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Velarization degree and coarticulatory resistance for /l/ in Catalan and German

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This paper compares formant values and patterns of linguopalatal contact for [l] in the sequences [ili] and [ala] in both Catalan and German, in order to determine whether differences in consonantal velarization between the two languages influence the degree of vowel-to-consonant coarticulation.

Significant F_2 and F_2–F_1 differences for [l] in the sequence [ili] indicate that the consonant is velarized in Catalan and non-velarized in German; F_2 data for male speakers show a 1500Hz threshold between the two consonantal varieties. This language-dependent significant difference was not found to hold for the dorsopalatal contact as measured by electropalatography; there is, however, a clear trend for dorsal contact at the palatal zone for German [l] to exceed that for Catalan [l]. Moreover, F_2 values suggest that the consonant may be less non-velarized in German than in other languages (Italian, Spanish, French).

The degree of coarticulation was not inversely related to the degree of velarization in the case analyzed in this paper, i.e., coarticulatory effects from [i] *vs*. [a] on [l] were not significantly different in German *vs*. Catalan. Velarized [l] in Catalan is highly resistant to coarticulatory effects from [i] since the two phonetic segments are produced with antagonistic tongue dorsum gestures, i.e., tongue dorsum lowering and retraction, and tongue dorsum raising and fronting. While being non-velarized, German [l] appears to be highly resistant to coarticulatory effects from [i] *vs*. [a]: F_2 values for [l] in both vowel environments are less extreme in German than in other languages showing a non-velarized variety of the consonant.

These findings suggest that the tongue dorsum for German [l] attains some target position, and are in support of the notion that the velarization/non-velarization distinction proceeds in a scalar, non-categorical fashion.

1. Introduction

One of the purposes of this research project was to study the articulatory and acoustic correlates of velarization during the production of [l]. Traditionally, languages have been divided into two groups depending on whether they present a

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velarized ("dark") or a non-velarized ("clear") variety of the consonant. X-ray tongue shapes for [l] in prevocalic and postvocalic position reported by Delattre (1965) confirm the existence of a non-velarized variety in German, Spanish and French, and a velarized variety in American English; descriptive accounts of the two consonantal types are found in Heffner (1950). The two varieties differ with respect to tongue body configuration (both are invariably characterized as apicoalveolar or apicodental). On the one hand, the tongue dorsum stays in a fairly high front position within the vocal tract for non-velarized [l]; less tongue predorsum height for this realization than for laminoalveolar consonants derives from its being an apical articulation (also Dart, 1991) and possibly from laterality requirements as well. On the other hand, the production of velarized [l] involves a good deal of tongue predorsum lowering and tongue postdorsum retraction (Giles & Moll, 1975; Sproat & Fujimura, 1993).

Differences in tongue dorsum configuration for these two varieties of [l] suggest the existence of different mechanisms of articulatory control. It can be hypothesized that non-velarized [l] is produced with a single apicoalveolar gesture and requires no active tongue dorsum control; tongue dorsum fronting and raising for this variety of [l] occur in a similar fashion to other dentoalveolar consonants. Instead, velarized [l] may be said to involve two lingual gestures, i.e., a primary gesture towards the achievement of an apicoalveolar closure, and a secondary gesture towards the achievement of a secondary dorsovelar or dorsopharyngeal constriction. EMG evidence on peak styloglossus activity for velarized [l] in American English (Leidner, 1973; see also Sproat & Fujimura, 1993) may reflect the actualization of this secondary lingual gesture. No EMG data on tongue dorsum activity are available during the production of non-velarized [l] in German, Spanish or French.

Recent experimental evidence supports the view that the articulation of [l] cannot be fully described with the labels "velarized" or "non-velarized". In the first place, data for languages or dialects in which the consonant is typically velarized show differences in velarization degree depending on segmental context, syllable position and/or phrase position [e.g., syllable-final or word-final [l] is more velarized than its syllable-initial or word-initial correlate in Catalan (Recasens, 1985) and American English dialects (Kenyon, 1950)].

