thus, for example, voicing degree for a given C3 was computed by averaging the voicing percentages for this consonant at the C3 position across C1C2 conditions (e.g., voicing degree for C3=/b/ across the eleven clusters /psb, tsb, ksb, fsb, msb, lsb, rsb, tʃb, mfb, lfb, rfb/). Also, voicing degree for C2=/p/ corresponds to the voicing percentage for this consonant at the C2 site averaged across the ten consonants which may appear in C3 position (/b, d, g, m, n, l, z, r, ʎ, j/) and the three consonants which may appear in C1 position (/l, r, s/). To the extent that these voicing percentages have been obtained across contextual conditions, they may be said to reflect the degree to which a given consonant resists the coarticulatory influence of the contextual consonants, i.e., its degree of voicing coarticulation resistance. Regarding the three-consonant clusters under investigation, coarticulatory resistance is most prone to be investigated in positions where consonants are expected to be fully voiced, i.e., for nasals and laterals in all positions and for obstruents in C3 position. In principle, syllable-final obstruents and syllable-initial trills ought to undergo some devoicing by virtue of their aerodynamic requirements irrespective of segmental context (see Section 1.2).

Voicing coarticulation aggressiveness for a given consonant is determined by the voicing percentages computed as a function of the triggering consonant at different cluster sites from its own across contextual consonant conditions. Thus, the regressive voicing effects exerted by a given C3 on C2 and on C1 have been computed by averaging the voicing percentages at C2 and C1, respectively, across clusters composed of all C1C2 combinations and the triggering C3. For example, the regressive voicing effect of C3=/b/ on a fricative C2 was obtained by averaging the C2 voicing percentages at the C2 site across all eleven clusters /psb, tsb, ksb, fsb, msb, lsb, rsb, tʃb, mfb, lfb, rfb/. The stronger the voicing effect, the more the resulting voicing percentage should approach the voicing degree for the triggering consonant. In order to analyze the progressive voicing effects on

C3, on the other hand, the voicing data at the C3 site were averaged for each C1C2 sequence across all C3 conditions, e.g., the progressive effect of /ps/ amounts to the voicing average at C3 across the clusters /psb, psd, psg, psm, psn, psl, psʎ, psj/.

The same methodology was applied in order to elicit the C2-to-C1 regressive and C1-to-C2 progressive effects in C1C2 sequences. Moreover, clusters had to be broken down into smaller groups so as to explore the voicing coarticulation scenarios in several cases. Thus, for example, differences in voicing degree between C2 = /f/ and C2 = /s/, and the extent to which these differences were dependent on C1 and were transmitted to C1, were evaluated using those sequences where the two fricatives were preceded by the same consonants /1, s, r/.

2.3. Statistics

In order to explore the patterns of voicing coarticulation resistance and aggressiveness involving the consonants of the clusters appearing in Table 1 and Appendix 1, several statistical tests were performed on the corresponding vocal fold vibration percentages.

Statistical analysis for several voicing effects were performed by means of one-way ANOVAs using the same design in the case of clusters with a fricative C2 and with a stop C2: C3 coarticulation resistance and aggressiveness were evaluated at C3, and at C1 and at C2, respectively, with C3 as factor and factor levels ‘b, d, g, m, n, l, ʎ, j’ and ‘b, d, g, m, n, l, z, r, ʎ, j’; C1 resistance at C1 and C2 resistance at C2, as well as progressive effects from C1C2 onto C3, were tested with C1C2 as factor and factor levels ‘ps, ts, ks, fs, ms, ls, rs, tʃ, mf, lf, rf’ and ‘lp, rp, sp, lk, rk, sk’. For these and most of the ANOVAs referred to below, eta-squared values reflecting the proportion of variability in voicing percentage explained by the independent variables were obtained.

Differences in coarticulatory resistance among consonants appearing at the initial and medial cluster position, as well as regressive C2-to-C1 effects and progressive C1-to-C2 effects, were also analyzed statistically. As for clusters with a stop C2, two-way ANOVAs were carried out on the C1 and C2 voicing data with the independent variables ‘C1’ (factor levels ‘l, s, r’) and ‘C2’ (‘p, k’). Several tests were performed on the C1 and C2 voicing data for clusters with a fricative C2 in view of the fact that /s/, /ʃ/ and /f/ combine with different preceding consonants both regarding number and place and manner characteristics: a two-way ANOVA for the clusters /mf, lf, rf, ms, ls, rs/ with ‘C2’ (factor levels ‘f, s’) and ‘C1’ (‘m, l, r’) as variables; a two-tailed *t*-test for the cluster pair /ts/–/tʃ/; two one-way ANOVAs for clusters with C2 = /s/ (factor levels ‘p, t, k, f, m, l, r’) and for clusters with C2 = /f/ (‘m, l, r’) with ‘C1’ as factor.

Statistical tests were performed on the durational and energy data for the clusters listed in Appendix 2. Two-way ANOVAs were run on the V, C1, C2, C3 and the C3 burst duration values in the case of the stop + fricative + stop pairs /psb/–/psp/, /tsd/–/tst/ and /ksg/–/ksk/, with the fixed variables ‘C3 voicing’ (levels ‘voiced, voiceless’) and ‘C3 place of articulation’ (levels ‘labial, dentoalveolar, velar’). As for the sonorant + stop + fricative pair /lpz/–/lps/, a one-way ANOVA was also performed on all those dependent variables except for burst duration, with the fixed variable ‘C3 voicing’. Absolute and relative noise energy values for the alveolar fricative, i.e., C2 or C3 depending on the case, were analyzed statistically using the same design as above.

All ANOVAs were carried out on mean data across tokens with ‘speaker’ as a random factor using IBM SPSS Statistics version 19. The statistical model included the main effect(s) and the two-way interaction between two fixed variables whenever available. Pairwise comparisons using the Bonferroni correction were carried out in order to uncover significant differences among three or more levels of those analysis factors which yielded a main effect. In all statistical tests, the significance threshold was set at $p < 0.05$. A reason for performing univariate ANOVAs instead of ANOVAs with repeated measures was due essentially to the fact that speaker LO did not contribute /fsC/ cluster data (see Section 2.2.1).

3. Results

3.1. Vocal fold vibration

Both for the clusters with a fricative C2 and for those with a stop C2 listed in Appendix 1, results for voicing degree and coarticulation resistance, i.e., differences in degree of vocal fold vibration among consonants at their own cluster site across contextual consonants, will be presented in the first place (see Sections 3.1.1.1 and 3.1.2.1). Data on voicing coarticulation aggressiveness, i.e., on the extent to which consonants influence vocal fold vibration in consonants placed at other cluster sites, will be reported in the second place as follows: regressive effect of C3 on the preceding consonants; progressive effect of these consonants on C3; regressive and progressive effects between C1 and C2 (see Sections 3.1.1.2 and 3.1.2.2).

3.1.1. Clusters with a fricative C2

3.1.1.1. Voicing degree and coarticulation resistance. C3-dependent differences in voicing degree may be seen in Fig. 4 (right graph) displaying voicing percentages for each C3 across C1C2 conditions at the C3 position within the cluster. In agreement with our initial expectations, ANOVAs yielded a main C3 effect ($F(7, 49) = 14.65$, $p < 0.001$) which according to post-hoc tests is related to a greater voicing degree for sonorants than for stops. Further differences conform to the progression the approximant /j/ (97.1%) > the laterals /l, ʎ/ (85.8–92%) > the nasals /m, n/ (73.8–82.7%) > the stops /b, d, g/, with the labial showing more voicing than the dental and the velar (51.1–66.3%). The percentages for /b, d, g/ include data for both stop and approximant realizations: when split into the two manner classes, voicing percentages turned out to be higher for the approximant realizations [β, ð, ɣ] (70–95%) than for the voiced realizations [b, d, g] (30–50%). In order to find out whether the individual speakers' behavior is consistent with the general pattern observed across speakers, C3 voicing percentages for all subjects have been plotted along the vertical axis of Fig. 5 (left graph). Data reveal that, as expected, sonorants (filled symbol) exhibit more voicing than obstruents (unfilled symbol). As noted in Section 2.2.4 and in line with voicing data for the same consonants in other cluster positions, these C3-dependent differences in voicing may be taken to reflect the fact that approximants, nasals and laterals are more resistant to contextual devoicing effects induced by the preceding contextual consonants than voiced stops.

