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The Effect of Contextual Consonants on Voiced Stop Lenition: Evidence from Catalan

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Abstract
This study uses acoustic energy measures for /b, d, g/ after /f, s, ʃ, l, r/ in Catalan in order to test whether postconsonantal voiced stop lenition is ruled by minimization of articulatory effort, acoustico-perceptual continuity of an ongoing prosodic constituent or some other principle of articulatory organization. Data for eight speakers reveal that lenition is more prone to operate on /g/ than on /b, d/, after a sonorant than after a fricative, and when the two cluster consonants are heterorganic than when they are (quasi)-homorganic. Moreover, a positive correlation was found to hold between the degrees of stop lenition and stop voicing. The /fC/ sequences had an exceptional behaviour since, in comparison to other consonants appearing in C1 position, /f/ was at the same time less intense and triggered more stop-like realizations of /b, d, g/. These results indicate that, while regularly treated as a phonological process, postconsonantal voiced stop lenition in Catalan is subject to much contextual variability, and should be dealt with by a production-based model which takes into consideration several articulatory and aerodynamic factors such as constriction degree and intraoral pressure level for C1 and C2, as well as homorganicity degree between the two consecutive consonants.

Keywords
Stop lenition, Catalan, acoustic energy measures, homorganicity, voicing

1 Introduction

While it is commonly accepted that obstruent lenition is achieved through a reduction in gestural duration and in articulatory displacement and constriction degree (Browman & Goldstein, 1991, 1992; Parrell, 2014), there is less consensus about the phonetic factors which cause lenition to operate mostly on specific stop consonants and in several segmental contextual conditions rather than others. The paper attempts to gain a better understanding about the production mechanisms

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involved in the spirantization of [b, d, g] into [β, ð, ɣ]. This sound change occurred, for example, in Old French where the endproducts [β, ð, ɣ] of Latin /b, d, g/ changed manner of articulation ([β] > [v], as in *cheval* derived from CABALLU 'horse') or dropped ([ð, ɣ] > [ø] as in *suer* SUDARE 'to sweat' and *août* AGUSTU 'August').

Two major explanatory accounts of stop lenition have been proposed in the literature. According to a production-based approach, stop lenition involves minimization of articulatory effort through a decrease in articulatory displacement and articulatory speed (Kirchner, 2001). If so, stops should lenite more easily when occurring next to open vowels than to close vowels because, at least for dentoalveolars and velars, the stop closure is located further away from the constriction location for /a/ than from that for /i, e/. This proposal has been subject to criticism. The meaning and implications of the term 'articulatory effort' remain unclear in several respects (Bauer, 2008; Blevins, 2004; Kaplan, 2010). Indeed, in light of the considerable degrees of freedom for the speech articulators during the production of consonants differing in place and manner of articulation, it is hard to imagine how the amount of articulatory effort ought to be quantified in physiological terms. Also, articulatory effort is not always correlated with articulatory displacement; thus, it could very well be that, in spite of the fact that articulatory displacement is less for [pp] than for [tp], holding the lips together for the geminate bilabial stop requires more, not less, effort than raising the tongue front and protruding the lips for the heterorganic dental–bilabial stop cluster (Ohala, 1990).

According to an acoustico-perceptual based approach, the goal of lenition is to diminish the extent to which the target consonant interrupts the stream of speech by raising its intensity level in more open contextual segments (Kirchner, 2001, 2004). Moreover, as several languages show, the degree of stop lenition is prone to be conditioned by opening variations in the contextual consonants rather than in the contextual vowels since consonants differ in openness and intensity amongst themselves to a much greater extent than vowels do. Indeed, while several studies report a trend for voiced stop lenition to operate after more versus less open vowels (Spanish: Colantoni & Marinescu, 2010; Hualde, Simonet, Shosted, & Nadeu, 2010; Catalan: Hualde, Nadeu, & Simonet, 2010), others have found no positive relationship between degree of lenition and contextual vowel opening (Spanish: Cole, Hualde, & Iskarous, 1999; Kingston, 2008; American English: Bouavichith & Davidson, 2013). The trend for lenition to correlate with degree of opening in the preceding consonant would account for why stops are typically realized as stops after stops and as approximants after sonorants in languages such as Spanish and Catalan (see below). A problem with this explanatory account is that it cannot predict why /b, d, g/ fail to spirantize after consonants which exhibit relatively high intensity levels such as nasal stops and fricatives, or why lenition depends on the place of articulation for the target stop (see section 1.1.1).

The present paper goes beyond the two approaches by exploring in detail the phonetic motivation for voiced stop lenition as a function of the preceding consonant in Catalan heterosyllabic consonant clusters. A production-based account of lenition is proposed which renders lenition degree in consonant clusters dependent on several articulatory and aerodynamic factors for C1 and C2, mostly constriction degree, intraoral pressure level and whether the two consecutive consonants are homorganic or heterorganic. The rationale underlying this theoretical approach is that, as pointed out above, concepts such as 'minimization of articulatory effort' or 'acoustico-perceptual optimization of an ongoing prosodic constituent' do not appear to be too suitable for predicting postconsonantal stop lenition in light of the complex mechanisms involved in the production of heterosyllabic consonant clusters (see Recasens & Pallarès, 2001b regarding this issue).

In Catalan (also Spanish), the bilabial, dental and velar voiced stop phonemes /b, d, g/ may be realized as stops if involving complete stoppage of airflow ([b, d, g]), and as shorter and frictionless approximants if allowing the passage of air through a central constriction ([β, ð, ɣ]). According to descriptive studies for those languages (see, for example, Navarro Tomás, 1971 for Spanish), syllable-initial [b, d, g] and [β, ð, ɣ] are in complementary distribution. In Catalan (Recasens, 2014), the stop allophones are found after a pause and after heterosyllabic consonants which block the air passage at the location where /b, d, g/ are articulated, namely, after a homorganic nasal in the case of /b, d, g/ and after the alveolar and alveolopalatal laterals /l/ and /ʎ/ in the case of /d/ ([mb] *àmbar* 'amber', [nd] *endins* 'inward', [ŋg] *enfangat* 'filled with mud', [ld] *el dia* 'the day', [ʎd] *full daurat* 'golden leaf'). Otherwise the approximant allophones occur, that is, after a vowel, a fricative, a rhotic or an approximant in the case of /b, d, g/ and after a lateral in the case of /b, g/ ([β] *acabat* 'finished', *cabra* 'goat', [ð] *cada* 'each', [ɣ] *figa* 'fig', [zð] *és dur* 'it is tough', [zɣ] *és gros* 'it is big', [rð] *perdó* 'pardon', [jβ] *rei bo* 'good king', [jɣ] *aigua* 'water', [lɣ] *alga* 'alga').

Within the theoretical framework sketched above, lenition degree for Catalan voiced stops will be investigated as a function of their place of articulation and of the manner of articulation characteristics of the preceding consonant (section 1.1). Moreover, in order to achieve a more precise understanding of how stop lenition operates, voiced stop lenition (as determined acoustically) will be related to voicing degree during the target consonant; the assumption being that voicing for /b, d, g/ should increase as the stop becomes more intense and less constricted (section 1.2). The implications of synchronic lenition for sound change implementation will also be looked into (section 1.3).

1.1 Articulatory factors

1.1.1 Target stop. A first research issue to be addressed is whether lenition degree and by extension frequency of occurrence of lenition depend on the place of articulation for the voiced stop target. Data from the literature on the Romance languages reveal a trend for lenition to apply most frequently to velars and least often to labials, dentals falling in between. Indeed, the lenition scale has been reported to be /g/ > /d/ > /b/ in Florentine Italian and Balearic Catalan (Villafaña Dalcher, 2006; Wheeler, 2005, p. 320–324) and /d, g/ > /b/ in Rome Italian (Hualde & Nadeu, 2011b). However, this place of articulation hierarchy does not hold necessarily when the frequency of occurrence of stop and approximant/fricative variants of /b, d, g/ in the world's languages is taken into consideration (Gurevich, 2004, 2011; Kaplan, 2010), and also according to other experimental studies besides those just cited (/d/ > /b, g/ in Argentine Spanish; Colantoni & Marinescu, 2010). Using an acoustic energy measure (see section 2), the present study will explore the extent to which differences in lenition degree among /b/, /d/ and /g/ conform to the place of articulation hierarchies reported for Spanish, Catalan and Italian dialectes elsewhere.

The reason why lenition affects more often /g/ than /b, d/ may be sought in the formation of a widespread and less tight dorsal closure at the velar zone, which results in the stop release being less abrupt and exhibiting a longer and less intense frication noise (see also Kirchner, 2004 and Lavoie, 2001, p. 133–138). A similar explanation could account for sound change data for the Romance languages showing a trend for an incomplete closure and to a large extent voicing to bear upon voiceless velar stops rather than upon their labial and dental cognates (Cravens, 2002; Hualde, Simonet, & Nadeu, 2011; Torreira & Ernestus, 2011). Dental consonants, on the other hand, may favour lenition, presumably since they are especially short and exhibit a relatively small-sized tongue front closure or constriction. The trend for /b/ to resist lenition to a larger extent than /d, g/ has been attributed to a lower air pressure level and a larger surface of vocal tract compliance including the entire tongue and part of the cheeks (Hualde & Nadeu, 2011a; Hualde, Nadeu, & Simonet, 2010). In our view, this explanation accounts for why /b/ preserves voicing better than /d, g/ (Ohala & Riordan, 1979) but cannot fully explain consonant-dependent differences in frequency of lenition, which ought to depend on other articulatory factors such as degree of constriction.

1.1.2 Preceding segment. As for the effect of consonant context on voiced stop lenition, which is the main research topic of the present investigation, there is some disagreement as to whether lenited outcomes of /b, d, g/ should be favoured by preceding fricatives, laterals or rhotics (excluding mostly the clusters /ld, ʎd/ where C2 is expected to be realized systematically as a stop; see above). Studies on Spanish and Galician find that this lenition process applies least often after fricatives in line with the high oral pressure level required for the passage of considerable airflow through a narrow constriction and the generation of an intense frication noise; both /l/ and /r/ ought to favour stop lenition to a larger extent since their production involves the passage of air through wide lateral passages (the lateral) and a short and often incomplete closure (the rhotic) and thus, requires a lower intraoral pressure level (Carrasco, Hualde, & Simonet, 2012; Eddington, 2009, 2011; Hualde, Shosted, & Scarpace, 2011; Martínez-Celdrán & Regueira, 2008). Descriptive evidence for Balearic Catalan (Wheeler, 2005, p. 324–325) indicates, however, that voiced stop lenition may operate more often after lingual fricatives than after a lateral or a rhotic presumably since, in principle, /s, ʃ/ but not /l, r/ lack central linguopalatal contact and allow continuous airflow. A goal of this paper is to investigate which one of the two accounts better suits the productions of postconsonantal /b, d, g/ by speakers from the Eastern and Western Catalan dialects.

