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Coarticulation in Catalan Dark [ɫ] and the Alveolar Trill: General Implications for Sound Change

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Abstract

Coarticulation data for Catalan reveal that, while being less sensitive to vowel effects at the consonant period, the alveolar trill [r] exerts more prominent effects than [ɫ] on both adjacent [a] and [i]. This coarticulatory pattern may be related to strict manner demands on the production of the trill. Both consonants also differ regarding the relative prominence of the consonant-to-vowel anticipatory and carryover effects in VCV sequences: while [r] and [ɫ] exert much anticipatory coarticulation on the preceding vowel, carryover effects on the following vowel turn out to be more salient for [r] than for [ɫ]. These consonant-dependent differences in coarticulatory direction parallel the directionality patterns observed in related vowel assimilatory and glide insertion processes occurring in the Romance languages, in Early Germanic, in Old, Middle and Modern English, and in Arabic when the target consonant is not [ɫ] or [r] but a pharyngealized dentoalveolar.

Keywords

Alveolar trill, coarticulation, dark alveolar lateral, Romance languages, sound change

1 Introduction

A number of recent studies show the relevance of phonetic detail for the study of the causes of sound change. Thus, for example, based on the notion that consonant vocalization may be associated with the acoustic equivalence between the input and output sounds (Ohala, 1974), it has been shown that a low 800–1000 Hz steady-state F2 and, to a lesser extent, an early occurrence of the vowel transitions, contribute to the categorization of [ɫ] (dark *l*) as [w] (Recasens & Espinosa, 2010). Also, stop epenthesis in consonant clusters such as [ls] and [ns] should be more prone to take place in dialects where a short stop element is likely to develop at the boundary between the two original consonants in the cluster (e.g., American English) than in other dialects where the stop in question does not occur on a regular basis (e.g., Southern African English) (Fourakis & Port, 1986).

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Data from the literature presented below reveal that [ɫ] and the trill [r] exhibit very similar articulatory and coarticulatory properties: they involve the formation of an apical closure and tongue dorsum lowering and retraction, are highly resistant to vowel coarticulation, and exert prominent effects on the adjacent vowels. However, evidence on phonetic detail also indicates that the two consonants differ in relatively small but robust articulatory and acoustic characteristics. The goal of this paper is to investigate the production mechanisms of [ɫ] and [r], and to show that these mechanisms may account for the typology and direction of specific sound changes. Data for several speakers of Catalan will be used for this purpose. The rationale underlying this line of research is that detailed information about articulation and coarticulatory effects should contribute to a better understanding of the motivation of sound change processes.

A word of caution needs to be put forward regarding the extrapolation from synchronic data to diachronic patterns. While experimental evidence on [ɫ] and [r] reported in this paper has been gathered from a small number of speakers from a single language, it is claimed that the general trends observed in the data may be used for explaining sound change patterns occurring in many languages. In any case, given the large amount of variation that these consonants may exhibit as a function of speaker, phonetic context and prosodic condition (see Jones, unpublished, regarding trills), these experimental-diachrony links should be considered as suggestive.

The paper is structured as follows. This Introduction section presents a description of the articulatory, acoustic and coarticulatory characteristics for the two consonants. An experimental evaluation of the consonant-dependent patterns of vowel-to-consonant (V-to-C) and consonant-to-vowel (C-to-V) coarticulation follows. In the third section, the paper shows that these patterns of coarticulatory behavior may account for relevant changes affecting vowels in the Romance, Germanic and Arabic languages.

1.1 Phonetic characteristics and coarticulation

The dark apico-alveolar lateral and the apico-alveolar trill are produced with similar tongue configurations, namely, they both involve tongue predorsum lowering, postdorsum retraction and a relatively low jaw position. This is so for American English [ɫ] (Browman & Goldstein, 1995; Delattre, 1965, pp. 89–90; Giles & Moll, 1975), Spanish [r] (Delattre, 1965, pp. 72–75; Proctor, 2009) and Italian [r] (Romano & Badin, 2009). Tongue predorsum depression is associated with the dark consonant quality and the need to let the air pass through the sides of the mouth for [ɫ], and with apico-alveolar trilling, that is, the performance of several successive short linguo-alveolar contacts, for [r]. While this contributes to the formation of a secondary pharyngeal or velar constriction in the case of [ɫ], articulatory and acoustic data from several languages indicate that the tongue dorsum retraction motion may be less salient for the trill. This observation is partly based on the second spectral formant (F2) frequency which is directly correlated with dorsopalatal contact degree and inversely related to tongue postdorsum retraction, as revealed by data for Catalan [ɫ], [r] (Recasens, 1987, 1986, pp. 82, 96; Recasens & Espinosa, 2005), Spanish [r] (Massone, 1988; Quilis, 1981, p. 292) and Italian [r] (Ferrero, Genre, Boë, & Contini, 1979, p. 138; Ladefoged & Maddieson, 1996, p. 220). Indeed, a cross-language comparison between F2 for [ɫ] and [r] in intervocalic position in the context of [i] indicates that this formant frequency is higher for [r] (1200–1600 Hz) than for a strongly dark variety of the alveolar lateral (850–1300 Hz) and, less so, for the more moderately dark variety (1250–1450 Hz). The two consonants also differ in the context of [a] where F2 is again higher for the trill (1050–1500 Hz) than for [ɫ] (strongly dark: 850–1150 Hz; moderately dark: 1000–1250 Hz). Finally, [ɫ] and [r] show a similar F2 frequency at about 1000 Hz when appearing next to [u] ([r]: 850–1000

Hz; strongly dark *l*: 750–950 Hz; moderately dark *l*: 850–1050 Hz). These F2 consonant-dependent differences match articulatory data for Eastern Catalan exhibiting more tongue dorsum contact at the sides of the palatal zone for the trill than for moderately dark *l* in symmetrical VCV sequences with [a] and, less so, with [i] (Recasens & Pallarès, 2001, pp. 74–75, 80–81). On the other hand, the first spectral formant (F1), which appears to be positively related to the cross-sectional area of the lateral constriction and thus to tongue predorsum lowering and oral opening (Bladon, 1979; Fant, 1960), is as high for [r] as for strongly dark *l* (250–450 Hz in high vowel contexts, 400–650 Hz in the context of [a]), and somewhat higher for the trill than for moderately dark *l*.

As for the primary constriction location, [r] may exhibit a more posterior alveolar articulation than [ɫ] presumably in line with the strict articulatory and aerodynamic requirements involved in the performance of trills (Solé, 2002). A typical dental or front alveolar closure location for the dark alveolar lateral may occur in order to assist both the formation of lateral openings and the lowering and retraction of the tongue dorsum, while contributing to an increase in the size of the cavity behind the primary constriction and a decrease in F2 frequency. A more retracted (postalveolar) realization for the trill than for [ɫ] has been reported to occur in Eastern Catalan (Recasens, Fontdevila, & Pallarès, 1996; Recasens & Pallarès, 1999) but not necessarily in other languages where [r] may also be postdental or front alveolar such as Spanish (Fernández, 2000; Gili Gaya, 1921; Navarro Tomás, 1972, p. 121; Quilis & Fernández, 1972, p. 132; Russell, 1918–1919), Italian (Tagliavini, 1965, p. 155) and others (Ladefoged & Maddieson, 1996, pp. 221–222). In line with these consonant-dependent differences in constriction location, the frequency of the front-cavity-dependent third spectral formant (F3) is generally lower for [r] than for [ɫ] at least next to [i] and [a], namely, about 2300 Hz for [r], 2500 Hz for moderately dark *l* and 2600 Hz for strongly dark *l* in dialects of Catalan. Dentoalveolar or dental varieties of [r] exhibit higher F3 frequencies (Lindau, 1985).

In light of the data just reviewed, it may be speculated that the rhotic is less vowel coarticulation resistant than the lateral since both the tongue dorsum position and F2 are higher for [r] than for [ɫ] in the context of [i]. This speculation is based on the assumption that, given that the consonant and the high front vowel are produced with antagonistic lingual gestures, the lower the tongue dorsum for the consonant, the more resistant it should be to the tongue dorsum fronting and raising effects induced by the vowel. However, it seems more plausible to assume instead that a higher tongue dorsum position for [r] than for [ɫ] next to [i], and next to [a] as well, is associated with the stringent requirements on the performance of trilling than with a lower degree of tongue body constraint. If so, the trill would be more constrained than the lateral and, therefore, more resistant to vowel coarticulation. In line with data reported by several studies mentioned above, this hypothesis is fully consistent with a trend for [r] to exhibit smaller differences in tongue dorsum contact, F2 frequency and constriction location as a function of [i] vs. [a] than [ɫ].

Data on Catalan reported in earlier publications (Recasens, Pallarès, & Fontdevila, 1997, 1998; Recasens & Pallarès, 1999) also indicate that the two consonants under investigation resemble each other in exerting a great deal of tongue dorsum lowering and retraction upon the antagonistic vowel [i], that is, F2 for [i] may lower down to 550–700 Hz next to both [ɫ] and [r]. Much C-to-V anticipation for the lateral and the rhotic is associated with an early lowering of the tongue dorsum with respect to the raising motion of the tongue tip (see Sproat & Fujimura, 1993 regarding the alveolar lateral).