Moreover, languages or dialects may differ among themselves in the degree of velarization assigned to the consonant. For example, while [l] is clearly velarized in the New York City dialect of American English and in Eastern Catalan, the degree of velarization is more pronounced in the former dialect *vs.* the latter (Recasens & Farnetani, 1990). Our hypothesis is that the realization of [l] may also differ across languages having a "clear", non-velarized variety such as French, Spanish, Italian and German. More specifically, this study investigates the articulatory and acoustic attributes of [l] in German, and seeks to understand whether they differ from those in other languages.

A second goal of this research was to test the hypothesis that differences in articulatory complexity between the two varieties of [l] affect the degree of coarticulatory sensitivity exhibited by the consonant. Given that the tongue body position is highly constrained for velarized [l], this particular consonantal variety should be highly resistant to coarticulatory effects from the palatal vowel [i]; this ought to be so since the two phonetic segments are produced with antagonistic lingual gestures. On the other hand, non-velarized [l] (which does not involve the formation of a secondary dorsal constriction) should allow much more tongue dorsum coarticulation. This general hypothesis appears to work for languages with very different varieties of [l] such as Italian and Catalan (Recasens & Farnetani, 1990, 1992). Within this framework, this paper investigates the issue of coarticulatory sensitivity for German [l].

2. Method

Acoustic data and linguopalatal contact data (by means of electropalatography or EPG) were collected simultaneously for the symmetrical sequences [ili] and [ala] with stress on the first syllable. Two languages were selected for analysis: Catalan (5 male speakers: DR, JP, JS, DP, JC) and German (4 male speakers: HT, PJ, BP, MV; 1 female speaker: PP). All speakers repeated the speech material five times each; overall, 100 tokens i.e., 2 sequences × 5 repetitions × 10 speakers) were recorded and analyzed. In Catalan, V2 = /a/ undergoes systematic vowel reduction in unstressed position and is thus realized as [ə].

As stated in the Introduction section, the two languages differ with respect to the velarization characteristic in the consonant. The consonant has been traditionally described as "dark" or velarized in Catalan (Recasens & Farnetani, 1990) and as "clear" or non-velarized in German (Schubiger, 1970), independently of possible position-dependent allophonic varieties within each language. The presence of velarized [l] is quite general in the Eastern Catalan dialect around the Barcelona area analyzed here, although the degree of velarization may decrease with speaker's age; auditory perception reveals indeed the presence of velarization in [l] for the five Catalan speakers, with speaker JC exhibiting the least "dark" realization. German speakers PJ, PP, BP and MV were born in dialectal areas known to have a "clear" [l] (Baviera and Swabia); this consonantal quality was confirmed by auditory impression in all cases, with speaker BP showing the least "clear" realization of all Germans. The German speaker HT exhibits a distinctively "clear" realization of the consonant in spite of having been born in the Rhineland, a geographical zone reported to favour a "dark" variety of [l].

The Reading electropalatographic system was used in the recording session (Hardcastle, Jones, Knight, Trudgeon & Calder, 1989); it allows displaying one pattern of contact every 5 ms. As shown in Fig. 1, 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 surface of the electropalate (above right). The alveolar zone comprises the 4 front rows and the palatal zone comprises the 4 back rows; the distance between adjacent rows is much less in the alveolar zone than in the palatal zone. The corresponding articulatory subdivisions along the palatal surface, as well as the articulatory subdivisions of the tongue surface, are shown on an X-ray tracing below.

The EPG data on linguopalatal contact patterns were processed with reference to the set of contact indices characterized in Section 3.2. The acoustic data were submitted to spectral analysis using the linear prediction coding method (LPC). Articulatory and acoustic measurements for the consonant were taken at the midpoint of the central closure period, as determined from the EPG data; acoustic

