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Underlying Voicing in Majorcan Catalan Word-Final Stop-Liquid Clusters

Daniel Recasens[a] Aina Espinosa[b] Antoni Solanas[c]

[a] Universitat Autònoma de Barcelona and Institut d'Estudis Catalans,
[b] Institut d'Estudis Catalans and [c] Universitat de Barcelona, Barcelona, Spain

Abstract

This study investigates the extent to which phonetic voicing is maintained in word-final clusters composed of an underlying voiced stop followed by non-syllabic /l/ or /r/ in Majorcan Catalan. Electropalatographic and acoustic data for five speakers of this Catalan dialect reveal that, in agreement with the non-syllabic status of the liquid, voicing for /l/ is only available if occurring during the preceding stop. The rhotic is always phonetically voiceless. Speakers differ regarding the extent to which they keep the underlying stop voicing distinction and the production strategies they use for that purpose. This distinction is highly robust and distributed over the entire syllable in nasal-stop-/l/ clusters for some speakers, but much less clear or absent for those speakers who devoice /l/ as a general rule. Underlying stop voicing is cued primarily by stop closure duration and vocal fold vibration, or else by closure duration rather than by voicing. It may be concluded that the word-final devoicing process operating in Catalan does not apply to Majorcan Catalan tautosyllabic stop clusters with a liquid, and that phonetic voicing may affect just the stop or both the stop and the liquid. The implications of these findings for sound change are discussed.

Introduction

Research Goal

Majorcan Catalan, a Catalan dialect spoken in the island of Majorca, allows stop clusters with C2 = /l/ and with C2 = /r/ (also /fl, fr/) to occur in word-final position. The clusters under consideration always belong to the 1st and 3rd person forms of the present tense of verbs, and may be preceded by a vowel (e.g., *obr* 'I open', *dobl* 'I double') or by a nasal consonant agreeing in place with the stop (e.g., *empr* 'I use', *m'assembl* 'I resemble'). In contrast with English dialects where syllabic /l/ may be found after almost any consonant (e.g., *ladle*, *bottle*, *funnel*, *missile*, *vigil*), those and only those clusters show up word- and syllable-finally in the Catalan dialect under

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Daniel Recasens
Departament de Filologia Catalana
Universitat Autònoma de Barcelona
Bellaterra, Barcelona (Spain)
Tel. +34 3 457 81 83, Fax +34 3 581 27 82
E-Mail daniel.recasens@uab.es

consideration. Moreover, their liquid happens to be non-syllabic. Thus, native speakers of Majorcan Catalan count *obr* 'I open' as monosyllabic and *m'assembl* 'I resemble' as bisyllabic, and syllabify the entire final cluster with the initial vowel of a following word, e.g., the words *obr* 'I open' and *això* 'this' syllabify ([ɔ])([bɾə])([ˈʃɔ]) in the sequence [ɔbɾəˈʃɔ] 'I open this'.

The present investigation is concerned with the phonetic status of the underlying voicing distinction for the stop and the liquid in Majorcan Catalan word-final clusters. In Catalan, underlyingly voiced stops become voiceless before a pause; moreover, final devoicing affects all consonants in word-final clusters without a liquid, e.g., the words *tubs* 'tubes', *arxipèlags* 'archipelagos' are realized [tups] and [ərʃiˈpɛləks]. The central goal of this paper is to find out whether this devoicing process operates on word-final clusters with an underlying voiced stop followed by a liquid or, on the contrary, if the liquid helps to preserve the underlying voicing status of the preceding stop at the phonetic level.

In addressing this research topic we take the position that word-final voicing neutralization in Catalan is complete, i.e., that underlying voiced stops show no traces of voicing in absolute word-final position. Some inconclusive evidence in support of incomplete stop voicing neutralization has been reported to occur in other languages, i.e., German [Port and Crawford, 1989, but see Janker and Piroth, 1999 and Piroth and Janker, 2004], Polish [Slowiaczek and Dinnsen, 1985; Slowiaczek and Szymanska, 1989, but see Jassem and Richter, 1989] and Dutch [Jongman, 2003; Ernestus and Baayen, in press]. Incomplete voicing neutralization has also been claimed to apply in Catalan word-final stops based on data on vowel and closure duration [Dinnsen and Charles-Luce, 1984] and on voicing into closure [Charles-Luce and Dinnsen, 1987]. It appears, however, that minimal pairs used in the former study include unfamiliar words as well as non-alternating stops or stops whose underlying voicing specification is the reverse of the one assigned to them [Mascaró, 1987].

Experimental and descriptive evidence for the Majorcan Catalan clusters of interest suggest that the phonetic implementation of the voicing contrast is contextually conditioned and that a gradual stop devoicing process may be under way. Thus, while acoustic data show that the underlying voicing distinction may be kept postnasally [Llach, 1999; Dols and Wheeler, 1995], impressionistic phonetic transcriptions reveal that listeners may perceive the C1 voiced stop consonant as voiceless postvocalically, i.e., [ɔpr] *obr* 'I open' [Alcover and Moll, 1929–1932], [kɔpr] *cobr* 'I earn', [məˈlekr] *m'alegr* 'I become happy' [Bibiloni, 1983]. Analogous examples involving stop and liquid devoicing may be found in Alguerès Catalan where the rhotic is clearly realized as a trill ([ɔpr̥] *obr* 'I open', [ampr̥] *ampr* 'I use' [Kuen, 1932–1934; Loporcaro, 1997]. If a trend towards stop voicing neutralization is at work in Majorcan Catalan, our goal is to determine which voicing cue(s) lead the process and which ones are prone to remain unmodified.

Factors Affecting Voicing

In the light of these remarks, the phonetic implementation of underlying voicing in Majorcan Catalan word-final clusters with a non-syllabic liquid will be analyzed by means of electropalatographic (EPG) and acoustic data. Possible stop voicing cues will be sought during the stop and during the segments preceding and following the stop.

Stop Consonant

The underlying stop voicing distinction is cued by vocal fold vibration during the closure period for voiced versus voiceless stops, and by longer and more extended closures and more intense release bursts for voiceless versus voiced stops resulting from differences in supraglottal air pressure and perhaps in articulatory effort [Lisker, 1986; Farnetani, 1990]. Several factors may affect the prominence of these voicing cues. Thus, it has been found that voicing during closure is disfavoured word-finally before a pause and by velar as opposed to more anterior stops [Keating et al., 1983; Docherty, 1992; Ohala, 1983; Keating, 1984], and that differences in closure duration between underlying voiced and voiceless stops may be position dependent as well (e.g., they have been reported to occur preferentially in medial post-stress position in English) [Lisker, 1970]. Factors below may affect the robustness of these stop voicing cues in word-final clusters with a liquid.

Phonetic voicing in the cluster may be influenced by the syllabic status of the liquid. Descriptive evidence from the literature indicates that, if syllabic, the liquid stays voiced not only after a voiced consonant but also after a voiceless one such that vocal fold vibration is associated with the liquid itself and does not depend on the presence of voicing during the stop (e.g., Czech [petr̩] *Petr* 'Peter', [vi:tr̩] *vitr* 'wind') [Hála, 1973]. Therefore, the production of syllabic consonants involves voicing starting immediately after stop release [Lehiste, 1964; Catford, 1977]. The underlying stop voicing distinction is not neutralized in these circumstances.

The requirement that syllabic consonants be essentially voiced has led phonologists to state that a requirement for syllabicity is that the liquid occupies the syllable sonority peak [Barry, 2000], and that voiced consonants are more prone to be syllabic than their voiceless correlates [Blevins, 1995]. Indeed, syllabic voiceless consonants are not frequent in the world's languages though syllabic voiceless fricatives outnumber their syllabic voiced cognates [see Bell, 1978, and also Malmberg, 1974 and Bloomfield, 1964 regarding the presence of syllabic fricatives in the interjections [pst], [ʃ(t)])].

If non-syllabic, the presence of phonetic voicing during the liquid appears to be tied to vocal fold vibration during the preceding stop consonant. Thus, the liquid is devoiced in clusters with an underlying voiceless stop, as shown by non-syllabic /r/ in Russian ([pjotr̥] 'Peter', [vʲixr̥ʲ] 'whirl-wind') and Polish ([vjatr̥] *wiatr*), and by non-syllabic /l/ and /R/ in French ([pœpl̥] *peuple* 'people', [ɛtR̥] *être* 'to be') [Hála, 1973; Jakobson and Waugh, 1979; Tranel, 1987]. On the other hand, it may stay voiced but also undergo devoicing if the stop is underlyingly voiced. Indeed, clusters with an underlying voiced stop may conform to three possibilities in this respect: both the liquid and the stop stay voiced (Russian [tʲigr] 'tiger' [Comrie and Corbett, 1993, p. 830]; the liquid is devoiced while the stop remains completely or partly voiced (French [tabl̥] *table* 'table', Marebbano Ladin [libr̥] 'book', [ʒənédl̥] 'knee' [Malmberg, 1974; Jaberg and Jud, 1928–1940, maps 162, 763]; both the liquid and the stop are voiceless [Alguerès Catalan [ɔpr̥] *obr* 'I open'; see above]. According to Steriade [1999], languages may differ as to whether they admit the first two options (e.g., Russian) or necessarily undergo C1 and C2 devoicing (e.g., Polish). A joint consideration of the three possibilities just referred to indicates that the underlying stop voicing distinction may be maintained or neutralized in word-final clusters with a non-syllabic liquid.