The consonants [ɫ] and [r] differ, however, in relevant respects regarding the size and temporal extent of the C-to-V coarticulatory effects, as well as the direction of the effects in question, namely, as to whether these effects occur at the anticipatory level during the preceding vowel (V1) or at the carryover level during the following vowel (V2). In the publications on Catalan referred to above, the temporal extent of the C-to-V anticipatory effects was found to be somewhat more prominent for [r] than for [ɫ] both during antagonistic [i] and during [a], which may be taken to indicate that the lingual gesture for the trill begins earlier than that for the lateral (articulatory and acoustic activity for the consonant during preceding [i] was observed for about 80–90 ms for [r] and for 52–64 ms for [ɫ]). Analogous consonant-dependent differences occurred at the carryover level. Thus, the C-to-V carryover effects on [i] and on [a] lasted longer for the trill than for the lateral (temporal effects on [i] were about 70–100 ms for [r] and 54–68 ms for [ɫ]). The rationale for this finding may be sought in the strict postural and aerodynamic requirements for trills not only at consonant onset but at consonant offset as well. Moreover, when the C-to-V coarticulation data for the individual speakers were taken into consideration, [ɫ] was found to exert stronger anticipatory than carryover effects or a similar degree of anticipatory and carryover coarticulation, while [r] could favor either the anticipatory or the carryover direction of the C-to-V coarticulatory effects.

1.2 Summary and research goal

Production and coarticulation data reported in previous studies show some clear-cut differences between dark [ɫ] and [r]. The tongue tip is generally placed further back and the tongue dorsum is somewhat higher and may be less retracted for the trill than for the lateral, while the entire tongue body resists vowel coarticulation to a larger extent for the former consonant than for the latter. Moreover, consonantal effects on the adjacent vowels, mostly on [i], reflect these consonant-dependent differences in degree of articulatory constraint in that the trill appears to be more stringent than the lateral and that the effects for the former consonant but not those for the latter may favor the carryover over the anticipatory direction.

The goal of the present paper is to explore more thoroughly the differences in V-to-C and C-to-V coarticulation between [ɫ] and [r] in Catalan reported in previous publications, and to relate these differences to several sound changes which are triggered by one or the two consonants such as the lowering of front vowels (Corsican [ˈtara] < Latin [ˈtɛra] "land"; Rohlfs, 1966, p. 130). Our approach will be to determine which one of the two consonants causes the adjacent vowels to deviate most from their prototypical formant frequencies and thus, for example, F2 for [i] to become lower than 2000 Hz. The greater the deviation from these vowel formant frequencies, the higher the chances that the consonant acts as the trigger of an assimilatory change. This hypothesis is consistent with the finding that coarticulatory effects for liquids may have perceptual consequences (West, 1999).

The present investigation will also ascertain whether presumable differences in C-to-V coarticulation between [ɫ] and [r] should account for the relative prominence of specific regressive and progressive assimilatory vowel changes. Our initial prediction in this respect is that the changes in question ought to be regressive in the case where the C-to-V effects are anticipatory (C-to-V1) rather than carryover (C-to-V2), and progressive if the C-to-V coarticulatory effects favor the carryover over the anticipatory direction.

2 Experiment

2.1 Method

In order to study the differences in V-to-C and C-to-V coarticulation between [ɫ] and [r], linguopalatal contact and acoustic data for the nonsense (quasi)-symmetrical VCV sequences [ˈiɫi], [ˈaɫə],

[ˈiri] and [ˈarə] were recorded in isolation five times each by five native speakers of Eastern Catalan of 30–40 years of age who speak Catalan in their daily life (DR, JP, JS, DP, JC). Catalan is known for having a dark variety of the alveolar lateral with darkness degree varying according to speaker. This speech material was part of the database of the ESPRIT–ACCOR project dealing with the study of coarticulation in several European languages (Marchal et al., 1991). The flanking vowel in the [ˈaCə] sequences will be referred to as [a] throughout the paper though [ə] is the unstressed allophone of /e, ɛ, a/ in the Catalan dialect under study. In principle, differences in stress and vowel quality between V1 and V2 should be of little relevance to the initial goal of the present investigation, namely, a comparison between the articulatory characteristics and the coarticulatory patterns for [ɫ] and [r], since the same contextual conditions and prosodic structures were used for the VCV sequences with the two consonants. As for the naturalness of the speech material, other publications using the same ACCOR material show that phonetic data for phonemes embedded in nonsense isolated sequences such as those subjected to analysis in the present paper do not differ substantially from those obtained from longer meaningful utterances (Recasens and Pallarès, 2001).

Linguopalatal contact and acoustic data were recorded simultaneously at the University of Reading using the Reading electropalatographic (EPG) system (Hardcastle, Jones, Knight, Trudgeon, & Calder, 1989). The linguopalatal contact data were obtained by means of artificial palates that speakers had been wearing for about one hour before the recording session started. The two consonants [ɫ] and [r] were taken to last from onset to offset of central alveolar contact on the EPG record (see Recasens et al., 1997 and Recasens & Pallarès, 1999 for details). The trill [r] was composed of two or three (much less often four or even five) short alveolar closures separated, respectively, by one or more intense opening periods exhibiting some formant structure. No variations in manner of articulation which could result from articulatory overshoot were observed for the phonetic realizations of the alveolar trill (see Jones, unpublished, for several possibilities in this respect) owing perhaps to the laboratory speech conditions under which the consonants were produced.

The articulatory data for each sequence token were converted into two contact index values: the quotient of overall electrode activation at the palatal zone or Qp and the degree of alveolar contact anteriority or CAa. The former index measures the degree to which the tongue dorsum contacts the hard palate, and the latter the degree of alveolar constriction fronting. For the calculation of these index values, the artificial palate was divided into an alveolar zone extending over the four front rows of electrodes, and a palatal zone extending over the back four rows (see Figure 1). Qp was calculated by dividing the number of activated electrodes at the palatal zone by the total number of electrodes at this zone (32). CAa was computed using the formula presented in Fontdevila, Pallarès and Recasens (1994). F1, F2 and F3 measurements were carried out by placing a cursor in the center of the formants on 0–5 kHz spectrographic displays using the Kay Pentax CSL analysis system.

The Qp, F1, F2 and F3 values were obtained at the consonant midpoint, and every 5 ms during the vowels preceding (V1) and following (V2) the intervocalic consonant. The CAa values were gathered at the midpoint of [ɫ] and [r], and also at the onset of [r] given that the constriction degree for the trill may be greater at this temporal point than later on during the consonant; they were not collected during V1 and V2 since vowels barely show any alveolar contact on the linguopalatal contact patterns.

Cross-speaker differences in Qp and CAa, and in F1, F2 and F3 frequency, between the two consonants at consonant midpoint were evaluated statistically by means of repeated measures ANOVAs (RM ANOVAs) with ‘consonant’ and ‘vowel’ as factors. The factor levels were ‘l’

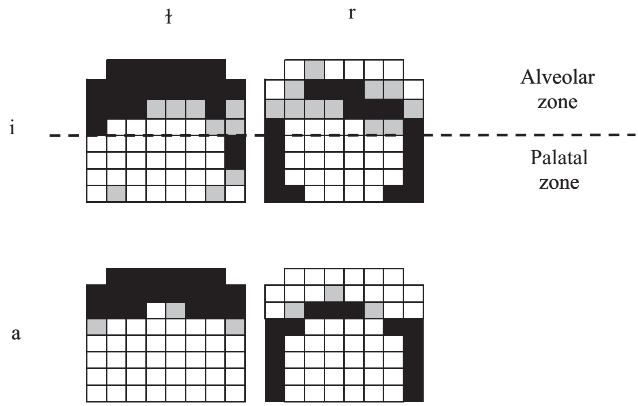

Figure 1. Mean linguopalatal contact patterns across seven tokens of [ɫ] and [r] in symmetrical VCV sequences with [i] and [a] measured at consonant midpoint. Electrodes are represented in black, grey or white depending on contact activation across repetitions (80–100%, 40–80% and less than 40%, respectively). Data correspond to speaker DR.

and 'r' for 'consonant' and 'i' and 'a' for 'vowel'. Huynh–Feldt corrected degrees of freedom were performed on the main effects in order to account for violations of the sphericity assumption. Moreover, in order to ascertain the speaker-dependent trends, data for each subject were submitted to two-way ANOVAs using the same analysis conditions. In order to interpret the significant two-factor interactions, another set of ANOVAs (repeated measures or univariate depending on the case) were run on the articulatory or acoustic data values for the two levels of each factor while keeping one level of the other factor constant. Statistical comparisons for the CAa data were carried out at consonant onset (only for [r]) and at consonant midpoint (for both [ɫ] and [r]) though only the results for the latter temporal point will be reported since they turned out to be very similar to those obtained at the former temporal point. In all statistical tests, Bonferroni post-hoc tests were applied to the main effects and the significance threshold was set at $p < 0.05$.