Voicing percentages for C2 = /f, s, ʃ/ across C1 and C3 contextual conditions plotted in Fig. 4, middle graph, reveal the presence of little voicing for all three fricatives: voicing ranges are 19.9–29.3% for /f/ and 11.2–41.8% for /s/, while the voicing percentage for /ʃ/ after /t/ amounts to 8%. Moreover, voicing differences among fricatives failed to reach significance for /s/ vs /ʃ/ in clusters with C1 = /t/, and turned out to be significantly higher for /s/ than for /f/ in clusters with C1 = /m, l, r/ ($F(1,35) = 10.81$, $p < 0.002$) which is in agreement with data for Catalan two-consonant clusters showing less voicing for /f/ than for /s/ in syllable final position.

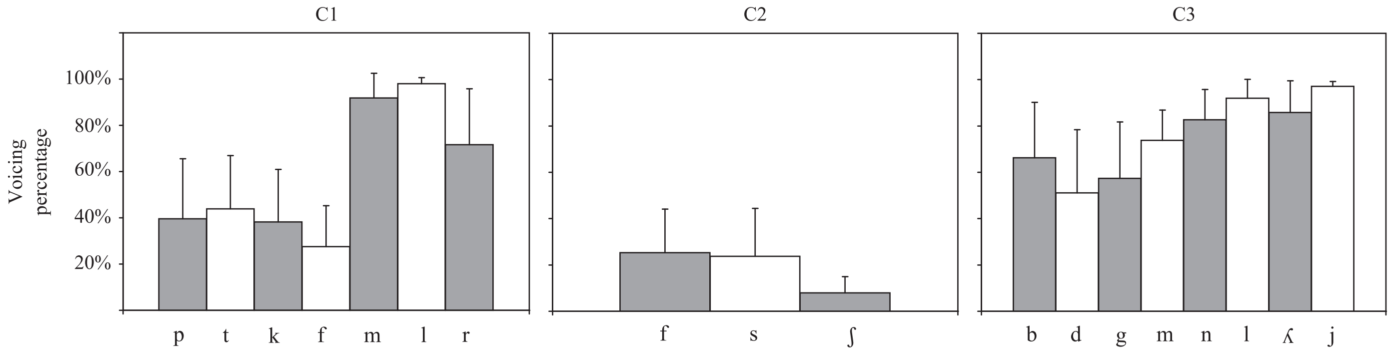

Fig. 4. Voicing percentages for C1, C2 and C3 in clusters with a fricative C2 plotted at their cluster location across contextual consonants and speakers. Error bars correspond to one standard deviation.

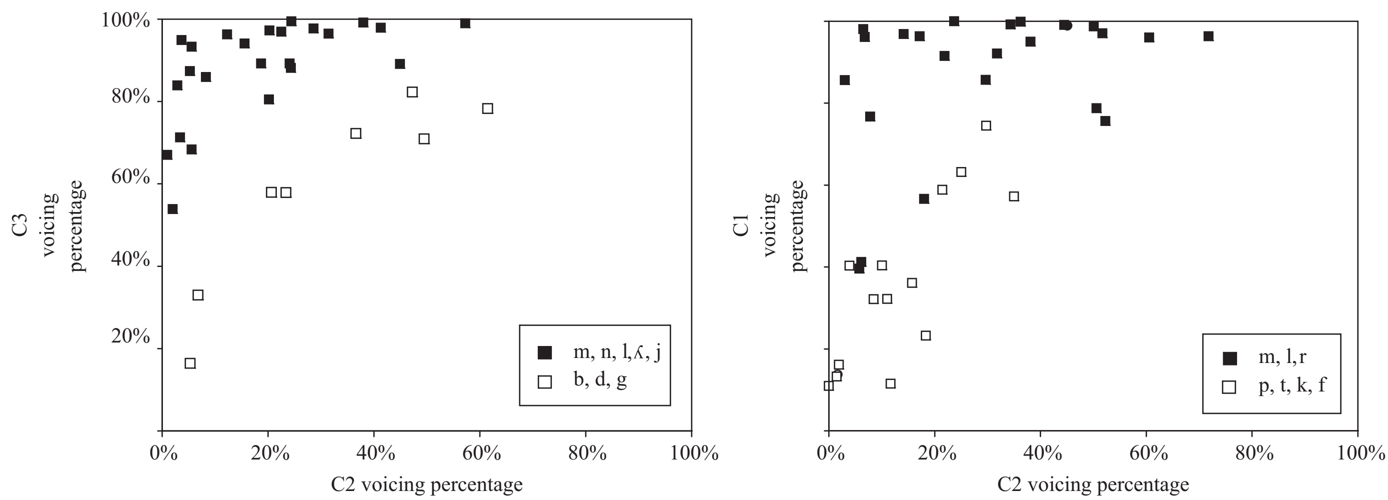

Fig. 5. Speakers' voicing percentages for clusters with a fricative C2. (Left) Voicing percentages for C3 plotted at the C3 site (vertical axis) against the C2 location (horizontal axis). (Right) Voicing percentages for C1 plotted at the C1 site (vertical axis) against the C2 location (horizontal axis).

C1-dependent differences in voicing degree across C2 and C3 conditions plotted in the left graph of Fig. 4 reveal the presence of low voicing percentages for obstruents /p, t, k, f/ (27.4–44.9%), intermediate percentages for the rhotic /r/ (about 70%), and maximal voicing for the sonorants /m, l/ (89.1–98.8%). These consonant-dependent differences in voicing degree turned out to be significant according to one-way ANOVAs run on all eleven clusters ($F(10,69)=29.48$, $p<0.001$), on all seven clusters with C2=/s/ ($F(6,41)=29.12$, $p<0.001$) and on all three clusters with C2=/f/ ($F(2,14)=5.23$, $p<0.020$).

Judging from the voicing percentages for syllable final stops and fricatives placed in the C1 and C2 positions, it appears that the degree of voicing for syllable-final obstruents is below 45% which questions the validity of the regressive assimilation voicing rule. Analogously to the scenario for C3 (see above), data on C1 and C2 voicing degree also indicate that voicing coarticulation resistance is higher for sonorants than for obstruents, /r/ falling in between.

Practically all ANOVAs performed on the C1 and C2 voicing data yielded a main speaker effect which, in parallel with the voicing assimilation data for two-consonant clusters reported in our previous paper, turned out to be related to a lesser degree of voicing for speakers from the Barcelona area and for Western Catalan speakers than for Eastern Catalan speakers born outside Barcelona. Voicing percentages were thus minimal for SO (3.64%), EV (4.35%), PE (13.84%) and MA (16.96%), and maximal for VA (42.07%), DR (35.93%), MO (33.85%) and LO (32.21%). Fig. 1 presents a voiceless and a voiced realization of /p/ and /s/ in the cluster /psm/ produced, respectively, by speakers MA (left graph) and VA (right graph). It remains unclear whether the voicing differences among speakers referred to in this section are dialect-dependent or not.

3.1.1.2. Voicing coarticulation aggressiveness. Fig. 6 allows studying the effect of C3 on the degree of voicing in the preceding consonants. The right graph of the figure, which is identical to the right graph of Fig. 4, plots the degree of voicing for /b, d, g, m, n, l, ʎ, j/ at the C3 position. The two left graphs plot voicing values at the C1 and C2 sites as a function of each C3 averaged across C1C2 sequences. If, as claimed by the DAC model, there is a positive relation between coarticulation resistance and aggressiveness, the voicing differences among consonants in the middle and left graphs should parallel those available in the right graph. Voicing percentages at C2 and C1 were found to vary significantly as a function of C3 ($F(7,49)=4.97$, $p<0.001$; $F(7,49)=5.15$, $p<0.001$) though, according to post-hoc tests, they were associated with higher voicing percentages for /b, d/ than for laterals and nasals and, therefore, did not match those available at C3. Higher voicing effects for lenited vs non-lenited realizations of C3=/b, d, g/ could be traced at C2 when the stop was labial and dental (39% vs 27%; 42% vs 29%) but not when it was velar (29% vs 28%), and did not extend until C1 for any of the three places of articulation. In sum, in agreement with the DAC model, while some consonants allowing for maximal voicing at C3 (/j/, approximant allophones of /b, d, g/) cause more voicing to occur during C1 and C2 than other consonants, this is not so for nasals and laterals which exhibit high voicing percentages at the C3 site (80–100%) while causing C1 and C2 to show less voicing than expected. Lower eta-squared values at C1 (0.424) and at C2 (0.416) than at C3 (0.677) in Table 2(a) denote a poor correspondence between the voicing differences among /b, d,