Liquid devoicing may be accompanied by some frication noise as a greater release of pulmonary air occurs through an open glottis (e.g., in French and Majorcan Catalan

[Tranel, 1987; Llach, 1999]) and may cause the liquid to fail to be perceived (French [tab(l̥)] *table* ‘table’, [ɛt(R̥)] *être* ‘to be’, Majorcan Catalan [ɔp] *obr* ‘he opens’ [Tranel, 1987; Alcover and Moll, 1929–1933]).

In addition to the syllabic status of the liquid, the presence of vocal fold vibration during the stop is related to the production requirements for /l/ and /r/. The initial expectation is that stop voicing should be favored by /l/ rather than by /r/ since the lateral involves a lower intraoral pressure level than the rhotic mostly so if the latter is realized as a trill [Solé, 2002].

Regarding Majorcan Catalan, no substantial differences in stop voicing degree are expected to take place if the phonetic realization of the two liquids in word-final clusters coincides with that occurring word-finally after a vowel, i.e., typically dark or velarized/pharyngealized in the case of /l/ and a tap in the case of /r/ [Bibiloni, 1983; Recasens, 1996]. It may be, however, that the high intraoral pressure level involved in stop closure formation causes non-syllabic /r/ to be implemented as a trill rather than as a tap and the stop to undergo devoicing in this cluster class. The manner of articulation of the rhotic, and thus presumably the presence versus absence of voicing during the stop, may also depend on its syllabicity status: non-syllabic /r/ is prone to be realized as a tap (e.g., in the Majorcan Catalan clusters of interest) and syllabic /r/ as a trill. Indeed, syllabicity has been correlated with articulatory and acoustic stability, namely, the achievement of a more than minimal duration and an unreduced and context-independent articulatory target. Accordingly, Slovak /r/ has more contacts and is more retracted if syllabic than if non-syllabic [Podhradská, 2002], and dentoalveolar trills appear to be by far the most frequent syllabic rhotics in the world’s languages [Bell, 1978].

Stop voicing should also be facilitated by an increase in gestural overlap between the two consecutive consonants in the cluster. The expected trend here is for voiced stops to allow an earlier onset of the apical gesture for the following liquid than voiceless stops just as VCV sequences exhibit larger degrees of V-to-C anticipation when the intervocalic stop is voiced than when it is voiceless [Farnetani, 1990; Kohler, 1984]. Temporal superposition is expected to be more obvious in clusters with /l/ than in those with /r/ in line with the aerodynamic requirements involved (see above) and with the fact that /l/ is typically dark in Majorcan Catalan. Indeed, prominent anticipatory effects associated with tongue dorsum lowering for dark /l/ have been reported to occur during the preceding vowel [Sproat and Fujimura, 1993], or during a preceding bilabial or velar stop in syllable-initial position [Gibbon et al., 1993] and in clusters with syllabic /l/ [Giles and Moll, 1975; Abercrombie, 1967; Kenyon, 1950; Lehiste, 1964; O’Connor, 1967]. Word finality could contribute to the temporal separation between the two consecutive consonants in line with data in the literature showing that syllable-final complex consonants and clusters may undergo gestural dissociation [Goldstein, 1994; Krakow, 1999].

In the absence of gestural superposition, phonetic differences between underlying voiced and voiceless stop clusters may be related to the duration of a short opening period occurring between the stop and the liquid. Evidence for this opening period derives from clusters with a syllabic liquid. Thus, [l̩], [ɹ̩], [n̩] and [əl], [əɹ], [ən] may be in free alternation in English (American English *idol*, British English *Hungary*, *ligthening* [Trager and Bloch, 1941; Roach and Miller, 1991], and [ə] is about 60–80 ms or less in those VC sequences [Lehiste, 1964]. Slovak [r̩] may also insert a transitional vocalic element between C1 and C2, e.g., [pᵊˈɾᵊst] for *prst* ‘finger’ [Podhradská, 2002]. In Romance dialectal areas, this opening interval appears to have been categorized as a separate vowel in clusters with a liquid which became word final after deletion of the following vowel, e.g., Northern Italian [ˈnegəɾ] 'black', [ˈfoɾen] 'oven', [ˈpadəɾ] 'father', [ˈfeveɾ] 'fever' from Latin NIGRU, FURNU, PATRE, FEBRE, respectively [Rohlfs, 1966]. In agreement with this hypothesis the Northern Italy-Ladin-Friulian complex exhibits related forms such as [lavr] and [ˈlabəɾ] 'lip' for Latin LABRU, and [imˈvɛrn] and [imˈvɛrən] 'winter' for HIBERNU [Jaberg and Jud, maps 165, 314]. Alternatively, a vowel may have been inserted at liquid release, e.g., [i] in Friulian ([ˈdopli] 'double', [ˈkwatɾi] 'four' from Latin DUPLU, QUATTUOR [Maiden and Parry, 1997] and [ə] or [œ] in French ([ˈtablᵊ] 'table', [ˈsykrᵊ] 'sugar').

Stop voicing may also be favored by the presence of a preceding nasal (as opposed to a preceding vowel) in line with factors contributing to a decrease in intraoral pressure level during the oral stop in this contextual condition, i.e., closure shortening and coarticulated nasal leakage through the velar port. This effect has been reported to occur in the Majorcan Catalan clusters under study (see 'Research Goal' above) and accounts for instances of progressive stop voicing assimilation in nasal-stop clusters (e.g., S. Italian [nəm biˈovə] *non piove* 'it is not raining', Gascon [kanˈda] from Latin CANTARE 'to sing', [Rohlfs, 1966, 1970].

Preceding and Following Segments

Other voicing cues for the stop may be found during the segment preceding the stop consonant.

Vowels are expected to be shorter and more open before voiceless versus voiced stops perhaps in line with differences in sustention of muscular activity in the vowel gesture [Raphael, 1972, 1975; Kohler, 1984]. Moreover, the F1 vowel transitions exhibit a shorter cutoff and a higher offset frequency, and the F2 and F3 vowel transitions may end at lower frequencies and move more abruptly, before a voiceless versus voiced stop [Lisker, 1957, 1975; Summerfield and Haggard, 1977]. Different vowel formant trajectories may be associated with differences in the articulatory power of the closing movement, and in the relative timing of events at the larynx and at the supraglottal place of articulation [Kohler, 1984; Abramson and Lisker, 1973].

Nasal stop closure durations are also expected to be significantly longer before underlying voiced versus voiceless stops, presumably because air leakage through the velopharyngeal passage contributes to a decrease in intraoral pressure which facilitates stop voicing [Raphael et al., 1975]. A related voicing-dependent factor is the ratio between nasal closure duration and the duration of the overall nasal stop + oral stop period, which is expected to be higher in clusters with voiced stops than in those with their voiceless counterparts.

Other stop voicing cues may also occur during the liquid. As reported above, devoicing and possible frication are expected to take place during Majorcan Catalan non-syllabic liquids (mostly /r/). In these circumstances, differences in oral pressure level as a function of stop voicing could cause the liquid and/or the frication period to be longer in clusters with voiceless stops than in those with voiced stops.

Summary of Cues

EPG and acoustic data for Majorcan Catalan word-final clusters with non-syllabic /l/ or /r/ will allow checking whether the liquid is realized without vocal fold vibration after an underlying voiceless stop, and the extent to which clusters with an underlying voiced stop are implemented through C1 and C2 voicing, C1 voicing and C2 devoicing or C1 and C2 devoicing.

The spatiotemporal articulatory characteristics of the liquid will be investigated, i.e., whether /l/ is dark and /r/ is a tap or a trill, liquid devoicing results in frication or liquid deletion (mostly so for /r/), and C2 overlaps with C1 or there is an opening element between the two consonants (mostly so in clusters with /l/).

Stop voicing cues will be looked for during the stop, and during the liquid and the segment preceding the stop. In comparison with their voiceless correlates, underlying voiced stops are expected to exhibit shorter closures, less tongue contact, longer closure voicing periods and less salient stop releases. Several factors may affect the implementation of stop voicing, i.e., the stop place of articulation, whether the segment preceding the stop is a nasal consonant or a vowel, and whether the segment following the stop is a lateral or a rhotic. Moreover, in comparison with clusters with a voiceless stop, those with a voiced stop ought to show more overlap between C1 and C2, a shorter liquid, a shorter frication period during the liquid and a longer preceding nasal.

The relative salience of these stop voicing cues will also be investigated under the assumption that robust phonetic characteristics ought to be most resistant to loss. Thus, it may turn out that Majorcan Catalan speakers differ regarding the extent to which they devoice the liquid and/or the stop consonant and thus, that the phonetic implementation of the clusters of interest is highly variable and/or that a sound change is in progress. Previous findings in the literature are relevant in this respect, namely, the stop voicing distinction appears to be cued by closure duration rather than by the burst and the formant transitions in word-final position [Raphael, 1981], and by preceding nasal duration rather than by preceding vowel duration [Raphael et al., 1975]. Preliminary data for Majorcan Catalan also reveal that differences in nasal and oral stop closure duration may become specially relevant in marking the voicing distinction for postnasal stops in word-final stop-liquid clusters [Llach, 1999].