In order to analyze the relative influence of [ɫ] and [r] upon the adjacent vowels, dorsopalatal contact and F2 frequency values were compared statistically over the entire VC or CV trajectories in VCV sequences with the vowels [i] and [a]. This procedure differs from the one applied in previous coarticulation studies where consonant-dependent differences in size and temporal extent of C-to-V coarticulation were estimated by comparing the articulatory and acoustic values along the VC or CV trajectories with the corresponding values at the steady-state vowel period. We believe that the present procedure is more suitable for studying the relationship between coarticulation and sound change because it assumes that speakers do not need to use information about the steady-state vowel for extracting information about the degree of C-to-V coarticulation. One-way ANOVAs ($p < 0.05$) were performed on the Qp, F1, F2 and F3 data for [iɫi] and [iri], and for [aɫə] and [arə], for each speaker every 10 ms starting at closure onset and proceeding backwards until V1 onset and from closure offset forwards until V2 offset. V1 onset and V2 offset were taken to occur at the onset and offset of the shortest of all five trajectories lined up at consonant onset and offset, respectively. The method for measuring C-to-V coarticulation is exemplified for the sequences [iɫ(V)] and [ir(V)] (top graphs) and [(V)ɫi] and [(V)ri] (bottom graphs) in Figure 2. Thus, for example, the upper left graph allows the measuring of Qp differences between the two VC trajectories

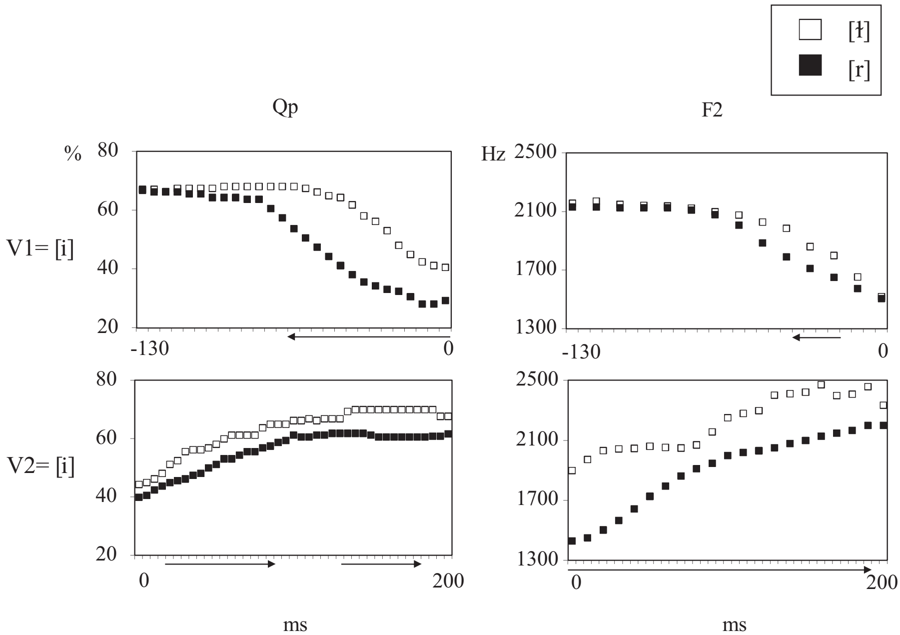

Figure 2. Qp and F2 trajectories for [ɫ] (empty squares) and [r] (filled squares) during preceding V1 = [i] (top) and following V2 = [i] (bottom). 0 values correspond to V1 offset/C onset in the case of the anticipatory condition and to C offset/V2 onset in the case of the carryover condition. The arrows below the graphs extend along the temporal span of the significant C-to-V coarticulatory effects. Data correspond to speaker JC.

during V1 = [i] at each temporal point starting at consonant onset backwards until 130 ms before the consonantal period, and the bottom left graph plots Qp differences between the two CV trajectories during V2 = [i] from consonant offset until 200 ms after the consonant period.

2.2 Results

2.2.1 Consonant midpoint. We first review the consonant-dependent articulatory and acoustic differences. Mean data for the tongue contact indices and for the formant frequencies at consonant midpoint are plotted in Figure 3 as a function of consonant, contextual vowel and speaker. As pointed out in the Introduction, the values for Qp and F2 (top graphs), as well as those for CAa and F3 (middle graphs), may be studied jointly since they are related to the same articulatory dimension, namely, tongue dorsum raising and fronting (Qp, F2) and constriction location and front cavity size (CAa, F3).

Before proceeding with the consonant-dependent articulatory and acoustic differences, the speaker-dependent characteristics in darkness degree for [ɫ] need to be referred to. As indicated in the Introduction, the consonant may be considered to be strongly or moderately dark depending on whether F2 occurs at about 1000 Hz (800–1300 Hz range) or 1300 Hz (1250–1450 Hz range) in the context of [i]. Judging from the F2 values in this vowel context shown by the unfilled bars in the top right graph of Figure 3, [ɫ] appears to be moderately dark for all Eastern Catalan speakers, and slightly darker for speakers DR, JP and DP than for speakers JS and JC. This scenario also holds to

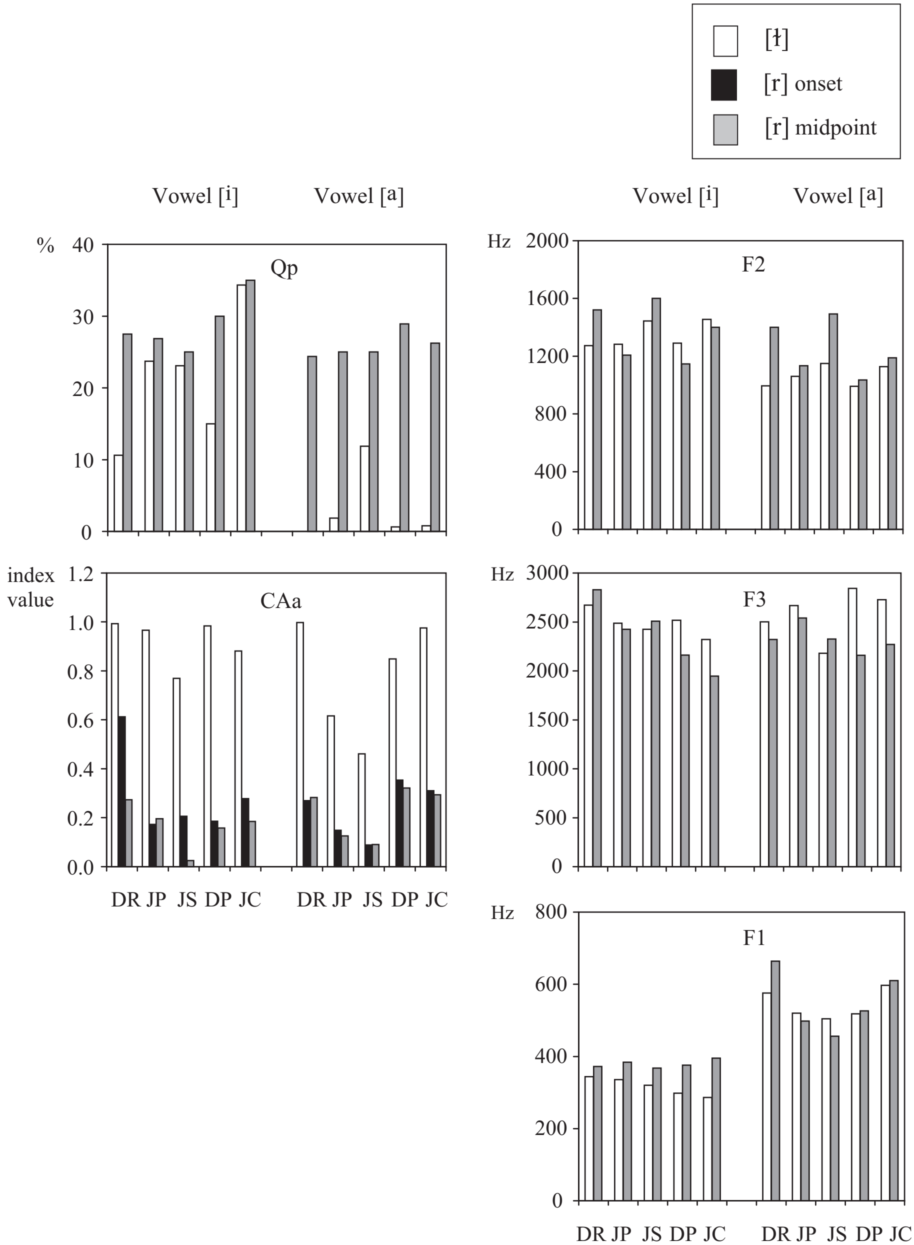

Figure 3. Mean articulatory and acoustic values at the midpoint of [ɫ] (unfilled bars) and [r] (filled bars) in the context of [i] and [a] as a function of speaker. CAa data for the trill are presented at consonant onset (black bars) and at consonant midpoint (grey bars).

a large extent in the context of [a] where F2 values range between 1000 Hz and 1150 Hz. Speaker-dependent differences in F2 frequency and dorsal retraction for [ɫ] have been reported to occur in other languages (English, Scottish; Scobbie & Pouplier, 2010).

It is hard to know the extent to which these differences in formant frequency reflect differences in darkness or else are associated with speaker-dependent differences in vocal tract size and/or palate height. Data on palate curvature for the five speakers under analysis reveal no obvious relationship between formant frequency and the height of the palatal vault which suggests that the former option is more plausible than the latter (Recasens, 2010). Thus, for example, while exhibiting the flattest palate of all speakers, speaker DP does not differ radically from the other subjects regarding the F1 and F2 frequency values for [ɫ] (see the top and bottom right graphs of Figure 3).