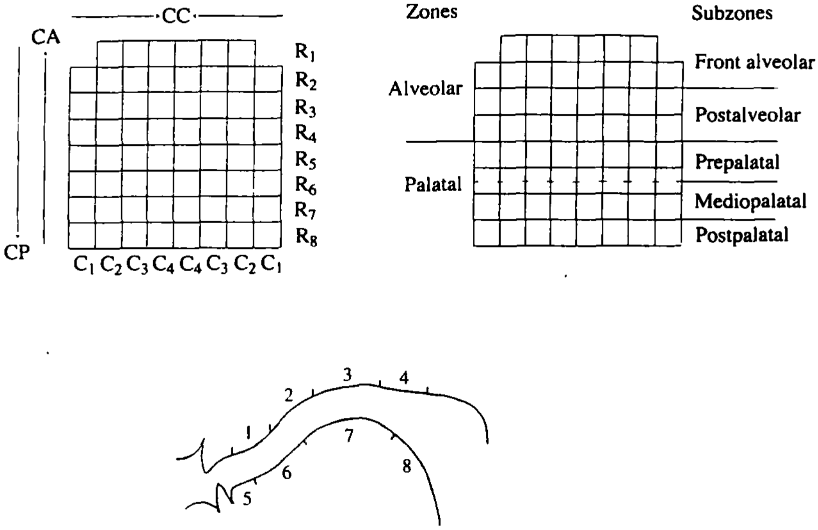

Figure 1. Top left: Distribution of rows R_1 through R_8 along the anteriority (CA) and posteriority (CP) dimensions, and of columns C_1 through C_4 along the centrality (CC) dimension on both sides of the electropalate. Top, right: Articulatory zones and subzones on the electropalate. Bottom: Vocal 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.

measurements for the steady-state vowels were taken at one fourth of V1 duration and at the V2 midpoint.

3. Results

3.1. *Acoustic characteristics*

The degree of velarization in [l] was derived from a phonetic analysis of the sequence [ili] (see Sproat & Fujimura, 1993 as well). Our initial prediction was that velarized [l] should show less coarticulatory effects from adjacent [i] than non-velarized [l]. Differences in the amount of coarticulation between velarized and non-velarized [l] are in accordance with the fact that tongue dorsum activity for [i] is essentially antagonistic to that for velarized [l] but not so to that for non-velarized [l]. Indeed, while [i] is produced with a tongue dorsum raising and fronting gesture, the production of velarized [l] involves a tongue dorsum lowering and backing gesture. Non-velarized [l], on the other hand, may be said to require no active tongue dorsum gesture; tongue dorsum raising and fronting in this case may just occur as a consequence of the coupling effects between the dorsum of the tongue and the primary apical articulator.

The degree of consonantal velarization was inferred from the acoustic data. The rationale for choosing acoustic data instead of contact data for that purpose was twofold. While the EPG data reflect contact variations at the palatal surface (thus involving only a portion of the tongue dorsum surface), formant frequencies are sensitive to modifications in overall tongue body activity. Moreover, the information derived from EPG is less accurate than the acoustic information obtained by means of LPC. This is due to several reasons: on the one hand, the placement of electrodes on the surface of the artificial palate leaves large interelectrode areas for which no contact data can be obtained (e.g., there are only three rows of electrodes over the entire palatal zone); on the other hand, the EPG technique provides information as to whether electrodes are "on" or "off" but no information on the pressure level with which the tongue touches the palate.

Two separate acoustic measures were taken as indicative of the degree of consonantal velarization: F_2 frequency, and the frequency distance between F_2 and F_1 (F_V in this paper). The latter measure differs from the former in that it takes into account the joint contribution of two spectral formants related to the velarization characteristic. F_2 frequency is positively correlated with tongue dorsum fronting and raising (Fant, 1960) and thus, inversely related to the degree of velarization. F_V also takes into account the contribution of F_1 which is known to be inversely related with dorsopalatal contact size (Bladon, 1979) and thus, directly related to velarization. Therefore, an increase in degree of velarization causes an F_1 increase, and F_2 decrease and an F_V decrease.

Statistical analysis showed that significant F_2 differences between Catalan [l] and German [l] in the same VCV sequences were not due to language-dependent vocalic differences but to differences associated with the consonant. One-way ANOVAs across male speakers (acoustic data for the female German speaker PP were excluded because of presumable sex-related differences in vocal tract size) revealed non-significant F_2 frequency differences between German and Catalan during the steady-state portion of V_1/V_2 = [i] (about 2200 Hz) and V_1/V_2 = [a] (about 1300 Hz). Vowel F_2 values across male speakers and for each individual subject are given in Table I.