The frequency of application of voiced stop lenition in postconsonantal position may also depend on two other production characteristics which have not been submitted to an in-depth analysis so far.

Firstly, lenition degree could be affected by subtle differences in constriction degree for a given contextual C1. In particular, /b, d, g/ could be more stop-like after more versus less constricted fricatives and whenever preceding /r/ is realized as a trill rather than as a shorter and less constricted one-contact tap or approximant, and lenition degree should depend on non-segmental factors such as speech rate, stress position and speaker as well (see Martínez Celdrán, 2008 and Lavoie, 2001, p. 80–81 for Spanish). If articulated with a narrow constriction the approximant allophones may lack visible formant structure, while if produced with a wide constriction they show intense formants which are often indistinguishable from those for the adjacent vowels on spectrographic displays. Approximants may also exhibit frication in specific circumstances as, for example, after a fricative in sequences like /sb, sd, sg/.

In the second place, lenition degree is expected to be influenced by whether C1 and C2 are (quasi-) homorganic, and thus articulated with the same or nearby articulators, or heterorganic. The rationale underlying this trend is that articulatory undershoot and thus lenition is more prone to take place whenever the constriction formation for /b, d, g/ proceeds independently of that for the preceding consonant than when the two consonants are articulated at about the same location. Regarding the consonant clusters under investigation in the present study and as accounted for next, (quasi-) homorganicity is expected to be at work for /fb/ and for /sd, ʃd, rd/ as well:

1. (Quasi-)homorganicity takes place in the case of the cluster /fb/ since /f/ is implemented through a constriction between the lower lip and the upper teeth while /b/ is bilabial. In this consonant sequence, /b/ is often produced as a stop in stressed position (*baf bo* ‘a good steam’) while other realizations may occur whenever /fb/ is situated away from sentence stress ([ᵛβ], [bb] *bolígraf boníssim* ‘a very good pen’). The stop realization of /b/ in the cluster /fb/ may occur in order to prevent the short and low intensity frication noise for /f/ from fading away which could certainly occur if /b/ exhibited a wide constriction (see Jongman, Wayland, & Wong, 2000 and Gordon, Barthmaier, & Sand, 2002 regarding the acoustic cues for /f/ vis-a-vis /s, ʃ/). The little prominence of the fricative noise for /f/ as compared to that for the two lingual fricatives follows from a lesser expense of airflow and from the airstream being directed towards the lip instead of towards the teeth (Stevens,

1998, p. 389; Whitehead & Barefoot, 1983). An interpretation of why lenition for /b/ may fail to apply after /f/ based on the (quasi-) homorganic relationship between C1 and C2 rather than on the little acoustic salience of the frication noise seems fully appropriate since the latter characteristic ought to favour rather than disfavour lenition in the following voiced stop consonant.

2. A trend for C2 to be stop-like whenever C1 and C2 are (quasi-)homorganic may also operate on the clusters /sd, ʃd, rd/ whenever the place of articulation for /d/ is located not at the teeth but at the centroalveolar or postalveolar zone (Recasens, 2014). This change in constriction location from dental to alveolar may be attributed to progressive coarticulatory or assimilatory place effects induced by the two lingual fricatives and the rhotic on /d/, and is expected to take place mostly when the contextual fricative is sufficiently constricted and /r/ is realized as a trill or exhibits a trill-like realization.

1.2 Voicing

The present study will also investigate whether there is a positive relationship between degree of lenition and voicing for /b, d, g/ after fricatives and /l, r/. Voicing is expected to be maintained for a longer period of time in more lenited than in less lenited realizations of /b, d, g/ to the extent that the former consonant productions exhibit a lower intraoral pressure level than the latter.

Along these lines, voicing and lenition degree could be less after fricatives than after the sonorants /l/ and /r/, that is, in comparison to /l/ and /r/, highly constricted fricatives could cause /b, d, g/ to be more obstructed and more devoiced. Indeed, while an open glottis for the passage of considerable airflow and a high oral pressure level prevent voicing from sitting easily on fricatives (Ohala & Solé, 2010; Solé, 2010), the sonorants /l, r/ are likely to keep uninterrupted voicing during /b, d, g/ since they allow unconstricted airflow during their production. This progressive action also accounts for why /p, t, k/ become voiced after /l, r/ (also after nasals) in Italian dialects ([ˈsolgo] *solco* 'furrow', [marˈda] *maritare* 'to marry', [ˈbjaŋgo] *bianco* 'white', [ˈdɛnde] *dente* 'tooth'; Rohlfs, 1966, p. 347, 363, 375). A positive relationship between voicing and lenition is not expected to hold, however, in specific cases: in sequences like /ld/, where C2 stays voiced and is generally realized as a stop since the two adjacent consonants are homorganic; voicing should be greater for more anterior /b/ than for /d, g/ in line with consonant-dependent differences in back cavity size and vocal tract compliance, while lenition is more likely to apply on /g/ than on /b, d/ (and perhaps on /d/ than on /b/).

C2 voicing and lenition in /fC/ sequences deserve special attention. In principle, /f/ ought to be more prone to keep continuous voicing than /s, ʃ/ since, analogously to the voicing differences between /b/ and /d, g/, the former fricative is more anterior and has a lower intensity noise than the two latter ones (Haggard, 1978; Stevens, Blumstein, Glicksman, Burton, & Kurowski, 1992). Experimental data for Catalan reported elsewhere (Recasens & Mira, 2012) show, however, less and more variable voicing for /f/ than for /s, ʃ/ in scenarios where the three fricatives are expected to assimilate in voicing to the following segment (Wheeler, 2005): syllable-finally in C#C sequences with a voiced C2 (*do*[z] *bancs* 'two benches', *pe*[ʒ] *dolç* 'sweet fish'); word-finally before a word-initial vowel (*do*[z] *anys* 'two years', *fe*[ʒ] *ample* 'large bundle'). This unexpected voicing behaviour could be attributed to at least two factors: the lack of phonological contrast between /f/ and /v/ in most Catalan dialects (while /s/ and /ʃ/ contrast with /z/ and /ʒ/); the need to preserve the acoustic integrity of the fricative in view of the little acoustic prominence of its frication noise and the rarity of commonly used lexical items ending in /f/ in Catalan (essentially the oxytones *baf* 'steam', *buf* 'blow', *golf* 'golf', *surf* 'surfing', *tuf* 'foul smell' and *xef* 'chef', and a few paroxytones). In these circumstances, it deserves to be studied whether /f/ causes not only /b/

but also /d, g/ to be realized as stops rather than as approximants and to undergo considerable devoicing.

1.3 Implications for sound change

The synchronic scenario for the stop and approximant allophones of /b, d, g/ in Catalan has come to exist through sound change involving the lenition or spirantization of [b, d, g] into [β, ð, ɣ]. While only synchronic data will be subject to evaluation in the present study, it is believed that they should provide valuable information about the segmental conditions acting on the implementation of the historical process of voiced stop lenition. Indeed, data on postconsonantal stop lenition should contribute to improve our understanding about the evolutionary path from the initial lenition stages where stops undergo variable articulatory reduction in unstressed position and fast speech, to a more stable situation where stop and approximant realizations may be considered to be in complementary distribution. The central issue is the extent to which the allophonic scenario in languages like Spanish or Catalan is truly categorical (as implied by descriptive and phonological studies; see above), or else proceeds gradually and is thus subject to pervasive variation depending on the manner and place characteristics of the preceding consonant. In some respects, this gradual scenario resembles that for other articulatory features and phonological processes which have proven to proceed gradually rather categorically in the world's languages, as for darkness degree in /l/ which may vary with word and utterance position as well as with segmental context, dialect and speaker (Recasens, 2011), and regressive place assimilation in consonant clusters which may apply gradually or categorically depending at least on segmental composition and speaker (see data for English and German /tC, nC/ clusters in Bergmann, 2012 and Ellis & Hardcastle, 2002).

1.4 Summary of research goals and hypotheses

Acoustic energy measures will be used in order to explore differences in lenition degree for /b, d, g/ in Catalan as a function of preceding fricatives, rhotics and laterals. The initial hypothesis is that stop lenition should affect velars rather than dentals and labials, and ought to occur after sonorants rather than after fricatives, after less versus more constricted C1 realizations (as in the case of the tap versus trill realizations of /r/), and whenever C1 and C2 are heterorganic than when they are (quasi-)homorganic. Moreover, lenition degree ought to be positively associated with voicing degree when the progressive action of C1 is taken into account. Special attention will be paid to the lenition and voicing behaviour in the case of the /fC/ sequences. The implication of the results will be discussed regarding the categorical versus gradual allophonic status of /b, d, g/, production- and perception-based lenition models, and sound change implementation.

2 Method

2.1 Recording procedure

The speech material subject to analysis in the present investigation is composed of all C#C combinations of C1 = /f, s, ʃ, l, r/ and C2 = /b, d, g/. According to literature accounts, in Catalan, the three voiced stops are realized as approximants in these consonant sequences except for /ld/ where /d/ ought to be articulated as [d] systematically and of /fb/ where /b/ may also be realized as a stop (see Introduction). The consonant clusters under analysis occur before a low or mid vowel in the seven- or eight-syllable long meaningful sentences listed in Table 1. In the list, the word-final fricatives correspond to underlying voiceless phonemes and thus are realized as voiceless in intervocalic

Table 1. List of Catalan sentences with English glosses. The consonant clusters under analysis appear underlined.