Method

Seventeen clusters differing in underlying stop voicing, in the presence of /l/ or /r/ and in the presence or absence of a homorganic nasal consonant before the stop were read sentence-finally in short meaningful Catalan sentences, e.g., *aquest ganivet l'empr* 'I use this knife' (tables 1, 2). Sentences had a similar number of syllables so as to ensure that all consonant clusters would exhibit comparable durations. Several CC combinations were excluded from the reading list due to lexical or phonotactic restrictions, namely, a postvocalic or postnasal voiceless velar followed by /r/, a postvocalic voiceless bilabial stop followed by /r/, and a potvocalic or postnasal dental stop followed by /l/. Indeed, the combinations /tl, dl, ntl, ndl/ are impossible in Catalan while postvocalic /pr, kr, nkr/ occur in uncommon words such as *estuprar* 'to rape' and *lucrar* 'to receive benefit'. Exclusion of these CC combinations renders the corpus of consonant clusters somewhat unbalanced. Thus, there are 9 clusters with postnasal stops and 8 with postvocalic stops, 10 clusters with underlying voiced stops and 7 with underlying voiceless stops, 8 clusters with /l/ and 9 with /r/, and 7 clusters with labials, 4 with dentals and 6 with velars. In the light of the segmental composition of these unavailable consonant sequences, special attention will be paid to the interpretation of significant statistical differences between data for clusters with dentals and those for clusters with labials and velars.

Linguopalatal contact and acoustic data were recorded seven times by five male speakers of Majorcan Catalan of 30 (AR, MJ), 40 (ND) and 55 (BM, CA) years of age. All five speakers were born

Table 1. Majorcan Catalan words used for experimental analysis

C1	C2 = /l/		C2 = /r/	
	postvocalic stop	postnasal stop	postvocalic stop	postnasal stop
Voiced bilabial	*dobl* 'I double'	*assembl* 'I resemble'	*cobr* 'I earn'	*sembr* 'I sow'
Voiceless bilabial	*acopl* 'I fit together'	*umpl* 'I fill'	–	*empr* 'I use'
Voiced dental	–	–	*quadr* 'I match'	*xelindr* 'I roll flat'
Voiceless dental	–	–	*empotr* 'I embed'	*entr* 'I go in'
Voiced velar	*arregl* 'I fix'	*ungl* 'I mark'	*alegr* 'I cheer'	*sangr* 'I bleed'
Voiceless velar	*xucl* 'I sip'	*vincl* 'I bend'	–	–

Table 2. Majorcan Catalan sentences used for experimental analysis

1	/bl/	*Aquest suma la dobl*	'I double this sum'
2	/mbl/	*Jo m'hi assembl*	'I resemble him/her'
3	/pl/	*Aquestes peces les acopl*	'I fit these pieces together'
4	/mpl/	*La bassa l'umpl*	'I fill the pool'
5	/gl/	*La casa l'arregl*	'I fix the house'
6	/ngl/	*El pa l'ungl*	'I mark the bread with my nails'
7	/kl/	*Aquesta beguda la xucl*	'I sip this drink'
8	/nkl/	*Aquest ferro el vincl*	'I bend this iron piece'
9	/br/	*Els deutes els cobr*	'I cash these debts'
10	/mbr/	*Les llavors les sembr*	'I sow these seeds'
11	/mpr/	*El ganivet l'empr*	'I use this knife'
12	/dr/	*Jo els contes no els quadr*	'The accounts do not match'
13	/ndr/	*La placeta la xelindr*	'I roll the square'
14	/tr/	*Aquest ferro l'empotr*	'I embed this iron piece'
15	/ntr/	*Ara ja entr*	'I go in already'
16	/gr/	*La festa l'alegr*	'I cheer the party'
17	/ngr/	*Per aquesta ferida sangr*	'I bleed through this wound'

in Majorca, i.e., in Manacor (AR), Algaida (BM), Valldemossa (MJ), Palma (ND) and Santanyí (CA). They have always lived in the island where they carried out university studies in Catalan Philology (except for speaker BM who studied at the University of Barcelona between 1970 and 1975), and use Majorcan Catalan almost exclusively in their everyday life.

Speakers were instructed to read the list of sequences reproduced in table 2 as naturally as possible at the authors' phonetics laboratory in Barcelona. Their cluster productions should not have been influenced by the spelling of the stops (since all verbal forms in table 1 are highly frequent in Catalan) or by the more prestigious Barcelona variety of Catalan (since word-final stop-liquid clusters do not appear in any other Catalan dialect besides Majorcan).

Linguopalatal contact configurations were gathered with the Reading EPG-3 system every 10 ms using artificial palates equipped with 62 electrodes. Acoustic data were digitized at 10 kHz, filtered at 4,8 kHz and processed with a Kay CSL analysis system using the same temporal resolution as the EPG

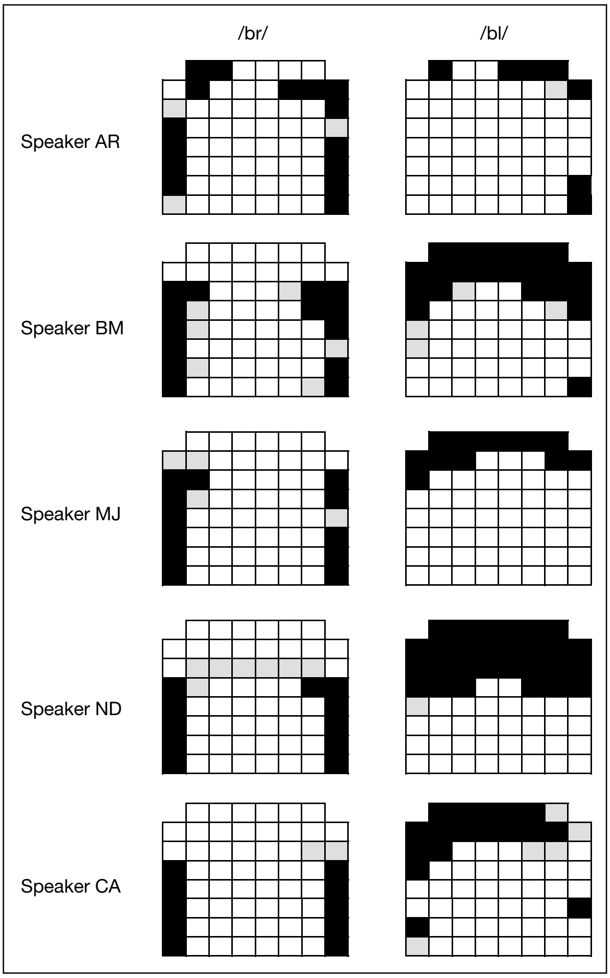

Fig. 1. Linguopalatal contact configurations for /r/ (left) and /l/ (right) in the words *sembr* 'I sow' and *m'assembl* 'I look like' according to the five speakers under analysis in this study. Electrodes are assigned three grey shades depending on the frequency of activation, i.e., 80–100% (black), 40 to <80% (grey), 0 to <40% (white).

data. As shown by the linguopalatal configurations in figure 1, electrodes on the surface of the artificial palate are distributed into four front rows at the alveolar zone and into four back rows at the palatal zone (at the upper half and at the bottom half of each EPG pattern, respectively) and into eight columns grouped evenly at the left and right sides of the artificial palates. Electrodes appear in black, grey or white depending on percentages of electrode activation, i.e., 80–100% (black), 40 to <80% (grey), 0 to <40% (white). These percentages correspond to the number of on-times for each electrode (established at consonant midpoint) over the number of repetitions.

Events *(a)* through *(k)* below were measured. Segmentation criteria were based on the EPG signal whenever possible. Otherwise, the crucial measurement points along the time axis were identified from inspection of simultaneous representations of the acoustic waveform, spectrogram and linguopalatal contact pattern such as the one reproduced in figure 2. Measurements involving events which were not always easily identifiable on spectrographic displays were checked twice, e.g., *(a)* and *(b)* due to the low intensity of the nasal murmurs. Possible stop voicing cues in the vowel preceding the stop, i.e., vowel duration and F1 transition duration and offset frequency (see Introduction), were not subject to analysis. The reason for this was that pairs of words differing in stop voicing had different vowels in them or differed regarding the place of articulation of the consonant preceding the vowel.

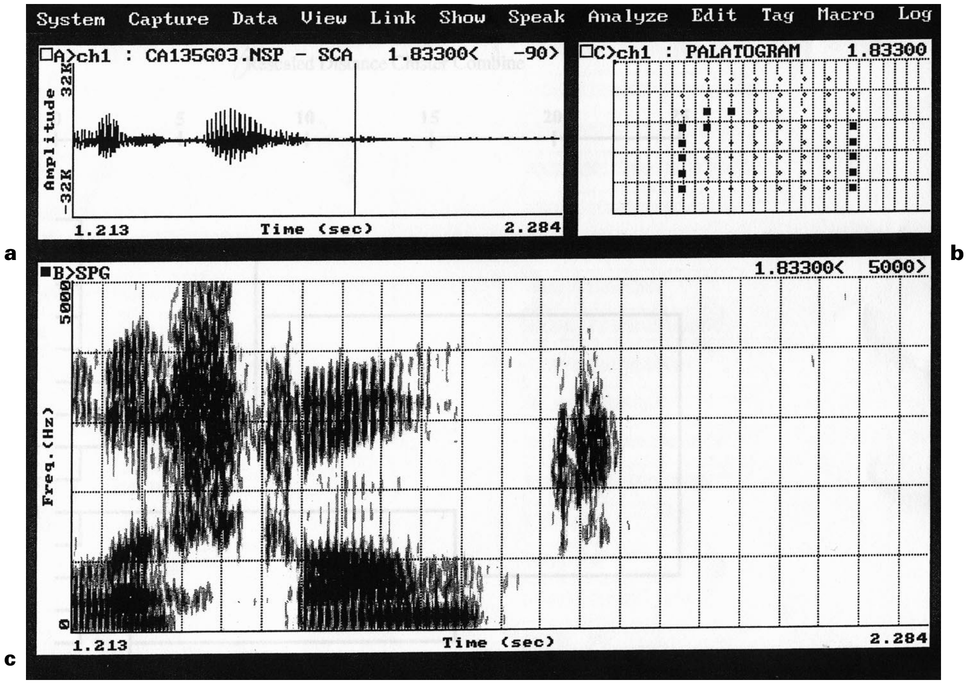

Fig. 2. Representation of the acoustic waveform (**a**), linguopalatal contact configuration (**b**) and spectrogram (**c**) for the word-final cluster /pr/ in the sequence *els compr* 'I buy them'. The EPG configuration corresponds to the rhotic at the temporal frame where the cursor appears on the waveform.