Mean F_2 and F_V values for [l] across male speakers in each language are shown in Table II. The consonant exhibits a higher F_2 in German (1681.14 Hz $\pm$ 337.15) than in Catalan (1349.04 Hz $\pm$ 114.39) with a difference between means of 332.1 Hz; the two languages show little overlap when the 95% confidence interval is taken into account (119.44 Hz, which represents 35.97% of the total difference between means). The F_V value is clearly smaller in Catalan (1042.04 Hz $\pm$ 132.35) than in German (1426.11 Hz $\pm$ 370.78) with a difference between means of 384.07 Hz; the overlap between languages is 118.66 Hz (which represents 30.90% of the total difference between means). One-way ANOVAs across speakers reveal that these language-dependent differences in F_2 ($F(1, 7) = 10.17$, $p < 0.0153$) and in F_V ($F(1, 7) = 11.03$, $p < 0.0127$) are significant.

A comparison between these F_2 values and those for other languages reported in the literature (in the same [ili] sequence and for male speakers only) suggests the following trends. The consonant is less velarized in Catalan than in some dialects of American English; indeed, F_2 for American English [l] occurs at about 1150 Hz [Lehiste, 1964 (3 Midwestern American English speakers); Chafcouloff, 1972 (3 Southern California speakers)]. On the other hand, F_2 frequency is higher in German than in French [1829.67 Hz; Chafcouloff, 1985 (6 Southern French speakers)] and Spanish [2195.5 Hz according to Recasens, 1987 (2 Castilian Spanish speakers); 1850 Hz according to Chafcouloff, 1972 (3 Argentinian Spanish speakers)].

These data are in agreement with the traditional phonetic descriptions stating that

TABLE I. Mean F_2 values (in Hz) for V_1 and V_2 in the sequences [ili] and [ala] in Catalan and German (male speakers only). Standard deviations have been included within parenthesis

Across speakers	Catalan		German	
	V_1	V_2	V_1	V_2
i	2173.44	2240.52	2188.60	2217.31
	(74.91)	(127.65)	(131.78)	(136.44)
a	1296.21	1332.07	1217.65	1235.20
	(57.88)	(63.57)	(85.48)	(124.85)

Individual speakers	i		a	
	V_1	V_2	V_1	V_2
Catalan				
DR	2305.80	2393.60	1323.80	1311.40
	(80.01)	(83.59)	(20.90)	(68.35)
JP	2137.40	2299.20	1347.80	1372.80
	(47.09)	(96.15)	(20.47)	(42.60)
JS	2151.20	2130.40	1230.80	1421.80
	(84.68)	(119.57)	(39.10)	(51.95)
DP	2122.40	2087.20	1236.40	1276.60
	(86.06)	(45.88)	(59.08)	(116.18)
JC	2150.40	2292.20	1342.25	1277.75
	(39.27)	(122.88)	(17.21)	(27.86)
German				
HT	2162.80	2280.20	1343.00	1395.20
	(65.94)	(38.89)	(41.84)	(46.69)
PJ	2013.00	2013.40	1156.80	1138.00
	(29.69)	(75.75)	(18.20)	(86.01)
BP	2276.60	2301.40	1170.40	1134.00
	(60.88)	(146.16)	(30.81)	(28.61)
MV	2302.00	2274.25	1200.00	1273.60
	(49.90)	(51.17)	(34.17)	(44.59)

[l] is velarized in Catalan and non-velarized in German. Moreover, there appears to be an F_2 velarization threshold roughly about 1500Hz lying halfway between the mean F_2 frequency for the German and Catalan male speakers analyzed in the present study. Therefore, two [l] varieties (i.e., "clear" and "dark") can be distinguished depending on whether F_2 is above or below this frequency limit. An important finding is that languages belonging to the two groups may differ with respect to the F_2 frequency assigned to the consonant: thus, there are some indications that [l] may be less "clear" in German than in French or Spanish, and less velarized in Catalan than in American English. As stated above, this information does not apply necessarily to all dialects of these languages.