Contextual and speaker-dependent spectral changes for [r] in Figure 3 are probably associated with the overall tongue configuration, that is, degree of predorsum lowering and of postdorsum retraction, rather than with number of contacts. Indeed, [r] was produced basically with two or three contacts and lasted for 70–85 ms (two-contact trill) and 95–105 ms (three-contact trill) (Recasens & Pallarès, 1999). Since differences in number of contacts and consonant duration could occur within a given speaker, they are not expected to have much impact on the articulatory and coarticulatory trends reported in the paper.

Articulatory and spectral differences between the two consonants at the consonant period are reported next. Results for the repeated measures ANOVA run on the Qp data across speakers yielded a main effect of consonant which was associated with a higher value for [r] than for [ɫ], $F(1, 4) = 33.37$, $p = 0.004$, and a significant consonant × vowel interaction according to which this consonant-dependent difference was larger in the context of [a] than in the context of [i], $F(1, 4) = 24.2$, $p = 0.008$. These consonant-dependent differences also achieved significance according to results from the statistical tests run on the individual speakers' data (see Figure 3, top left graph). As for F2, the RM ANOVA yielded no main consonant effect or significant consonant × vowel interaction, while the statistical tests performed on the individual speakers' data yielded a significant difference for [r] > [ɫ] in the two vowel contexts for some speakers (DR, JS), and in the context of [a] but not in the context of [i] for others (JP, JC) (see Figure 3, top right graph).

These statistical results indicate the presence of more dorsopalatal contact and, to a lesser extent, a higher F2 for the trill than for the lateral mostly in the [a] context condition. In fact, four speakers exhibited extremely low Qp values for [ɫ] next to the low vowel meaning that the tongue dorsum occupies a considerably low position such that not even lateral contact is made in this case. The linguopalatal contact configurations for [ɫ] and [r] displayed in Figure 1 illustrate this scenario, namely, less electrode activation at the palatal zone for the lateral than for the trill next to both vowels [i] and [a].

Repeated measures ANOVAs also yielded a main consonant effect for CAa which was associated with a higher value and thus, a more anterior realization for [ɫ] than for [r], $F(1, 4) = 549.3$, $p = 0.000$ (see Figure 3, middle left graph). Moreover, this consonant-dependent difference occurred more clearly at the midpoint than at the onset of [r] since the trill is produced with a more open articulatory configuration at the former temporal period than at the latter (compare the unfilled bars with the grey and black bars). The same statistical results were obtained for the individual speakers' data. A higher F3 for the lateral than for the trill was, however, non-significant across speakers and significant for the speakers JP, DP and JC but not for DR and JS (see Figure 3, middle right graph).

Cross-speaker F1 frequency values are higher for [r] than for [ɫ] and this difference approached significance, $F(1, 4) = 7.42$, $p = 0.053$. Moreover, as revealed by the mean data plotted in the bottom right graph of Figure 3 and by the statistical results for the speakers DP and JC, F1 differences between the trill and the lateral hold most clearly in the [i] context condition.

Results for the vowel-to-consonant effects follow. Repeated measures ANOVAs run on the Qp and F2 data at consonant midpoint yielded a main vowel effect which was associated with higher values in the context of [i] vs. [a], $F(1, 4) = 14.17$, $p = 0.020$ for Qp, $F(1, 4) = 110.34$, $p = 0.000$ for F2, and a significant consonant × vowel interaction according to which this vowel effect was larger and more often significant for [ɫ] than for [r] thus indicating that the lateral is more vowel sensitive than the trill, $F(1, 4) = 24.2$, $p = 0.008$ for Qp, $F(1, 4) = 165.49$, $p = 0.000$ for F2. The vowel factor achieved significance for F1 as well: this formant frequency was significantly higher in the context of [a] vs. [i], $F(1, 4) = 50.12$, $p = 0.002$, but not for CAa or F3. Statistical tests run on all five individual speakers' data also yielded a main vowel effect for Qp, F2 ([i] > [a]) and F1 ([a] > [i]).

A higher degree of vowel coarticulation for the lateral than for the trill becomes apparent when the articulatory and acoustic values for [ɫ] and [r] next to [i] and [a] are subtracted from each other. Bars displaying the results for Qp, F2 and F1 in Figure 4 show indeed larger vowel-dependent differences and thus more vowel coarticulation for the lateral than for the trill in the case of all or most speakers (top and bottom graphs). A similar, albeit less clear, trend holds for F3 but not for CAa (middle graphs).

To summarize, the articulatory and acoustic data for Eastern Catalan presented above indicate that, in comparison to a moderately dark realization of the alveolar lateral, the alveolar trill is articulated at a more retracted location and exhibits a higher tongue body (most clearly in the context of [a]) and presumably more oral opening and a lower jaw (at least next to [i]). Moreover, in comparison to the lateral, the trill appears to be less sensitive to vowel-dependent effects in tongue body height and perhaps in jaw height as well.

2.2.2 Vowel period. Results for the size of the consonant-to-vowel effects are reported in the first place. Table 1 displays significant differences in Qp, F2, F1 and F3 between the two consonants during V1 and V2. As indicated in the table caption, L denotes a higher value for [ɫ] than for [r] and R the reverse relationship.

Analogously to the consonant-dependent differences occurring at the consonantal period, the bottom panel of the table indicates the presence of higher Qp and F2 values for the rhotic than for the lateral during preceding and following [a] in 18 out of 20 cases. This scenario is illustrated for speaker JC in the graphs of Figure 5 where the VC and CV trajectories for the trill (filled squares) run higher than those for the lateral (empty squares) during both V1 = [a] and V2 = [a].

Also in parallel to the overall situation at the consonant midpoint, the number of significant Qp and F2 differences is smaller during the vowel [i] than during the vowel [a] (compare the top and bottom panels of Table 1). Moreover, while the Qp values at the midpoint of the consonant were consistently higher for [r] than for [ɫ] next to [i], the corresponding dorsopalatal contact trajectories during the adjacent vowel [i] are lower for the trill than for the lateral in 6 out of 10 cases while the reverse relationship occurs only once. Data for speaker JC in Figure 2 show indeed lower Qp values for the trill (filled squares) than for the alveolar lateral (empty squares) during preceding and following [i]. A trend towards the presence of lesser linguopalatal contact size for [r] than for [ɫ] during the vowel but not during the consonant may be related to the strict requirements on trilling: it appears that the preparation of trilling requires a low tongue dorsum position during the antagonistic vowel [i] while the execution of the trilling motion during the consonant period is facilitated by a relatively high position of the tongue body. The consonant-dependent differences in F2 frequency during [i] are more consistent with those observed at the midpoint of the consonant, that is, values are lower for [r] than for [ɫ] in the case of speakers JP, DP and JC but not of speakers DR and JS (see the top right graph of Figure 3 and F2 trajectories for speaker JC in Figure 2).

In close relationship to the consonant-dependent CAa and F3 differences at consonant midpoint (Figure 3, two middle graphs), Table 1 reveals the presence of a higher F3 for [ɫ] than

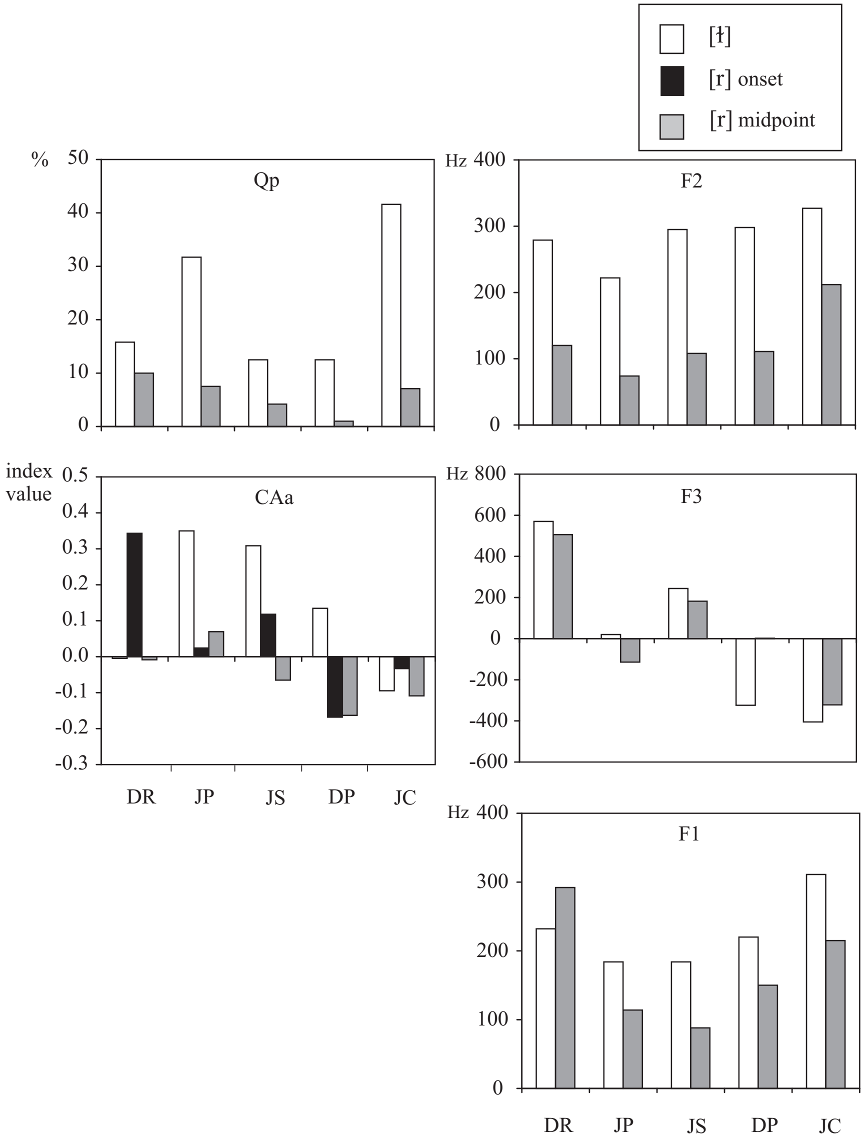

Figure 4. Articulatory and acoustic differences between [i] and [a] for [ɫ] and [r] at consonant midpoint as a function of speaker. CAa data for the trill are presented at consonant onset (black bars) and at consonant midpoint (grey bars).

for [r] in the two vowel contexts as a general rule. Also in parallel to the scenario at the midpoint of the consonant (Figure 3, bottom graph), F1 runs higher for [r] than for [ɫ] during the adjacent vowel [i] in most cases; as for the [a] context condition, this formant frequency turns out to be generally higher for [r] than for [ɫ] at the anticipatory level and the reverse at the carryover level.