(a) Nasal stop closure duration. Nasal consonants were taken to extend from the offset of the formant structure period for the preceding vowel until the offset of the nasal murmur on spectrographic displays.

(b) Stop closure duration. Closure for dental /t, d/ was identified with a front alveolar closure period on the EPG record. Whenever alveolar closure was incomplete (presumably since central contact was made exclusively at the teeth), consonant onset was taken to occur at the offset of the formant structure period for the preceding vowel, and consonant offset at the stop release burst or at the onset of a short vocalic element between C1 and C2. This acoustic criterion was always applied to bilabials and velars given that consonants of the former group do not involve the formation of a lingual closure and closure for velars often occurs behind the posterior rows of the artificial palate. If not clearly detectable on the spectrographic displays, closure offset for velars was taken to coincide with a decrease in tongue contact at the posterior rows of electrodes of the artificial palate.

(c) Alveolar stop contact index at /t, d/ closure midpoint. This index was equated with the percentage of electrode activation at the alveolar zone and expressed in numerical values between 0 and 1. For that purpose, we obtained the percentage of on-electrodes over the first four rows for each repetition of a given cluster (at /t, d/ closure midpoint) and averaged all percentages across repetitions of that cluster.

(d) Duration of the period of continuous voicing during stop closure from inspection of the voicing bar on spectrographic displays.

(e) Presence versus absence of a stop burst at consonantal release on spectrographic displays. Bursts were implemented by one energy spike or, less often, by two spikes (e.g., in the case of clusters with velar stops for speaker MJ).

(f) Duration of a vocalic period between stop closure offset and the onset of the liquid, see *(h)*. The existence of this vocalic element was inferred from the presence of voicing and formant structure on spectrographic displays.

(g) Duration of the period of articulatory overlap between the liquid and the preceding stop consonant. This period was equated with the temporal distance between the onset of the liquid, see *(h)*, and stop closure offset on the EPG record. No overlap was expected to occur for the homorganic clusters /tr, dr/ since the rhotic is realized after stop release in this case.

(h) Duration of /l/ and /r/. The articulatory period for /l/ was determined by the presence of electrode activation at two or more central columns of electrodes at the alveolar zone. In the case of speaker AR, for whom central contact for /l/ was seldom available, the lateral was taken to occur as long as there were one or more on-electrodes anywhere at the two frontmost alveolar rows of electrodes. The duration of the rhotic was estimated from the only alveolar contact period available or from the first of two consecutive contact periods. Consonantal onset in this case was determined by the presence of alveolar contact at the four central columns of electrodes, and consonantal offset by the frame showing no on-electrodes at any of those columns. Otherwise, the temporal boundaries of the rhotic were signalled by the presence of electrode activation anywhere at the six central columns of electrodes (whenever there was little central contact) or else by a change in contact fronting at the two lateralmost columns at both sides of the artificial palate (if there was no central contact at all). Regarding the clusters /tr, dr/ where C1 and C2 exhibited the same or a close place of articulation, the onset of the rhotic was taken to occur just after stop release as long as it was articulated with some central contact at the two frontmost alveolar rows. The rhotic was identified by the presence of a constriction narrowing at rows 7 and 8 in those velar stop clusters in which it was velar or uvular (for speaker BM only).

(i) Alveolar contact index at the midpoint of the liquid. This index was equated with the percentage of electrode activation at the alveolar zone following the same procedure as in *(c)*, and expressed in numerical values between 0 and 1.

(j) Duration of the voicing period during the liquid from inspection of the voicing bar on spectrographic displays.

(k) Duration of the frication period after stop release, and of the period of overlap between frication and the liquid.

Parameters *(a)* through *(k)* were submitted to statistical analysis except for the vocalic period between the stop and the liquid, see *(f)* which will be referred to in the Results section but was not tested statistically since it showed up only in a few tokens mostly for one speaker. The ratio between nasal closure duration and the duration of the nasal stop + oral stop period, *(a′)* from now on, was also treated as a dependent variable in the statistical tests. This parameter derives from the basic measures *(a)* and *(b)* and, as pointed out above ('Preceding and Following Segments'), may cue stop voicing in clusters. The periods of temporal overlap between articulatory events were converted into percentages for statistical analysis. Therefore, measures *(d)*, *(g)* and *(j)* will be reported as percentages of voicing over oral stop closure duration *(d)* and over liquid duration *(j)*, and as percentages of anticipatory activity for the liquid over preceding stop closure duration *(g)*. Other measures expressed as percentages were nasal closure duration over the duration of the nasal + stop period, *(a′)*, and frequency of occurrence of stop bursts, *(e)*.

In order to identify bundles of phonetic parameters signalling the underlying stop voicing distinction and the relative contribution of these parameters within each bundle, we performed a factor analysis on data across repetitions and speakers inserting unity in the principal diagonal of the correlation matrix. Additional factor analyses were also carried out on data across repetitions for each individual speaker in order to gain information about the production mechanisms used by each speaker for the implementation of the voicing distinction. Seven measures were included in those analyses, i.e., *(b)*, *(d)*, and *(g)* through *(k)*. Other variables could not be entered in the factor analyses, i.e., frequency of stop bursts since it proceeds categorically (i.e., bursts were either present or absent), and nasal closure duration, nasal/nasal + stop closure ratio and alveolar stop contact index since they were available for a subset of consonant sequences only. Factors were computed according to Kaiser's criterion. A hierarchical cluster analysis using Ward's method was also carried out in order to find out proximities between the seventeen consonant sequences under study based on the extracted factors [Aldenderfer and Blashfield, 1984].

Inferential statistical tests were also performed so as to gain more precise information about the contribution of each potential voicing cue and to obtain statistical results for those variables excluded from the factor analyses. ANOVAs were run on the entire data set and on the data of each speaker, one for each of the dependent variables *(a)*, *(a')*, *(b)* through *(d)*, and *(g)* through *(k)*. All ANOVAs had four independent factors, i.e., the segment preceding the stop consonant (vowel, nasal), stop voicing (voiced, voiceless), stop place of articulation (labial, dental, velar) and liquid (/l/, /r/). Moreover, 'speaker' was treated as a fifth independent factor in the ANOVAs for the entire data set. Main effects and interactions were computed at the $p < 0.05$ level. Data on nasal closure duration and on nasal/nasal + stop closure ratio were tested for clusters with a nasal consonant only. Only statistical results for the individual speakers' data will be reported in the Results section in view of the fact that statistical tests for the whole data set yielded highly significant effects for the factors 'voicing' and 'speaker' in most instances, i.e., $p < 0.000$ in six ANOVAs and $p < 0.03$ in two ANOVAs in the case of 'voicing' and $p < 0.000$ in all ten ANOVAs in the case of 'speaker'.

χ^2 tests were applied to the non-continuous variable *(e)*, i.e., frequency of occurrence of stop bursts, as a function of the same independent variables used in the ANOVAs. They were used in order to compare the ratio between the number of tokens with a burst and the overall number of tokens for the voiceless stop category, with the corresponding ratio for the voiced stop category.

Results

The factor analysis performed on data across speakers yielded two orthogonal factors explaining up to 86.1% of the total variance (see the two leftmost columns in table 3). The first factor, i.e., factor 1 in the table, accounts for 60.5% of the variance and encompasses five measures exhibiting high factor loadings which happen to be associated with the liquid consonant, i.e., *(g)*, *(h)*, *(i)*, *(j)*, *(k)*. The second factor, i.e., factor 2 in the table, explains 25.6% of the total variance and is characterized essentially by dependent measures *(b)* and *(d)* which are primarily associated with stop voicing. These two factors will be referred to as the liquid factor (factor 1) and the stop voicing factor (factor 2), and will be analyzed below ('Spatiotemporal Articulatory Characteristics for the Liquid' and 'Stop Voicing Distinction').

Spatiotemporal Articulatory Characteristics for the Liquid

The liquid factor for the cross-speaker condition shows positive and high factor loadings above 0.9 for liquid/stop closure overlap, liquid duration and alveolar contact index for the liquid (0.91, 0.96 and 0.93, respectively), a high but negative factor loading for frication duration (−0.94), and a positive and slightly lower factor loading for liquid voicing (0.68). These results are in accordance with the predicted differences between /l/ and /r/ and are indicative of salient articulatory differences between the two liquids. Thus, in comparison with /r/, /l/ is longer and articulated with more alveolar contact, and involves more voicing, more anticipation during the preceding stop and less frication after stop release. As expected, measures associated with the stop, i.e., stop closure duration and stop closure voicing, exhibit low factor loadings in factor 1.