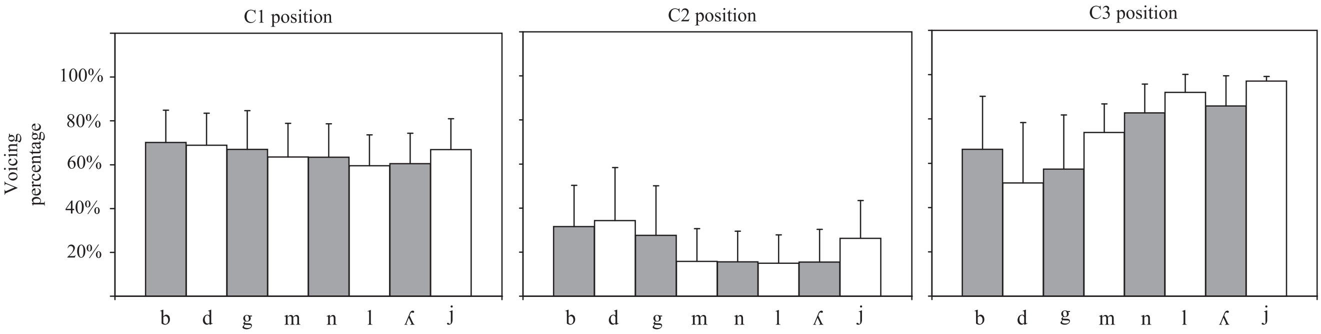

Fig. 6. C3-dependent voicing percentages at the C1, C2 and C3 sites for clusters with a fricative C2. Error bars correspond to one standard deviation.

Table 2
eta-squared values for ANOVAs run on the voicing data for clusters with a fricative C2. Information about whether these values are linked to statistical significance (*) or not (n.s.) is attached. The fixed or independent variables are presented on the left column and the dependent variables on the three right columns.

	Voicing at C1	Voicing at C2	Voicing at C3
(*a*) *One-way ANOVA, all C1C2 combinations*			
C3	0.424 (*)	0.416 (*)	0.677 (*)
C1C2	0.810 (*)	0.527 (*)	0.063 (n.s.)
(*b*) *One-way ANOVA, C1C2 sequences /ps, ts, ks, fs, ms, ls, rs/*			
C1	0.815 (*)	0.558 (*)	–

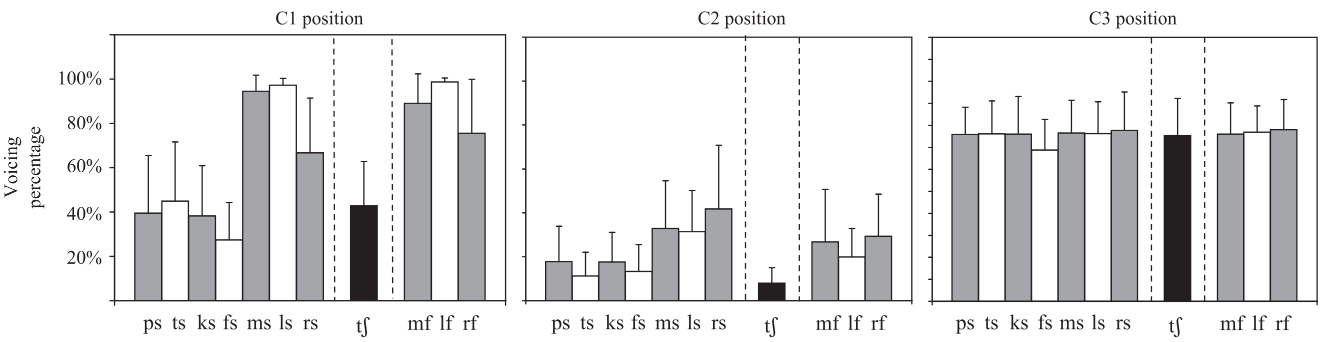

Fig. 7. Voicing percentages for all C1C2 sequences at the C1, C2 and C3 sites in the case of clusters with a fricative C2. Error bars correspond to one standard deviation.

g, m, n, l, ʎ, j/ at C3, and at the C1 and C2 sites. Overall, in parallel to findings for two-consonant clusters, the resistance for obstruents to voice before nasals and laterals may be attributed to the need to preserve their phonetic integrity when followed by consonants involving adverse aerodynamic characteristics (see Section 1.1).

In order to investigate the extent to which C3-dependent regressive voicing effects occur during the preceding fricative for the individual speakers, the left graph in Fig. 5 plots the speakers' voicing percentages for C3 at C3 (vertical axis) and at C2 (horizontal axis). The voicing percentages at the two consonant positions do not exhibit a linear relationship ($r=0.315$ across speakers) since fricative voicing is by no means higher before a sonorant than before a stop. Therefore, also when the individual speakers' data are taken into consideration, voicing during C2 is not clearly associated with the C3-dependent voicing differences.

Progressive effects from C1C2 on C3, and voicing effects between C1 and C2, may be studied with reference to Fig. 7. The right graph plots the voicing percentages for each of the eleven C1C2 sequences averaged across all eight C3 conditions /b, d, g, m, n, l, ʎ, j/ and, therefore, allows studying the progressive voicing effects exerted by the C1C2 string onto the last consonant in the cluster. Voicing differences among consonants in the graph are very small and turned out to be non-significant, which should be taken as indicative that no C1C2-dependent progressive effects on C3 occur in the clusters under investigation. The corresponding eta-squared value amounts to only 0.063 (Table 2(a)) which is in agreement with the lack of statistically significant results.

The middle graph of the Fig. 7 reporting data for each C1C2 sequence at the C2 location shows that C2 is subjected to some progressive effects from the preceding consonant, i.e., fricatives show more voicing after sonorants than after obstruents. Progressive C1-to-C2 voicing effects achieved significance when tested for all eleven C1C2 combinations and for those with C2=/s/ ($F(10,69)=7.7$, $p<0.001$; $F(6, 41)=8.61$, $p<0.001$), but not when tested for the three C1C2 sequences with C2=/f/. According to pairwise comparisons for the two former tests and as shown by the graph, voicing degree turned out to be greater after sonorants (/m, l, r/) than after all or a subset of obstruents (/p, t, k, f/). These data are in accordance to a large extent with the eta-squared values presented in Table 2(a and b): the test run on the data for the eleven C1C2 sequences yielded a high value of 0.527 at C2 (the value at C1 is 0.81), which appears to be associated with C1, as shown by the similar value obtained according to the one-way ANOVA performed on the C1C2 sequences /ps, ts, ks, fs, ms, ls, rs/ (0.558). In order to find out whether progressive C1-to-C2 voicing effects hold for the individual speakers, the right graph in Fig. 5 plots C1-dependent voicing percentages at C1 (vertical axis) against those at C2 (horizontal axis) for all speakers. The two voicing percentages are positively correlated ($r=0.660$) since, analogously to the cross-speaker scenario, an increase in voicing among consonants placed at the C1 site causes the degree of voicing during the following fricative to increase.

As for the regressive C2-to-C1 effects and in line with the significant voicing differences obtained during C2 (see Section 3.1.1.1), the initial expectation is that C2 = /s/ should cause some more voicing than C2 = /f/ to occur during C1. The left graph of Fig. 7 shows instead that voicing during C1 varies according to whether C1 is sonorant or obstruent, not depending on whether C2 is /f/, /s/ or /ʃ/, and therefore that no regressive C2-to-C1 voicing effects take place in Catalan clusters with a fricative C2. Statistical analyses reveal no significant voicing differences between C2 = /f/ and C2 = /s/ during C1 = /m, l, r/, nor between C2 = /s/ and C2 = /ʃ/ during preceding /t/.