Table 1. Instances of significant Qp, Fl, F2 and F3 differences between [i] and [r] during preceding (Vl) and following (V2) [i] and [a]. L indicates the presence of a higher value for [i] than for [r], and R the reverse relationship.

	Qp	F2	Fl	F3	Qp	F2	Fl	F3
	Vl = [i]				V2 = [i]			
Speaker DR	L	**R**	L					
Speaker JP	L	L	**R**	L		L		L
Speaker JS	L	**R**	**R**					
Speaker DP	L	L	**R**	L	**R**	L	**R**	L
Speaker JC	L	L	**R**	L	L	L	**R**	L
	Vl = [a]				V2 = [a]			
Speaker DR	**R**	**R**	**R**	**R**	**R**	**R**	L	L
Speaker JP	**R**	**R**	**R**		**R**	L	L	L
Speaker JS	**R**	**R**	L	L	**R**	**R**	L	**R**
Speaker DP	**R**	**R**	**R**	L	**R**		L	L
Speaker JC	**R**	**R**		L	**R**	**R**	**R**	L

Results for the direction of the consonant-dependent effects are discussed next. Trends in coarticulatory direction were evaluated by comparing the temporal extent of the significant consonant-dependent differences during the vowels preceding and following the target consonant. Only differences conforming to the prevailing patterns present in Table 1 will be accounted for: a higher

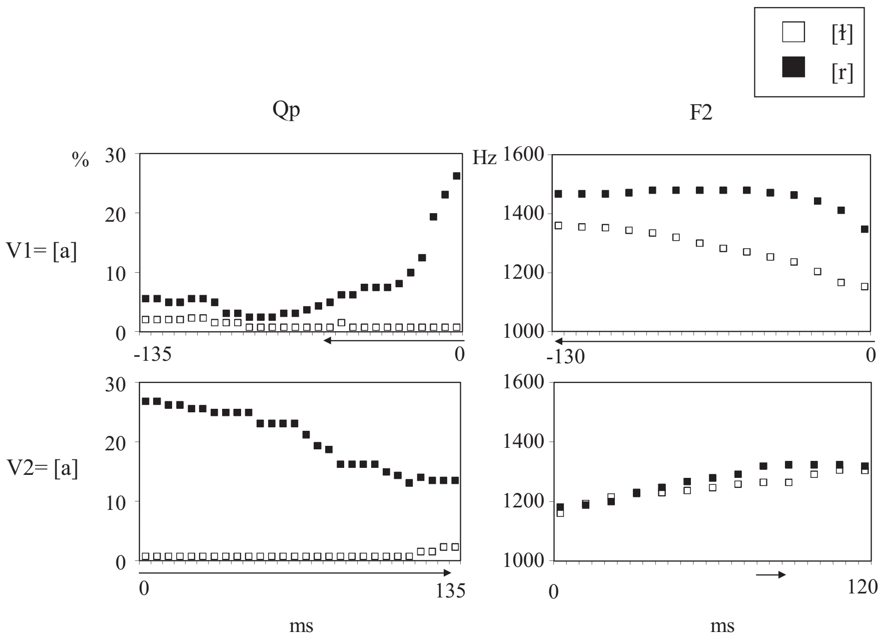

Figure 5. Qp and F2 trajectories for [ɫ] (empty squares) and [r] (filled squares) during preceding V1 = [a] (top) and following V2 = [a] (bottom). The arrows below the graphs extend along the temporal span of the significant C-to-V coarticulatory effects. Data correspond to speaker JC.

Qp and F2 for [r] vs. [ɫ] during [a] and the reverse during [i]; a higher F3 for [ɫ] vs. [r] in the two vowel contexts; a higher F1 for [r] than for [ɫ] during preceding and following [i] and during preceding [a], and the reverse during following [a].

Figures 6 and 7 plot the consonant-dependent Qp and F2 differences over time during the two vowels [i] and [a] both as a function of coarticulatory direction (differences during V1 in the left graphs and during V2 in the right graphs) and speaker (DR, JP, JS, DP, JC). In the figures, horizontal dotted lines have been drawn at V1 onset (left graphs) and at V2 offset (right graphs). Vertical lines extend from onset to offset of those temporal intervals during which the statistical tests yielded a significant consonant-dependent difference conforming to the expected trend; crosses correspond to isolated time points at which significant differences occurred. Inspection of the graphs reveals that the consonantal differences in question may start at or close to vowel onset (as, for example, all lines in the bottom left graph of Figure 7) and extend until or nearby vowel offset (e.g., all lines in the top right graph of Figure 7), or else begin at about V1 midpoint (e.g., all lines in the top left graph of Figure 6) and end at about V2 midpoint (e.g., the line for speaker JP in the bottom right graph of Figure 6). Moreover, the significant differences between [ɫ] and [r] are usually continuous but may be discontinuous as well (e.g., line for speaker JS in the top left graph of Figure 6).

According to Figure 6, Qp and F2 differences between [ɫ] and [r] in the [i] context are less numerous but last longer when occurring during V2 (they stay until the second half of V2 or until V2 offset) than during V1 (they begin at about the V1 midpoint). A similar pattern applies to the F1

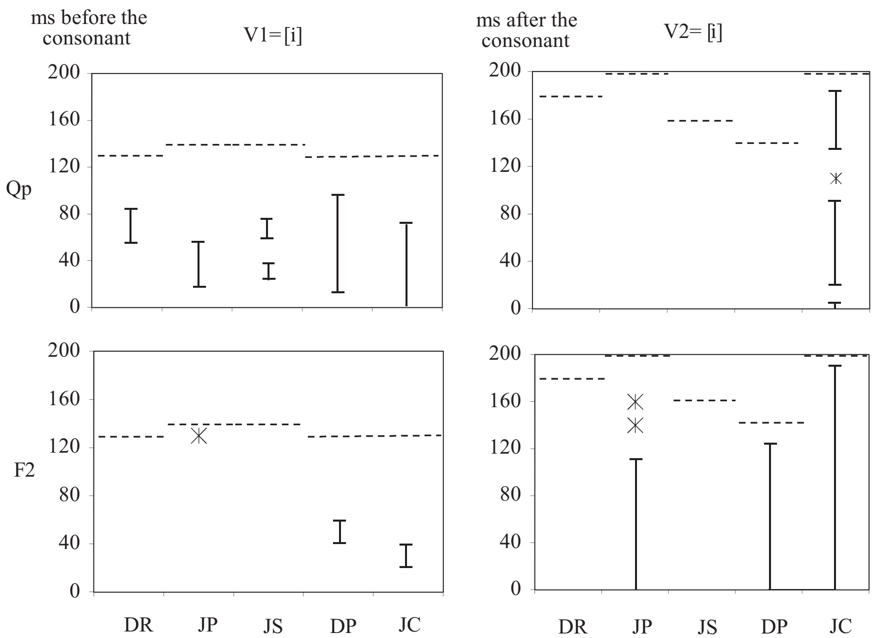

Figure 6. Temporal periods during which expected differences in Qp, F2 and F1 between the vowel trajectories for[iɫi] and [iri] were found to be significantly different. Data have been plotted independently for V1 (left) and V2 (right), and for the speakers DR, JP, JS, DP and JC. Crosses have been placed at isolated temporal points showing a significant consonant-dependent difference, and dashed lines at V1 onset (left) and V2 offset (right).