These factor loadings for the liquid factor are generally in agreement with those obtained from factor analyses performed on data for the individual speakers (see the remaining ten columns in table 3). A more precise analysis of the articulatory properties contributing to the liquid distinction and an evaluation of the most relevant speaker-dependent differences are presented below.

Table 3. Factor loadings for the first and second factors (i.e., factors 1 and 2) according to factor analyses performed on variables associated with the stop voicing distinction

	Across speakers		Speaker AR		Speaker BM		Speaker MJ		Speaker ND		Speaker CA	
	factor 1	factor 2	factor 1	factor 2	factor 1	factor 2	factor 1	factor 2	factor 1	factor 2	factor 1	factor 2
(b) Stop closure duration, ms	0.200	−0.887	0.168	0.806	−0.178	0.898	0.015	0.797	0.181	−0.881	0.103	−0.674
(d) Stop closure voicing, %	0.301	0.913	−0.375	0.795	0.782	−0.017	0.409	−0.698	0.089	0.924	0.244	0.918
(g) Liquid/stop closure overlap, %	0.908	0.303	0.593	−0.111	0.925	0.216	0.591	0.429	0.902	0.272	0.854	0.347
(h) Liquid duration, ms	0.959	−0.101	0.737	−0.086	0.768	0.198	0.945	0.007	0.950	−0.102	0.986	−0.076
(i) /l, r/ alveolar contact index (0–1)	0.929	−0.034	−0.666	−0.529	0.633	0.553	0.698	−0.148	0.959	−0.117	0.955	0.101
(j) Liquid voicing, %	0.680	0.467	0.667	−0.029	0.856	−0.178	0.452	0.717	0.491	0.681	0.466	0.768
(k) Frication duration, ms	−0.942	−0.031	−0.675	−0.251	−0.230	−0.856	−0.861	−0.098	−0.538	−0.114	−0.079	−0.930

Factors are given for statistical tests on data across speakers and on data for the speakers AR, BM, MJ, ND and CA.

Regarding segmental duration, variable *(h)*, positive and high factor loadings between about 0.74 and 0.99 hold for all speakers, meaning that /l/ and /r/ differ considerably in duration. The rhotic was usually implemented as a one-contact alveolar tap and was much shorter than the lateral for all speakers, i.e., /r/ durations ranged between 27 and 80 ms with an overall mean across speakers of 51 ms (SD = 21) while /l/ durations ranged between 104 and 184 ms with a mean of 132 ms (SD = 46). Both consonants turn out to be longer in the clusters of interest than in other word positions in Catalan, possibly as a result of final lengthening, i.e., intervocalic /l/ has been reported to last for about 50 ms and the duration of the tap amounts to 15–30 ms in intervocalic position and to 20–50 ms in postconsonantal and preconsonantal position [Recasens, 1986].

In addition to segmental duration, both consonants differ in contact degree and place of articulation at the alveolar zone. Variable *(i)* exhibits positive and high factor loadings for all speakers except for speaker AR, which is in agreement with the presence of higher alveolar contact index values for /l/ than for /r/, i.e., $\bar{X} = 0.5$, SD = 0.15 versus $\bar{X} = 0.42$, SD = 0.22 (speaker BM), $\bar{X} = 0.39$, SD = 0.08 versus $\bar{X} = 0.35$, SD = 0.12 (speaker MJ), $\bar{X} = 0.66$, SD = 0.33 versus $\bar{X} = 0.55$, SD = 0.33 (speaker ND) and $\bar{X} = 0.43$, SD = 0.23 versus $\bar{X} = 0.39$, SD = 0.21 (speaker CA). In agreement with these values, the EPG contact configurations for /l/ reveal the existence of well-defined articulatory characteristics (fig. 1, right) which resemble closely the realizations for word-initial and intervocalic /l/ for the same speakers [Recasens and Espinosa, unpubl. data]. This consonant is generally realized with complete alveolar closure at row 1 only (speaker MJ), or at rows 1 and 2 or 1, 2 and 3 (speakers BM, ND, CA). The fact that closure occurs invariably at the frontmost row of the artificial palate allows one to conclude that /l/ is typically dental in Majorcan Catalan. Moreover, the absence of much contact at the four back rows suggests that the lateral is heavily velarized/pharyngealized in this Catalan dialect. Linguopalatal contact configurations for the lateral show no substantial differences as a function of the preceding consonant, presumably due to the dentality and darkness attributes. Indeed, V-to-C coarticulation data in the literature reveal that dark /l/ is more coarticulation resistant than clear /l/ and that the fact that the tongue tip needs to form a dental closure prevents vowel coarticulation at the tongue front from occurring [Recasens et al., 1995; Farnetani et al., 1989].

Speaker AR often shows some front contact at one side of the alveolar zone which may be indicative of a decaying /l/ articulation. This individual pattern is reflected in table 3 since the factor loading for the variable *(i)* has the opposite sign from the factor loadings for other variables associated with the liquid, thus meaning that /l/ was produced with less, not more alveolar contact than /r/.

The place of articulation for the rhotic often shows no central contact and is more retracted than that for /l/ (fig. 1, left). Percentages of electrode activation for all clusters reveal that /r/ is articulated at rows (1–)2 for speaker AR, 2 or 2–3 for speakers CA and MJ, 3 for speaker ND, and 1, 3 or 7–8 for speaker BM, depending on whether the preceding consonant is dental, labial or velar, respectively.

Factor loadings for liquid voicing (variable *(j)*) are positive and relatively high (about 0.5–0.85) for speakers BM, ND and CA. Mean data for these speakers reveal that voicing was available for /l/ in a few clusters with a postnasal voiced labial stop, i.e., /bl/ ($\bar{X} = 97.8\%$ of voicing over liquid duration, all repetitions), /mbl/ ($\bar{X} = 64.93\%$, all repetitions) and /ngl/ ($\bar{X} = 88\%$, all repetitions) for speaker CA, /mbl/ ($\bar{X} = 39.5\%$, all repetitions) and /ngl/ ($\bar{X} = 8.43\%$, 5 repetitions) for speaker ND, and /mbl/ ($\bar{X} = 9.49\%$, 3 repetitions) for speaker BM. It thus appears that voicing during /l/ is necessarily tied to vocal fold vibration during stop closure and cannot restart after the release of a voiceless stop. The alveolar lateral was always voiceless for speakers AR and MJ, and the rhotic was voiceless for all speakers and all consonant sequences under analysis.

Articulatory activity for the liquid during the preceding stop, variable *(g)*, was found to hold in clusters with /l/. Onset of central alveolar contact for the rhotic occurred generally a few voiceless temporal frames after stop closure offset, perhaps since /r/ involves a higher oral pressure level than /l/ (the presence of a postnasal labial stop could induce some /r/ overlap for speaker BM only). Overall, /l/ anticipation was mostly present for speakers BM ($\bar{X} = 24.5\%$ over stop closure duration, SD = 26.8), ND ($\bar{X} = 29.8\%$, SD = 23.7) and CA ($\bar{X} = 42.5\%$, SD = 31.6), which explains why factor loadings for variable *(g)* for these 3 speakers are positive and about 0.9. As shown in figure 6, degree of /l/ overlap was found to be higher postnasally versus postvocalically for all three speakers [$F = 14.67$ (1, 49), $p < 0.001$; $F = 12.39$ (1, 44), $p < 0.001$; $F = 25.29$ (1, 48), $p < 0.000$], and there was also a trend for clusters with underlying voiced stops to exhibit more overlap than those with voiceless stops for speakers ND and CA (see 'Stop Voicing Distinction' below).

A 20 to 40-ms opening period between the stop and the following liquid was present in clusters exhibiting voicing during the stop closure period i.e., /mbl/ (the vocalic period was 20 ms long and occurred in 2 repetitions of this case), /ngl/ (20 ms, 1 repetition), /dr/ (40 ms, 1 repetition), /ndr/ (30–40 ms, 7 repetitions) and /ngr/ (40 ms, 4 repetitions) for speaker CA, and /mbl/ (20 ms, 1 repetition) and /ngl/ (40 ms, 2 repetitions) for speaker ND. The presence of a nasal facilitates the insertion of the vocalic element.

Cross-speaker mean durations for the frication interval after the stop burst, variable *(k)*, were higher in clusters with /r/ ($\bar{X} = 69$ ms, SD = 43) than in those with /l/ ($\bar{X} = 39$ ms, SD = 43). The frication period varies in duration according to speaker, and is significantly longer for /r/ than for /l/ for all speakers except for speaker CA. Mean frication duration values are 61 ms for /r/ versus 11 ms for /l/ for speaker AR [$F = 18.47$ (1, 105), $p < 0.000$], 111 versus 98 ms for speaker BM [$F = 11.98$ (1, 105), $p < 0.001$], 97 versus 27 ms for speaker MJ [$F = 81.67$ (1, 105), $p < 0.000$], 17 versus 6 ms for speaker ND [$F = 17.59$ (1, 98), $p < 0.000$], and 61 versus 54 for speaker CA. In agreement with these statistical results, frication duration exhibits higher negative factor loadings in the liquid factor for speakers AR, BM, MJ and ND than for speaker CA (table 3). This consonant-dependent difference in frication duration appears to be associated with the aerodynamic requirements involved in the production of rhotics versus laterals, and is in agreement with the complementary finding that frication overlaps to a larger extent with /r/ than with /l/ for all speakers, i.e., mean percentages of overlap across speakers were 47.71% for /r/ (SD = 39,46) and 25.2% for /l/ (SD=31.91). Inspection of the linguopalatal contact configurations for the two liquids in figure 1 suggests that airflow for frication exits through lateral channels located at or behind the palatal zone for /l/ and through an alveolar central channel for /r/.

