Journal of Phonetics (1996) **24,** 165–185

Linguopalatal coarticulation and alveolar-palatal correlations for velarized and non-velarized /l/

Daniel Recasens*, Jordi Fontdevila and Maria Dolors Pallarès
Laboratori de Fonètica, Institut d'Estudis Catalans, c/Carme, 47, Barcelona 08001, Spain

Received 29th July 1994, and in revised form 5th June 1995

Acoustic and electropalatographic data are presented involving palatal and alveolar contact coarticulation and alveolar-palatal contact correlations for Catalan velarized /l/ (5 speakers) and German non-velarized /l/ (4 speakers) in different vowel environments. Coarticulatory effects and significant alveolar-palatal correlations for German exceed those for Catalan which is consistent with the tongue body being more constrained for the velarized than the non-velarized realization. In comparison to non-velarized /l/, active predorsum lowering for velarized /l/ largely prevents dorsopalatal coarticulation with /i/ and tongue front–tongue dorsum coupling effects from occurring. Vowel-dependent variations in tongue dorsum position result in closure fronting differences for speakers of both languages which suggests that they use coordination mechanisms between the tongue tip and the tongue dorsum; however, not all speakers change closure location across vowel contexts.

1. Introduction

X-ray microbeam data for American English apicoalveolar /l/ adjacent to /i/, reported by Sproat & Fujimura (1993), indicate that the syllable-final velarized allophone ("dark" /l/) exhibited greater tongue dorsum retraction and lowering than the syllable-initial non-velarized allophone ("clear" /l/); moreover, maximum dorsal movement preceded maximum apical movement for the former while the opposite temporal relationship occured for the latter. This finding lead the authors to propose that the two English allophones involve two lingual gestures (i.e., apical and dorsal), the phonetic implementation of which depends on syllable position.

The same contrasting articulatory strategy appears to be at work for syllable-final /l/ in languages with "dark" /l/ (Catalan) *vs.* languages with "clear" /l/ (Italian) (Recasens & Farnetani, 1994). Electropalatographic data for syllable-final /l/ after /i/ in Catalan were found to show little or no dorsopalatal contact with considerable decrease in dorsopalatal contact throughout the vowel prior to tongue tip raising. Italian syllable-final /l/, on the other hand, showed a larger extent of dorsopalatal contact and a gradual decrease in dorsopalatal contact occurring after vowel offset.

* Also at Universitat Autònoma de Barcelona.

0095-4470/96/010165 + 20 $12.00/0

It seems to us that, while Sproat & Fujimura's proposal may account for articulatory differences between contextual allophones of /l/ within the same language (e.g., American English), the cross-language scenario described here supports the view that Catalan /l/ is a complex segment (involving two lingual gestures, i.e., apicoalveolar and postdorso-velopharyngeal) and Italian /l/ is a simple segment (produced with an apicoalveolar gesture only). Along these lines we will assume that, when articulated with adjacent /i/, an active tongue dorsum lowering and backing gesture for velarized /l/ blocks to a large extent tongue dorsum raising and fronting for the vowel; on the other hand, non-velarized /l/ allows effects from /i/ much more freely since this consonantal realization does not require the formation of a dorsal constriction (see Fig. 1; Recasens & Farnetani, 1990). This assumption is supported by VCV coarticulation data (Öhman, 1966; Choi & Keating, 1991) showing smaller or larger transconsonantal effects depending on whether the tongue dorsum is involved in the production of an intervocalic consonant (e.g., in Russian, Bulgarian, or Polish, all languages with contrastive palatalization) or not (e.g., in Swedish or English).

Results from a previous study (Recasens, Fontdevila & Pallarès, 1995) suggest however that, like Catalan velarized /l/, German non-velarized /l/ may undergo little vowel-related tongue dorsum raising and lowering because of a high degree of tongue dorsum control. Reported mean formant values for /ili/ obtained across several Catalan and German speakers conform to the language-dependent difference in velarization degree, with Catalan exhibiting a lower F_2 (1349.04 Hz $\pm$ 114.39) than German (1758.98 Hz $\pm$ 176.01). The fact that these F_2 values were highly correlated with the amount of dorsopalatal contact across speakers and languages was taken as evidence that they reflected speaker-dependent differences in degree of velarization. (It should be recalled that F_2 is positively correlated with tongue dorsum fronting and raising and thus inversely related to velarization; Fant, 1960). Contrary to our expectations, although essentially non-velarized, German /l/ was found to be highly resistant to F_2 coarticulatory effects associated with /i/ *vs.* /a/ (there being no significant differences in F_2 coarticulatory sensitivity between German non-velarized /l/ and Catalan velarized /l/). More specifically, in comparison with data from other languages showing a non-velarized variety of the consonant (French: Chafcouloff, 1985; Spanish: Recasens, 1987), German /l/ showed a higher F_2 in the sequence /ala/ and a lower F_2 in the sequence /ili/.

As an extension of Recasens *et al.* (1995), the present study reports linguopalatal contact data on Catalan velarized /l/ and German non-velarized /l/ recorded by the same speakers in the same experimental session. The previous contribution was an analysis of acoustic coarticulation; contact patterns for /ili/ and /ala/ were simply reproduced in order to illustrate language- and speaker-dependent differences in velarization degree. The motivation underlying this extension is to determine whether the tongue is equally constrained in both languages (which would match the acoustic coarticulatory effects reported in our previous paper) or else is less constrained in German than in Catalan (which would conform to the traditional differentiation between non-velarized and velarized /l/). Three main topics will be addressed in this respect.

A first topic of investigation is the extent to which small context-dependent differences in acoustic measures for German and Catalan are matched by a small degree of articulatory coarticulation. For that purpose coarticulatory effects in

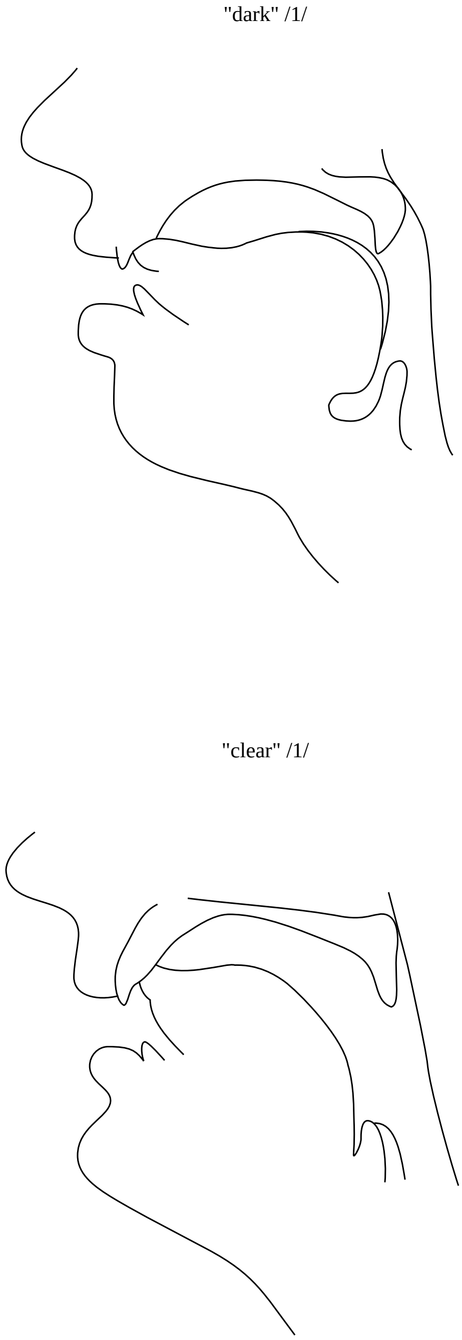


Figure 1. Sagittal configurations of the vocal tract for "dark" /l/ in Russian (top) and for "clear" /l/ in German (bottom) (from Ladefoged & Maddieson, 1986).

tongue dorsum contact as a function of /i/, /a/, and /u/ are analyzed for both /l/ types in order to verify possible differences in V-to-C coarticulation between the two consonantal varieties (Section 3.1). Two coarticulatory outcomes may occur. It may be the case that German /l/ shows more dorsopalatal coarticulation than Catalan /l/, in accordance with language–dependent differences in degree of consonantal velarization; smaller coarticulatory effects at the acoustic level than at the articulatory level for German /l/ in these circumstances could result from movement constraints at articulatory regions other than the tongue dorsum surface (e.g., postdorsum, lips, jaw). Alternatively, little acoustic variability for German /l/ could be matched by small coarticulatory effects in dorsopalatal contact; this finding would show that the tongue dorsum is quite constrained during the production of non-velarized /l/ in German. A more accurate account of the degree of dorsopalatal contact coarticulation for German /l/ can be obtained through comparison with analogous data for non-velarized /l/ in a language (Italian) exhibiting greater vowel-dependent acoustic variability (Recasens & Farnetani, 1990; Recasens, Farnetani, Ní Chasaide, Fontdevila, Pallarès, Provaglio & Fealey, 1991).