1. /fb/	a la cuina hi ha un xef basc	'there is a Basque chef at the kitchen'
2. /fd/	d'allí en sortia un baf dolç	'a sweet steam was coming from there'
3. /fg/	a la cuina hi ha un xef gal	'there is a French chef at the kitchen'
4. /sb/	aquell fou un pedaç bo	'it was a good chunk'
5. /sd/	el nen begué un xerès dolç	'the kid drank a sweet sherry'
6. /sg/	ells m'han venut un gos guerxo	'they have sold me a one-eyed dog'
7. /ʃb/	no hi arribo al calaix baix	'I cannot reach the low drawer'
8. /ʃd/	canvia'm aquest peix dolç	'give me another sweet fish'
9. /ʃg/	a la cuina esbandeix gots	'he/she rinses glasses at the kitchen'
10. /lb/	reberen un regal bo	'they received a good present'
11. /ld/	la història té un final dolç	'the story has a happy end'
12. /lg/	diu que aquell era un mal gat	'he/she says that it was a bad cat'
13. /rb/	entrava un militar baix	'a short soldier was coming in'
14. /rd/	l'home tenia un cor dolç	'that man had a sweet heart'
15. /rg/	aquella copa és d'or gòtic	'that cup is made of Gothic gold'

word-medial position (the underlying obstruent voicing distinction is neutralized syllable-finally in Catalan).

Other factors were controlled for. Care was taken to keep stress position constant in order to avoid possible effects of stress on frequency of lenition by having lexical stress fall on the two consecutive syllables and sentence stress on the syllable with C2 at its onset (regarding the effect of stress on stop lenition in Spanish, see Carrasco & Hualde, 2009; Cole et al., 1999; Eddington, 2011; Ortega-Llebaria, 2003). Moreover, except for *gal* 'Gaulish, French', the words containing the target voiced stops are fairly frequent in Catalan which should prevent word frequency effects on lenition degree from taking place (Eddington, 2011): the adjectives *dolç* 'sweet', *bo* 'good' and *baix* 'low' and the nouns *got* 'glass' and *gat* 'cat' are highly frequent, while *basc* 'Basque', *guerxo* 'one-eyed' and *gòtic* 'Gothic' are also widely used though less often than the five words above. Finally, all target stop consonants were placed word-initially in order to account for the fact that /ʃb, ʃd, ʃg/ do not show up word-internally in Catalan (as for the effect of word position on lenition degree, see Cole et al., 1999 and Kingston, 2008).

Acoustic and electroglottographic (EGG) data were recorded simultaneously by five women (EV, MA, PE, LO, VA) and three men (SO, MO, DR) of 25 to 55 years of age using the multichannel Kay Pentax system. The main reason for using EGG was to collect voicing data for C2, and also for C1, in order to study the topic described in section 1.2 (see section 2.2 for details about the voicing analysis procedure). The eight speakers whose productions were submitted to acoustic analysis 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 (MO, Banyoles; LO, Montblanc; DR, Tarragona; VA, Cadaqués); the remaining two subjects speak Western Catalan and were born in the Baix Urgell region (EV, MA). No special differences in lenition degree for /b, d, g/ were expected to occur between Eastern and Western Catalan and thus, between the six former speakers and the two latter ones. The sentences listed in Table 1 were read seven times at the speakers' normal speech rate, and speakers DR and MO recorded four more repetitions of the sentences 1–9. It was felt that a higher number of repetitions for the fricative + /b, d, g/ sequences ought to be recorded and analysed in view of the possibility that considerable voicing variability for voiced stops after fricatives (see Recasens & Mira, 2013 and also section 3.4) could also induce much

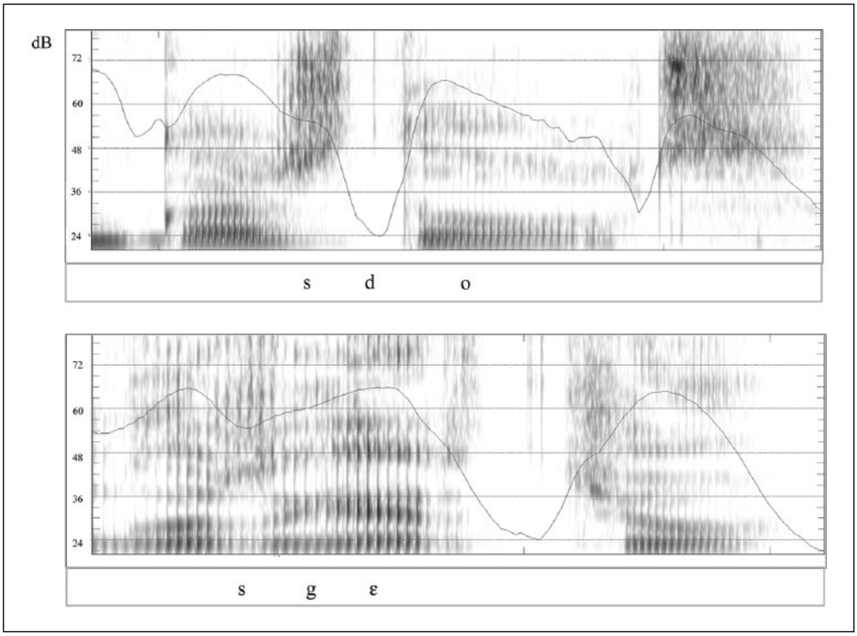

Figure 1. Energy contours overlaid on spectrographic displays of portions of the sentences 5 and 6 (see Table 1) which include C1, C2 and the following vowel. The top graph shows an instance of low energy, stop realization of /d/, and the bottom graph an example of high energy, approximant realization of /g/.

variability in lenition degree; unfortunately these additional recordings could only be carried out for two out of the eight subjects. While speakers were instructed to read the sentences as naturally as possible, we are aware of the fact that elicitation of read speech in the laboratory may have yielded a higher number of stop versus approximant realizations of /b, d, g/ than if the speech material had been produced less formally. The main reason for collecting read speech data was in order to strictly control for factors such as sentence length and stress position which could affect stop lenition degree as well as C1 and stop intensity level and duration.

The acoustic data were acquired 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. The two signals were acquired at 44100 Hz, and downsampled to 22050 Hz for the acoustic signal and to 500 Hz for the EGG signal. The EGG signal was smoothed using three steps depending on the degree of noisiness of the glottal signal and analysed with the MatLab script Peakdet 2 (Abadal & Recasens, 2009).

2.2 Segmentation and data analysis

According to spectrographic representations of the speech material under analysis, /b, d, g/ showed formant structure with different intensity levels when realized as approximants and a closing phase and an optional burst when realized as stops, and could show some frication noise mostly if preceded by a fricative (see Introduction section and Figure 1 regarding the two former possibilities).

For all sequence tokens, the segmental boundaries for C1, C2 and the following vowel were identified visually on spectrographic and waveform displays using Computer Speech Laboratory

(CSL) from Kay Pentax. Segmental onsets and offsets occurred at the beginning and end of a high frequency patch of noise for fricatives and of a period of formant structure for laterals and approximants. The segmental boundary between /l/ and approximant realizations of following /b, d, g/ was taken to occur at intensity and spectral discontinuities in view of the fact that the lateral has a higher intensity level and often a higher F1 than all three approximants. Whenever C2 = /b, d, g/ were realized as stops, their onset was determined by the beginning of a closing period devoid of acoustic energy except for the voicing bar and by the end of formant structure for preceding /l/ and of a noise patch for a preceding fricative, and their offset by a stop burst if available or by the onset of formant structure for the following vowel. Stop bursts were then excluded from the stop duration measures. The segmentation criteria for the /rC/ sequences was straightforward: C1 = /r/ exhibited one short alveolar closure for all clusters and speakers except in the case of speaker LO's productions of the sequence /rb/ where the rhotic was articulated with two apical contacts; moreover, the rhotic could also include a short vowel-like opening phase before /b, d, g/ and between two successive apicoalveolar contacts.

For all C#C tokens subject to analysis, low-smoothed 5 ms-window energy contours such as those plotted in Figure 1 were obtained for the entire sentences using the CSL analysis programme. Lenition degree for /b, d, g/ was then quantified using the acoustic energy measures referred to in (a), (b) and (c) below. (Energy values expressed in dB are obtained by multiplying intensity by duration; Dorman, Studdert-Kennedy, & Raphael, 1977).

(a) Energy difference between /b, d, g/ and the following vowel, also referred to as CV energy difference. The assumption underlying this methodological criterion is that acoustic energy variations reflect the degree to which approximant productions become more vowel-like or more stop-like and therefore allow more or less airflow to exit the vocal tract. Moreover, the energy level for /b, d, g/ was measured relative to that for the adjacent phonetic segments in order to account for variations in intensity which may occur from utterance token to token and from speaker to speaker (Cole et al., 1999).

Following the same procedure used in other studies (Colantoni & Marinescu, 2010; Hualde, Shosted, & Scarpace, 2011), the highest energy value for the vowel was subtracted from the energy minimum value for /b, d, g/. The subtraction operation always yielded positive values. Energy differences which are considerably higher than zero correspond to stop-like realizations of /b, d, g/ and those lying closer to zero to highly lenited and thus vowel-like consonant productions. The assumption that the CV energy difference ought to reflect lenition degree is consistent with the energy level for the vowel following /b, d, g/ being highly constant across all VC#CV combinations subjected to investigation (it ranged between 61.1 and 65.9 dB). Results for the ratio between the energy levels for /b, d, g/ and the following vowel (an increase in energy ratio corresponds to more stop-like realizations of /b, d, g/) were also computed but will not be reported since they mirror very closely the CV energy differences.

(b) Energy difference for /b, d, g/ relative to the preceding consonant also referred to as CC energy difference. C1 energy was measured at the first or only alveolar contact phase for /r/ which is where the energy minimum occurred, and at consonant midpoint for fricatives and /l/ in order to account for the fact that the energy contour decreased gradually from the preceding vowel until the onset of C2 = /b, d, g/ in this case. The rationale for computing the CC energy difference was that /b, d, g/ lenition should vary with the manner and place characteristics for the preceding consonant in ways referred to in the Introduction. In particular, since energy is related to airflow volume, it was expected that the CC energy difference would be higher in clusters with the lateral and with fricative consonants (and more so in sequences with /s, ʃ/ than in those with /f/; see section 1.1.) than in

clusters with the rhotic since the former consonants are produced with more considerable continuous airflow than the latter. Moreover, since the energy level for C1 did not remain constant, the resulting CC energy difference (which was positive most of the time but could also be negative) turned out to depend on the energy values for both /b, d, g/ and the preceding consonant.