3.1.2. Clusters with a stop C2

3.1.2.1. Voicing degree and coarticulation resistance. In parallel to clusters with a fricative C2, a main C3 effect at the C3 location ($F(9, 63)=13.45$, $p<0.001$) was related to higher voicing percentages for nasals, laterals and approximants than for stops, fricatives and the trill: /m, n, l, ʎ, j/ (80–95%) > /b, d, g, z, r/ (45.4–58.9%) (see Fig. 8, right graph). Stop voicing varied as a function of place of articulation in the progression /b, d/ (58%) > /g/ (45.4%), though only the difference between /d/ and /g/ achieved significance. Lower voicing percentages for /b, d, g/ in clusters with a stop C2 than in those with a fricative C2 follow from differences in lenition degree, i.e., /b, d, g/ turned out to lenite less often after a stop (24.5% for /g/, and only 3.8% for /b/ and 4.2% for /d/) than after a fricative (71.7% for /g/, 47.2% for /b/ and 42% for /d/). Analogously to the clusters with a fricative C2, voicing percentages were much higher for the approximant vs stop realizations of /g/ (70.9% vs 35.5%). Moreover, the C3 voicing percentages turned out to be also higher for sonorants (filled symbol) than for obstruents and /r/ (empty symbol) when data for all eight individual speakers are taken into consideration (Fig. 9, left graph, vertical axis). In sum, differences in voicing during C3 vary essentially in the same progression as for clusters with a fricative C2 and may be taken as an index of voicing coarticulation resistance (see also voicing data for sonorants vs obstruents at the C1 position below).

As shown by mean data across contextual conditions in the middle graph of Fig. 8, voicing values for the stop C2 resemble those for fricatives in the same position in being less than 40–50%. C2 was slightly higher for /p/ (52.9%, 40.2% and 6.1% after /l, r, s/, respectively) than for /k/ (51.7%, 33.3% and 5.8%) though this difference did not reach significance. The speaker-dependent differences for the stop proceeded in a similar way to the fricative clusters, i.e., voicing percentages were lower for EV (10.20%), SO (14.31%), MO (17.50%), MA (22.44%) and PE (33.56%) than for VA (66.29%), DR (46.60%) and LO (43.33%).

As revealed by the left graph of the figure, the voicing values for consonants placed at the C1 position yielded a significant difference ($F(2, 35)=152.46$, $p<0.001$) which, as expected, was related to more voicing for the lateral /l/ (99%) than for the rhotic /r/ (70–77%), and least voicing for the fricative /s/ (11–23%).

Analogously to the scenario for clusters with a fricative C2, the fact that syllable-final obstruents in clusters with a stop C2 exhibit very low voicing percentages do not seem to corroborate the validity of the regressive Catalan assimilation voicing rule.

3.1.2.2. Voicing coarticulation aggressiveness. Patterns of voicing coarticulation for clusters with a stop C2 are also similar to those obtained for clusters with a fricative C2. C3-dependent differences in voicing were significantly higher for /d, z/ > /m, r/ at C2 ($F(9, 63)=4.16$, $p<0.001$), and did not achieve significance at C1 (Fig. 10, middle and left graphs). Moreover, voicing differences between lenited and non-lenited realizations of C3 = /g/ could be traced to some extent only during the preceding consonant (46.57% vs 34.3%). As also reported in Section 3.1.1.2, these C3-dependent differences behaved as expected in some cases (i.e., regressive voicing was maximal for /j/ and minimal for /r/, and greater for the approximant vs stop realizations of /b, d, g/) but not in others (i.e., nasals and laterals exhibited maximal voicing at C3 while causing minimal voicing to occur during C2). In line with these results, eta-squared values shown in Table 3(a) indicate that C3 contributes much less to the voicing variability during C2 (0.373) and C1 (0.165) than during C3 (0.658). Moreover, data for the individual speakers in Fig. 9, left graph, reveal no clear relationship between the C3-dependent voicing differences at C3 and at C2 ($r=0.377$), i.e., in comparison to the empty symbols for obstruents, the filled symbols for sonorants are not located higher up and more to the right in the graphs.

Differences in voicing degree during C3 as a function of the preceding consonants were found to be non-significant (see Fig. 11, right graph), which is consistent with the negligible eta-squared value of 0.07 in Table 3(a). Voicing effects involving C1 and C2 were also in agreement with findings reported for the clusters with a fricative C2 in that they turned out to hold at the progressive level ($F(2, 35)=43.78$, $p<0.001$) but not at the regressive level (non-significant). According to results for pairwise comparisons and as shown by the middle graph of Fig. 11, voicing during C2 decreases significantly with C1 voicing in the progression /l/ (51.7–52.9%) > /r/ (33–40%) > /s/ (6%). On the other hand, bars in the left graph show essentially no differences as a function of C2 = /p/ vs C2 = /k/ which is not surprising since the two stops were found not to differ significantly in voicing at the C2 cluster site (see Section 3.1.2.1). This difference in coarticulatory direction is reflected by the eta-squared values presented in Table 3(a and b): while

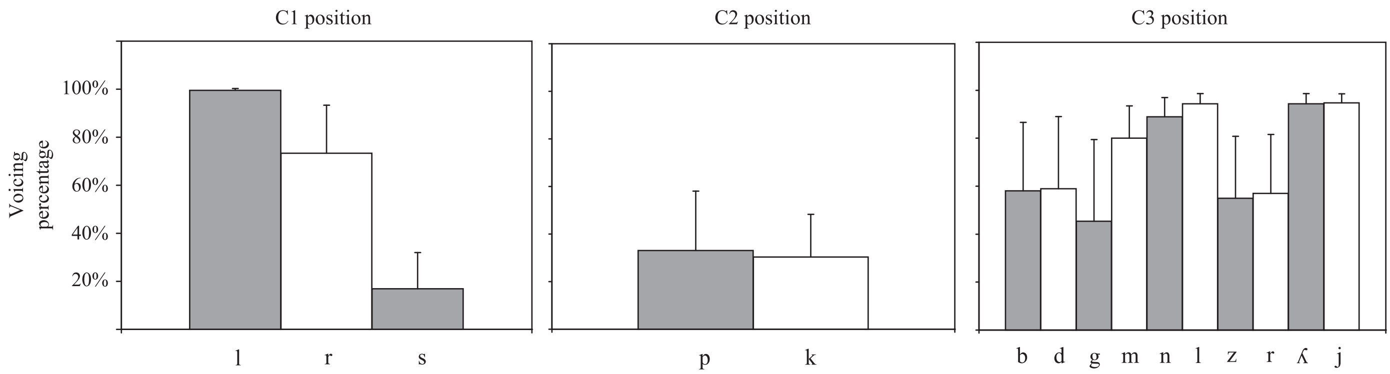

Fig. 8. Voicing percentages for C1, C2 and C3 in clusters with a stop C2 plotted at their cluster location across contextual consonants and speakers. Error bars correspond to one standard deviation.

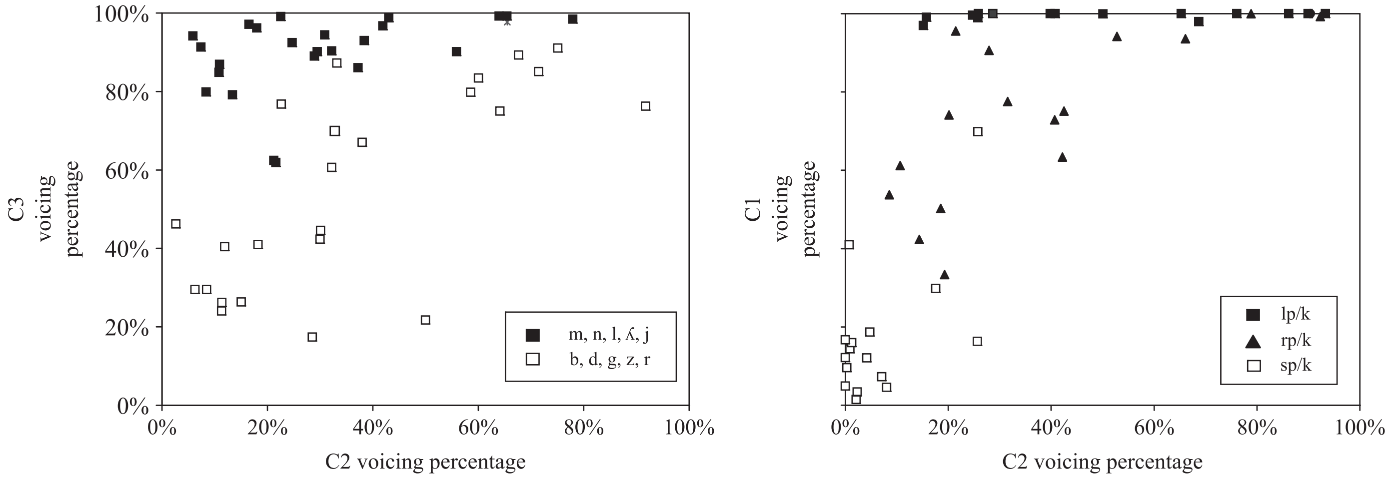

Fig. 9. Speakers' voicing percentages for clusters with a stop C2. (Left) Voicing percentages for C3 plotted at the C3 site (vertical axis) against the C2 location (horizontal axis). (Right) Voicing percentages for C1 plotted at the C1 site (vertical axis) against the C2 location (horizontal axis).