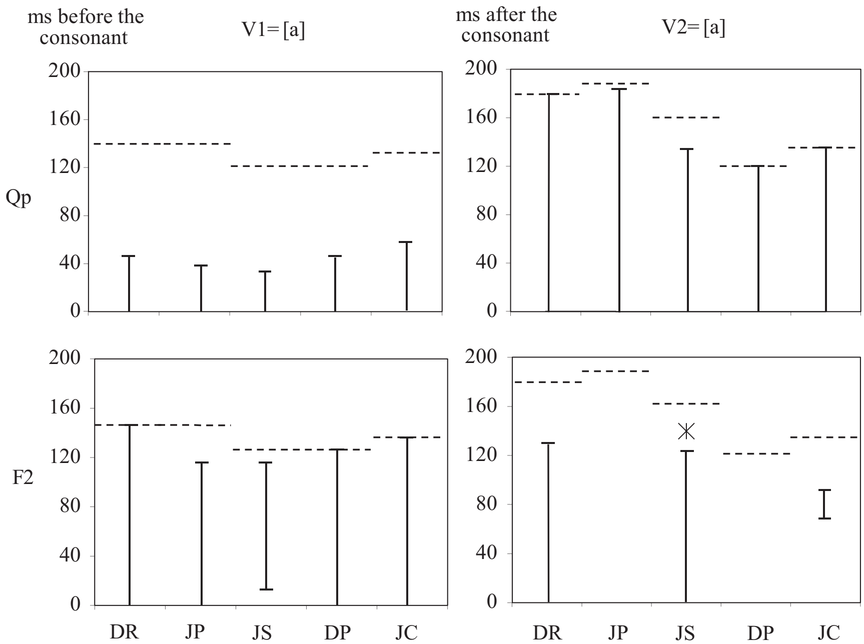

Figure 7. Temporal periods during which expected differences in Qp, F2 and F1 between the vowel trajectories for [aɫə] and [arə] yielded a significant effect. Data have been plotted independently for V1 (left) and V2 (right), and for the speakers DR, JP, JS, DP and JC. Crosses have been placed at isolated temporal points showing a significant consonant-dependent difference, and dotted lines at V1 onset (left) and V2 offset (right).

data (not shown). This scenario may be illustrated with the data for speaker JC in Figure 2. As indicated by the arrows appended under the graphs, consonant-dependent differences during V1 achieve significance from consonant onset at 0 ms back to -70 ms at about V1 midpoint in the case of the Qp data (top left graph), and between -20 ms and -40 ms somewhere during the second half of V1 for F2 (top right graph). Differences at the carryover level, on the other hand, may be traced during practically the entire V2 period, namely, between +20 ms and +90 ms and between +135 ms and +185 ms for Qp (bottom left graph), and between consonant offset and +195 ms for F2 (bottom right graph).

The temporal extent of the consonant-dependent differences during the vowel [a] (Figure 7) reveals a similar scenario: differences last longer at the carryover level than at the anticipatory level at least for the Qp data (also for the F1 data, not shown). More specifically, consonant-related differences in anticipatory coarticulation begin at 35–60 ms before the consonant for Qp and at about V1 onset for F2, while differences in carryover coarticulation approach V2 offset for Qp and stop somewhat earlier for F2. The graphs in Figure 5 may be adduced in order to illustrate the scenario just described. A comparison between the top and bottom left graphs shows indeed that the Qp trajectories for [ɫ] and [r] stay different for a much longer time during V2 (between consonant offset and +135 ms at V2 offset) than during V1 (from consonant onset back to -60 ms). As for the F2 data (right graphs), differences last somewhat longer during V1 (from consonant onset back to -130 ms at V1 onset) than during V2 (from +80 ms until +90 ms).

To summarize, robust differences between the two consonants were found to occur not only at consonant midpoint but also during the preceding and following vowels. Thus, the tongue body generally occupies a higher position for [r] vs. [ɫ] during [a] and the reverse during [i], while constriction location appears to be more anterior for [ɫ] than for [r] during the two vowels. Based on these findings, it has been proposed that trilling requirements cause [r] to be more resistant than [ɫ] to vowel coarticulation during the consonant and to exert more prominent effects on the adjacent vowels. As for coarticulatory direction and because of the same aerodynamic demands, C-to-V effects appear to last longer for the trill than for the alveolar lateral at the anticipatory level (during the preceding vowel) and even more so at the carryover level (during the following vowel), and this pattern operates to a larger extent during [i] than during [a].

3 Implications for sound change

Experimental data reported in the previous section allow us to draw several conclusions regarding the relationship between articulation and coarticulatory trends for [ɫ] and [r] and possible consonant-related changes in vowel quality. The Qp, F2 and F1 scenario indicates that, in comparison to the lateral, the trill ought to be more prone to induce the raising of [a] and presumably of other vowels and the lowering of [i] and possibly of other vowels as well. Moreover, these and other sound changes are expected to occur at the regressive level for the two consonants and at the progressive level for the trill.

This section investigates whether the articulatory and coarticulatory characteristics for the two consonants account for the typology and direction of the relevant vowel quality changes. In addition to vowel raising and lowering shifts directly related to the coarticulatory effects explored in the Results section, other sound changes which appear to be associated with the articulatory characteristics of [ɫ] and [r] will also be reviewed. These changes include shifts in vowel backing and rounding, and instances of vowel or glide insertion triggered by the perceptual categorization of an acoustic transitional event as an independent segment by the listener (regarding the articulatory characteristics of this incidental acoustic element, see Gick & Wilson, 2006). Glide insertions will be referred to as such or as vowel breaking depending on whether emphasis is put on the inserted segment itself or on the replacement of a vowel by a diphthong, respectively.

3.1 Romance languages

Several aspects of the phonetic realization of the alveolar lateral and the alveolar trill in the Romance languages need mentioning. The alveolar lateral is dark, not clear, in several Romance languages (Catalan, Portuguese, Occitan dialects) and must have been also dark in varieties exhibiting a clear variety nowadays (French, dialects of Italy, perhaps Spanish and Romansh) (Meyer-Lübke, 1974, pp. 430–431; Straka, 1968, p. 287). Therefore, its production involves tongue body lowering and backing rather than a relatively high and anterior tongue body position. As for the trill, it occurs typically in syllable initial position and appears to have had an alveolar realization in the past in languages showing a uvular variety today; thus, [ʀ] is a recent innovation in French (XVIIth century) and an even more recent one in Portuguese and Occitan dialects (Lausberg, 1970, pp. 411–412; Parkinson, 1988, pp. 137–138). Possible actions involved in this change may be tongue dorsum retraction and apical contact loss, which are prone to occur syllable finally. In this paper we will consider instances of a trill or a trill-like realization of [r] such as those occurring not only syllable initially but also syllable finally whether before a consonant or a pause.

As for the regressive changes, the trill [r], and, to a lesser extent, [ɫ] may trigger the insertion of a preceding low vowel in word initial position in Romance (see (1)). This case of vowel epenthesis may be associated with anticipatory tongue predorsum lowering and postdorsum retraction preceding closure formation for the consonant, and more so for the trill presumably due to the strict aerodynamic requirements. It is most likely to have been preceded by elision of the unstressed front vowel placed between the rhotic and the following consonant whenever the articulatory gestures for the two consonants overlap sufficiently in time (James Scobbie, pers. comm.).

(1) Tuscan Italian from Cortona [**a**rmaˈne] < Latin [remaˈneɾe] "to remain"; middle Italian from the Marche [**a**rtɾoˈve] for Italian *ritrovare* "to find again"; Northern Italian from Emilia-Romagna [**a**lˈdam] < Latin [leˈtame] "manure"; Surmeiran Romansh [**a**lˈveːr] < Latin [leˈvaɾe] "to raise", [**a**rnuˈeːr] < [renoˈvaɾe] "to renew"; Gascon Occitan [**a**ˈriw] < Latin [ˈrivʊ] "river". (Rohlfs, 1966, pp. 171, 224; Lutta, 1923, pp. 141–142; Millardet, 1910, p. 122)

Glides with a lower F2 than the target vowel may also be inserted before [ɫ] and [r] in VC sequences. The quality of the appended segment may be essentially [ɛ, a] after [i], and [a] after mid front and back rounded vowels (see the phonetic characters in boldface appearing in the output forms in (2)). Regressive glide insertion explains the generation of falling diphthongs which may have shifted to rising diphthongs at a later date; thus, the Occitan variant [ˈfjɛlo] must have been derived from Latin [ˈfilat] through the intermediate stages [ˈfiɛ̯lo]. This glide insertion process appears to result from the categorization of the F2 vowel transitions, which in VC sequences with [ɫ] and [r] are falling if the target vowel is front and mostly flat and low frequency if the vowel is back. This direction of the vowel transitions is in line with the tongue dorsum lowering and backing motion involved in the implementation of the two consonants.

(2) Occitan [ˈfj**ɛ**lo] < Latin [ˈfilat] "he/she spins", [ˈvj**a**rdo] < Latin [ˈvɪɾɪde] "green", [eˈtj**a**lo] < Latin [ˈstella] "star", [ˈtj**a**ro] < Latin [ˈtɛra] "earth", [so**a̯**l] < Latin [ˈsolʊ] "alone"; Romagnol Northern Italian [po**a̯**rk] < Latin [ˈpɔrkʊ] "pig". (Bouvier, 1976, pp. 247–249; Ronjat, 1930, pp. 157, 388; Schürr, 1970, p. 127)

In parallel to the vowel and glide insertion processes just reviewed, vowel assimilatory changes triggered by [ɫ] and [r] are essentially regressive. Regressive C-to-V effects cause high or mid vowels to lower (see (3)), and front or low vowels to become mid back rounded (see (4)).