(c) Velocity of the CV and CC energy transitions. The speed of the energy transition between the target and contextual segments was also evaluated, the assumption being that it ought to be inversely related to lenition degree for the target voiced stop. Indeed, the energy transition in question may be more or less abrupt as the articulators move faster or slower for more stop-like versus more vowel-like realizations of /b, d, g/ (Kent & Moll, 1972; Ortega-Llebaria, 2004).

Measures of CV energy transition speed were obtained by dividing the CV energy difference by the time interval elapsed between the energy minimum for /b, d, g/ and the energy maximum for the vowel (for a similar procedure see Hualde, Shosted, & Scarpace, 2011 and Ortega-Llebaria, 2004). Measures of energy speed were also taken for the CC energy transition by dividing the CC energy difference by the time interval between the energy landmarks for /b, d, g/ and the preceding consonant.

Energy measures were taken after filtering the acoustic signal with a pass Hann band filter between 250 Hz and 10 kHz with the programme Praat (Boersma & Weenink, 2013). This operation was performed in order to exclude from the energy calculation high and low frequency effects. In addition to background noise, these effects included the voicing bar which, as revealed by a pilot study run on a selected set of data, may raise the intensity value for stop or stop-like realizations of /b, d, g/ relative to the following vowel as much as by a factor of two (about 6.5 dB for the unfiltered signal and 15 dB for the filtered signal), thus rendering those occluded realizations more similar acoustically to less occluded ones than they should be. A 250 Hz cutoff frequency boundary was preferred to the 500 Hz cutoff borderline which has been applied in other studies (Hualde, Nadeu, & Simonet, 2010) since the latter may eliminate relevant information for F1, which occurs between 300 Hz and 500 Hz in the case of approximant realizations of /b, d, g/.

The MatLab script Peakdet 2 was used for estimating voicing duration for /b, d, g/ on the EGG signal. As described in detail in Recasens and Mira (2012), Peakdet 2 allows identifying the onset and offset of voicing at the positive peaks of the first derivative of the glottal waveform, which correspond to glottal closing instants. At a later stage, voicing ratios, namely, percentages of voicing duration over consonant duration, were calculated.

A Linear Mixed Model analysis with repeated measures was run on the CC and CV energy differences and the corresponding energy transition velocities, and on the C1 and C2 voicing ratios and duration values, using SPSS version 20. The statistical model included the C2 and C1 main effects (with levels ‘b’, ‘d’ and ‘g’, and ‘f’, ‘s’, ‘ʃ’, ‘l’ and ‘r’, respectively), and the C1*C2 interaction. Bonferroni post-hoc tests were carried out on the significant C1 and C2 effects, and simple effects tests on the significant C1*C2 interactions. The significance level was established at $p < 0.05$.

3 Results

3.1 CV sequence

As pointed out in section 2.2, the energy difference between C2 = /b, d, g/ and the following vowel should be indicative of the degree of lenition for the voiced stop: small energy differences imply that the approximant variants of /b, d, g/ are endowed with a wide constriction, and large energy differences that these variants are articulated with a narrow constriction and thus exhibit a stop or a stop-like realization.

Energy differences between /b, d, g/ and the following vowel yielded C1 and C2 main effects, $F(4, 206.1) = 82.37$, $p < 0.001$; $F(2, 343.54) = 66.96$, $p < 0.001$, and a significant C1*C2 interaction, $F(8, 131.98) = 7.32$, $p < 0.001$. As shown in Figure 2 (left graph), energy differences decrease with the C2 place of articulation in the progression /b, d/ > /g/ and with the consonant preceding /b, d, g/ in the progression /f/ > /s, ʃ/ > /l, r/. It is therefore the case that voiced stops are more prone to lenite if dorsovelar than if articulated further forward in the mouth, after the lateral and the rhotic than after the three fricatives, and after the more retracted alveolar and palatoalveolar fricatives than after the more anterior labiodental fricative. Moreover, C2 = /b/ did not exhibit a higher energy difference than C2 = /d/ which is not in support of earlier reports showing that the labial should be less prone to lenite than the dental (see Introduction section). According to results from post-hoc tests run on the voiced stop duration data and as shown in Figure 3 (right graph), /b/ turned out to be significantly longer than /d, g/, $F(2, 355.93) = 61.08$, $p < 0.001$, thus suggesting that resistance to lenition can be related to the voiced bilabial stop being longer than /d, g/.

Simple effects tests performed on the significant C1*C2 interaction revealed that /b, d, g/ are prone to be more stop-like when C1 and C2 are (quasi-)homorganic than when they are heterorganic. This is so for the clusters with C1 = /f/ and C1 = /s/ where, as shown in Figure 2 (left graph), the CV energy differences decrease in the progression /fb/ > /fd/ > /fg/ and /sd/ > /sb/ > /sg/ and, therefore, reach their maximum in the case of the sequences /fb/ and /sd/. This trend also holds to some extent for the clusters with C1 = /l, r, ʃ/ since, although non-significantly, CV energy differences were highest for /ʃd/, /ld/ and /rd/ (according to the statistical results, the actual C2-dependent effects varied in the progression /ʃb, ʃd/ > /ʃg/ and /lb, ld/ > /lg/ and reached significance for the sequences with C1 = /ʃ/ only). As Figures 2 (left graph) and 3 (right graph) show and as revealed by a significant C1*C2 interaction for the C2 duration values, $F(8, 216.19) = 51.31$, $p < 0.001$, there appear to be some similarities between C2 lenition degree and C2 duration in clusters in that C2 was significantly longer for /fb/ than for /fd, fg/, and shorter for the velar than for the labial and the dental when occurring after /l, r/.

In principle, the speed of the CV energy transition should increase as the CV energy difference increases and the energy minimum for /b, d, g/ decreases and, therefore, the target consonant exhibits a more stop-like realization. Energy speed varied significantly as a function of C1 and C2, $F(4, 149.86) = 19.26$, $p < 0.001$; $F(2, 313.77) = 90.53$, $p < 0.001$, and there was a significant C1*C2 interaction, $F(8, 105.34) = 15.32$, $p < 0.001$. As shown in Figure 2 (right graph), energy velocity was lower for /g/ than for /b, d/ and decreased with the preceding consonant in the progression /ʃ/> /f, s/ > /l, r/. A comparison with the data plotted in the left graph of the figure reveals that these main effects match those for the CV energy differences: velocity decreases with lenition degree for the voiced stop and is therefore lower for velar versus non-velar consonants and after sonorants versus fricatives. Also in agreement with results for the CV energy differences, CV energy velocity values turned out to be highest for clusters composed of (quasi-)homorganic consonants whenever C1 was /f, s, l/ (/fb/ > /fd/ > /fg/; /sd/ > /sb, sg/; /ld/ > /lb/ > /lg/) but not when it was /ʃ, r/ (/ʃb, ʃd/ > /ʃg/; /rb, rd/ > /rg/).

3.2 CC sequence

The CC energy differences yielded a C1 and C2 main effect, $F(4, 136.9) = 151.49$, $p < 0.001$; $F(2, 282.72) = 48.14$, $p < 0.001$, and a significant C1*C2 interaction, $F(8, 128.9) = 3.53$, $p < 0.001$. According to the post-hoc tests for the main effects and as shown in Figure 4 (left graph), significant differences among the C2 variable levels varied in the progression /b, d/ > /g/ and those among the C1 variable levels in the progression /s, ʃ, l/ > /r/ > /f/. These consonant-dependent differences were positively related to the C1 absolute energy values, that is, /l/ > /s, ʃ/ > /r/ > /f/,

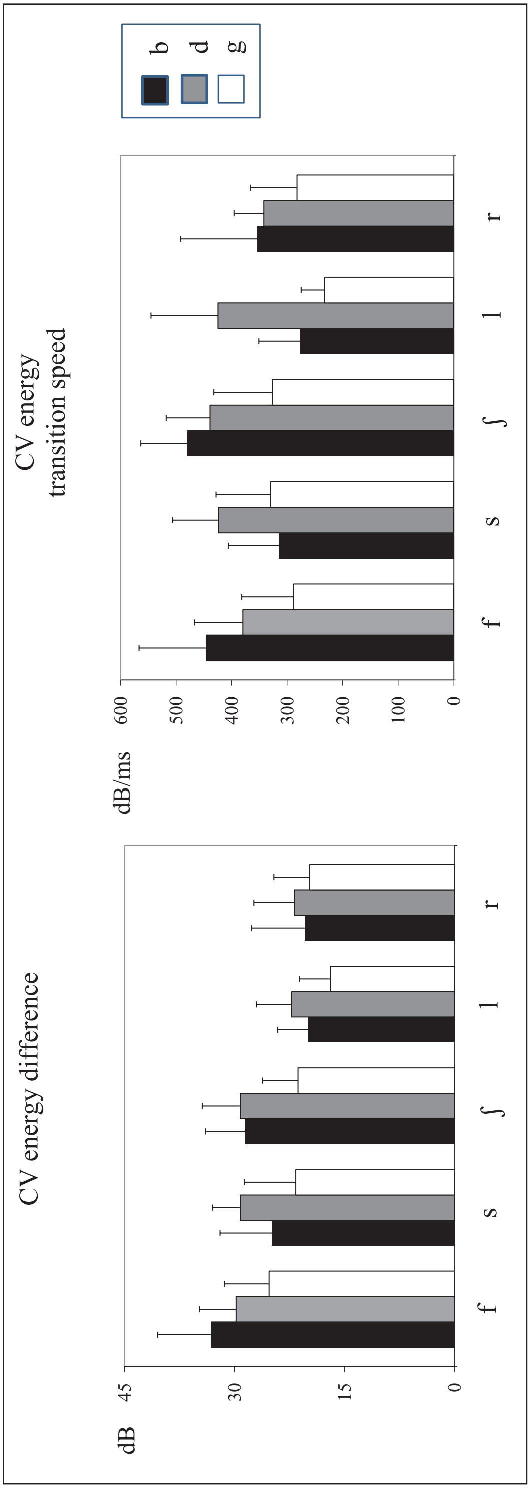

Figure 2. Cross-speaker CV energy differences (left) and CV energy transition velocities (right) for C2 = /b, d, g/ plotted as a function of C1 = /f, s, ʃ, l, r/. Error lines correspond to one standard deviation.