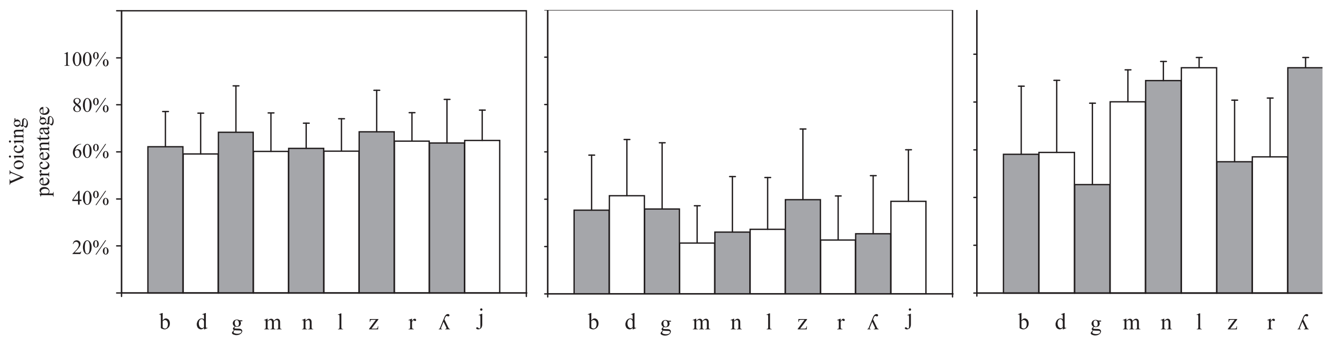

Fig. 10. C3-dependent voicing percentages at the C1, C2 and C3 sites for clusters with a stop C2. Error bars correspond to one standard deviation.

Table 3
eta-squared values for ANOVAs run on the voicing data for clusters with a stop C2. Information about whether these values are linked to statistical significance (*) or not (n.s.) is attached. The fixed or independent variables are presented on the left column and the dependent variables on the three right columns.

	Voicing at C1	Voicing at C2	Voicing at C3
(a) One-way ANOVAs, all C1C2 combinations			
C3	0.165 (n.s.)	0.373 (*)	0.658 (*)
C1C2	0.898 (*)	0.717 (*)	0.070 (n.s.)
(b) Two-way ANOVAs, all C1C2 combinations			
C1	0.925 (*)	0.772 (*)	–
C2	0.292 (n.s.)	0.055 (n.s.)	–

the one-way ANOVAs run on all six C1C2 sequences yielded high values at C1 (0.898) and at C2 (0.717), values obtained for the two-way ANOVAs show that the contribution of C1 is much greater than that of C2 not only at the first consonant position (contribution of C1 = 0.925, contribution of C2 = 0.292) but at the second consonant position as well (contribution of C1 = 0.772, contribution of C2 = 0.055). The prominence of the C1-to-C2 voicing effects is also in accordance with data for all individual speakers reported in Fig. 9, right graph, revealing a high correlation between voicing degree at the two consonant sites decreasing in the progression /l/ >/r/ > /s/ ($r = 0.736$).

3.2. Other voicing cues

Consonant and vowel duration for the cluster pairs listed in Appendix 2 happened to vary as a function of the C3 voicing status in several instances. Regarding the stop+/s/+stop clusters, C3 was significantly longer if underlyingly voiceless than underlyingly voiced ($F(1, 15) = 8.03$, $p < 0.05$) though, as revealed by a significant voicing x place interaction and as shown in the top three graphs of Fig. 12, this duration difference holds for /p/ vs /b/ and for /t/ vs /d/ in the case of the /psb/–/psp/ and /tsd/–/tst/ pairs (left and middle graphs) but not for /k/ vs /g/ in the case of the /ksg/–/ksk/ pair (right graph). The fact that Catalan voiced stops are realized more often as approximants than as stops when preceded by a fricative should contribute to this duration contrast since approximants are more prone to stay voiced than their stop correlates (see Section 3.1.1). Most importantly, for all three cluster pairs and as shown in the same graphs, C2 = /s/ duration is affected by the C3 voicing status as predicted: the fricative was significantly longer when C3 is voiceless than when it is voiced ($F(1, 15) = 12.45$, $p < 0.01$). However, C1 and V did not exhibit significant differences in

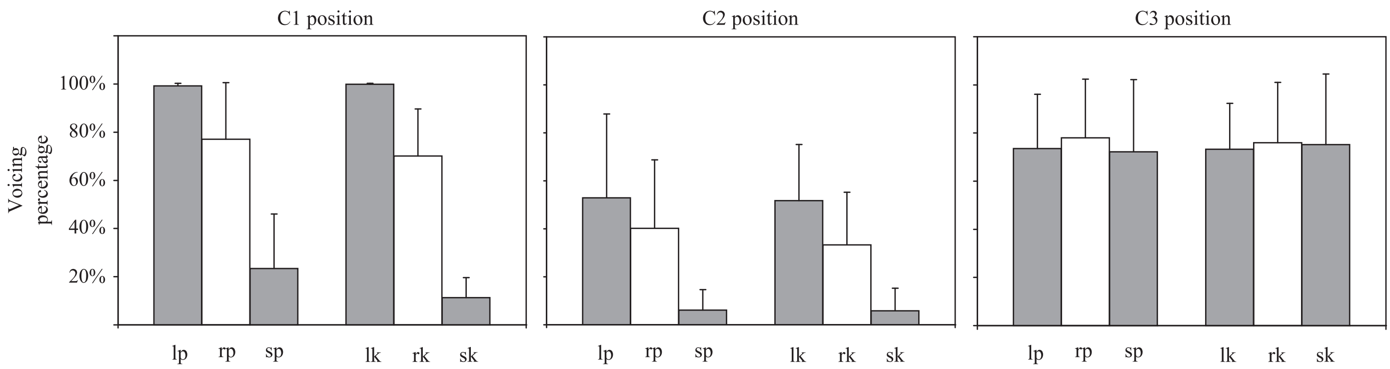

Fig. 11. Voicing percentages for all C1C2 sequences at the C1, C2 and C3 sites in the case of clusters with a stop C2. Error bars correspond to one standard deviation..

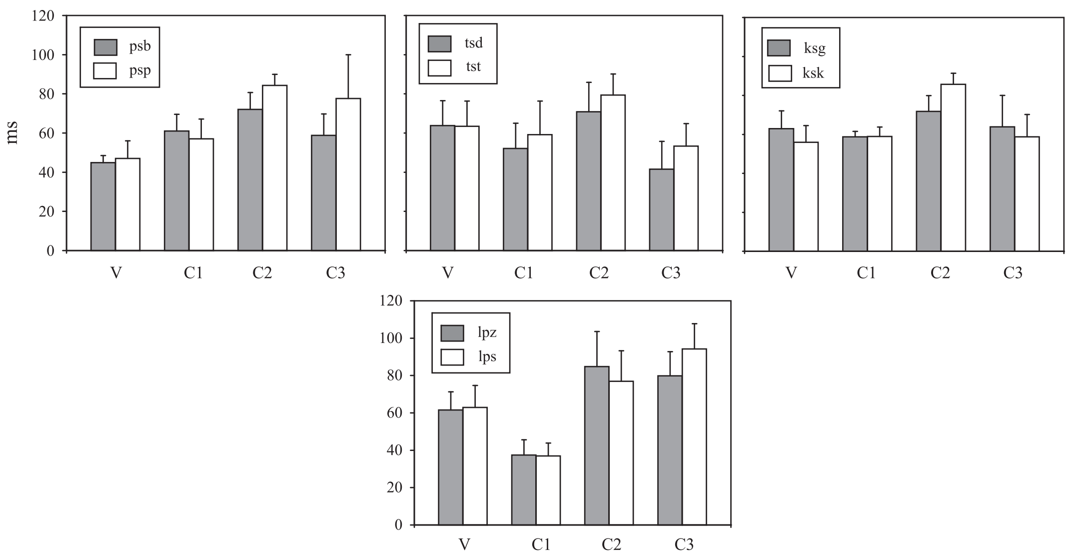

Fig. 12. V, C1, C2 and C3 duration values as a function of C3 voicing in three stop +/s/+stop cluster pairs (top) and a /l/+stop+fricative pair (bottom). Error bars correspond to one standard deviation.

duration as a function of C3 voicing. Moreover, the C3 stop burst was longer for /p, t, k/ in the clusters /psp, tst, ksk/ (14.64 ms, 20.08 ms, 24.90 ms) than for /b, d, g/ in those tokens of the clusters /psb, tsd, ksg/ where C3 exhibits a stop realization (10.27 ms, 14.47 ms, 19.33 ms), and this difference reached statistical significance ($F(1, 15)=54.91$, $p<0.001$).