A second goal of this paper is to investigate the degrees of freedom for different tongue regions during the production of the two varieties of /l/ (Section 3.2). Vowel-dependent coarticulatory effects at the alveolar zone will be measured for the two consonantal varieties to test the following hypothesis: if the entire tongue body is more constrained for Catalan velarized /l/ than for its German non-velarized counterpart, a higher degree of coarticulatory resistance for the former *vs.* the latter variety should be obtained not only at the tongue dorsum but at the tongue front as well. This situation is analogous to that found for consonants exerting different demands on tongue body configuration according to manner of articulation characteristics. Thus, in a video-fluorographic experiment on British English CC clusters with /t/, /n/, /l/, and /s/, the first three consonants were found to present greater coarticulatory adjustments at the tongue front than the last (Bladon & Nolan, 1977). Also, tongue movement data obtained using electromagnetic mid-sagittal articulometry (EMA) revealed differences in degree of vowel-dependent variability at the tongue front for /n/, /l/ > /d/ > /t/ > /s/ (Hoole, Gfroerer & Tillmann, 1990). Little apicoalveolar sensitivity to coarticulatory effects is expected if German non-velarized /l/ involves a high degree of tongue body constraint. This outcome would co-occur presumably with little dorsopalatal contact sensitivity and would be in accordance with this consonant showing little F_2 variability as a function of the adjacent vowels.

A third research goal of this study is to infer the mechanisms of tongue tip–tongue dorsum coordination during the production of the two varieties of /l/ from an investigation of the correlations between alveolar contact and palatal contact (Section 3.3). Data on coarticulatory effects at the palatal zone (Section 3.1) and at the alveolar zone (Section 3.2) provide independent information about the degree of coarticulatory sensitivity at the tongue dorsum and at the tongue tip. A study of the alveolar-palatal contact correlations in Section 3.3 puts us in a better position to suggest production mechanisms involving the two lingual regions. A previous paper (Recasens, Fontdevila & Pallarès, 1992) reports a coordinative strategy between tongue front contact and tongue dorsum contact during the production of /n/ with adjacent vowels: closure location is postalveolar adjacent to back vowels /a/ and /u/, and extends towards the front alveolar zone adjacent to a vowel involving tongue dorsum raising and fronting, i.e., /i/. The tap /ɾ/ shows analogously a contact increase towards the front alveolar zone in the context of /i/ *vs.* /a/, /u/ (Catalan: Recasens, 1991).

It appears that apicoalveolar consonants not involving much tongue dorsum constraint undergo alveolar contact fronting and widening when the tongue dorsum is raised in the context of /i/ as opposed to when it is not (e.g., in the context of /a/). The following predictions about tongue tip-tongue dorsum coordination can be made for the two varieties of /l/: non-velarized /l/ should show an analogous coordination mechanism to that found for other apicoalveolar consonants provided that the tongue dorsum is sufficiently raised in the context of /i/; this should not be the case for velarized /l/ since active tongue dorsum lowering and retraction prevents this lingual region from being raised by adjacent /i/.

By using data from a large number of speakers (nine), this paper also allows study of subject-dependent differences in dorsopalatal and apicoalveolar coarticulation, and in alveolar-palatal coordination. A comparison between languages and individuals will address whether such differences proceed gradually from speakers who velarize the most to those who velarize the least.

2. Method

Electropalatographic (EPG) data on linguopalatal contact were recorded for the symmetrical sequences /ili/, /ala/, and /ulu/ with stress on the first syllable. As stated in the Introduction, Catalan and German were chosen since /l/ is known to be velarized in the former language (Recasens & Farnetani, 1990) and non-velarized in the latter (Schubiger, 1970). These sequences were repeated 5 times each by the speakers used in Recasens *et al.* (1995), i.e., 5 male speakers of the Eastern Catalan dialect and 3 male and 1 female speakers of German. Auditory judgments by the experimenters confirm the presence of velarization in /l/ for the 5 Catalan speakers and a non-velarized realization of the consonant for the 4 German speakers. In Eastern Catalan, /a/ in V2 position undergoes systematic vowel reduction in unstressed position and is thus realized as [ə].

The Reading electropalatographic system was used to collect the EPG data (Hardcastle, Jones, Knight, Trudgeon & Calder, 1989). As shown in Fig. 2 (top), the artificial palate is equipped with 62 electrodes arranged in eight horizontal rows (R1, . . . , R8) and four vertical columns on each half of the palatal surface (C1, . . . , C4). The figure also shows the articulatory subdivisions along the tongue surface (on a midsagittal cross-section; bottom) and along the palatal surface (both on a palatographic and on an X-ray configuration; top and bottom, respectively). The alveolar zone includes the 4 front rows and the palatal zone includes the 4 back rows; the distance between adjacent rows is much smaller at the former zone than at the latter. This EPG system allows display of one pattern of contact every 5 ms.

Catalan and German speakers have been assigned a numerical code with the highest number for the speaker with the most velarized realizations and the lowest number for the speaker with the least velarized /l/ (i.e., CAT1, CAT2, CAT3, CAT4, CAT5, GER1, GER2, GER3, GER4) taking the F_2 frequency values for /ili/ in Recasens *et al.* (1995) as the criteria for classification. These numerical codes will be used for speaker identification throughout this paper. To a large extent, these F_2 frequency values are directly related to lingual contact size at the palatal zone (see

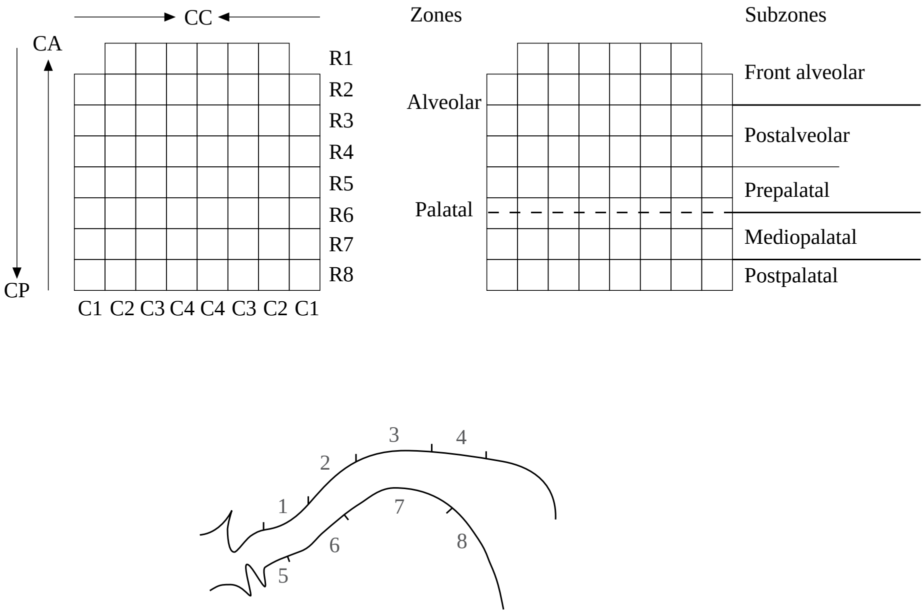


Figure 2. Top left: Distribution of rows R1 through R8 along the anteriority (CA) and posteriority (CP) dimensions, and of columns C1 through C4 along the centrality (CC) dimension on both sides of the electropalate. Top, right: Articulatory zones and subzones on the electropalate. Bottom: Vocal tract representation with articulatory zones and subzones, and tongue regions: (1) alveolar, (2) prepalatal, (3) mediopalatal, (4) postpalatal, (5) tongue tip and tongue blade, (6) predorsum, (7) mediodorsum, (8) postdorsum.