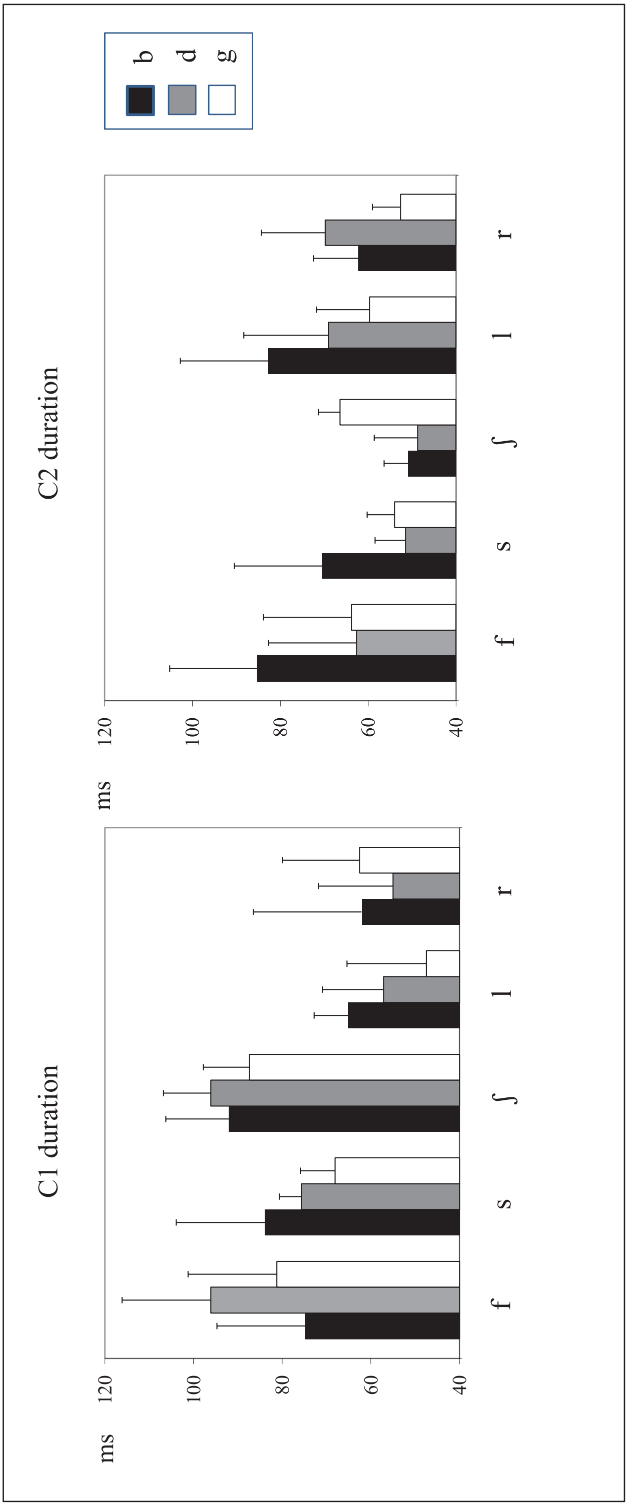

Figure 3. Cross-speaker durations for C1 = /f, s, ʃ, l, r/ as a function of C2 = /b, d, g/ (left) and for C2 = /b, d, g/ as a function of C1 = /f, s, ʃ, l, r/ (right). Error lines correspond to one standard deviation.

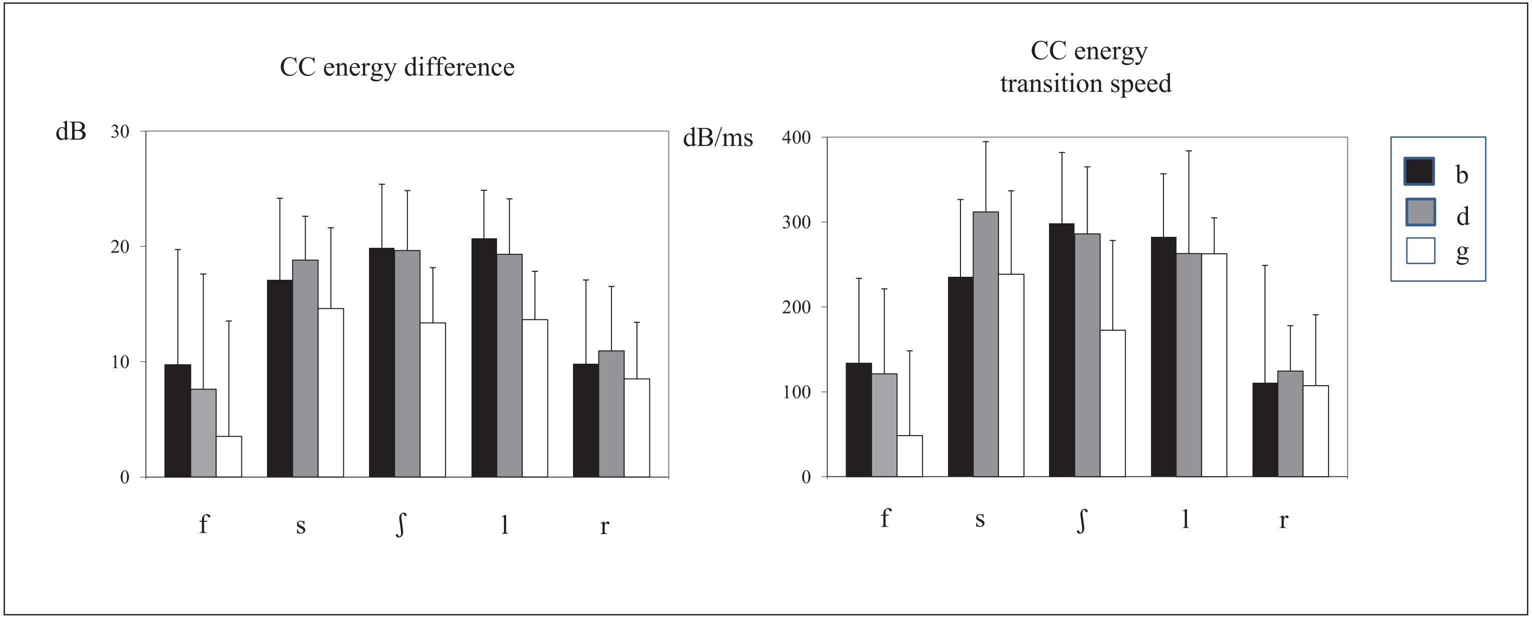

Figure 4. Cross-speaker CC energy differences (left) and CC energy transition velocities (right) for C2 = /b, d, g/ plotted as a function of C1 = /f, s, ʃ, l, r/. Error lines correspond to one standard deviation.

$F(4, 151.39) = 530.66$, $p < 0.001$, and to a lesser extent to C1 duration which, as shown in Figure 3 (left graph), was greater for the three fricatives than for /l, r/, $F(4, 170.93) = 176.72$, $p < 0.001$. As expected, excluding /f/ (see section 3.3), fricatives and /l/ had high energy values since they allow considerable airflow expenditure; on the other hand, the presence of low CC energy differences and C1 energy values for the cluster /rC/ is consistent with the rhotic being realized with one tongue contact and thus as a tap rather than as a trill. The significant C1*C2 interaction for the CC energy differences was related to the presence of C2-dependent effects for all C1 conditions except for C1 = /r/.

As for the velocity of the CC energy transitions (see Figure 4, right graph), the statistical test yielded a main effect of C1 and C2, $F(4, 183.72) = 174.8$, $p < 0.001$; $F(2, 227.6) = 27.15$, $p < 0.001$, and a significant C1*C2 interaction, $F(8, 104.6) = 8.38$, $p < 0.001$. According to the post-hoc tests and analogously to the CC energy differences referred to above, the speed of the CC energy transitions varied with C2 in the progression /b, d/ > /g/ and with C1 in the progression /s, ʃ, l/ > /r/ > /f/. This close relationship was also available when the C2-dependent effects for each C1 were taken into consideration, with a few exceptions such as the noticeably higher velocity values for /sd/ than for /sb, sg/.

3.3 CV and CC sequences compared

At this point, a comparison between the CV and CC energy differences and corresponding velocity values is in order. The two sets of values agree regarding the effect of C2 place of articulation: in comparison to the energy values for /b/ and /d/, those for /g/ lie closer to those for both C1 and the following vowel, which indicates that lenition degree is higher for the velar than for the labial and the dental. As for the role of C1, however, the CV and CC scenarios match only in part: the CV energy differences vary in the progression /f/ > /s, ʃ/ > /l, r/ while the CC energy differences do so in the progression /s, ʃ, l/ > /r/ > /f/. The two scales are closely related in the case of /s, ʃ/ versus /r/ and, to a lesser extent, for /s, ʃ/ versus /l/ as well, which results from C2 being more stop-like when C1 is a lingual fricative than when it is a sonorant in line with differences in intraoral pressure between the two sets of contextual consonants. A major discrepancy between the CC and CV energy differences concerns the consonant clusters with C1 = /f/: in spite of exhibiting a lower energy level, /f/ triggers more stop-like articulations of /b, d, g/ than /s, ʃ, l, r/ (and most especially stop-like and long realizations of C2 = /b/). A plausible interpretation for these findings will be provided in the Discussion section.

3.4 Voicing

The present study also looks into whether degree of lenition for /b, d, g/ is positively related to voicing degree for the stop consonant. If so, those realizations of /b, d, g/ which are less constricted should also be more prone to become voiced than those that are more stop-like. Moreover, this relationship is expected to hold when the progressive voicing effects from C1 on C2 but not the differences in C2 place of articulation are taken into account; thus, as referred to in section 1.2, voicing during C2 is expected to be greater after /l, r/ than after fricatives (and less so after /f/ than after /s, ʃ/) though not greater for /g/ than for /b, d/.