As for the /l/+stop+fricative cluster pair (Fig. 12, bottom graph), C3=/s/ turned out to be significantly longer than C3=/z/ ($F(1, 3)=15.03$, $p<0.05$), and C2=/p/ was significantly longer, not shorter, before the voiced fricative than before the voiceless one ($F(1, 3)=14.39$, $p<0.05$). C1 and V duration yielded no significant differences as a function of C3 voicing.

The intensity level of the /s/ frication noise was also affected by voicing. Thus, as shown in Fig. 13 (top graphs), C2=/s/ was found to exhibit a significantly higher energy level before a voiceless vs voiced C3 in all three stop+/s/+stop cluster pairs (absolute energy: $F(1, 15)=15.90$, $p<0.001$; relative energy: $F(1, 15)=27.88$, $p<0.001$). Regarding the /l/+stop+fricative sequences, a slightly higher absolute and relative energy level for C3=/s/ than for C3=/z/ (Fig. 13, bottom graphs) did not achieve significance.

4. Summary and discussion

In comparison with two-consonant clusters (Recasens & Mira, 2012), data for three-consonant clusters reported in the present investigation show lower percentages of vocal fold vibration in all three consonants as a general rule. Thus, voicing percentages across speakers and contextual conditions for syllable final obstruents subjected to voicing assimilation amounted to 5–45% in CCC sequences and to 30–45% in CC sequences in the case of fricatives, and to 5–55% in three-consonant clusters and to 55–60% in two-consonant clusters in the case of stops. In line with modeling work on voicing in consonants and consonant sequences (Westbury & Keating, 1986), these percentages confirm the hypothesis that voicing degree should decrease with the number of consonants in the cluster and thus with an increase in the aerodynamic and articulatory demands involved.

Consonant voicing percentages in three-consonant clusters differ considerably as a function of manner and place of articulation. Both at C3 and at C1 (also for obstruents located in the C2 position when compared with the preceding and following sonorants), the vocal fold vibration period varies in duration in the progression nasals, laterals, approximants>stops, fricatives. Moreover, in agreement with data for two-consonant clusters, fricatives were found to show less voicing than stops in syllable final position but not syllable initially where fricatives and stops are underlyingly voiced. A trend for fricatives to exhibit less voicing than stops syllable finally may be attributed to the larger amplitude of the devoicing gesture for the former vs the latter consonant class. The rhotic /r/ is partly voiceless when realized as a two- or three-contact trill in C3 position, and shows intermediate voicing values between those for nasals and laterals, and for stops, when occurring before a heterosyllabic consonant presumably because it exhibits one- and, less often, two-contact trill-like realizations in this

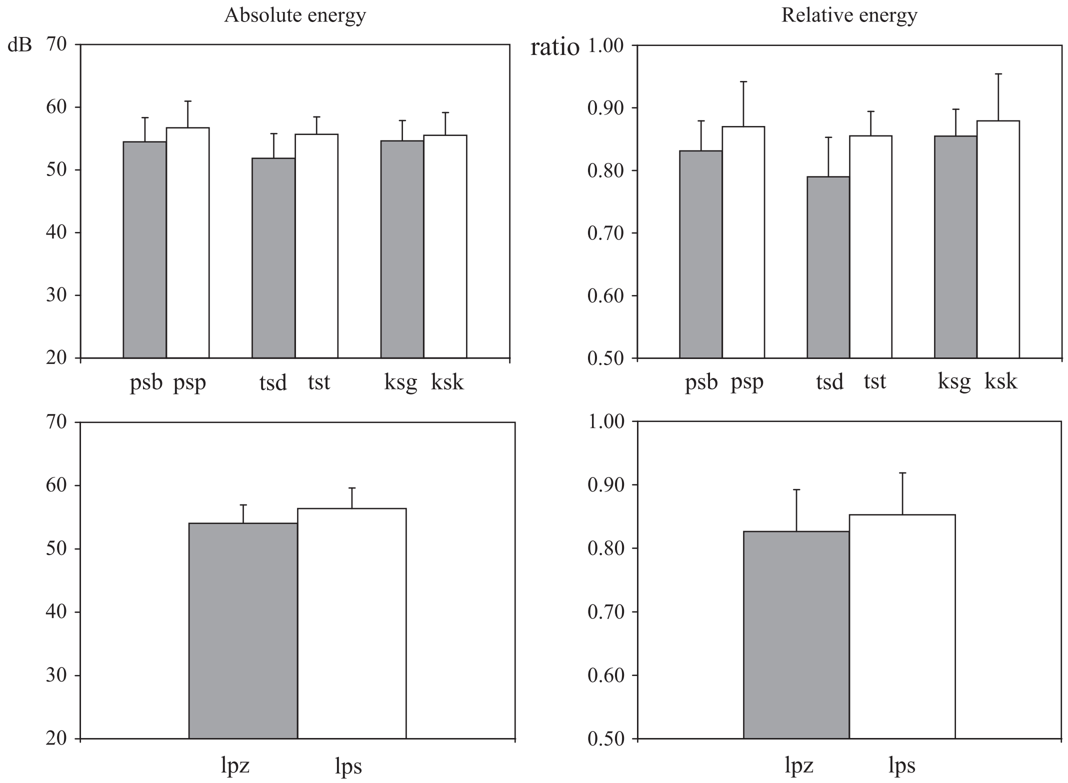

Fig. 13. Absolute and relative energy values for C2 = /s/ as a function of C3 voicing in three stop +/s/+ stop cluster pairs (top), and for C3 = /z/ and /s/ in a /lpz/–/lps/ pair (bottom). Error bars correspond to one standard deviation.

case (see Section 2.2.1). The reason for this voicing characteristic is to be sought in the fact that setting the tongue tip into vibration for well-formed trills involves stringent aerodynamic requirements which conflict with voicing to a larger extent, i.e., a sufficient supraglottal pressure level, some tongue predorsum lowering and postdorsum retraction, and the appropriate tongue muscle tension (Solé, 2002). This argues in support of the view that trills are special with regard to other sonorants in that they require a high intraoral pressure level and are not produced with unimpeded airflow, and may also account for why /r/ does not induce much regressive voicing in the preceding obstruent(s). Moreover, in agreement with data reported in our previous study, the voicing percentages turned out to increase with closure or constriction anteriority for stops in some cases, i.e., the vocal fold vibration period was longer for /b/ than for /d, g/ or for /b, d/ than for /g/ at the C3 site and slightly, though not significantly longer for /p/ vs /k/ at the C2 site (there were no voicing differences among C1 = /p, t, k/). As for fricatives, voicing was less, not more for C2 = /f/ than for C2 = /s/ in spite of the labiodental being more anterior than the alveolar due perhaps to restrictions on the occurrence of /f/ in word final position in Catalan (see Section 1.1).

Voicing coarticulation effects from specific consonants on others yielded little support for the Catalan regressive voicing rule. The contribution of C3 to voicing in the preceding syllable/word final consonants was relatively small and did not always agree with the initial prediction that regressive voicing should increase with voicing degree in the triggering consonant. In particular, there was little voicing during obstruents when followed by a nasal or a lateral perhaps in order to allow for sufficient intraoral pressure build-up for the generation of turbulent airflow and a burst which could be impaired by anticipatory nasalization for nasals and an earlier apical constriction for laterals (see Section 1.1). Duration data reveal that the effect in question may be accompanied by C2 shortening mostly when C3 is a nasal. C3-dependent regressive effects were more in agreement with the DAC model in other cases, e.g., there was little regressive voicing for /r/, and more regressive voicing for approximant vs stop realizations of /b, d, g/. C3-dependent voicing effects hardly extended into C1.