(3) Gallurese, Corsican, and Leccese Southern Italian [ˈt**a**ra] < Latin [ˈt**ɛ**ra] "land"; Western Catalan [f**a**ˈre] < Latin [f**e**ˈraɾjʊ] "blacksmith", [t**a**ˈrɔs] derived from Latin [ˈt**ɛ**ra] "clod", [d**a**ˈle] < Latin [d**e**ˈliɾjʊ] "eagerness", [p**ɛ**l] < Latin [ˈp**ɪ**lʊ] "hair"; Catalan [s**ɔ**l] < Latin [ˈs**o**le] "sun"; French [**ɔ**ʀˈti] < Latin [**ʊ**rˈtika] "nettle", [b**œ**ʀ] < [ˈbyre] < Latin [ˈb**u**tiɾʊ] "butter". (Blasco, 1984, p. 183; Rohlfs, 1966, pp. 130, 132; Recasens, 1996, pp. 75–76, 84, 146; Lausberg, 1970, p. 268)

(4) Northern French from the Ardennes [l**o**r] < Latin [ˈl**a**rdʊ] "lard; Piedmontese Northern Italian [ˈs**ɔ**lva] < Latin [ˈs**ɪ**lva] "forest"; Pugliese Southern Italian [ˈs**ɔ**lə] < Latin [ˈs**a**le] "salt"; Tuscan Italian [ˈnesp**o**lo] < Latin [ˈnesp**ɪ**lʊ] "medlar"; Milanese Northern Italian [ˈ**o**lter] < Latin [ˈ**a**lteɾʊ] "another one". (Bruneau, 1913, p. 233; Rohlfs, 1966, pp. 38, 81, 174, 471)

Except for the changes [ʊ, o] > [ɔ] in (3), these C-to-V assimilatory processes appear to be associated with F2 lowering as the tongue predorsum lowers ([ɪ] > [ɛ], [y] > [œ] and [e, ɛ] > [a] in (3)) or the tongue dorsum undergoes backing or raising toward the upper pharyngeal region ([ɪ, a] > [ɔ, o] in (4)). The sound change data presented in (3) and (4) also reveal that the lowering of mid front vowels is stronger for the trill than for the lateral perhaps in accordance with differences in tongue dorsum lowering during the vowel (see Results section), while the backing and rounding of front and low vowels occurs more often before the lateral than before the trill perhaps in line with differences in postdorsum constriction degree between the two consonants (see Introduction). Moreover, the lowering of high and mid back rounded vowels ([ʊ, o] > [ɔ] in (3)) suggests that the posterior tongue dorsum constriction for [ɫ] and [r] may oscillate between the pharynx and the velar region. In support of this explanation one may also refer to possible Spanish lexical forms where Latin stressed [ʊ] did not undergo the regular evolution [ʊ] > [o] (Spanish [ˈl**o**ðo] < Latin [ˈl**ʊ**tu] "mud") but was raised to [u] before the lateral at a time when the consonant must have been dark ([aˈθ**u**fɾe] < [ˈs**ʊ**lfʊɾe] "sulphur", [emˈp**u**xa] < [imˈp**ʊ**lsat] "he/she pushes", [ˈk**u**mbɾe] < [ˈk**ʊ**lmɪne] "summit").

The small number of cases of regressive [a] raising into a mid front vowel before the alveolar lateral and the alveolar trill in Romance does not allow confirmation of the prediction made in the Results section that low vowels should raise to a larger extent before the latter vs. former consonant (Romagnol Northern Italian [t**ɛ**rt] < Latin [ˈt**a**rde] "late", [k**ɛ**lt] < Latin [ˈk**a**lɪdʊ] "hot"; Rohlfs, 1966, pp. 41, 49). In any case, the fact that the second consonant in the cluster is a dental stop in the two examples suggests that the tongue dorsum has to adopt a considerably raised position for [a] raising to apply. The low vowel raising process appears to be more prone to operate before a tap, as, for example, Tuscan Italian [marg**e**ˈɾita] < Latin [marg**a**ˈɾita] "daisy", [ˈmask**e**ɾa] < Arabic *mask***a***ra* "mask", [ˈtsukk**e**ɾo] < Arabic *sukk***a***r* "sugar" (Tuttle, 1974).

Consonant-induced sound changes may also occur at the progressive level. Instances of progressive vowel assimilation take place immediately after the trill but not after the alveolar lateral. They are documented in Old Romanian where [r] caused following [e] and [i] to undergo lowering and centralization into [ə] and [ɨ], respectively ([r**ə**w] < Latin [ˈr**e**ʊ] "bad, mean", [r**ɨ**w] < Latin [ˈr**i**vʊ] "river"; Lausberg, 1970, p. 268), and in several Romance languages where unstressed vowel backing and rounding may operate after [r] and often before a labial consonant (Occitan [r**u**ˈzi(n)o] < Latin [r**e**ˈzina] "resin"; Tuscan [r**o**veʃˈʃaɾe] < Latin [r**e**verˈsjaɾe] "to overturn", [r**u**ˈbello] < Latin [r**e**ˈbelle] "rebel"; Sardinian [r**o**ˈmazu] < Latin [r**e**ˈmansʊ] "thin"; Wartburg, 1922–… , vol. 10, p. 299; Maiden, 1995, p. 44; Tekavčić, 1980, p. 74; Rohlfs, 1966, p. 169). Also, in the Occitan region of Gévaudan, pretonic [e] may often lower before or after the trill but only before, not after, the lateral (see (5)).

(5) Gévaudan [b**a**ˈrul] < Latin [v**e**ˈɾʊkʊlʊ] "bolt", [dʒ**a**rˈmo] < Latin [g**e**rˈmanʊ] "brother", [f**a**ˈrado] < Latin [f**e**ˈrata] "bucket", [r**a**ˈdundo] < [r**e**ˈtʊnda] < Latin [roˈtʊnda] "round (fem.)", [r**a**ˈmɛdi] < Latin [r**e**ˈmɛdjʊ] "remedy", [d**a**liˈkat] < Latin [d**e**liˈkatʊ] "delicate", [dʒ**a**ˈga] < Latin [g**e**ˈlaɾe] "to freeze". (Camproux, 1963, pp. 96–97)

Data on dissimilatory fronting and unrounding of back rounded vowels next to [ɫ] and [r] provide additional evidence in support of differences in the direction of the C-to-V effects associated with the two consonants. Indeed, in Catalan, the change of unstressed [u] into [ə] in the context of a stressed high vowel is prone to take place before the lateral and the trill and after the trill but not after the lateral ([p**ə**lˈmo] < Latin [p**ʊ**lˈmone] "lung", [**ə**rˈtiɣə] < Latin [**ʊ**rˈtika] "stinging nettle", [r**ə**ˈmo] < Latin [r**u**ˈmore] "rumour"; Recasens, 1996, p. 150).

A progressive action could also explain the raising of unstressed [a] to [e] and of unstressed [e] to [i] after a word initial trill, not an alveolar lateral, in lexical forms taken from Spanish ([r**e**ŋˈkor] < Latin [raŋˈkoɾe] "bitterness", [r**e**naˈkwaxo] derived from Latin [ˈr**a**na] "tadpole"; Menéndez Pidal, 1968, p. 69) and dialectal Catalan ([r**e**ˈfal] < Arabic *rahl* "shed", [r**e**ˈʒɔla] < Arabic *lağûra* "tile", [r**i**ˈpunt] < Latin [r**e**ˈpʊŋktʊ] "backstitching", [r**i**sˈklɔzə] < Latin [r**e**sˈklawza] "dam"; Recasens, 1996, p. 103; Alcover & Moll, 1968–1975, vol. 9, pp. 395, 405).

3.2 Early Germanic and Old English

Analogous regressive changes to those just reviewed for the Romance languages have occurred in Early Germanic (Denton, 2003; Krahe, 1994, p. 73; Vennemann, 1972). Vowel lowering accounts for several vowel shifts operating before /r/: stressed short /i, u/ > /ɛ, ɔ/ and unstressed /e/ > /a/ in Ghotic; /aj/ > /ɛ/ and /aw/ > /ɔ̃/, as well as /ew/ > /eo/ before a non-high vowel in the following syllable, in Old High German; /aj/ > /aː/ in North Germanic. Also, when appearing before preconsonantal /l, r/, short /a/ failed to raise and front to /e/ through umlaut induced by a high front vocalic segment in the following syllable in Old High German. Parallel regressive sound changes have taken place in Old English such as the breaking of /i, e, æ/ into /io, eo, æa/, respectively, before preconsonantal /r/ and to a lesser extent before preconsonantal /l/, the retraction process /æ/ > /a/ before preconsonantal /l/ and before /r/ followed mostly by a labial consonant, and the retraction and rounding processes /i/ > /u/ and /e/ > /o/ after /w/ and before preconsonantal /r/ (Campbell, 1959, pp. 54–60).

Judging from the sound changes just described it can be assumed that /l/ and /r/ were pronounced with a more or less marked lowered and retracted tongue body position in the Germanic languages (Prokosch, 1939, p. 114). Regarding /l/, this would mean that, as assumed for Old English (Lass, 1992, p. 41), the alveolar lateral was more or less dark and thus involved different degrees of postdorsum retraction. The articulatory characteristics of the rhotic deserve special attention. As for Early German, Vennemann (1972) has pointed out that the rhotic might have been an alveolar trill ([r]), a uvular trill ([ʀ]) or a retroflex continuant ([ɹ]), while recent evidence suggests that the first and third alternatives are more plausible than the second one (Denton, 2003). As argued below, [ʀ] and [ɹ] resemble [r] articulatorily in many respects and could thus trigger regressive vowel lowering and retraction as well.