The statistical test run on the C2 voicing ratios yielded a significant main effect of C2 and C1, $F(2, 884.98) = 6.57$, $p < 0.001$; $F(4, 885.19) = 53.16$, $p < 0.001$, which was associated with more voicing for /b/ than for /d, g/ and with C1-dependent voicing differences in the progression /l, r/ > /s/ > /f, ʃ/ (Figure 5, right graph). There appears to be then a positive relationship between C2 voicing and lenition degree regarding the role of C1 (voiced stops were more vowel-like and exhibited

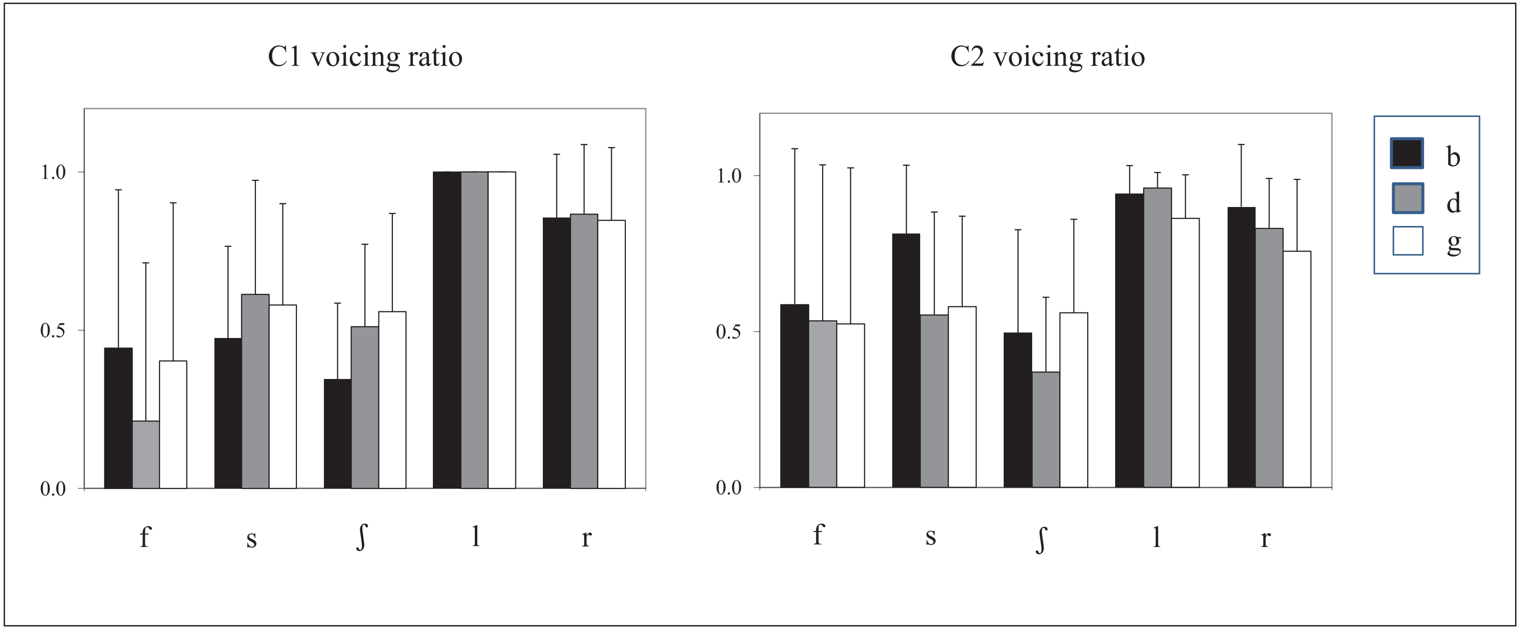

Figure 5. Cross-speaker voicing ratios for C1 = /f, s, ʃ, l, r/ as a function of C2 = /b, d, g/ (left) and for C2 = /b, d, g/ as a function of C1 = /f, s, ʃ, l, r/ (right). Error lines correspond to one standard deviation.

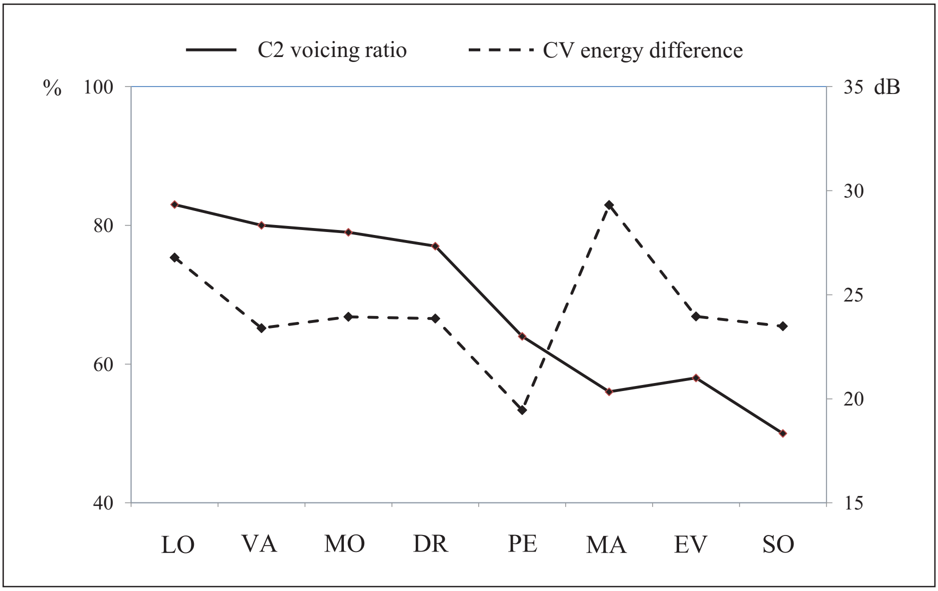

Figure 6. Speaker-dependent C2 voicing ratios (left axis, continuous line) and CV energy differences (right axis, discontinuous line) plotted across /b, d, g/ in all consonant sequences. The speakers' initials appear below the horizontal axis.

more voicing after sonorants than after fricatives) but not C2 place of articulation (/g/ was most prone to lenite while /b/ was most prone to stay voiced). As the figure reveals, there was also a significant C1*C2 interaction, $F(8, 884.98) = 3.2$, $p < 0.001$, according to which higher voicing ratios for /b/ than for /d, g/ occurred mostly after /s/.

Inspection of the data for the individual speakers show that, while all speakers exhibit considerable voicing for /b, d, g/ after /l, r/, progressive C2 devoicing exerted by a preceding fricative takes place for a subset of speakers only, namely, for subjects EV, MA, PE and SO, who for the most part are also reluctant to voice syllable-final obstruents before a voiced consonant in the case of other Catalan C#C sequences (Recasens & Mira, 2012). On the other hand, a comparison between the C2 voicing ratios and the CV energy differences across clusters for the individual speakers in Figure 6 reveals that there is a lack of correlation between stop voicing and lenition degree. Thus, as shown by the figure, while speakers MA and LO had more constricted realizations of /b, d, g/ than the other speakers (the CV energy difference was 29.31 dB and 26.79 dB for those two subjects and less than 24 dB for the remaining ones), they differed considerably in voicing degree among themselves (voicing was much less for MA than for LO, i.e., 56% versus 83%). Also, as revealed by Figure 6, among subjects exhibiting lower and similar CV energy differences (23–24 dB), some showed more voicing than others (voicing was about 80% voicing for DR and VA and 50%−60% for EV and SO).

C1-dependent voicing differences during C2 = /b, d, g/ were in line with differences in voicing during the consonant preceding the voiced stop. Indeed, as shown by Figure 5 (left graph), voicing during C1 varied in the progression /l/ > /r/ > /s/ > /ʃ/ > /f/, $F(4, 885.07) = 188.06$, $p < 0.001$ and was thus less for fricatives than for sonorants and for /f/ than for the two lingual fricatives. Voicing degree during C1 also depended to some extent on the following consonant: it was slightly higher before /g/ than before /b/, $F(2, 884.99) = 3.38$, $p < 0.034$ and, as revealed by a significant C1*C2 interaction, $F(7, 114.69) = 40.6$, $p < 0.001$, it varied as a function of C2 to a larger extent in clusters with a fricative C1 (/fb, fg/ > /fd/; /sd, sg/ > /sb/; /ʃd, ʃg/ > /ʃd/) than in those with C1 = /l, r/.

4 Discussion

The main goal of the present study was to ascertain differences in voiced stop lenition in Catalan heterosyllabic C#C sequences composed of C1 = /f, s, ʃ, l, r/ and C2 = /b, d, g/, as evaluated from energy measures involving the target consonant, and the following vowel and the preceding consonant. In line with other works on the subject for Spanish, Italian and Catalan, results show that stop lenition achieved through segmental shortening and undershoot is a variable process whose phonetic implementation depends on the consonants and vowels involved.

In agreement with previous studies, a greater lenition degree has been found to hold for /g/ than for /b, d/. As pointed out in section 1.1, the rationale for this finding may be sought in the difficulty involved in closure formation for true velars which may result in air leakage through the dorsal constriction. Contrary to several previous reports, while being longer than /d/ and /g/, /b/ did not turn out to be more resistant to lenition than /d/ across context conditions. Regarding the effect of the preceding consonant, voiced stops were more stop-like after fricatives than after sonorants (see Hualde, Shosted, & Scarpace, 2011 and Martínez-Celdrán & Regueira, 2008). This finding is in accordance with differences in intraoral pressure: the production of lingual fricatives requires a high oral pressure level associated with the passage of considerable airflow through a narrow supraglottal constriction; less oral pressure for /l, r/ is consistent with the passage of airflow through wide oral openings in the case of the lateral and of a short central contact which barely impedes airflow for the one-contact rhotic, which was essentially the only realization of preconsonantal /r/ available in the present investigation.

Lenition degree was found to be positively correlated with voicing degree when the effect of C1 on C2 was taken into consideration. Indeed, /b, d, g/ exhibited higher voicing ratios after sonorants than after fricatives also in agreement with differences in intraoral pressure between these consonant types. Similar voicing differences for a stop C2 as a function of a preceding sonorant versus obstruent C1 have been reported to occur in Catalan CC#C sequences with a voiced C3, which does not appear to be too much in line with voicing assimilation in heterosyllabic consonant clusters being a regressive process in this language (Recasens & Mira, 2013). The positive relationship between lenition degree and voicing in the C#C sequences under analysis in the present study is not related to C2 place of articulation however: while lenition varies in the progression /g/ > /b, d/ (presumably due to the specific characteristics of the velar constriction), /b/ is more prone to stay voiced than /d, g/ (which is in agreement with the labial exhibiting a larger back cavity and more vocal tract wall compliance than the dental and the velar).