The patterns of voicing interaction between C1 and C2 lend some support to the hypothesis that voicing effects should be stronger if involving consonants located within the same syllable and word (i.e., C1 and C2) than across a syllable and word boundary (i.e., C1 or C2, and C3). As for the cross-syllabic effects and in addition to the finding of weak or no C3-dependent voicing assimilation, no progressive C1C2-dependent voicing differences were found to occur during C3. On the other hand, intrasyllabic voicing effects applied at the progressive level but not at the regressive level: the period of vocal fold vibration during C2 = /s/ was longer after sonorants than after obstruents, and voicing percentages during a stop C2 also varied with C1 voicing in the progression /l/ > /r/ > /s/. While differing a great deal regarding the amount of voicing for syllable final obstruents, all or most individual speakers were in agreement with the patterns of voicing coarticulation just mentioned.

In addition to vocal fold vibration, results reported in this paper show that voicing assimilation may be signaled by segmental duration and intensity. In particular, there was a clear trend for C2 = /s/ to be longer and more intense, and for C2 = /p/ to be shorter, before a voiceless vs voiced C3. These same C2 duration differences were found to hold for CC clusters in our previous study (see Introduction). C3 stop burst duration was also greater for clusters with a voiceless C3 than for those with a voiced C3 in stop+/s/+stop clusters. Duration effects associated with the C3 voicing distinction could not be traced, however, during C1 or the vowel preceding the cluster. These segment duration and intensity data suggest that speakers of languages where voiced stops exhibit voicing lead may use not only vocal fold vibration but other phonetic characteristics that depend more closely on air pressure and airflow for cueing the voicing contrast in clusters. Morever, in line with the vocal fold vibration data, this trend was found not to hold for long-distance duration effects occurring two or more phonetic segments away from the trigger.

The vocal fold vibration and segmental duration and intensity data just summarized indicate that, contrary to current descriptive and phonological accounts, voicing assimilation in Catalan three-consonant clusters with a voiced C3 cannot be modeled as a purely regressive process (Wheeler, 2005). C3-dependent regressive voicing effects occur less than predicted by the phonological rule: obstruents are mostly voiceless when ocurring in

C1 and C2 position, and effects extend to some extent into C2 but barely into C1. Segmental duration and intensity data also indicate a quite restricted regressive assimilation scenario: C2 duration, but not C1 or preceding vowel duration, was found to vary with the C3 voicing contrast, and a relationship between /s/ intensity and underlying voicing was found to hold for C2 as well. Vocal fold vibration data provide some support for voicing dependency between C1 and C2 and thus consonants placed in the same syllable final position. It thus appears that, as for other processes such as stop epenthesis (see Section 1), voicing assimilation may be conditioned by syllable and word affiliation. Moreover, considerable voicing effects between the two syllable final consonants occur at the progressive but not at the regressive level. Failure for regressive effects between those two consonants to occur is due most probably to the fact that obstruents placed at the C2 position show little voicing and differ little in voicing degree.

An interpretation of the voicing data for three-consonant clusters will be carried out next with reference to the voicing data for Catalan two-consonant clusters reported in Recasens and Mira (2012). Voicing data for CC sequences indicate that, even when vocal fold vibration is partially or almost fully absent during an obstruent C1, segmental duration and intensity may be used by speakers as voicing cues. Therefore, it may be claimed that voicing assimilation is at work systematically in heterosyllabic two-consonant sequences even in the case of speakers showing little vocal fold vibration. There are good reasons to call into question the notion that regressive voicing assimilation in Catalan CCC sequences operates as specified by the phonological rule. This is so since, while, in parallel to two-consonant sequences, C3-dependent regressive voicing in three-consonant clusters applies to a greater or lesser extent to C2, the process does not extend to distant C1. Moreover, voicing coarticulation operates between C1 and C2 rather than between C3 and C2, i.e., effects occurring within the same syllable (at the progressive level) are more prominent than those taking place across a syllable boundary and conforming to the phonological rule (regressive C3-to-C2 effects).

In sum, experimental data throw new light on the patterns of voicing assimilation in complex consonant clusters in Catalan (and possibly in other languages with heterosyllabic three-consonant clusters and voiced stops with negative VOT), while drawing attention to the fact that these patterns cannot be formulated simply by stating that voicing assimilation is a long-distance process ruled by the last consonant in the cluster. Instead, data reported in this paper suggest that voicing adaptation may occur both at the regressive and progressive levels, affects consecutive segments rather than distant ones both regarding vocal fold vibration and segmental duration and intensity, and is determined by consonant place and manner of articulation and by syllable/word affiliation.

Acknowledgments

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Appendix 1

Fricative C2		
1. /psb/	ara ens porten els taps baixos	"they bring us the low corks now"
2. /psd/	et vendrà aquests xarops dolços	"he/she will sell you these sweet syrups"
3. /psg/	de regal sempre reps gots	"he/she always receives glasses as a gift"
4. /psm/	asseca'ls aquests taps molls	"dry these wet corks"
5. /psn/	ara posa-hi els taps nous	"put the new corks over there now"
6. /psl/	de la granja tu reps làctics	"you get dairy products from the farm"
7. /psʎ/	renta'ls bé aquests draps llargs	"wash these long cloths well"
8. /psj/	de regal sempre reps iots	"you always receive yachts as a gift"
9. /tsb/	es tracta de debats bàsics	"these are basic debates"
10. /tsd/	aquestes són edats dolces	"these are sweet ages"
11. /tsg/	hi formaren soldats gals	"they trained French soldiers over there"
12. /tsm/	m'agraden els calçats macos	"I like nice footwear"
13. /tsn/	cal posar-se calçats nous	"one must use new footwear"
14. /tsl/	hi havia molts soldats laics	"there were many secular soldiers"
15. /tsʎ/	escrigueren dos mots llargs	"they wrote two long words"
16. /tsj/	van conèixer aquells fets ianquis	"they learned about those American deeds"
17. /tʃb/	al got posa-m'hi un raig bo	"pour a good drop of wine into my glass"
18. /tʃd/	al got posa-m'hi un raig dolç	"pour a sweet drop of wine into my glass"
19. /tʃg/	fou a París el maig gal	"the French May 1968 took place in Paris"
20. /tʃm/	li regalà un estoig maco	"he/she gave him/her a nice case as a gift"
21. /tʃn/	li regalà un estoig nou	"he/she gave him/her a new case as a gift"
22. /tʃl/	no va a missa aquell boig laic	"that mad secular fellow does not attend mass"
23. /tʃʎ/	hi va caure un raig llarg	"a long beam fell over there"
24. /tʃj/	l'empresari era un boig ianqui	"the entrepreneur was a mad American fellow"
25. /ksb/	em fumava uns tabacs bons	"I used to smoke good tobacco"
26. /ksd/	cal posar-hi alguns tocs dolços	"one should give it a sweet buzz"
27. /ksg/	li regalà uns jocs gals	"he/she gave him/her French games as a gift"
28. /ksm/	asseca'ls aquests sacs molls	"dry these wet sacks"
29. /ksn/	posa'ls dins aquests sacs nous	"put them inside these new sacks"