EPG configurations for /ili/ in Figs. 3 and 4, below). German speakers exhibiting a high F_2 frequency at about 1800–1900 Hz (i.e., GER2, GER3, and GER4) present maximum dorsopalatal contact; GER1 shows less dorsopalatal contact and a somewhat lower F_2 frequency. In Catalan, the consonant is clearly velarized for CAT1, CAT2, and CAT3, as indicated by its being produced with little dorsopalatal contact and a low F_2 frequency below 1300 Hz; speakers CAT5 and (less so) CAT4, on the other hand, show a consonantal realization involving more dorsopalatal contact and a somewhat higher F_2 frequency at about 1450 Hz.

The EPG data were measured at the midpoint of consonantal closure. The EPG patterns were analyzed with reference to four contact indices at each articulatory zone, i.e., alveolar contact indices Qa, CAa, CPa, and CCa, and palatal contact indices Qp, CAp, CPp, and CCp. The index Q (overall contact index) is calculated by adding up the number of activated electrodes at a given articulatory zone. The other three indices express contact directionality, i.e., contact anteriority towards the front (CA), contact posteriority towards the back (CP), and contact centrality towards the median line (CC) (see Fig. 2). Values for these indices proceed from 0 (least anterior, posterior, and central) to 1 (most anterior, posterior, and central). The calculation procedure for the CA, CP, and CC contact indices is explained in Appendix 1 (Fontdevila, Pallarès & Recasens, 1994). Mean contact index values (including Q) are given in Appendix 2.

In order to measure whether alveolar and palatal coarticulatory effects were significant, one-way ANOVAs (Scheffé) were performed separately for each speaker with alveolar and palatal contact indices as the dependent variable and contextual vowel as the independent variable. The interactions between alveolar contact and palatal contact were measured by means of a correlation analysis between the contact index values at the two articulatory zones (i.e., alveolar × palatal) for each speaker across the three vowel conditions.

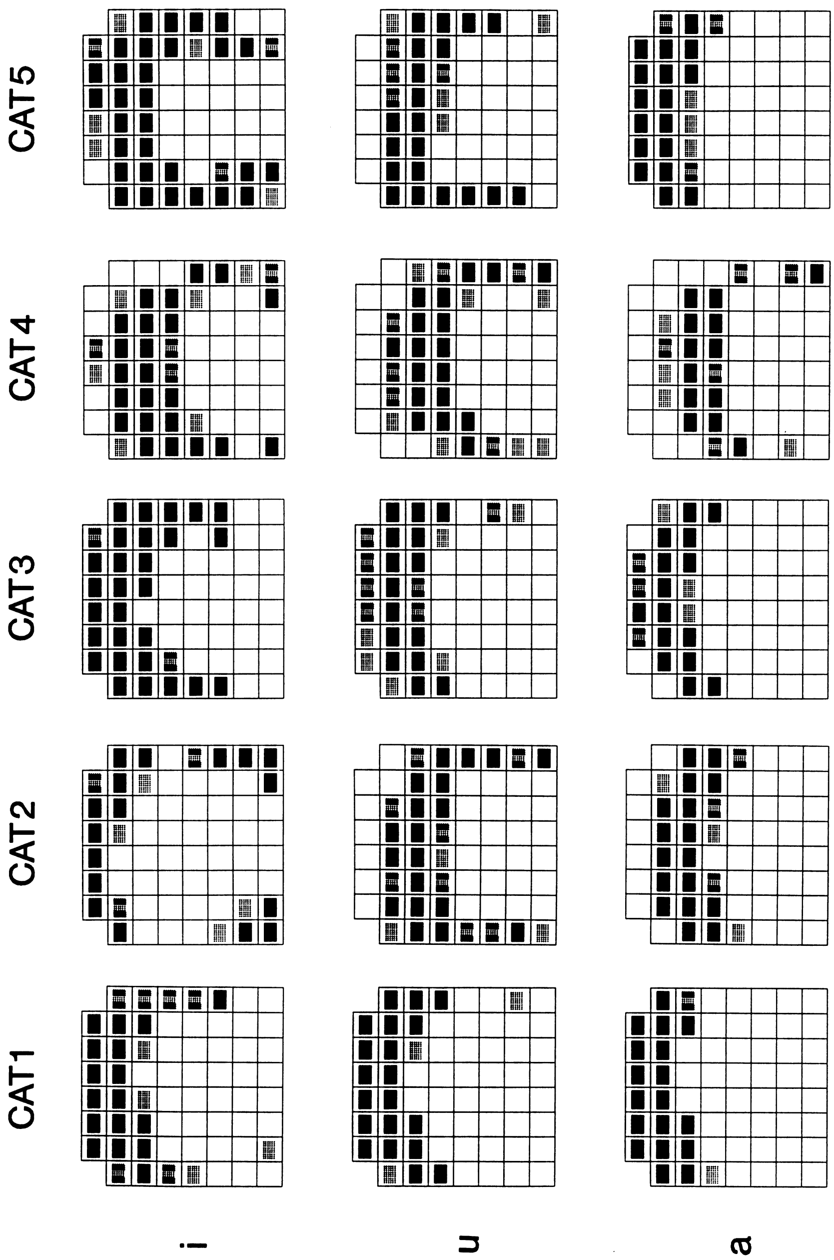
3. Results

3.1. *Coarticulatory effects at the palatal zone*

An estimate of the degree of coarticulatory sensitivity at the palatal zone (and thus of tongue dorsum coarticulation) is inferred from the percentage of significant effects across contact indices, vowel contexts, and speakers. As shown in Table I, this overall percentage is smaller in Catalan (51.67%) than in German (79.17%). Figs. 3 and 4 give the linguopalatal contact patterns for the 5 Catalan speakers (Fig. 3)

Table I. Significant coarticulatory effects in contact index values for intervocalic /l/ as a function of different vowel pairs ($p < 0.01$). Data are displayed for each of the nine speakers. Speakers are ordered according to degree of /l/ velarization. CAT = CATALAN, GER = GERMAN

	Alveolar zone				Palatal zone			
	CAa	CPa	CCa	Qa	CAp	CPp	CCp	Qp
ili/ala								
CAT1					*		*	*
CAT2	*	*				*	*	*
CAT3		*		*	*		*	*
CAT4								*
CAT5		*			*	*	*	*
GER1			*		*	*	*	*
GER2	*	*	*	*	*	*	*	*
GER3		*		*	*	*	*	*
GER4	*	*	*	*	*	*	*	*
ulu/ala								
CAT1								
CAT2						*	*	*
CAT3								
CAT4								*
CAT5	*	*			*	*	*	*
GER1						*		*
GER2	*			*	*	*	*	*
GER3		*		*	*	*	*	*
GER4	*	*	*	*	*	*	*	*
ili/ulu								
CAT1							*	*
CAT2	*	*				*	*	
CAT3					*		*	*
CAT4								
CAT5	*						*	*
GER1			*		*	*	*	*
GER2		*		*				*
GER3								
GER4						*	*	*