The /fC/ sequences exhibited an exceptional behaviour in that /f/ triggered more stop-like realizations of /b, d, g/ than /s, ʃ, l, r/ while being less intense than the two lingual fricatives and the two sonorants /l, r/. As pointed out in the Introduction section, the reason why /b/ was prone to be realized as a stop after /f/ may be sought in the fact that an approximant realization of the voiced bilabial consonant could impair the weak /f/ frication noise. The fact that resistance to voiced stop lenition in /fC/ sequences applied to /d/ and /g/ as well implies that other factors must be at work. One such factor could be the low frequency of occurrence of /f/ in word-final position in Catalan mostly when monosyllabic and bisyllabic words are taken into account. This hypothesis appears to be supported by data for other Catalan phonological processes: in word-final intervocalic position where fricatives undergo voicing in Catalan, the labiodental fricative exhibits less voicing and is longer than the alveolar and palatoalveolar fricatives (Recasens & Mira, 2012); unlike /s#s/ and /ʃ#ʃ/, the sequence /f#f/ does not simplify into [f] (Pons-Moll, Lloret, & Jiménez, 2011); as shown in Figure 5 (left graph), /f/ showed less voicing than /s, ʃ/ when followed by /b, d, g/ (in Catalan, syllable-final obstruents are supposed to assimilate in voicing to any following voiced syllable-initial consonant), and there was considerable progressive devoicing in the case of the sequences /fb, fd, fg/. All these data support the view that /f/ is 'strengthened' in conditions which could endanger its phonetic integrity by, among other possible mechanisms, causing following /b, d, g/ to be more stop-like and to exhibit less voicing than expected.

Another finding is that /b, d, g/ are prone to be more stop-like when C1 and C2 are (quasi-) homorganic than when they are heterorganic, mostly in sequences with a fricative C1 such as /sd/ and also /fb/, where /b/ was longer than /d, g/ in the sequences /fd, fg/. Homorganicity facilitates the application of other relevant phonetic or phonological processes in consonant clusters, such as stop insertion or manner assimilation (e.g., /ns/ > [nts] and /tl/ > [ll] in Catalan; Recasens, 2014). It appears to also play an active role in C2 lenition in the clusters /lg, rg/ where some approximation of the tongue dorsum rear to the pharyngeal wall or the velar region (Proctor, 2009) may cause /g/ to fall short of its dorsovelar target; in agreement with this interpretation, /g/ was found to be shorter and less intense than /b, d/ after /l, r/ (see Figure 2, left graph, and Figure 3, right graph).

Data presented in this investigation reveal that the energy difference measure captures quite successfully differences in postconsonantal /b, d, g/ lenition as a function of the target voiced stop and the preceding consonant. In many instances the velocity of the CV and CC energy transitions was also found to be positively associated, respectively, with the size of the CV and CC energy differences. Thus, for example, values for the two parameters (energy difference and velocity) were higher for VC#CV sequences with C2 = /b, d/ than for those with C2 = /g/ and for clusters with a fricative than for those with a sonorant in C1 position.

In some cases there was, however, a mismatch between the acoustic energy data and articulatory evidence for the clusters under analysis. Thus, as reported in previous studies (Hualde, Shosted, & Scarpace, 2011), the homorganic sequence /ld/ yielded higher CV energy differences than expected in spite of /l/ and /d/ showing a complete dentoalveolar closure and therefore /d/ being realized typically as a stop in this cluster (see relevant electropalatographic data for this consonant sequence in Recasens & Pallarès, 2001a). The finding that /d/ exhibited energy values well above zero in spite of being occluded could be ascribed to airflow going through lateral passages located behind the lingual closure and the front sides of the palate not only during /l/ but during following /d/ as well. In these circumstances /l/ and /d/ can still differ in that /l/ exhibits more airflow and is thus more intense than /d/, and /d/ but not /l/ is produced with a more or less prominent burst. A similar situation applies to the cluster /nd/ where /d/ is articulated with a complete closure and may show some acoustic excitation whenever it becomes nasalized. The data just referred to reveal that, in partial disagreement with Hualde, Shosted, & Scarpace (2011), the intensity difference between /b, d, g/ and the following vowel is not always inversely correlated with labial or lingual constriction opening for the target stop consonant such that the lower the intensity difference the wider the constriction. Indeed, using articulatory data for /b/, Parrell (2010) has shown that this and other acoustic intensity measures are not too highly correlated with articulatory measures of degree of constriction. This lack of a correlation is due to at least two factors: airflow may exit the mouth not only through the central constriction but also through the mouth sides, as for the /ld/ case referred to above; an increase in airflow volume across the glottis and the supraglottal constriction should contribute to an increase in formant intensity more or less independently of constriction size.

This paper shows different lenition degrees for /b, d, g/ as a function of the manner and place characteristics of the preceding and target consonants, which is indicative that the lenition process does not apply categorically in Catalan. This scenario appears to be consistent with a production-based model which takes into consideration several articulatory and aerodynamic factors rather than with other accounts stating that lenition involves the minimization of articulatory effort or the acoustico-perceptual optimization of an ongoing prosodic constituent (see Introduction). Indeed, there is no apparent reason why differences in articulatory effort should cause voiced stops to lenite after heterorganic consonants rather than after homorganic ones or after liquids rather than after obstruents. In fact, since articulatory effort is expected to be less in homorganic than heterorganic consonant sequences lenition ought to be more prone to operate on the former clusters than on the latter which is just the opposite of what appears to be taking place. On the other hand, several principles ruling postconsonantal stop lenition in consonant clusters are based on production constraints and cannot be formulated in acoustico-perceptual terms. In particular, lenition depends crucially on place of articulation and constriction degree for the target voiced stop (for velars > labials, dentals), on intraoral pressure level for C1 (for fricatives > liquids) and on whether C1 and C2 are homorganic or heterorganic (C2 is often realized as a stop in the sequences /fb, ld/ and less often in /sd, ʃd, rd/, and mostly as an approximant in the remaining segmental combinations). Other factors may also play a role such as the frequency of occurrence for the word-final consonant (as for C1 = /f/ in Catalan), speech rate and prosodic prominence.

These Catalan data and data on dialect-dependent differences in lenition degree may throw light on the evolutionary pathway from the early stages of lenition to scenarios where approximant realizations become much more frequent or [b, d, g] and [β, ð, ɣ] may be considered to occur in complementary distribution. Whether derived from originary voiceless or voiced stops, lenition involves gestural reduction at its first evolutionary stages which is usually manifested through shortening and a decrease in articulatory displacement and in tongue or lip contact at closure location. At this point the lenition process is highly variable, as in Rome Italian where intervocalic /d, g/ may be realized as stops or approximants and may even be deleted ([ˈlado] and [ˈla(ð)o] for [ˈlato] 'side'; Hualde & Nadeu, 2011b). A highly variable phonetic scenario also applies to /k/ lenition in Pisan Italian (Marotta, 2008). At its final stage, lenition may yield the systematic effacement of the approximant realizations, as in Old French where /d, g/ were effaced in intervocalic position (see section 1).

A stable allophonic scenario is that of Spanish and Catalan where lenition operates extensively postvocalically and after certain consonants though, in disagreement with descriptive accounts, not categorically but more or less often depending on articulatory and aerodynamic factors. In this case we appear to be facing a gradual process with one of the two allophones prevailing upon the other at the extremes of the lenition scale (approximant realizations are clearly favoured by a preceding vowel and by consonants which allow freely the passage of airflow and a low intraoral pressure level, and stop realizations by a pause and occluded consonants), and allophonic differences shrinking towards the middle of the scale (both stop and approximant realizations may show up after fricatives).

Now the question arises as to why lenited and non-lenited allophones may survive in such a contextually determined, albeit variable and apparently unstable, situation. As found by Gurevich's language survey this finding is consistent with lenition processes being overwhelmingly meaning-maintaining (they result in free variation or allophonic distribution but not in phonological neutralization), as it occurs precisely in Spanish or Catalan where [β, ð, ɣ] cannot be confused with other existing sounds (Gurevich, 2004). This appears to be in line with listeners being largely insensitive to the phonetic difference between voiced stop and approximant realizations of /b, d, g/, and definitely less sensitive to this manner distinction than to the contrast between voiced and voiceless stops (Kaplan, 2010). In order to explore this issue, future research should test the extent to which listeners are sensitive to lenition differences between more approximant-like and more stop-like realizations of /b, d, g/ by manipulating acoustic parameters such as consonant intensity and duration in synthetic speech experiments.

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References

Abadal, S., & Recasens, D. (2009). *Peakdet2. An instructions manual*. Retrieved from http://voiceresearch.free.fr/egg.

Bauer, L. (2008). Lenition revisited. *Journal of Linguistics*, *44*, 605–624.

Bergmann, P. (2012). Articulatory reduction and assimilation in n#g sequences in complex words in German. In P. Hoole, L. Bombien, M. Pouplier, Ch. Mooshammer & B. Kühnert (Eds.), *Consonant clusters and structural complexity* (pp. 311–344). Berlin/New York: Mouton de Gruyter.

Blevins, J. (2004). *Evolutionary phonology: The emergence of sound patterns*. Cambridge, UK: Cambridge University Press

Boersma, P., & Weenink, D. (2013). *Praat: Doing phonetics by computer*. Retrieved from http://www.praat.org.

Bouavichith, D., & Davidson, L. (2013). Segmental and prosodic effects on intervocalic voiced stop reduction in connected speech. *Phonetica*, *70*, 182–206.

Browman, C. P., & Goldstein, L. (1991). Gestural structures: Distinctiveness, phonological processes, and historical change. In I. G. Mattingly & M. Studdert-Kennedy (Eds.), *Modularity and the motor theory of speech perception* (pp. 313–338). Hillsdale, NJ: Lawrence Erlbaum Associates.

Browman, C. P., & Goldstein, L. (1992). Articulatory phonology: An overview. *Phonetica*, *49*, 155–180.

Carrasco, P., & Hualde, J. I. (2009, June 17–18). *Spanish voiced allophony reconsidered*. Paper presented at the Phonetics and Phonology in Iberia Conference, Las Palmas de Gran Canaria, Spain.

Carrasco, P., Hualde, J. I., & Simonet, M. (2012). Dialectal differences in Spanish voiced obstruent allophony: Costa Rican vs. Iberian Spanish. *Phonetica*, *69*, 149–179.