3.2. *Articulatory-acoustic correlations*

Articulatory-acoustic correlations were performed for [l] in the sequence [ili] across male speakers and languages (thus excluding the female speaker PP). The analysis

TABLE II. Mean F_2 and F_V (F_2–F_1) values (in Hz) for [l] in the sequence [ili] in Catalan and German (male speakers only). Standard deviations have been included within parenthesis

Across speakers	Catalan	German
F_2	1349.04 (92.14)	1681.14 (211.88)
F_V	1042.04 (106.61)	1426.11 (232.77)
Individual speakers	F_2	F_V
Catalan		
DR	1274.00 (64.04)	942.20 (71.89)
JP	1282.00 (48.68)	960.40 (37.56)
JS	1444.40 (46.92)	1134.60 (45.21)
DP	1289.80 (63.17)	996.20 (54.37)
JC	1455.00 (87.60)	1176.80 (79.26)
German		
HT	1914.20 (64.10)	1643.80 (78.73)
PJ	1795.00 (62.79)	1604.80 (75.19)
BP	1447.60 (92.84)	1179.60 (87.61)
MV	1567.75 (71.73)	1276.25 (52.52)

was performed using two acoustic parameters (F_2 and F_V), and four contact indices at the palatal zone (Q_p, CA_p, CP_p, CC_p). Q_p is calculated adding up the overall number of activated electrodes at the palatal zone. The other three indices allow measuring contact distribution, i.e., the degree of contact anteriority towards the front of the palatal zone (CA_p), the degree of contact posteriority towards the back of the palatal zone (CP_p), and the degree of centrality towards the median line at the palatal zone (CC_p) (see Fig. 1). In addition to Q_p, data on these three contact indices allowed detecting with precision the most relevant articulatory zone(s) for the velarization distinction. The calculation procedure of the CA_p, CP_p, and CC_p contact indices is explained in the Appendix (see also Fontdevila, Pallarès & Recasens, 1994). Values for CA_p, CP_p and CC_p run from 0 (least anterior, posterior and central, respectively) to 1 (most anterior, posterior and central, respectively). Contact index values at the alveolar zone have not been calculated since alveolar contact is not a straightforward articulatory indicator of velarization degree (see Section 3.1.).

Significant articulatory-acoustic correlations were obtained for both F_2 and F_V with Q_p and CC_p (but not so with CA_p and CP_p). The **r** (Pearson correlation coefficient) values across speakers for the sequence [ili] are 0.92 for F_V–Q_p, 0.91 for F_2–Q_p, 0.84 for F_V–CC_p and 0.81 for F_2–CC_p (see Figs 2–3). It can be concluded that the most satisfactory EPG correlate of the degree of velarization is the amount of lingual contact along the coronal dimension, which reflects the degree of tongue dorsum raising. Thus, variations in dorsopalatal contact occur towards the median line rather than towards the front or the back of the palatal zone. In other words, front palatal contact and back palatal contact remain more constant than central palatal contact with changes in degree of velarization (and, thus, in amount of tongue dorsum raising and lowering).

Table III shows the mean Q_p and CC_p index values for [l] in the sequence [ili] in the two languages (male speakers only; see also Fig. 4). They are both lower in