Stop Voicing Distinction

All Speakers

The factor analysis performed on data across speakers assigned highest loadings for factor 2 to the articulatory properties of the stop consonant, namely, −0.89 to stop closure duration and 0.91 to stop voicing (table 3). A negative relationship between these measures is the expected outcome since an increase in closure voicing should be correlated with a decrease in closure duration. Moderate positive factor loadings between 0.3 and 0.5 were obtained for variables *(g)* and *(j)* meaning that liquid/stop closure overlap and voicing during the liquid may be related to the presence of voicing during the stop (see 'Spatiotemporal Articulatory Characteristics for the Liquid'). A joint evaluation of the factor loadings for these four dependent variables indicates that stop closure duration and stop closure voicing play a central role in marking the underlying stop voicing distinction, while liquid anticipation and the presence of vocal fold vibration during the liquid act as secondary stop voicing cues.

Relevant information about the conditions favoring the phonetic implementation of the stop voicing contrast may be gained from results from the hierarchical cluster analysis (fig. 3). According to the dendrogram, the seventeen consonant sequences are split into two different groups at the highest level, i.e., a group including all sequences with /r/ and another group including all sequences with /l/. This first subdivision is clearly associated with the first factor, i.e., the liquid factor, of the factor analysis. Furthermore, each of these two groups is divided into two subgroups: for consonant sequences with /l/ and for those with /r/, consonant clusters with a nasal and a voiced stop are grouped separately from those without a nasal consonant and those with a nasal and a voiceless stop. Thus, the sequences /ndr, ngr, mbr/ are grouped independently from /br, tr, dr, gr, ntr/, and the sequences /mbl, ngl/ are separated from /gl, pl, kl, mpl, nkl, bl/. There is only one exception, i.e., the cluster /mpr/, which is associated with /ndr, ngr, mbr/ rather than with /br, tr, dr, gr, ntr/, though at an outer level. The distribution of the seventeen sequences into these four subgroups appears to be associated with the second factor, i.e., the stop voicing factor, and reveals that the phonetic implementation of underlying stop voicing is strongly dependent on the presence of a nasal consonant before the stop. The dendrogram also shows that /l/ helps marking the postnasal stop voicing contrast better than /r/ since the dissociation between the postnasal voiced stop sequences and the remaining clusters occurs at a higher level for /l/ than for /r/.

Speakers ND and CA

Factor analyses for speakers ND and CA yielded results highly similar to those reported in section 'All Speakers' above. Indeed, as shown by table 3, factor loadings for closure duration and closure voicing in the stop voicing factor are high and inversely related (between −0.67 and −0.88 for *(b)*, and 0.92 for *(d)*), while those for liquid/stop closure overlap and liquid voicing exhibit the same sign as closure voicing and are relatively high (about 0.3 for *(g)* and 0.7 for *(j)*). Hierarchical cluster analysis for both speakers yield analogous CC sequence groupings to those occurring in the dendrogram of figure 3, i.e., CC sequences composed of a nasal consonant followed by a voiced stop are dissociated from the rest and /l/ helps setting those consonant clusters apart to a larger extent than /r/. The only exceptions are /mpl/ for speaker ND (which is grouped with postnasal voiced stop clusters) and /mbr, bl/ for speaker CA (which are grouped with oral and postnasal voiceless clusters).

The presence of a nasal consonant helps to maintain the underlying stop voicing distinction in the case of the four stop voicing cues *(b)*, *(d)*, *(g)* and *(j)*. Indeed, ANOVAs yielded a significant nasal × voicing interaction for all four variables in the case of speaker ND [$F = 37.63$ (1, 93), $p < 0.001$; $F = 43.71$ (1, 93), $p < 0.001$; $F = 4.79$ (1, 93), $p < 0.05$; $F = 35.09$ (1, 93), $p < 0.001$], and for variables *(b)*, *(d)*

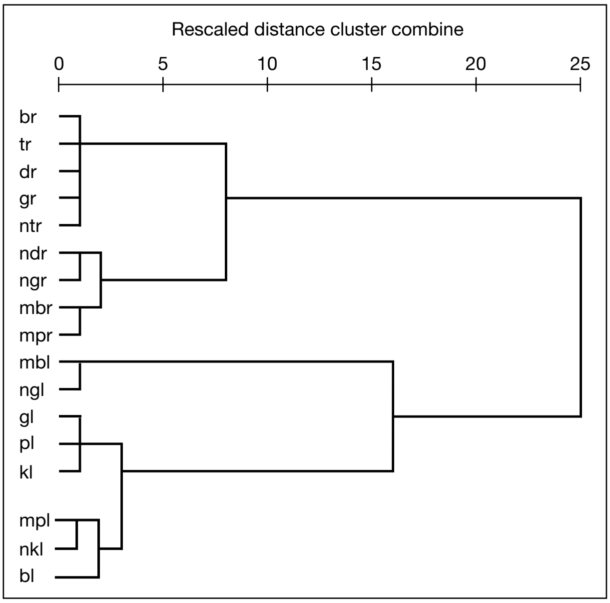

Fig. 3. Dendrogram showing groupings of consonant sequences according to a hierarchical cluster analysis performed on data across all five Majorcan Catalan speakers.

and *(j)* in the case of speaker CA [$F = 25.51$ (1, 104), $p < 0.001$; $F = 35.04$ (1, 104), $p < 0.001$; $F = 5.81$ (1, 104), $p < 0.05$]. In agreement with these statistical results, bars for these speakers in figure 4 (stop closure duration), figure 5 (stop closure voicing) and figure 6 (liquid/stop closure overlap) indicate the presence of the shortest stop closures and highest percentages of stop closure voicing and liquid/stop overlap in voiced stop clusters only if the stop is preceded by a nasal. Data for liquid voicing have already been presented in section 'Spatiotemporal Articulatory Characteristics for the Liquid' above, i.e., vocal fold vibration during the liquid occurs for /bl, mbl, ngl/ (speaker CA) or for /mbl, ngl/ (speaker ND).

The phonetic implementation of the underlying stop voicing contrast is also conditioned by stop place of articulation and the following liquid. Thus, voiced closures tend to be longer if the stop is labial (see bars for /mbr/ vs /ndr, ngr/, for /mbl/ vs /ngl/, and for /bl/ vs /gl/ in figure 4), and this place × voicing interaction turned out to be significant for speaker ND [$F = 4.96$ (2, 93), $p < 0.05$] and for speaker CA [$F = 5.93$ (2, 104), $p < 0.01$]. On the other hand, bars for speaker CA in figure 5 suggest that there is a tendency to have closure voicing in voiced stop clusters with /l/ rather than in those with /r/ [$F = 67. 82$ (1, 104), $p < 0.001$], and in voiced stop clusters with labials and dentals rather than in those with velars [$F = 22.07$ (1, 104), $p < 0,001$]; the sequence /bl/ for this speaker is somewhat exceptional in allowing voicing to occur during the entire closure period. As pointed out above, liquid voicing and liquid anticipation during a preceding voiced stop consonant were only available in clusters with /l/, and the presence of a labial appears to favor the phonetic implementation of the former measure.

For both speakers, the stop voicing distinction may also be cued by different articulatory properties from those exhibiting high factor loadings in the factor analysis. Regarding the articulatory properties associated with the nasal consonant, ANOVAs yielded significantly higher nasal/nasal + stop closure ratios for voiced versus voiceless

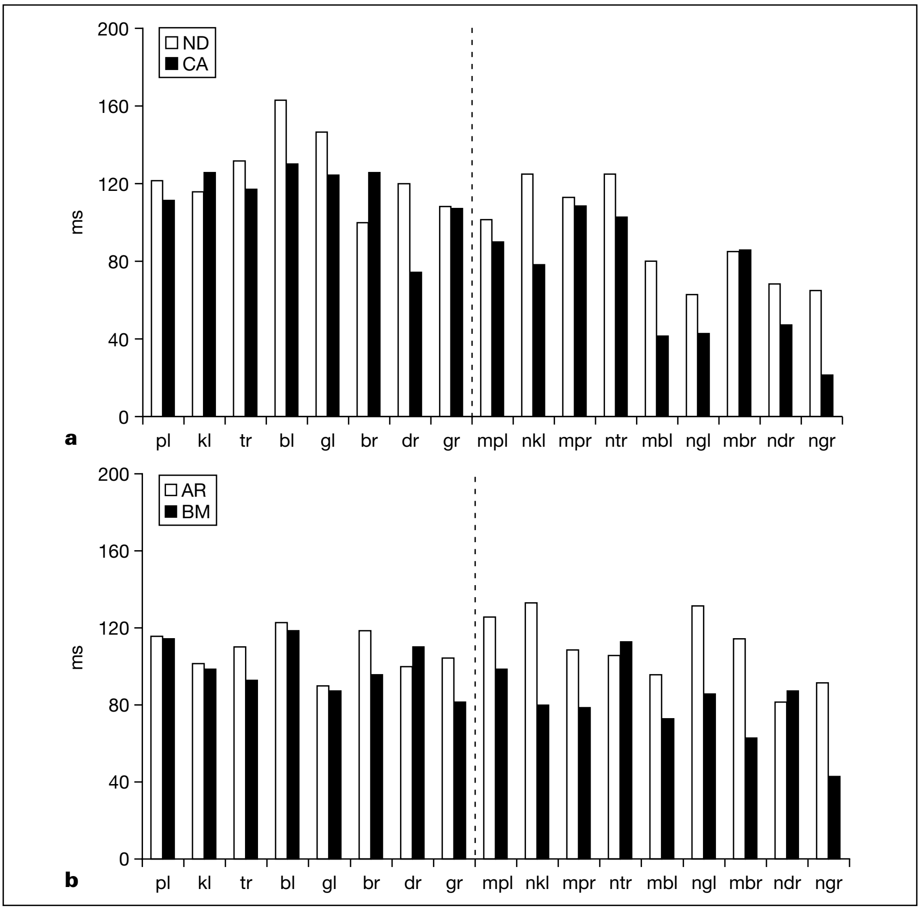

Fig. 4. Stop closure durations for postvocalic clusters (left) and for postnasal ones (right). Data are given for those speakers showing longer voiceless versus voiced stop closure durations, i.e., ND and CA (**a**) and AR and BM (**b**).