CAT5
CAT4
CAT3
CAT2
CAT1
i
u
a

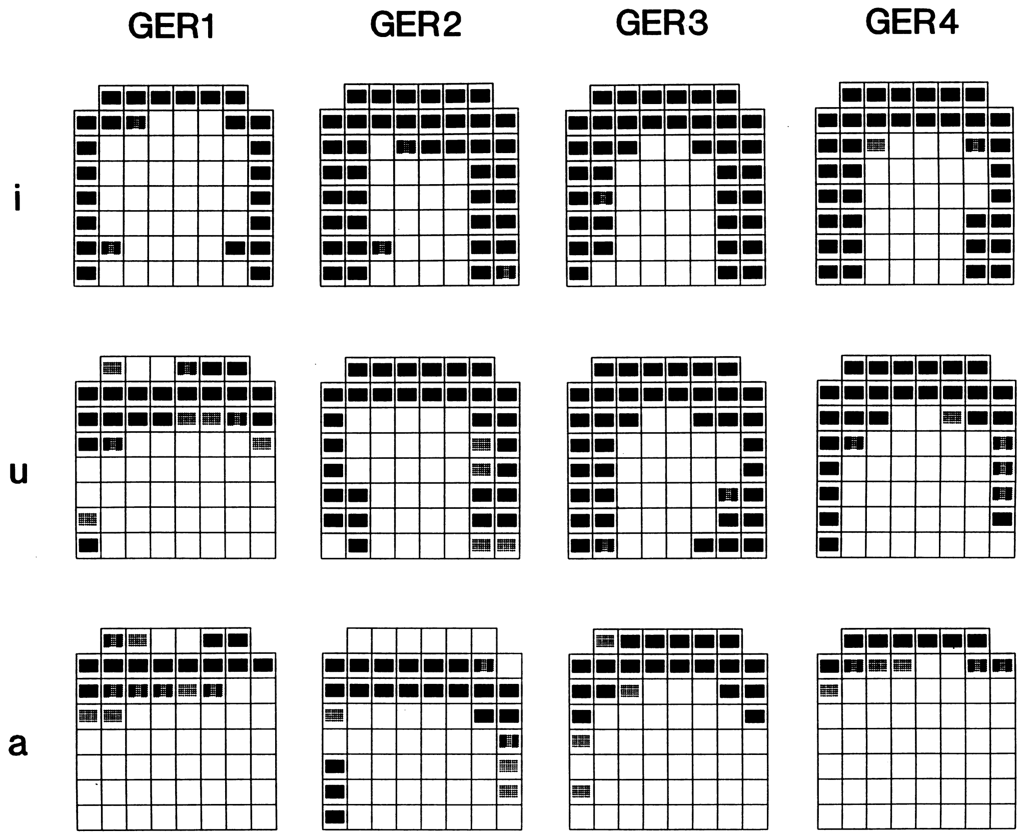


Figure 4. Linguopalatal contact configurations at the /l/ closure midpoint in the sequences /ili/, /ala/, and /ulu/ for 4 German speakers. Percentage of electrode activation: (■) 80–100%; ( ) 60–80%; ( ) 40–60%; (□) less than 40%.

and the 4 German speakers (Fig. 4). Inspection of the mean linguopalatal configurations in these figures, and of the mean contact index values in Appendix 2, will be used in interpreting the significant effects reported in Table I. Effects will be discussed for each pair of vowel contexts.

3.1.1. *High front* /i/ vs. *low back* /a/

Both languages allow a high percentage of significant coarticulatory effects as a function of /i/ *vs.* /a/, more so German (100%) than Catalan (70%). Significant differences are found regardless of whether /l/ involves considerable or little dorsopalatal contact in the sequence /ili/ since negligible dorsopalatal contact is found during the closure period in /ala/. They affect all contact indices for all 4 German speakers, and Qp and CCp for most Catalan speakers. In Catalan, effects at the front (CAp) and at the back (CPp) palatal zone occur less frequently, in line with /i/ causing little tongue dorsum raising during velarized /l/.

The size of the coarticulatory effects (see Appendix 2) is much larger for the non-velarized than for the velarized realizations of /l/. Indeed, the Qp difference between /ili/ and /ala/ exceeds 11 "on" electrodes for the non-velarized variety (GER4: 14.80; GER3: 13.80; GER2: 12.20), and is less than 7 "on" electrodes for the velarized variety (CAT2: 6.60; CAT3: 4.60; CAT4: 3.60; CAT1: 3.40). Qp effects of intermediate size occur for the Catalan speaker showing the least velarized realization (CAT5: 10.80) and for the German speaker showing the most velarized realization (GER1: 9.60). These language-dependent differences are mostly related to /i/ causing a larger increase in dorsopalatal contact for the non-velarized than for the velarized variety of /l/.

Coarticulatory effects associated with /i/ *vs.* /a/ should be even larger than those reported above whenever the vowel /a/ causes more tongue dorsum lowering than that reflected in the EPG data in Figs. 3 and 4.

3.1.2. *High back* /u/ vs. *low back* /a/

The overall percentage of significant effects at the palatal zone as a function of /u/ *vs.* /a/ is almost twice as large in German (87.50%) as in Catalan (40%).

Significant coarticulatory effects occur for all contact indices for the three German speakers showing a non-velarized variety of /l/ (GER2, GER3, GER4), and for the Catalan speaker exhibiting the least velarized realization (CAT5). However, the size of the Qp effects is smaller for the Catalan speaker (CAT5: 5.20) than for the three German speakers (GER3: 14.20; GER2: 8.20; GER4: 5.80). These coarticulatory effects are associated with contact differences resulting from the tongue dorsum being pulled downwards by adjacent /a/ (little or no contact occurs during the closure period in the sequence /ala/) but not (or less so) by adjacent /u/. (Contact at the sides of the palatal zone in the sequence /ulu/ is consistent with this vowel having active postdorsum raising and no active movement at fronter tongue dorsum regions.)

A different coarticulatory behaviour obtains for those Catalan speakers favouring a clearly velarized realization of /l/ (CAT1, CAT2, CAT3, and CAT4) and for the German speaker lacking a strongly non-velarized variety of the consonant (GER1). None of these speakers presents significant effects at the front palatal zone (in CAp), consistent with the tongue predorsum for velarized /l/ occupying a lowered position when adjacent to both /u/ and /a/. Speakers CAT2 and GER1 exhibit significant effects at the back palatal zone (for /ulu/ > /ala/), in line with /l/ sharing some postdorsum raising adjacent to /u/ but not adjacent to /a/. Speakers CAT1 and CAT3 show no significant effects since their consonantal realizations in the sequences /ulu/ and /ala/ are articulated with almost no dorsopalatal contact at closure midpoint. As expected, the size of the Qp effects for all five speakers of this group is smaller than that for the speakers of the first group (CAT2: 4.80; CAT4: 3.60; GER1: 1.40; CAT1, CAT3: 1.00). In summary, the fact that velarized /l/ and the back vowels /u/ and /a/ are produced with highly compatible lingual configurations prevents much V-to-C coarticulation at the tongue dorsum surface from occurring.

3.1.3. *High front* /i/ vs. *high back* /u/

The percentage of significant dorsopalatal effects associated with /i/ *vs.* /u/ is almost the same in the two languages (45% in Catalan, 50% in German).

Unlike the coarticulatory effects associated with /i/ *vs.* /a/ and /u/ *vs.* /a/, the degree of V-to-C coarticulation from /i/ *vs.* /u/ is not always inversely related to the degree of consonantal velarization. Non-velarized consonantal realizations allow coarticulatory effects for speakers GER1, GER2, and GER4 (with /ili/ showing more dorsopalatal contact than /ulu/) but not for GER3 (with both /ili/ and /ulu/ exhibiting a good deal of dorsopalatal contact). Among speakers producing a velarized variety, significant effects are absent for CAT4 (his /l/ showing little dorsopalatal contact in both /ili/ and /ulu/ sequences), but present for CAT1, CAT2, CAT3, and CAT5 (their /l/ being articulated with more contact in /ili/ than in /ulu/ at different locations over the palatal zone). It should be noticed that V-to-C effects from /i/ *vs.* /u/ in CAp (at the front palatal zone) and in CPp (at the back palatal zone) are frequently absent for the two realizations of /l/. In summary, in comparison to V-to-C effects in other vocalic conditions, effects from high /i/ and /u/ are clearly smaller in German since both vowels cause a good deal of dorsopalatal contact during non-velarized /l/; Catalan shows a similar degree of coarticulation as a function of this *vs.* other vowel pairs in line with /i/ and /u/ causing little dorsopalatal contact.