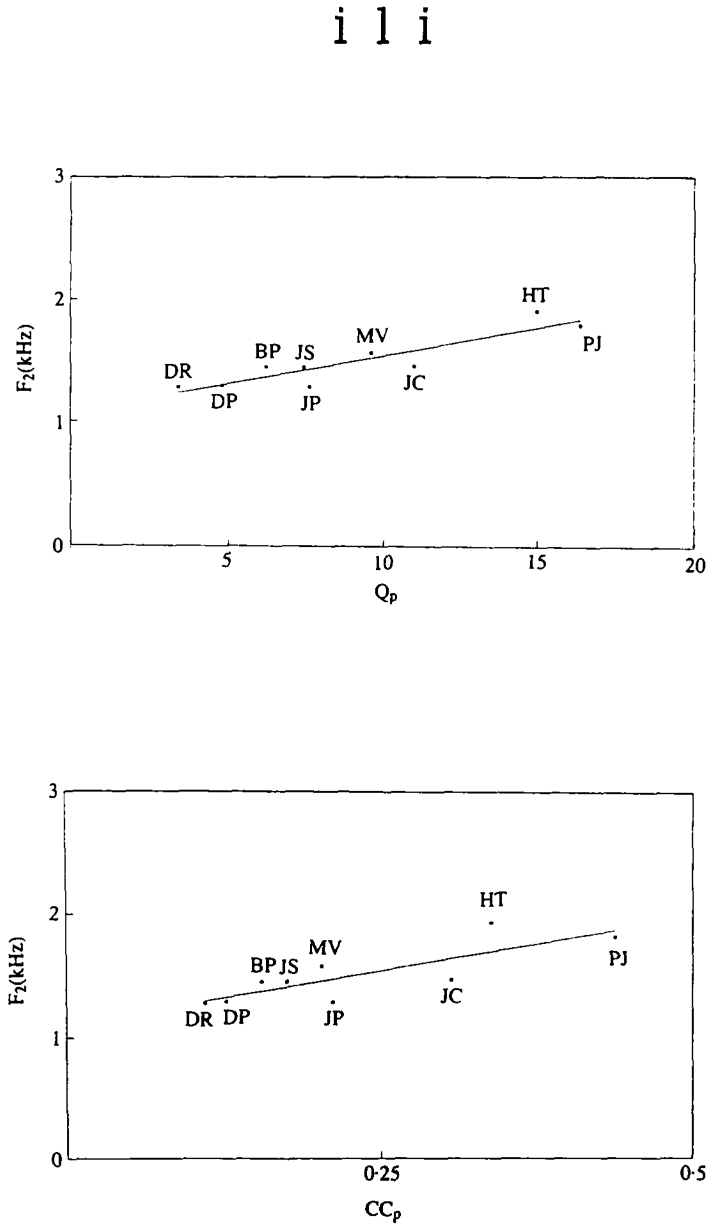

Figure 2. F_2–Q_p (above) and F_2–CC_p (below) plots with regression lines. Catalan speakers: DR, JP, JS, DP, JC; German speakers: HT, PJ, BP, MV.

Catalan than in German by a difference of 4.96 for Q_p ($\bar{X}$ for Catalan = 6.84 ± 3.63; $\bar{X}$ for German = 11.80 ± 7.55) and of 0.099 for CC_p ($\bar{X}$ for Catalan = 0.186 ± 0.098; $\bar{X}$ for German = 0.285 ± 0.208). The overlap between languages according to the 95% confidence interval exceeds the difference between means (6.22 for Q_p and 0.207 for CC_p), and is thus quite larger than that reported for the acoustic data (see Section 3.1.). One-way ANOVAs across speakers reveal that differences in Q_p and