stops for speaker ND [$\bar{X} = 54.7$ versus 47.2; $F = 5.09$ (1, 48), $p < 0.05$] and speaker CA [$\bar{X} = 69.5$ versus 51.5; $F = 32.68$ (1, 53), $p < 0.001$], but no significant effects of nasal closure duration. As for the stop consonant, alveolar stop contact index values were significantly higher for /t/ versus /d/ for speaker ND [$\bar{X} = 0.95$ versus 0.93; $F = 7.58$ (1, 21), $p < 0.01$] and for speaker CA [$\bar{X} = 0.71$ versus 0.55; $F = 32.54$ (1, 24), $p < 0.001$], and releases were significantly more frequent for voiceless versus voiced stops in clusters with /r/ for speakers ND and CA [100% versus 76.9%, $\chi^2 = 5.19$, $p < 0.05$; 100% versus 76.2%, $\chi^2 = 5.94$, $p < 0.05$]. In spite of exhibiting low factor loadings in the stop voicing factor most of the time, differences in liquid duration, *(h)*, alveolar contact index for the liquid, *(i)*, and/or frication duration *(k)* as a function of stop voicing turned out to be significant in some instances. Thus, in comparison with voiced stop clusters, voiceless stop clusters happened to exhibit significantly longer liquids for speaker ND [$\bar{X} = 119$ versus 114; $F = 9.39$ (1, 97), $p < 0.01$], significantly

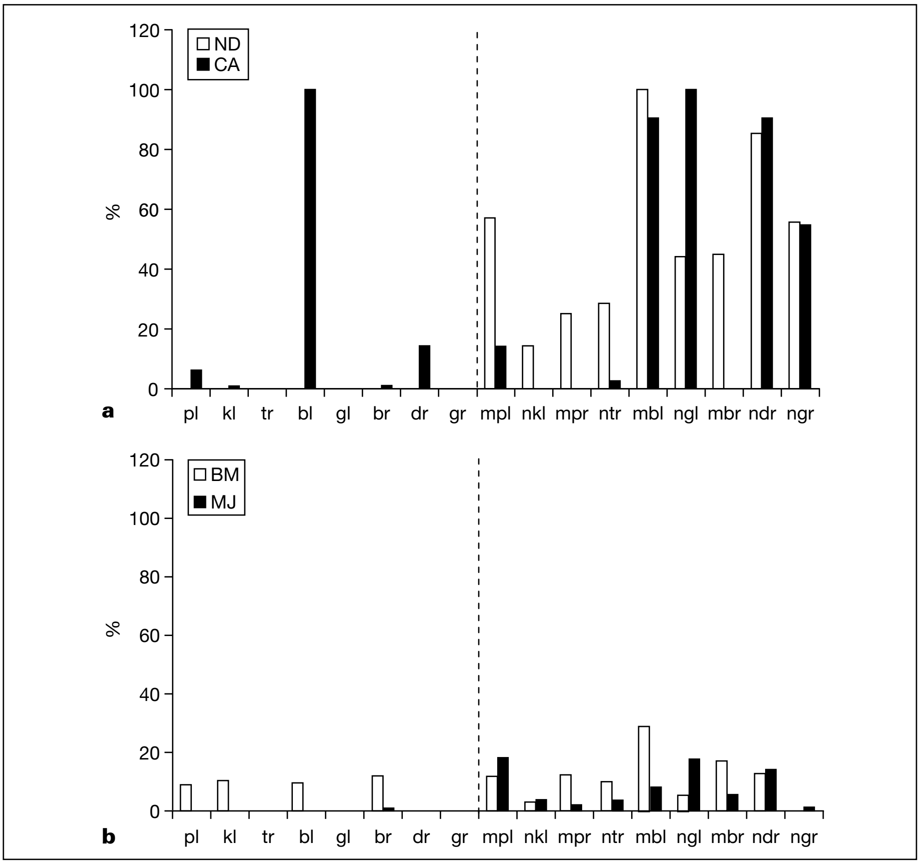

Fig. 5. Percentages of voicing during stop closure for postvocalic clusters (left) and for postnasal ones (right). Data are reported for speakers showing longer voicing periods for underlying voiced versus voiceless stops, i.e., ND and CA (**a**) and BM and MJ (**b**).

higher alveolar contact index values for the liquid in the case of speaker CA [$\bar{X}$= 0.43 versus 0.39; F = 6.35 (1, 103), $p < 0.05$), and significantly longer frication periods for speakers ND [$\bar{X}$ = 20 versus 6; F = 26.21 (1, 98), $p < 0.001$] and CA [$\bar{X}$ = 80 versus 42; F = 63.51 (1, 104), $p < 0.001$].

Speakers AR, BM, MJ

Results for the stop voicing factor for speakers AR, BM and MJ in table 3 are more difficult to interpret. Analogously to speakers ND and CA, factor loadings for stop closure duration and stop closure voicing for speakers BM and MJ are inversely related. Moreover, while both factors are equally salient for speaker MJ (0.80, −0.70), only closure duration appears to be a relevant voicing cue for speaker BM (0.90, −0.02). None of the remaining variables, with the inclusion of liquid/stop closure overlap and liquid voicing, contribute to the phonetic implementation of the stop voicing distinction

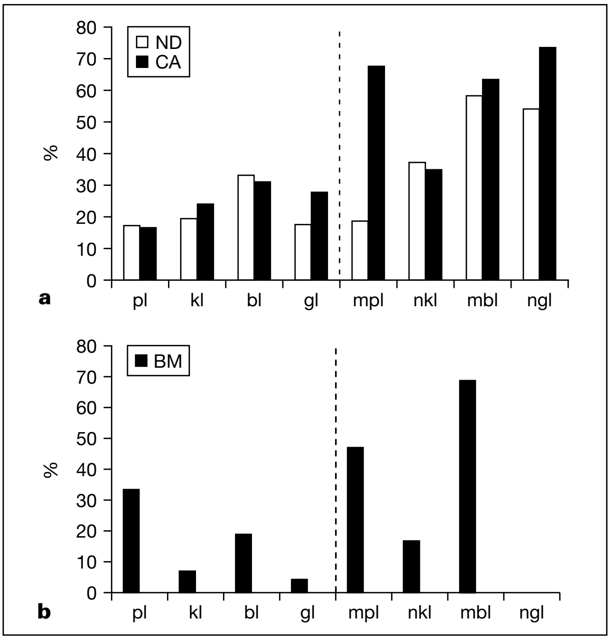

Fig. 6. Percentages of overlap between /l/ and the preceding stop in postvocalic stop clusters (left) and in postnasal stop clusters (right). Data are given for speakers ND and CA (**a**) and BM (**b**).

for either speaker BM or speaker MJ whether because of the sign or the low value of their factor loadings.

More accurate information about the possible cues signalling the stop voicing distinction for those two speakers may be gathered from inferential statistics. Thus, ANOVAs for speaker BM indicate that not only closure duration but also vocal fold vibration during stop closure may play a role in marking the stop voicing contrast, and that the phonemic distinction holds in nasal clusters only and is favored by labial versus non-labial stops. In particular, nasality and voicing were found to interact significantly for stop closure duration and stop closure voicing ($F = 5.36$ (1, 105), $p < 0.01$; $F = 8.18$ (1, 105), $p < 0.01$) and there was a significant place × voicing interaction for stop closure voicing as well ($F = 4.22$ (2, 105), $p < 0.05$). Accordingly, bars for speaker BM in figures 4 and 5 (bottom) reveal the presence of the shortest closures for postnasal voiced stops and of the longest vocal fold vibration periods for postnasal voiced labial stops. Vocal fold vibration may extend beyond stop closure into the liquid for cluster /mbl/.

ANOVAs for speaker MJ suggest that closure voicing rather than closure duration may cue the underlying stop voicing distinction in this case. Indeed, this speaker exhibits a significant nasal × voicing interaction for the former versus latter dependent variable such that vocal fold vibration tends to occur in nasal clusters than in non-nasal ones [$F = 2.15$ (1, 105), $p < 0.05$; fig. 5, bottom].