However, it can be claimed that coarticulatory effects in dorsopalatal contact as a function of /i/ *vs.* /u/ are larger for the non-velarized than for the velarized variety of /l/. Indeed, the size of the Qp effects (see Appendix 2) is larger for the speakers of the first group (GER4: 9.00; GER1: 8.20; GER2: 4.00) than for most speakers of the second group (CAT3: 3.60; CAT1: 2.40; CAT2: 1.80; CAT4: 0.00). These coarticulatory differences between the two varieties of /l/ are associated with /i/ causing more tongue dorsum raising for non-velarized /l/ than for velarized /l/.

3.1.4. *Summary*

Data reported in this section can be viewed as supporting differences in coarticulatory resistance between the two consonantal varieties. Active tongue dorsum lowering for velarized /l/ causes some blocking of the tongue dorsum raising effects of /i/; the resulting lingual configuration is not very different from that obtained when velarized /l/ is adjacent to vowels /a/ and /u/ produced with low dorsal configuration analogous to that for the consonant. In the case of non-velarized /l/, the predorsum is pulled upwards by adjacent /i/ and downwards by adjacent /a/ (which is in agreement with both vowels involving active tongue dorsum displacement), but occupies an intermediate position in the sequence /ulu/ (since the front dorsum does not intervene actively in the production of /u/).

3.2. *Coarticulatory effects at the alveolar zone*

The results in Table I show that both languages allow a smaller percentage of significant vowel-dependent coarticulatory effects at the alveolar zone than at the palatal zone, suggesting that the tongue dorsum is more sensitive to vocalic influences than is the primary apicolaminal articulator. The table displays a larger number of significant effects across contact indices, vowel contexts, and speakers in German (36.67%) than in Catalan (16.67%), thus revealing that non-velarized /l/ allows more alveolar coarticulation than does velarized /l/. The average number of V-to-C effects for specific vowel pairs in the alveolar zone is highly similar to that reported for the palatal zone: German shows more alveolar coarticulation than Catalan as a function of high *vs.* low vowels (/i/ *vs.* /a/ = 25% in Catalan, 68.75% in German; /u/ *vs.* /a/ = 10% in Catalan, 50% in German) while the two languages are equally sensitive to effects in lingual fronting from /i/ *vs.* /u/ (15% in Catalan, 18.75% in German).

As before, the mean linguopalatal configurations in Figs. 3 and 4, and mean contact index values in Appendix 2, will be used in interpreting the significant effects reported in Table I.

3.2.1. *Catalan*

Significant effects for speaker CAT2 occur as a function of /i/ *vs.* /a/ and /u/. They take place in CAa (for /i/ > /a/, /u/) and in CPa (for /a/, /u/ > /i/), meaning that the apical closure is displaced either towards the front alveolar zone or towards the back alveolar zone, depending on whether the adjacent vowel is front or back. A lower (non-significant) CCa value in the context of front /i/ *vs.* back /a/ and /u/ results from the former context causing a very front closure location while preventing much articulatory coupling between tongue front and tongue dorsum from occurring.

Speaker CAT3 exhibits significant differences in closure retraction (in CPa and Qa) for /i/ > /a/, attributable to articulatory coupling between the tongue front and the tongue dorsum: more tongue dorsum raising during the closure period for /ili/ than for /ala/ causes a contact increase at the sides of the postalveolar zone. Higher (non-significant) CAa index values with adjacent /i/ *vs.* /a/, /u/ indicate closure fronting as a function of front *vs.* back vowels.

Speakers CAT1 and CAT4 show no significant coarticulatory effects. Closure location is fixedly front alveolar for CAT1 and non-significantly more front with adjacent front *vs.* back vowels for CAT4. The absence of significant effects in CPa and CCa for both speakers suggests that active articulatory coupling is not involved during the production of the sequence /ili/.

Finally, closure location for speaker CAT5 is more front adjacent to unrounded *vs.* rounded vowels at the front alveolar zone (as shown by significantly higher CAa values for /i/, /a/, *vs.* /u/) and more retracted with adjacent high *vs.* low vowels at the back alveolar zone (which results in significantly higher CPa values for /i/, /u/ *vs.* /a/). For this particular speaker, closure retraction appears to be associated with two gestures: on the one hand, lip rounding for /u/ causes an enlargement of the cavity in front of the closure location; on the other hand, tongue dorsum raising for /i/ causes an increase in contact at the postalveolar zone and may be associated with coupling effects.

In summary, some speakers (CAT1, CAT4) show a fixed closure placement across vowel conditions which is in accordance with a highly constrained tongue dorsum gesture for velarized /l/ preventing the tongue tip from adapting to the adjacent vowels. For CAT2, vowel-related changes in closure fronting reflect differences in tongue dorsum height which could be attributed to the following coordination mechanism: closure fronting co-occurs with tongue dorsum raising while tongue dorsum lowering conveys closure retraction. This mechanism of articulatory coordination appears to be independent of mechanical coupling effects since tongue dorsum raising for /i/ during the consonant does not cause an increase in contact at the back alveolar zone. Speaker CAT5 presumably uses another mechanism of articulatory coordination, with rounded /u/ causing a more posterior closure location than unrounded /i/ and /a/. Other coarticulatory effects for speakers

CAT3 and CAT5 result from articulatory coupling between the tongue front and the tongue dorsum; however, they are small and confined to the postalveolar zone since active tongue predorsum lowering for velarized /l/ (see Fig. 1) prevents much tongue front raising from occurring.

These data for Catalan reveal the presence of restricted alveolar contact in line with little articulatory coupling taking place in all instances. Closure placement is quite fixed for three speakers (CAT1, CAT3, CAT4) and varies according to some vowel dimension for the other two speakers (i.e., vowel height for CAT2; vowel backness for CAT5). Speaker-dependent differences in alveolar closure location do not appear to be related to degree of consonantal velarization.

3.2.2. *German*

The contact patterns in Fig. 4 show that /l/ is produced with a front alveolar closure by those German speakers exhibiting an obvious non-velarized variety of the consonant, i.e., GER2, GER3, and GER4. The articulator involved in this front closure formation should be the tongue tip. A vowel-dependent increase in tongue dorsum contact for these speakers conveys a contact increase towards the postalveolar zone (and presumably some laminal activation), as shown by significantly higher CPa, CCa, and/or Qa values for /ili/ and /ulu/ than for /ala/ (see Table I and Appendix 2). These effects are clearly associated with articulatory coupling between the tongue front and the tongue dorsum: raising the tongue dorsum causes some raising of the tongue blade, thus extending the contact area towards the postalveolar zone. Moreover, speaker GER2 allows some significant closure backing for /ala/ *vs.* /ulu/.

Coarticulatory effects for speaker GER1 (in CCa for /u/, /a/ > /i/) occur in closure fronting as a function of front *vs.* back vowels; these vowel-dependent effects suggest that this speaker uses a coordination strategy between closure fronting and tongue dorsum fronting and raising. Unlike the other German speakers, GER1 shows a restricted closure extent independently of vowel context which presumably indicates the presence of an apical articulation with no laminal involvement and thus, the absence of coupling effects between the tongue front and the tongue dorsum.

In summary, in comparison to the Catalan speakers, most German speakers (GER2, GER3, and GER4) show a more extensive degree of contact towards the postalveolar zone when /l/ is adjacent to /i/ and, less so, /u/; in these circumstances, tongue dorsum raising causes an increase in lamino-postalveolar contact while full contact is kept at the front alveolar zone. Closure placement remains fixed with adjacent /a/ for two of these speakers (GER3, GER4) but undergoes active retraction for a third speaker (GER2). The speaker showing the most velarized consonantal realization of all of the German speakers (i.e., GER1) resembles those Catalan speakers who present little postalveolar contact; analogously to CAT2, closure fronting for this speaker varies as a function of differences in vowel height.

3.3. *Alveolar-palatal correlations*

As was pointed out in the Introduction, a more thorough evaluation of the production strategies suggested in sections 3.1 and 3.2 follows from a study of the alveolar-palatal contact interactions. The significant alveolar-palatal correlations for

Table II. Significant alveolar-palatal correlations for [l] across vowel conditions in German ($p < 0.01$). r values are displayed separately for each speaker and for each pair of alveolar and palatal contact indices. Speakers are ordered according to degree of /l/ velarization.