Colantoni, L., & Marinescu, I. (2010). The scope of stop weakening in Argentine Spanish. In M. Ortega-Llebaria (Ed.), *Selected Proceedings of the 4th Conference on Laboratory Approaches to Spanish Phonology* (pp. 100–114). Somerville, MA: Cascadilla Proceedings Project.

Cole, J., Hualde, J. I., & Iskarous, K. (1999). Effects of prosodic and segmental context on/g/-lenition in Spanish. In O. Fujimura, B.D. Joseph, & B. Palek (Eds.), *Proceedings of the Fourth International Linguistics and Phonetics Conference* (pp. 575–589). Prague: The Karolinum Press.

Cravens, T. D. (2002). *Comparative historical dialectology. Italo-Romance clues to Ibero-Romance sound change*. Amsterdam: John Benjamins.

Dorman, M. F., Studdert-Kennedy, M., & Raphael, L. J. (1977). Stop-consonant recognition: Release bursts and formant transitions as functionally equivalent, context-dependent cues. *Perception and Psychophysics*, *22*, 109–122.

Eddington, D. (2009, June 17–18). *A gradient analysis of Spanish voiced approximants: New data undermine some traditional notions*. Paper presented at Phonetics and Phonology in Iberia, Las Palmas, Spain.

Eddington, D. (2011). What are the contextual phonetic variants of /β, ð, γ/ in colloquial Spanish?. *Probus*, *23*, 1–19.

Ellis, L., & Hardcastle, W. J. (2002). Categorical and gradient properties of assimilation in alveolar to velar sequences: Evidence from EPG and EMA data. *Journal of Phonetics*, *30*, 373–396.

Gordon, M., Barthmaier, P., & Sand, K. (2002). A cross-linguistic acoustic study of voiceless fricatives. *Journal of the International Phonetic Association*, *32*, 141–174.

Gurevich, N. (2004). *Lenition and contrast: The functional consequences of certain phonologically conditioned sound changes*. New York: Garland Publishing.

Gurevich, N. (2011). Lenition. In M. van Oostendorp, C. J. Ewen, E. Hume & K. Rice (Eds.), *The Blackwell companion to phonology* (pp. 1559–1575). Malden, MA: Blackwell.

Haggard, M. P. (1978). The devoicing of voiced fricatives. *Journal of Phonetics*, *6*, 95–102.

Hualde, J. I., & Nadeu, M. (2011a). Lenició i contrast fonèmic en català central i mallorquí. In M.R. Lloret & C. Pons (Eds.), *Noves aproximacions a la fonologia i la morfologia del català* (pp. 275–293). Alacant: Institut Universitari de Filologia Valenciana.

Hualde, J. I., & Nadeu, M. (2011b). Lenition and phonemic overlap in Rome Italian. *Phonetica*, *68*, 215–242.

Hualde, J. I., Nadeu, M., & Simonet, M. (2010). Lenition and phonemic contrast in Majorcan Catalan. In S. Colina, A. Olarrea & A. M. Carvalho (Eds.), *Romance linguistics 2009* (pp. 63–79). Amsterdam: John Benjamins.

Hualde, J. I., Shosted, R., & Scarpace, D. (2011). Acoustics and articulation of Spanish /d/ spirantization. In W.-S. Lee & E. Zee (Eds.), *Proceedings of the XVII International Congress of Phonetic Sciences* (pp. 906–909). Hong Kong: City University of Hong Kong.

Hualde, J. I., Simonet, M., & Nadeu, M. (2011). Consonant lenition and phonological recategorization. *Laboratory Phonology*, *2*, 275–300.

Hualde, J. I., Simonet, M., Shosted, R., & Nadeu, M. (2010, March 26–28). Quantifying Iberian spirantization: Acoustics and articulation. In *40th Linguistic Symposium on Romance Languages, Selected Proceedings* (pp. 26–28). Seattle, WA: University of Washington.

Jongman, A., Wayland, R., & Wong, S. (2000). Acoustic characteristics of English fricatives. *Journal of the Acoustical Society of America*, *108*, 1252–1263.

Kaplan, A. (2010). *Phonology shaped by phonetics: The case of intervocalic lenition* (Unpublished PhD dissertation). University of California, Santa Cruz.

Kent, R. D., & Moll, K. L. (1972). Cinefluorographic analyses of selected lingual consonants. *Journal of Speech, Language and Hearing Research*, *15*, 453–473.

Kingston, J. (2008). *Lenition*. In L. Colantoni & J. Steele (Eds.), *Selected Proceedings of the 3rd Conference on Laboratory Approaches to Spanish Phonology* (pp. 1–31). Somerville, MA: Cascadilla Press.

Kirchner, R. (2001). *An effort-based approach to consonant lenition* (PhD dissertation). London: Routledge.

Kirchner, R. (2004). *Consonant lenition*. In B. Hayes, R. Kirchner & D. Steriade (Eds.), *Phonetically based phonology* (pp. 313–345). Oxford: Oxford University Press.

Lavoie, L. (2001). *Consonant strength: Phonological patterns and phonetic manifestation*. New York: Routledge.

Marotta, G. (2008). Lenition in Tuscan Italian (Gorgia Toscana). In J. Brandão de Carvalho, T. Scheer & P. Ségéral (Eds.), *Lenition and fortition* (pp. 235–271). Berlin: de Gruyter.

Martínez Celdrán, E. (2008). Some chimeras of traditional Spanish phonetics. In L. Colantoni & J. Steele (Eds.), *Selected Proceedings of the 3rd Conference on Laboratory Approaches to Spanish Phonology* (pp. 32–46). Somerville, MA: Cascadilla Press.

Martínez-Celdrán, E., & Regueira, X. L. (2008). Spirant approximants in Galician. *Journal of the International Phonetic Association*, *38*, 51–68.

Navarro Tomás, T. (1971). *Manual de pronunciación española*, 19th edn. Madrid: Consejo Superior de Investigaciones Científicas.

Ohala, J. J. (1990). The phonetics and phonology of aspects of assimilation. In J. Kingston & M. Beckman (Eds.), *Papers in laboratory phonology I: Between the grammar and the physics of speech* (pp. 258–275). Cambridge: Cambridge University Press.

Ohala, J. J., & Riordan, C. J. (1979). Passive vocal tract enlargement during voiced stops. In J. J. Wolf & D. H. Klatt (Eds.), *Speech communication papers* (pp. 89–92). New York: Acoustical Society of America.

Ohala, J. J., & Solé, M. J. (2010). *Turbulence in phonology*. In S. Fuchs, M. Toda & M. Zygis (Eds.) *Turbulent sounds. An interdisciplinary guide* (pp. 37–97). Berlin: Mouton de Gruyter.

Ortega-Llebaria, M. (2003). Effects of phonetic and inventory constraints in the spirantization of intervocalic voiced stops: Comparing two different measurements of energy change. In M. J. Solé, D. Recasens & J.

Romero (Eds.), *Proceedings of the 15th International Congress of Phonetic Sciences* (pp. 2817–2820). Barcelona, Spain: Causal Productions.

Ortega-Llebaria, M. (2004). Interplay between phonetic and inventory constraints in the degree of spirantization of voiced stops: Comparing intervocalic /b/ and intervocalic /g/ in Spanish and English. In T. L. Face (Ed.), *Laboratory approaches to Spanish phonology* (pp. 237–254). Berlin: Mouton de Gruyter.

Parrell, B. (2010). Articulation from acoustics: Estimating constriction degree from the acoustic signal. *Journal of the Acoustical Society of America*, *128*, 2289.

Parrell, B. (2014). *Dynamics of consonant reduction* (Unpublished doctoral dissertation). University of Southern California, California.

Pons-Moll, C., Lloret, M.-R., & Jiménez, J. (2011). Rara afis, rara avis. O del comportament fonològic especial de les fricatives labiodentals en català. In M. R. Lloret & C. Pons (Eds.), *Noves aproximacions a la fonologia i la morfologia catalanes* (pp. 353–398). Alacant: Institut Universitari de Filologia Valenciana.

Proctor, M. (2009). *Gestural characterization of a phonological class: The liquids* (Unpublished PhD dissertation). Yale University, New Haven, CT.

Recasens, D. (2011). A cross-language acoustic study of initial and final allophones of /l/. *Speech Communication*, *54*, 368–383.

Recasens, D. (2014). *Fonètica i fonologia experimentals del català*. Barcelona, Spain: Institut d'Estudis Catalans.

Recasens, D., & Mira, M. (2012). Voicing assimilation in Catalan two-consonant clusters. *Journal of Phonetics*, *40*, 639–654.

Recasens, D., & Mira, M. (2013). Voicing assimilation in Catalan three-consonant clusters. *Journal of Phonetics*, *41*, 264–280

Recasens, D., & Pallarès, M. D. (2001a). *De la fonètica a la fonologia*. *(Les consonants i assimilacions consonàntiques del català)*. Barcelona, Spain: Ariel.

Recasens, D., & Pallarès, M. D. (2001b). Coarticulation, assimilation and blending in Catalan consonant clusters, *Journal of Phonetics*, *29*, 273–301

Rohlfs, G. (1966). *Grammatica storica della lingua italiana e dei suoi dialetti*. Turin, Italy: Einaudi.

Solé, M. J. (2010). Effects of syllable position on sound change: An aerodynamic study of final fricative weakening. *Journal of Phonetics*, *38*, 289–305.

Stevens, K. N. (1998). *Acoustic phonetics*. Cambridge, UK: The MIT Press.

Stevens, K. N., Blumstein, S., Glicksman, S., Burton, M., & Kurowski, K. (1992). Acoustical and perceptual characteristics of voicing in fricatives and fricative clusters. *Journal of the Acoustical Society of America*, *81*, 2979–3000.

Torreira, F., & Ernestus, M. (2011). Realization of voiceless stops and vowels in conversational French and Spanish. *Laboratory Phonology*, *2*, 331–353.

Villafaña Dalcher, C. (2006). *Consonant weakening in Florentine Italian: An acoustic study of gradient and variable sound change* (PhD dissertation). Georgetown University, Washington, DC.

Wheeler, M. (2005). *The phonology of Catalan*. Oxford, UK: Oxford University Press.

Whitehead, R. L., & Barefoot, S. M. (1983). Airflow characteristics of fricative consonants produced by normally hearing and hearing-impaired speakers. *Journal of Speech and Hearing Research*, *26*, 185–194.