Regarding speaker AR, factor loadings for stop closure duration and stop closure voicing are high but exhibit the same sign (table 3) which runs against the expected trend for stop closure to shorten as the voicing period during stop closure becomes longer. ANOVAs for this speaker show a main stop voicing effect on closure duration [$F = 5.84$ (1, 105), $p < 0.05$] but no main effect on closure voicing and no nasal × voicing interactions. Bars in figure 4 suggest that the expected differences in closure duration hold for nasal clusters only.

ANOVAs for the underlying stop voicing variables excluded from the factor analysis yielded no significant results for any of the speakers AR, BM and MJ, except for the alveolar stop contact index values which turned out to be significantly higher for /t/ vs /d/ in the case of speaker AR [$\bar{X} = 0.71$ versus 0.55; $F = 32.54$ (1, 24), $p < 0.001$].

Discussion

Data reported in the Results section reveal that voicing during the liquid is present as a continuation of closure voicing in clusters with underlying voiced stops, and is facilitated by the presence of /l/, a labial stop and a nasal in the cluster. Speakers differ with respect to the number of clusters exhibiting liquid voicing as well as to the duration of the voicing period in the progression speaker CA > speaker ND > speaker BM. Speakers AR and MJ did not allow for voicing during the liquid. This trend is consistent with other events associated with the liquid, i.e., gestural anticipation for /l/ (speaker CA showing more overlap between the liquid and the stop than speakers BM, ND) and a short vocalic element (for speaker CA and, less so, for speaker ND) occurring preferably in clusters with a nasal consonant and a voiced stop. The rhotic turned out to be consistently voiceless, exhibited longer frication periods than /l/, and was produced with one rather than two or more alveolar contact periods. All findings support the view expressed by native speakers of Majorcan Catalan that the liquid is non-syllabic in word-final clusters composed of stop and /l/ or /r/.

These results are also in agreement with previous reports stating that non-syllabic /l/ and /r/ may undergo devoicing in Majorcan Catalan (as well as in other languages), but in disagreement with the possibility that the liquid may be deleted since articulatory traces of those two consonants were consistently present in our speech material. Liquid devoicing is regularly accompanied by frication periods differing in duration according to liquid type (for /r/ > /l/) and to the underlying voicing status of the preceding stop for some speakers (for voiceless stops > voiced stops). Informal perception tests reveal that the liquid is not perceived whenever the frication noise becomes inaudible, e.g., *arregl, assembl, ungl* are perceived as [əˈrek], [əˈsɛmp], [uŋk] in the case of speaker BM, and *dobl, acopl, cobr* as [dop], [əˈkop], [kɔp] for speaker ND.

Regarding the status of the underlying voicing distinction, results from factor analysis show that stop closure duration and stop closure voicing are both relevant cues in marking the underlying stop voicing distinction. Hierarchical cluster analyses reveal that the presence of a preceding nasal consonant and, less so, the presence of following /l/ and the labial place of articulation for the stop, help to preserve the stop voicing contrast. The finding that the presence of a nasal contributes much to a reduction of the following oral stop closure is not due to the uncertainty in detecting the nasal murmur offset on spectrographic displays. As stated in 'Methods', nasal and stop closure durations were double-checked in order to make sure that this was not a problem. Some articulatory properties occurring outside the stop, i.e., liquid/stop overlap and liquid voicing, may be considered to be secondary stop voicing cues. Speakers fall to two groups regarding the robustness of the underlying voicing distinction and differ with respect to the production mechanisms used for its implementation. Perception tests are needed in order to find out whether those mesurements which have proved to be statistically significant separate the two voicing categories for speech communication.

Statistical data reveal that the phonetic distinction between underlying voiced and voiceless stops is robust for speakers ND and CA. An evaluation of the relative salience of cues shows that underlying stop voicing is mostly associated with stop consonant parameters but also with articulatory events occurring before and after the stop. Differences in supraglottal pressure and active vocal fold vibration for the stop cause differences in closure voicing, /l/ voicing, overlap between /l/ and the preceding stop and in nasal/nasal + stop ratio (for voiced stops > voiceless stops), and in stop closure duration, liquid duration, tongue contact degree for the stop and the liquid, frication duration and frequency of stop bursts (for voiceless stops > voiced stops). Moreover, the aerodynamic and articulatory conditions involved in the production of the three consecutive consonant segments in the cluster play a relevant role in the implementation of the stop voicing contrast. Indeed, the distinction is facilitated by the presence of a preceding nasal and, less so, by following liquid type (i.e., /l/) and stop place of articulation (i.e., labial).

The scenario for speakers ND and CA resembles that for Russian and French where syllable-final voiced stop clusters followed by /l/ and /r/ exhibit vocal fold vibration during the stop or during the stop and the liquid. Regarding Majorcan Catalan, the two liquids differ from each other in that phonetic voicing may occur throughout the entire cluster in sequences with /l/ but only during the stop in sequences with /r/. Data for speakers ND and CA allow one to conclude that final devoicing does not apply to stops in Majorcan Catalan clusters with a liquid. Vowel insertion between the stop and the liquid (in Majorcan Catalan) or immediately after the liquid (in other Romance languages and dialects) appear to be two different ways to cue the underlying stop voicing distinction at the phonetic level.

Data for speakers AM, BM and MJ conform to a different picture from the one for speakers ND and CA just referred to. Results obtained from the factor analyses suggest that closure duration and closure voicing may cue the underlying stop voicing contrast for speaker MJ, less so for speaker BM and perhaps not at all for speaker AR, and that no stop voicing cues occur beyond the stop consonant itself. It may be that, while failing to cue the stop vocing distinction at the perception level, some of those speakers or all of them may show some stop voicing traces in production. A look at the relative salience of stop voicing cues for those three speakers reveals that the phonemic distinction is related to the prominence of the stop closing gesture in so far as, in comparison with voiced stops, voiceless stops turned out to show longer closures (all speakers) and larger tongue contact areas (speaker AR). On the other hand, closure voicing may be present (speakers MJ and BM) or absent (speaker AR). Both cues are most prone to take place when the stop is labial and follows a nasal.

A data survey across speakers suggests that the phonetic implementation of present-day Majorcan Catalan word-final stop-liquid clusters is highly variable. This finding parallels the realization of analogous clusters with a non-syllabic liquid in French, Russian and Northern Italian (see Introduction). Moreover there are reasons to believe that a sound change process may be under way in the Catalan dialect. Indeed, while being robust for two out of three of the elder speakers (ND, CA), the voicing contrast is partially or completely neutralized in the case of the younger ones (AR, MJ). Judging from the phonetic cues and the contextual factors involved in stop devoicing, it may also be claimed that this sound change process proceeds gradually rather than abruptly. The initial devoicing stage appears to involve a restriction in the contextual conditions of phonetic implementation. Thus, while extending over the entire syllable, robust stop voicing cues for speakers CA and ND are only available if a nasal consonant is present. Data for the other three Majorcan Catalan speakers AR, BM and MJ indicate that, at a more advanced stage, phonetic cues for the underlying stop voicing distinction are not distributed over the entire consonant cluster and may be associated with aerodynamically conditioned differences in duration and prominence rather than with vocal fold vibration. Also in English, underlying stop voicing may be implemented through duration and intensity cues rather than through active voicing in sequences and word positions disallowing continuous vocal fold vibration.

While physiological cues for segmental syllabicity are not easy to come up with [Ladefoged, 1967], it seems to us that the syllabic versus non-syllabic status of the liquid in the word-final clusters /Cl/ and /Cr/ depends on whether the liquid may be phonetically voiced after a voiceless stop or not. Indeed, as revealed by data for Majorcan Catalan, voicing in non-syllabic liquids occurs as a continuation of closure voicing during the preceding stop closure period. On the other hand, voicing in syllabic liquids such as those in English or Slovak clusters may occur independently of the presence of phonetic voicing during the stop. It may thus be suggested that onset of vocal fold vibration is intentional in the latter clusters and unintentional in the former ones. Moreover, stop voicing is also related to voicing during the liquid such that underlying voiced stops exhibit vocal fold vibration if voicing extends into the liquid, and may undergo devoicing or not if the liquid is devoiced.

In view of this scenario, we would like to propose a reconstruction of those sound changes operating on word-final clusters with a liquid after the loss of word-final vowels in the transition from Latin to some Romance dialects. Let us assume to begin with that the liquid was syllabic after vowel loss. The change of syllabic status (i.e., from syllabic to non-syllabic) may have been accomplished through different mechanisms. Most frequently, there has been vowel epenthesis after the liquid or between the stop and the liquid (N. Italian [ˈnegər] from Latin NIGRU, Friulian [ˈdopli] from Latin DUPLU). A more uncommon strategy may have been to devoice the liquid after an underlying voiceless stop (i.e., as for speakers ND and CA in our study) and, later on, after an underlying voiced stop which has undergone partial or complete devoicing (i.e., as for speakers AR, BM and MJ in this paper). Data reported in the Results section show that voicing is an essential attribute of the syllabic status of the liquid such that a change in syllabic status links liquid voicing to the voicing in the preceding stop. On the other hand, stop devoicing may take place as long as the liquid is devoiced and thus, non-syllabic.

Results reported in this paper may be taken in support of the notion that sound change proceeds gradually across phonetic cues and speakers. They also suggest that the loss of a phonemic contrast occurs at the perceptual level before it takes place at the production level [see also Costa and Mattingly, 1981]. Indeed, while speakers produce the distinction between underlying voiced and voiceless stops as well as the following liquid systematically, phonetic transcriptions available in the literature suggest that phoneticians may hear the voiced stop as voiceless and fail to hear the liquid.

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