	CAa	CPa	CCa	Qa
GER1				
CAp	0.689		−0.728	
CPp				
CCp	0.666		−0.716	
Qp	0.679		−0.716	
GER2				
CAp	0.788			0.673
CPp	0.819		0.763	0.878
CCp	0.896			0.783
Qp	0.922		0.717	0.897
GER3				
CAp		0.760		
CPp		0.797		
CCp		0.860		0.665
Qp		0.898		0.731
GER4				
CAp	0.836	0.925	0.863	0.919
CPp	0.852	0.946	0.821	0.885
CCp		0.700		
Qp	0.707	0.806	0.681	0.742

the 4 German speakers are given in Table II. A corresponding table for the Catalan speakers is nor provided here because no Catalan speaker had more than two significant correlations. The average percent significant correlations was only 6.25% for the Catalan speakers, in comparison to an average 54.7% for the German speakers. The language-dependent difference in percentage of significant alveolar-palatal correlations (48.45) exceeds that for the significant effects at the palatal zone (79.17% for German—51.67% for Catalan = 27.5; see Section 3.1.) and at the alveolar zone (36.67% for German—16.67% for Catalan = 20; see Section 3.2.). As shown below, speakers differ with respect to the particular strategy used for consonantal production.

3.3.1. *Catalan*

In Catalan, some significant correlations for speakers CAT3 and CAT5 can be attributed to coupling effects between adjacent lingual regions; this trend was already suggested in Section 3.2.1 and is now confirmed by the correlation analyses. Speaker CAT3 shows significant correlations between Qa, on the one hand, and CCp ($r = 0.67$) and Qp ($r = 0.726$), on the other hand; these significant interactions reflect an increase in tongue dorsum raising (i.e., higher CCp and Qp values) for either /i/ > /u/ > /a/ or /i/ > /u/, /a/ causing an increase in laminoalveolar contact size (i.e., higher Qa values). As for speaker CAT5, a significant correlation between CPa and CAp ($r = 0.733$) indicates an increase in predorso-prepalatal contact (i.e., a higher CAp value), for /i/, /u/ > /a/ resulting in an increase in postalveolar contact (i.e., higher CPa values).

For speaker CAT2, differences in CCp or dorsal contact at the central palatal zone (for either /i/ > /u/, /a/ or /i/ > /u/ > /a/) are negatively correlated ($r = -0.646$) with differences in CPa or postalveolar contact (for either /a/, /u/ > /i/ or /a/ > /u/ > /i/). This significant correlation is in agreement with the strategy of articulatory coordination indicated in Section 3.2.1, with tongue dorsum raising conveying closure fronting and tongue dorsum lowering co-occurring with closure backing. The fact that the significant correlation between CPa and degree of palatal contact is negative instead of positive confirms the absence of mechanical coupling effects (Section 3.2.1); indeed, tongue dorsum raising for /i/ does not cause a contact increase at the postalveolar zone.

Speakers CAT1 and CAT4 show no relevant correlations, which is in support of the tongue tip forming a fixed closure location in this case (Section 3.2.1).

To summarize, a highly constrained lingual configuration for velarized /l/ explains the absence of significant alveolar-palatal interactions for some speakers (CAT1, CAT4). Other speakers may reveal the following significant alveolar-palatal interactions: covariations in apical fronting and in tongue dorsum raising which are attributed to a coordination mechanism (CAT2); covariations in extent of post-alveolar and dorsopalatal contact which have been assigned to coupling effects between adjacent tongue regions (CAT3, CAT5). Differences in apicoalveolar contact fronting as a function of rounded *vs.* unrounded vowels for speaker CAT5 (Section 3.2.1) are not correlated with dorsopalatal contact changes which may be taken in support of a coordination strategy involving the tongue tip and the lips.

3.3.2. *German*

According to Table II, significant correlations for those German speakers showing the least velarized variety of /l/ (i.e., GER3 and GER4) are clearly related to coupling effects between the tongue front and the tongue dorsum (see Section 3.2.2, as well). Indeed, a contact increase all over the palatal zone (i.e., for all palatal contact indices) as a function of high *vs.* low vowels conveys an increase in overall alveolar contact; thus, GER3 and GER4 show significant correlations between Qp and Qa. As expected, this alveolar contact increase occurs systematically at the postalveolar zone (in CPa) for the two speakers; a contact increase at the front alveolar zone (in CAa) is only found for GER4 in line with both speakers showing a fixedly advanced closure location.

Significant correlations for speaker GER1 can be attributed to the same mechanism of articulatory coordination pointed out for Catalan speaker CAT2, with changes in CAa or closure fronting being positively correlated with dorsopalatal contact variations (for either /i/ > /u/, /a/ or /i/ > /u/ > /a/). Table II also reveals significant negative variations between palatal contact (most contact indices) and central alveolar contact (CCa); this interaction is in accordance with closure being more extensive at the postalveolar zone (for /ala/ and /ulu/) than at the front alveolar zone (for /ili/).

Finally, speaker GER2 shows significant correlations which can be attributed to a coordination mechanism (between CAa and all palatal contact indices for /i/, /u/ > /a/) and to a coupling mechanism (between Qa and all palatal contact indices for either /i/, /u/ > /a/ or /i/ > /u/ > /a/). Coupling effects for this speaker coincide with those found for GER3 and GER4; in addition, GER2 shows active closure retraction when the tongue dorsum is not raised for a high vowel (see Section 3.2.2).

Unlike the Catalan speakers, all German speakers show alveolar-palatal interactions. Correlations associated with tongue front-tongue dorsum coupling are particularly salient (GER2, GER3, GER4) and occur when tongue dorsum raising causes an increase in postalveolar contact. Coordination mechanisms also take place when closure fronting is affected by tongue dorsum raising (GER1, GER2). Interestingly, the German speaker with the most velarized realization of /l/ (GER1) is the only speaker for whom coupling effects play no significant role.

4. Discussion and Conclusions

Data on coarticulatory effects and on alveolar-palatal correlations reported in this paper support the initial hypothesis that the tongue body is subject to more articulatory control for Catalan velarized /l/ than for German non-velarized /l/. It was found that the latter realization allows more alveolar and palatal coarticulation than the former.

Coarticulatory trends for Catalan and German are in agreement with differences in degree of velarization between the two consonantal realizations and with the notion that they are produced with either two ("dark" /l/) or one ("clear" /l/) lingual gestures. Differences in degree of dorsopalatal coarticulation between the two varieties of /l/ are mostly associated with sensitivity levels to tongue dorsum raising effects exerted by adjacent /i/ in the sequence /ili/. A trend towards a more context-independent articulatory configuration for velarized /l/ than for non-velarized /l/ is consistent with the former realization showing less dorsopalatal contact than the latter in the sequence /ulu/. Both consonantal varieties show no dorsopalatal contact in the sequence /ala/; indeed, the tongue dorsum position for the consonant is too low in this VCV sequence for the EPG technique to exhibit any contact traces. EPG patterns for Italian /ili/ and /ala/ in previous studies (see Introduction) have shown similar degrees of dorsopalatal contact to those reported here for German.

As pointed out by Recasens *et al.* (1995) (see Introduction), the small F_2 difference between /ili/ and /ala/ for German /l/ suggests that the tongue dorsum is directed towards some target position. According to the F_2 frequency values reported in that study, this non-velarized consonantal variety would be resistant to tongue dorsum lowering effects from /a/ and to tongue dorsum raising effects from /i/. Data for most German speakers reported in the present paper show a good deal of V-to-C coarticulation at the palatal zone and thus are not in support of our hypothesis. This is not surprising since EPG data do not provide information about the tongue dorsum surface position for /ala/, about lingual activity at the tongue postdorsum and at the tongue root, or about lip and jaw activity.