30. /ksl/	van expulsar aquells txecs laics	“they expelled those secular Czech fellows”
31. /ksʎ/	han talat doscents socs llargs	“they have cut down two hundred trunks”
32. /ksj/	sempre fuma tabacs ianquis	“he/she always smokes American tobacco”
33. /fsb/	a la cuina hi ha xefs bascos	“there are Basque chefs at the kitchen”
34. /fsd/	d'allí en sortien bafs dolços	“some sweet steam was going out of the kitchen”
35. /fsg/	l'any vinent tindrem xefs gals	“we will have French chefs next year”
36. /fsm/	preferiria xefs macos	“I would prefer nice chefs”
37. /fsn/	contractàrem dos xefs nous	“we hired two new chefs”
38. /fsl/	preferiria xefs laics	“I would prefer secular chefs”
39. /fsʎ/	a la cuina hi ha xefs llargs	“there are tall chefs at the kitchen”
40. /fsj/	no m'agraden els xefs ianquis	“I do not like American chefs”
41. /lfb/	aquest és un escalf bo	“this is a good warming”
42. /lfd/	aquest és un escalf dolç	“this is a sweet warming”
43. /lfg/	hi jugaren un golf gal	“they played French golf over there”
44. /lfm/	aquest sí que és un golf maco	“this is indeed a nice gulf”
45. /lfn/	hi jugaren un golf nou	“they played new golf over there”
46. /lfl/	hi jugaren un golf lògic	“they played efficient golf over there”
47. /lfʎ/	divisaren un golf llarg	“they descried a long gulf”
48. /lfj/	hi jugaren un golf ianqui	“they played American golf over there”
49. /lsb/	utilitzaren pals baixos	“they used low sticks”
50. /lsd/	hi ballaren un vals dolç	“they danced a sweet vals over there”
51. /lsg/	hi ballaren un vals gal	“they danced a French vals over there”
52. /lsm/	agafaren uns pals molls	“they grasped some wet sticks”
53. /lsn/	agafaren uns pals nous	“they grasped some new sticks”
54. /lsl/	utilitzaren pals lats	“they used large sticks”
55. /lsʎ/	utilitzaren pals llargs	“they used long sticks”
56. /lsj/	ells ballaren uns vals ianqui	“they danced an American vals”
57. /rfb/	al castell hi ha un serf basc	“there is a Basque servant in the castle”
58. /rfd/	al castell hi ha un serf dolç	“there is a sweet servant in the castle”
59. /rfg/	al castell hi ha un serf gal	“there is a French servant in the castle”
60. /rfm/	al castell hi ha un serf maco	“there is a handsome servant in the castle”
61. /rfn/	al castell hi ha un serf nou	“there is a new servant in the castle”
62. /rfl/	al castell hi ha un serf làbil	“there is a labile servant in the castle”
63. /rfʎ/	al castell hi ha un serf llarg	“there is a tall servant in the castle”
64. /rfj/	al castell hi ha un serf ianqui	“there is an American servant in the castle”
65. /rsb/	no em serveixen els ars baixos	“low rings are of no use to me”
66. /rsd/	les seves eren llars dolces	“hers were sweet homes”
67. /rsg/	no hi ha ningú als bars gals	“there is no one at the French bars”
68. /rsm/	agafaren uns ars molls	“they grasped some wet rings”
69. /rsn/	agafaren uns ars nous	“they grasped some new rings”
70. /rsl/	hi descobriren fars lats	“they discovered large lighthouses“
71. /rsʎ/	els dels poble són bars llargs	“the village bars are long”
72. /rsj/	aquelles eren llars ianquis	“those were American homes”
73. /mfb/	el nostre fou un triomf bo	“ours was a good victory”
74. /mfd/	el nostre fou un triomf dolç	“ours was a sweet victory”
75. /mfg/	celebraren el triomf gal	“they celebrated the French victory”
76. /mfm/	el nostre fou un triomf maco	“ours was a pleasant victory”
77. /mfn/	el nostre fou un triomf nou	“ours was a new victory”
78. /mfl/	el nostre fou un triomf lògic	“ours was a reasonable victory”
79. /mfʎ/	aquell fou un triomf llunyà	“that was a distant victory”
80. /mfj/	celebraren el triomf ianqui	“they celebrated the American victory”
81. /msb/	hi escamparen uns fems bons	“they spread good manure over there”
82. /msd/	eren millor que els fems d'au	“those were better than poultry manure”
83. /msg/	venen de França els fems gals	“French manure comes from France”
84. /msm/	escamparen uns fems macos	“they spread good manure”
85. /msn/	escamparen uns fems nous	“they spread new manure”
86. /msl/	crec que són millor els fems làctics	“I think that dairy manure is better”
87. /msʎ/	cal que podi aquests rams llargs	“I must prune these long branches”
88. /msj/	escamparen els fems ianquis	“they spread American manure”

Stop C2		
89. /lpd/	no pogué matar el talp dur	"he/she could not kill the tough mole"
90. /lpg/	ingressaren el calb gal	"the French bold fellow was hospitalized"
91. /lpn/	vàrem observar el talp nou	"we watched the new mole"
92. /lpl/	em va fer por aquell talp lat	"that large mole frigthened me"
93. /lpz/	adquiriren un talp zebra	"they bought a striped mole"
94. /lpr/	adquiriren un talp roig	"they bought a red mole"
95. /lpʎ/	hi vàrem veure un talp llarg	"we saw a tall mole over there"
96. /lpj/	ingressaren el calb ianqui	"the American bold fellow was hospitalized"
97. /lkb/	necessito aquest calc bo	"I need this good tracing"
98. /lkd/	per a la sopa molc dàtils	"I grind dates for the soup"
99. /lkm/	en lloc de cafè molc malta	"I grind malt instead of coffee"
100. /lkn/	abans de sopar molc naps	"I grind turnips before dinner"
101. /lkl/	aquest matí jo molc làctics	"I am grinding dairy products this morning"
102. /lkz/	és molt bonic el calc zebra	"the striped tracing is very nice"
103. /lkr/	em va vendre aquell calc roig	"he/she sold me that red tracing"
104. /lkʎ/	aquest sí que és un solc llarg	"this is indeed a long furrow"
105. /lkj/	no m'agrada aquest calc ianqui	"I do not like this American tracing"
106. /rpd/	m'hi ha sortit un barb dur	"a tough barb has come out of my skin"
107. /rpg/	conjugaren un verb gal	"they conjugated a French verb"
108. /rpn/	s'ha trobat una serp nova	"a new snake has been found"
109. /rpl/	a la frase hi ha un verb lògic	"there is a logical verb in the sentence"
110. /rpz/	és molt bonic el corb zebra	"the striped raven is very beatiful"
111. /rpr/	em va fer por la serp roja	"the red snake frigthened me"
112. /rpʎ/	em va fer por la serp llarga	"the long snake frigthened me"
113. /rpj/	al museu hi ha una serp ianqui	"there is an American snake at the museum"
114. /rkb/	l'enquadraré amb el marc bo	"I will put it into the good frame"
115. /rkd/	l'enquadraré amb el marc dur	"I will put it into the hard frame"
116. /rkm/	inauguren el parc maco	"they open the nice park"
117. /rkn/	inauguren el parc nou	"they open the new park"
118. /rkl/	no hi ha esglésies al parc laic	"there aren't any churches at the secular park"
119. /rkz/	a Hongria hi ha un parc zíngar	"there is a gypsy park in Hungary"
120. /rkr/	l'enquadraré amb el marc rus	"I will put it into a Russian frame"
121. /rkʎ/	vaig alimentar el porc llarg	"I fed the long pig"
122. /rkj/	visitàrem el parc ianqui	"we visited the American park"
123. /spd/	de la llet surt un cresp dolç	"a sweet skin comes out of the milk"
124. /spg/	hi plantaren un gesp gal	"they planted French grass"
125. /spn/	estrenàrem el gesp nou	"we released the new lawn"
126. /spl/	a la casa hi ha un gesp lat	"there is a large lawn at the house"
127. /spz/	és molt bonic el gesp zebra	"the striped lawn is very nice"
128. /spr/	hi plantaren un gesp roig	"they planted red grass over there"
129. /spʎ/	hi plantaren un gesp llarg	"they planted tall grass over there"
130. /spj/	hem comprat aquell gesp ianqui	"we have bought that American lawn"
131. /skb/	li posaren un casc baix	"they put a low helmet on him/her"
132. /skd/	no es va posar aquell casc dur	"he/she did not put on that hard helmet"
133. /skm/	s'ha posat aquell casc maco	"he/she put on that nice helmet"
134. /skn/	s'ha posat aquell casc nou	"he/she put on that new helmet"
135. /skl/	al museu hi ha un casc lígur	"there is a Ligurian helmet at the museum"
136. /skz/	és molt bonic el casc zebra	"the striped helmet is very nice"
137. /skr/	canvia-me'l el casc roig	"change me the red helmet"
138. /skʎ/	el soldat porta un casc llarg	"the soldier wears a long helmet"
139. /skj/	és ovalat el casc ianqui	"the American helmet is oval-shaped"

Appendix 2

1. /psb/	de dalt es veien caps baixos	"low heads could be seen from above"
2. /psp/	aquells d'allí eren caps pàl.lids	"those over there were pale heads"
3. /tsd/	m'agraden força els gats dolços	"I like sweet cats very much"
4. /tst/	fes carícies als gats tous	"stroke the soft cats"

5. /ksg/	de França són els sacs gals	“French sacks come from France”
6. /ksk/	no em donis aquests sacs cars	“do not give me these expensive sacks”
7. /lpz/	és de colors el talp zebra	“the striped mole is skin coloured”
8. /lps/	se m’esmunyia el talp savi	“the smart mole was slipping away from me”

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