Analogously to the alveolar trill, the uvular trill [ʀ] is articulated with considerable predorsum lowering, and postdorsum retraction and raising towards the uvular and upper pharyngeal regions (Malmberg, 1974, p. 159; Straka, 1965). Its spectral characteristics are similar to those for [r] though F2 is lower and F3 is higher: according to data from the literature, F1, F2 and F3 for Swedish [ʀ] are found at 530 Hz, 925–1250 Hz and 2425 Hz or somewhat higher, respectively (Engstrand, Frid, & Lindblom, 2007; Ladefoged & Maddieson, 1996, pp. 226, 229). On the other hand, the approximant [ɹ] exhibits low F1, F2 and F3 frequencies whether realized with a bunched dorsopalatal constriction, an apico-alveolar constriction or other lingual configurations (American English: Delattre, 1971a, 1971b; Delattre & Freeman, 1968; Zawadzki & Kuehn, 1980. Dutch: Scobbie & Sebregts, 2010). In particular, the formant frequencies for prevocalic [ɹ] in American English range between 330–430 Hz (F1), 880–1200 Hz (F2) and 1380–1610 Hz (F3) (Espy-Wilson, 1987; Hagiwara, 1995; Stevens, 1999; Westbury, Hashi, & Lindstrom, 1995); in this case, F2 appears to be mostly associated with a pharyngeal constriction whenever present, and F3 with a lip constriction and a large front cavity including a sublingual space (Espy-Wilson, Boyce, Jackson, Narayanan, & Alwan, 2000; Lindau, 1985; Stevens, 1999). Data from other languages also reveal low and close F2 and F3 frequencies for [ɹ], namely, F2 = 1265 Hz, F3 = 1798 Hz and F2 = 1097 Hz, F3 = 1542 Hz for the postalveolar and bunched Swedish realizations, respectively (Engstrand et al., 2007), and F2 = 1500–1800 Hz and F3 = 1800–2200 Hz for coda [ɹ] in Dutch (Scobbie & Sebregts, 2010). The acoustic parity between the alveolar approximant and dorsal rhotics may account for the change of alveolars into uvulars in several Germanic languages (Engstrand et al., 2007), and for the rhotic allophonic distribution in Dutch where [ʀ] occurs in onset position and [ɹ] in coda position (Scobbie & Sebregts, 2010).

As for C-to-V coarticulation, the uvular trill exerts prominent anticipatory effects on a preceding front vowel given that its realization involves anticipation of the tongue predorsum lowering and tongue root backing motion with respect to the tongue postdorsum raising gesture, and also salient and long lasting F2 carryover effects on the following vowel (Delattre, 1969, 1971a, 1971b). Regarding [ɹ], C-to-V coarticulatory effects appear to be anticipatory rather than carryover, as revealed by American English data showing that this rhotic causes F2 and F3 of the preceding front vowel to lower early in time (Boyce & Espy-Wilson, 1997; Lehiste, 1964).

3.3 Middle and Modern English

Other changes in vowel quality triggered by the rhotic have operated in Middle and Modern English (Dobson, 1968, vol. 2, pp. 715, 725–726, 759–763; Lass, 1999, pp. 108–113). Some are regressive: instances of schwa insertion (spellings *desyar* 'desire', *hyar* 'hire'), /e/ lowering (*hart* for *herte*), and the backing and rounding of stressed short /i/ before /r/ + a dental consonant (*brĭd* > *bĭrd* > *bŭrd*). Effects induced by the rhotic have taken place at the progressive level as well, which appears to be in agreement with orthoepists' referring to Middle and Modern English /r/ as a trilled sound (Dobson, 1968, vol. 2, pp. 945–946), as well as with experimental and descriptive data reported above indicating that the alveolar trill exerts more extensive carryover C-to-V effects than the alveolar lateral. This is so for the lengthening, retraction and rounding of stressed short /a/ to /ɒː/ (*wrath*), for the lowering of stressed /oː/ to /ɒː/ (*(a)broad*), and perhaps for the raising of stressed short /e/ to short /i/ before dental, velar and labial consonants (*rest* was paired with *wrist* by orthoepists). On the other hand, changes induced by /l/ are exclusively regressive, such as the generation of /awl, owl/ from / Vl/ sequences with a low or mid back rounded vowel (as in *gold, shoulder*). Apart from the weaker carryover effects for [ɫ] than for the trill, differences in the progressive action between the two consonants may be attributed to allophonic differences, namely, a trill in onset position and an approximant in coda position, and a clear realization of /l/ in onset position and a dark one in coda position as in present-day British English RP and Dutch (Bladon & Al-Bamerni, 1976; Warner, Jongman, Cutler, & Mücke, 2001).

3.4 A comparison with Arabic pharyngealized dentoalveolars

Other consonants exhibiting similar articulatory characteristics to those for [ɫ] and [r] such as Arabic pharyngealized dentoalveolars trigger similar C-to-V effects and analogous vowel quality changes.

Pharyngealized dentoalveolars involve tongue movement towards the upper pharyngeal wall, predorsal lowering and a low jaw position (Al-Ani, 1970; Giannini & Pettorino, 1982; Younes, 1994; Zeroual, Esling, & Hoole, 2011). These articulatory characteristics result in a dark sound exhibiting a lower F2 and higher F1 and F3 frequencies than the non-pharyngealized cognates (Yeou, 1997). This spectral structure is transferred to the adjacent vowels and accounts for the presence of contextual allophones such as [ɑ] (/a/), [ɛ] (/i/) and [o, ɔ] (/u/) (Corriente, 1977).

Phonological evidence indicates that categorical changes in vowel quality associated with the pharyngealization feature (also called emphasis) may spread just over the adjacent vowels, or else over the whole word whether bidirectionally or at the regressive rather than at the progressive level whenever a palatal segment is contextually present. This scenario is consistent with articulatory and acoustic data for pharyngealized dentoalveolars showing tongue backing coarticulation before and after the consonant (Laufer & Baer, 1988), as well as carryover effects diminishing along the temporal domain and being blocked by an antagonistic palatal vowel (Gazheli, 1981; Louali, 1990; Younes, 1994; Zawaydeh, 1999). Along these lines, Watson (1999, 2002) has suggested that the prevalence of regressive over progressive emphaticness may be phonetically based, that is, it occurs because pharyngealization is anchored on the onset phase of the primary articulation (Ladefoged & Maddieson, 1996, pp. 360–361; Ouni & Laprie, 2009).

It may be concluded that pharyngealized dentoalveolars behave more similarly to strongly dark varieties of the alveolar lateral than to the trill in that they may trigger bidirectional C-to-V effects while also favoring the anticipatory over the carryover direction. This assumption is consistent with the consonants in question lacking the trilling component or any other comparable manner requirement.

4 Overall summary and conclusions

The present investigation reveals that a detailed study of the articulatory configuration and coarticulatory properties of speech sounds may improve our understanding of the causes of sound change. It has tested the hypothesis that specific sound changes may arise from the perceptual categorization of F2 and other formant coarticulatory effects through a comparison of the patterns of C-to-V coarticulation and of vowel and glide insertion and vowel assimilation in sequences with the apical consonants [ɫ] and [r] produced with tongue predorsum lowering and postdorsum retraction. Results reveal that, in comparison with [ɫ], [r] exerts more tongue dorsum lowering on [i] and more tongue dorsum raising on [a], which is in support of the notion that the alveolar trill imposes stricter demands on the tongue than the dark alveolar lateral. Moreover, articulatory and acoustic data from the literature indicate that postdorsum retraction is greater for [ɫ] than for [r]. Data on several regressive sound changes in the Romance and Germanic languages appear to be consistent with these articulatory effects: high and mid vowel lowering which appears to be induced by the trill rather than by the lateral at least when the target vowel is front; front and low vowel backing with possible rounding which may be more prone to occur next to the lateral than to the trill. Low vowel raising into [e, ɛ] could depend on the presence of sufficient tongue dorsum raising during the consonant and, therefore, may be triggered by the trill and only by the lateral if followed by a dentoalveolar or palatal consonant. Similar production characteristics for Arabic pharyngealized dentoalveolars explain why these consonant realizations also exert vowel lowering and backing coarticulatory effects and may cause related sound change processes to occur.

A relevant point is that the sound changes just reviewed may be induced by both the trill and the lateral if the vowel precedes the consonant, but mostly by the trill if the vowel follows the consonant. These directionality patterns of sound change appear to be associated with consonant-dependent differences in manner of articulation and are consistent with differences in coarticulatory direction, namely, similar anticipatory effects for the two consonants (though more prominent for [r] than for [ɫ]) and more prominent carryover effects for the trill than for the lateral.

More conclusive evidence for the implications for sound change of the experimental and descriptive data presented in this paper should derive from perceptual studies. There is some evidence that speakers may perceive a schwa followed by [ɫ] as a back rounded vowel when presented with little acoustic information about the alveolar lateral consonant (Roussel & Oxley, 2010). In our particular scenario the relevant issue is whether listeners are sensitive to small but robust differences in vowel quality induced by consonants produced with similar but not identical lingual configurations such as [ɫ] and [r].

As pointed out in the Introduction, data for both [ɫ] and [r] from other languages besides Catalan are needed in order to make strong claims about the link between experimental phonetic data and sound change. In other words, it should be shown that the two consonants are produced similarly and exhibit similar coarticulatory strategies in different languages for the cross-language sound changes to be argued to depend on them. Data from a large survey from the literature presented in this paper reveal that this may be the case.

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