Another issue of interest is the degree of coarticulatory sensitivity at closure location. Context-dependent changes in tongue dorsum placement may cause more variation in alveolar contact (both in location and extent) for non-velarized /l/ than for velarized /l/ which may be adduced in support of the notion that the former variety involves less tongue body constraint than the latter. This language-dependent difference is mostly associated with coupling effects: active tongue predorsum lowering for velarized /l/ prevents much coupling with the tongue front and thus much lamino-postalveolar contact from occurring; on the other hand, coupling effects play a major role for non-velarized /l/ with tongue dorsum raising causing laminal involvement when the consonant is adjacent to high vowels. Variations in extent of alveolar contact as a function of tongue dorsum raising and fronting degree have also been reported for other unconstrained alveolar consonants (/n/ and /ɾ/; see Introduction).

Speakers of both languages do not clearly differ with respect to vowel-dependent changes in apicoalveolar closure placement (some undergo such changes and others do not). More specifically, it has been found that closure location for German /l/ occurs quite fixedly at the front alveolar zone which runs against data for other consonants (/n/ and /ɾ/; see Introduction) showing a postalveolar closure adjacent to back vowels and a front alveolar closure adjacent to /i/. It seems clear that a limited amount of contextual adaptability in closure placement for German /l/ is a language-specific characteristic which could be related to coarticulatory resistance in F_2 frequency and presumably at some vocal tract regions. This hypothesis is consistent with velarized /l/ for the Catalan speakers CAT1, CAT2, and CAT4 showing less variability in closure placement than /n/ (Recasens *et al.,* 1992) as a function of tongue dorsum changes associated with front *vs.* back vowels. Thus, CAT1 keeps a front alveolar closure for /l/ in the three vowel context conditions while showing a front alveolar closure for /ini/ and /ana/ and a more retracted one for /unu/. As for CAT2 and CAT4, differences between /n/ and /l/ are as follows: closure location is front alveolar for /ini/ and postalveolar (speaker CAT2) or prepalatal (speaker CAT4) for /ana/ and /unu/; while an analogous closure retraction is found in /ala/ and /ulu/, closure backing only reaches the centroalveolar zone for speaker CAT2 and the postalveolar zone for speaker CAT4. Data for these three speakers suggest the existence of more apical control during the production of velarized /l/ than during the production of /n/.

Language-dependent differences in degree of tongue front-tongue dorsum coupling explain why alveolar-palatal correlations are so much larger for German than for Catalan; as pointed out above, such differences conform to the requirement that the tongue predorsum be somewhat lowered for velarized /l/ but not for non-velarized /l/. Otherwise speakers using the two varieties of /l/ exhibit similar production mechanisms: some speakers keep a fixed closure location across vowel environments while allowing tongue dorsum raising to occur in sequences with high vowels (CAT1); others use a coordination mechanism which combines tongue dorsum raising and alveolar closure fronting, and tongue dorsum lowering and alveolar closure backing (CAT2). Differences in closure fronting may also reflect a coordination mechanism between lip rounding and closure backing (CAT5), presumably in order to facilitate the lowering of the formant frequencies associated with a rounded vowel.

In comparison to other speakers of the same language, speakers showing intermediate degrees of velarization present a specific behaviour of alveolar–palatal coordination. Thus, speaker GER1 does not show much interarticulatory coupling, possibly due to his exhibiting the most velarized /l/ of all the German speakers. In comparison to other Catalan speakers, CAT3 and CAT5 show more variation in extent of postalveolar contact as a function of differences in dorsopalatal contact, which we have attributed to coupling effects between adjacent tongue regions.

This research has been supported by the ESPRIT BRA-7098 ACCOR II Working Group of the EC and by DGICYT project CE93-0020 of the Ministry of Education and Science of Spain.

References

Bladon, R. A. W. & Nolan, F. J. (1977) A video-fluorographic investigation of tip and blade alveolars in English, *Journal of Phonetics,* **5**, 185–193.

Chafcouloff, M. (1985) The spectral characteristics of the lateral /l/ in French, *Travaux de l'Institut de Phonétique d'Aix,* Université de Provence, **10**, 63–98.

Choi, J. D. & Keating, P. (1991) Vowel-to-vowel coarticulation in three Slavic languages, *UCLA Working Papers in Phonetics,* **78**, 78–86.

Fant, G. (1960) *Acoustic Theory of Speech Production.* The Hague: Mouton.

Fontdevila, J., Pallarès, M. D. & Recasens, D. (1994) The contact index method of electropalatographic data reduction, *Journal of Phonetics,* **22**, 141–154.

Hardcastle, W. J., Jones, W., Knight, C., Trudgeon, A. & Calder, G. (1989) New developments in electropalatography: A state-of-the-art report, *Clinical Linguistics and Phonetics,* **3**, 1–38.

Hoole, P., Gfroerer, S. & Tillmann, H.-G. (1990) Electromagnetic articulatography as a tool in the study of coarticulation, *Forschungsberichte des Instituts für Phonetik,* Munich, **28**, 107–122.

Ladefoged, P. & Maddieson, I. (1986) *Some of the Sounds of the World's Languages,* UCLA Working Papers in Phonetics, **64**.

Öhman, S. E. G. (1966) Coarticulation in VCV utterances: spectrographic measurements, *Journal of the Acoustical Society of America,* **39**, 151–168.

Recasens, D. (1987) An acoustic analysis of V-to-C and V-to-V coarticulatory effects in Catalan and Spanish VCV sequences, *Journal of Phonetics,* **15**, 299–312.

Recasens, D. (1991) On the production characteristics of apicoalveolar taps and trills, *Journal of Phonetics,* **19**, 267–280.

Recasens, D. & Farnetani, E. (1990) Articulatory and acoustic properties of different allophones of /l/ in American English, Catalan and Italian, *Proceedings of the ICLSP 90,* Acoustic Society of Japan, **2**, 961–964.

Recasens, D. & Farnetani, E. (1994) Spatiotemporal properties of different allophones of /l/: phonological implications. In *Phonologica 1992* (W. V. Dressler, M. Prinzhorn & J. R. Rennison, editors), pp. 195–204. Torino: Rosenberg & Sellier.

Recasens, D., Farnetani, E., Ní Chasaide, A., Fontdevila, J., Pallarès, M. D., Provaglio, A. & Fealey, G. (1991) A study of the production and coarticulatory characteristics of palatal and palatalized consonants, *ACCOR Periodic Progress Report,* **2**, Aix en Provence.

Recasens, D., Fontdevila, J. & Pallarès, M. D. (1992) Alveolar-palatal correlations in coarticulatory activity for a selected group of Catalan consonants, *Bulletin de la Communication Parlée,* **2**, 59–72.

Recasens, D., Fontdevila, J. & Pallarès, M. D. (1995) Velarization degree and coarticulatory resistance for /l/ in Catalan and German, *Journal of Phonetics,* **23**, 37–52.

Schubiger, M. (1970) *Einführung in die Phonetik,* Walter de Gruyter, Berlin.

Sproat, R. & Fujimura, O. (1993) Allophone variation in English /l/ and its implications for phonetic implementation, *Journal of Phonetics,* **21**, 291–312.

Appendix 1

Contact index values were calculated using the following formula:

Alveolar contact indices

$$CAa = [\log[[(R4/8) + 9(R3/8) + 81(R2/8) + 547(R1/6)] + 1]]/[\log(639)]$$

$$CPa = [\log[[(R1/6) + 9(R2/8) + 81(R3/8) + 729(R4/8)] + 1]]/[\log(821)]$$

$$CCa = [\log[[(C1/6) + 9(C2/8) + 81(C3/8) + 729(C4/8)] + 1]]/[\log(821)].$$

Palatal contact indices

$$CAp = [\log[[(R8/8) + 9(R7/8) + 81(R6/8) + 729(R5/8)] + 1]]/[\log(821)]$$

$$CPp = [\log[[(R5/8) + 9(R6/8) + 81(R7/8) + 729(R8/8)] + 1]]/[\log(821)]$$

$$CCp = [\log[[(C1/8) + 9(C2/8) + 81(C3/8) + 729(C4/8)] + 1]]/[\log(821)].$$

In the ratios within parentheses, the number of activated electrodes on each row (i.e., R1, R2, R3 . . .) or column (i.e., C1, C2, C3 . . .) is divided by the total number of electrodes on the same row or column. This normalization procedure ensures that rows or columns containing different numbers of electrodes contribute equally to the contact index values. Each ratio is multiplied by a row-/column-specific coefficient number. These coefficients were calculated according to the following principle: the contribution of a given electrode to an index value exceeds the contribution of all electrodes located on the previous back rows (CA index), on the previous front rows (CP index), or on more lateral columns (CC index). The construction method of the coefficient values is explained below for the CAp index.

A coefficient of 1 was arbitrarily assigned to the backmost row R8. It follows from the contact index formula that the maximum CAp value for this row when all eight electrodes are activated is 1:

$$(8 \text{ activated electrodes}/8 \text{ electrodes available}) \times \text{coefficient value of } 1 = 1.$$

One "on" electrode on R7 should contribute more to the CAp index value than 1, which is the maximum CA index value for R8, namely,

$$(1 \text{ activated electrode}/8 \text{ electrodes available}) \times \text{unknown coefficient value} > 1.$$

It follows that the coefficient value for R7 should be higher than 8, namely, $(8 \times 1) + 1 = 9$.

To obtain the coefficient value for R6, one "on" electrode on this row should contribute more to the CAp index value than the previous rows R7 and R8. Since the addition of the maximum CAp index value for R7 and R8 is 10, it follows that:

if (l "on" electrode/8 electrodes available on R6) $\times$ coefficient value > 10,

then the coefficient value for R6 $= (8 \times 10) + 1 = 81$

The same operation was applied to the remaining indices. For the calculation of the CPp index coefficients, rows were considered in the reverse order (thus, R5 was assigned a coefficient of 1, R6 a coefficient of 9, and so on). Coefficients for the CCp index were constructed in increasing order from the sides to the center of the palatal surface. As shown in the contact index formula, the CA, CP, and CC index values were submitted to a logarithmic transformation in order to compensate for their exponential increase as we proceed from one row or column to the next. The resulting expressions are divided by the maximum possible value for each contact index so that a range from 0 to 1 is obtained.

Appendix 2

Mean contact index values at the alveolar zone and at the palatal zone for /l/ in the sequences /ili/, /ala/ and /ulu/ (Catalan and German speakers). Values represent averages across five tokens; standard deviations are given in parenthesis. Speakers are ordered according to degree of /l/ velarization.

Appendix 2 (*Contd.*)

		Alveolar zone			
CATALAN		CAa	CPa	CCa	Qa
CAT1	i	0.993 (0.012)	0.800 (0.036)	0.913 (0.025)	21.00 (1.87)
	u	0.998 (0.001)	0.832 (0.026)	0.930 (0.027)	21.40 (1.52)
	a	0.998 (0.003)	0.647 (0.149)	0.889 (0.047)	18.60 (3.58)
CAT2	i	0.966 (0.035)	0.451 (0.269)	0.835 (0.059)	12.40 (6.11)
	u	0.658 (0.186)	0.933 (0.103)	0.916 (0.024)	17.80 (2.17)
	a	0.617 (0.086)	0.953 (0.040)	0.906 (0.015)	18.40 (2.07)
CAT3	i	0.984 (0.025)	0.895 (0.020)	0.928 (0.013)	23.60 (1.14)
	u	0.872 (0.146)	0.852 (0.041)	0.912 (0.016)	19.60 (2.19)
	a	0.849 (0.155)	0.825 (0.009)	0.903 (0.035)	17.00 (3.39)
CAT4	i	0.770 (0.172)	0.962 (0.024)	0.960 (0.023)	20.60 (4.04)
	u	0.557 (0.182)	0.972 (0.018)	0.942 (0.033)	16.20 (4.09)
	a	0.461 (0.157)	0.953 (0.030)	0.908 (0.037)	13.80 (3.03)
CAT5	i	0.881 (0.122)	0.897 (0.034)	0.935 (0.025)	22.00 (2.24)
	u	0.660 (0.046)	0.923 (0.047)	0.910 (0.016)	18.80 (0.45)
	a	0.980 (0.040)	0.646 (0.188)	0.917 (0.026)	18.60 (3.65)
GERMAN					
GER1	i	0.990 (0.002)	0.780 (0.038)	0.802 (0.006)	14.60 (0.89)
	u	0.919 (0.047)	0.779 (0.160)	0.881 (0.046)	18.60 (2.61)
	a	0.912 (0.060)	0.651 (0.212)	0.866 (0.038)	15.40 (2.30)
GER2	i	0.994 (0.012)	0.901 (0.013)	0.940 (0.024)	24.00 (1.00)
	u	0.999 (0.000)	0.829 (0.028)	0.910 (0.016)	19.80 (0.84)
	a	0.685 (0.070)	0.839 (0.043)	0.890 (0.017)	16.40 (1.95)
GER3	i	0.995 (0.011)	0.899 (0.016)	0.899 (0.016)	23.60 (0.55)
	u	0.971 (0.064)	0.884 (0.020)	0.904 (0.002)	22.00 (1.73)
	a	0.972 (0.036)	0.816 (0.006)	0.892 (0.018)	19.60 (1.14)
GER4	i	0.999 (0.000)	0.852 (0.026)	0.900 (0.002)	20.80 (1.30)
	u	0.999 (0.002)	0.816 (0.078)	0.905 (0.035)	21.20 (3.42)
	a	0.986 (0.006)	0.302 (0.127)	0.819 (0.033)	10.00 (2.83)

		Palatal zone			
CATALAN		CAp	CPp	CCp	Qp
CAT1	i	0.682 (0.183)	0.466 (0.263)	0.110 (0.061)	3.40 (0.89)
	u	0.293 (0.352)	0.213 (0.307)	0.017 (0.019)	1.00 (1.22)
	a	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.00 (0.00)
CAT2	i	0.550 (0.260)	0.860 (0.050)	0.212 (0.053)	7.60 (3.65)
	u	0.640 (0.339)	0.735 (0.047)	0.092 (0.045)	5.80 (2.39)
	a	0.445 (0.409)	0.017 (0.017)	0.017 (0.017)	1.00 (1.00)
CAT3	i	0.798 (0.003)	0.220 (0.019)	0.127 (0.037)	4.80 (0.45)
	u	0.285 (0.292)	0.172 (0.190)	0.020 (0.021)	1.20 (1.30)
	a	0.135 (0.301)	0.004 (0.008)	0.004 (0.008)	0.20 (0.45)
CAT4	i	0.816 (0.071)	0.785 (0.069)	0.175 (0.073)	7.40 (2.70)
	u	0.851 (0.038)	0.747 (0.057)	0.226 (0.101)	7.40 (0.55)
	a	0.758 (0.085)	0.624 (0.184)	0.081 (0.063)	3.80 (1.10)
CAT5	i	0.826 (0.030)	0.791 (0.067)	0.308 (0.025)	11.00 (1.22)
	u	0.776 (0.039)	0.572 (0.166)	0.077 (0.006)	5.40 (0.55)
	a	0.023 (0.050)	0.072 (0.161)	0.004 (0.008)	0.20 (0.45)

CATALAN		CAp	Palatal zone CPp	CCp	Qp
GERMAN					
GER1	i	0.778 (0.038)	0.815 (0.038)	0.203 (0.034)	9.60 (0.89)
	u	0.059 (0.057)	0.680 (0.009)	0.024 (0.009)	1.40 (0.55)
	a	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.00 (0.00)
GER2	i	0.898 (0.002)	0.885 (0.019)	0.441 (0.093)	16.40 (0.89)
	u	0.829 (0.027)	0.804 (0.045)	0.352 (0.083)	12.40 (0.55)
	a	0.520 (0.265)	0.636 (0.147)	0.075 (0.048)	4.20 (2.05)
GER3	i	0.890 (0.017)	0.861 (0.003)	0.380 (0.061)	15.20 (0.84)
	u	0.855 (0.034)	0.920 (0.024)	0.460 (0.053)	15.60 (2.07)
	a	0.348 (0.338)	0.217 (0.313)	0.022 (0.025)	1.40 (1.67)
GER4	i	0.860 (0.000)	0.889 (0.017)	0.338 (0.008)	14.80 (0.45)
	u	0.651 (0.266)	0.706 (0.002)	0.080 (0.021)	5.80 (1.79)
	a	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.00 (0.00)