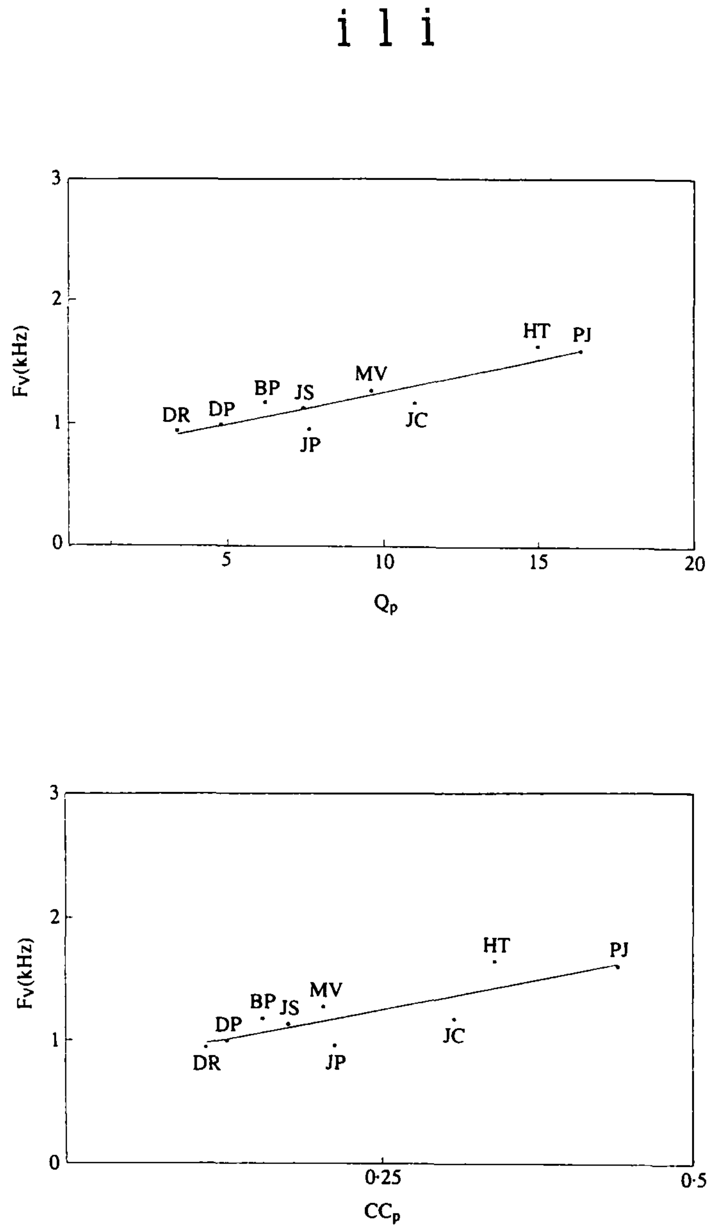

Figure 3. F_V–Q_p (above) and F_V–CC_p (below) plots with regression lines. Catalan speakers: DR, JP, JS, DP, JC; German speakers: HT, PJ, BP, MV.

CC_p between languages are not significant. In summary, while language-dependent differences in dorsopalatal contact are not significant, there is a clear trend for German to show more contact than Catalan in line with differences in degree of velarization in the consonant. This trend is also consistent with the EPG pattern for [ili] for the female speaker PP in Fig. 4; thus, values for Q_p ($\bar{X} = 15.20$, SD = 0.84) and CC_p ($\bar{X} = 0.380$, SD = 0.061) for this speaker are much closer to the mean German values than to the mean Catalan values.

TABLE III. Mean Q_p and CC_p values for [l] in the sequence [ili] in Catalan and German (male speakers only). Standard deviations have been included within parenthesis

Across speakers	Catalan	German
Q_p	6.84 (2.92)	11.80 (4.75)
CC_p	0.186 (0.079)	0.285 (0.131)
Individual speakers	Q_p	CC_p
Catalan		
DR	3.40 (0.89)	0.110 (0.061)
JP	7.60 (3.65)	0.212 (0.053)
JS	7.40 (2.70)	0.175 (0.073)
DP	4.80 (0.45)	0.127 (0.037)
JC	11.00 (1.22)	0.308 (0.025)
German		
HT	15.00 (0.00)	0.341 (0.000)
PJ	16.40 (0.89)	0.441 (0.093)
BP	6.20 (1.10)	0.155 (0.053)
MV	9.60 (0.89)	0.203 (0.034)

In agreement with our initial predictions, it appears that velarization for [l] is better accounted for by the acoustic data than by the linguopalatal contact data. This is not surprising since the velarization gesture is achieved with the activation of the entire tongue body; while the linguopalatal contact data reflect variations mostly in tongue predorsum and mediodorsum activity, F_2 is also sensitive to changes in the activity of the tongue postdorsum.

3.3. *Individual speakers*

Data for the individual male speakers were submitted to a cluster analysis (using the complete linkage or "furthest neighbour" clustering method) in order to find out whether they were grouped according to language or not. The analysis was performed using the F_2, F_V, Q_p and CC_p values for the sequence [ili].

Results are in agreement with German [l] showing more variability in acoustic and articulatory values than Catalan [l] (see standard deviations in Tables II and III). An homogeneity of variance test gave non-significant differences between the two languages, thus indicating that the two speaker populations are comparable. The grouping of speakers obtained from the application of the cluster analysis can be represented as follows: [(JP, DP, DR) (JS, JC, BP, MV)] (HT, PJ). At both extremes, we find three Catalan speakers (JP, DP, DR) and two German speakers (HT, PJ). Two other Catalan speakers (JS, JC) and two other German speakers (BP, MV) are grouped exclusively at one level, and with the other three Catalan speakers (JP, DP, DR) at another level. Indeed, according to the data for the individual German speakers in Tables II and III (also Fig. 4), BP and MV show lower F_2, F_V, Q_p and CC_p values than HT and PJ, and thus a less "clear" realization of [l] (which nevertheless barely reaches the velarization degree for Catalan [l]). A satisfactory correlation between linguopalatal contact and acoustic values indicates

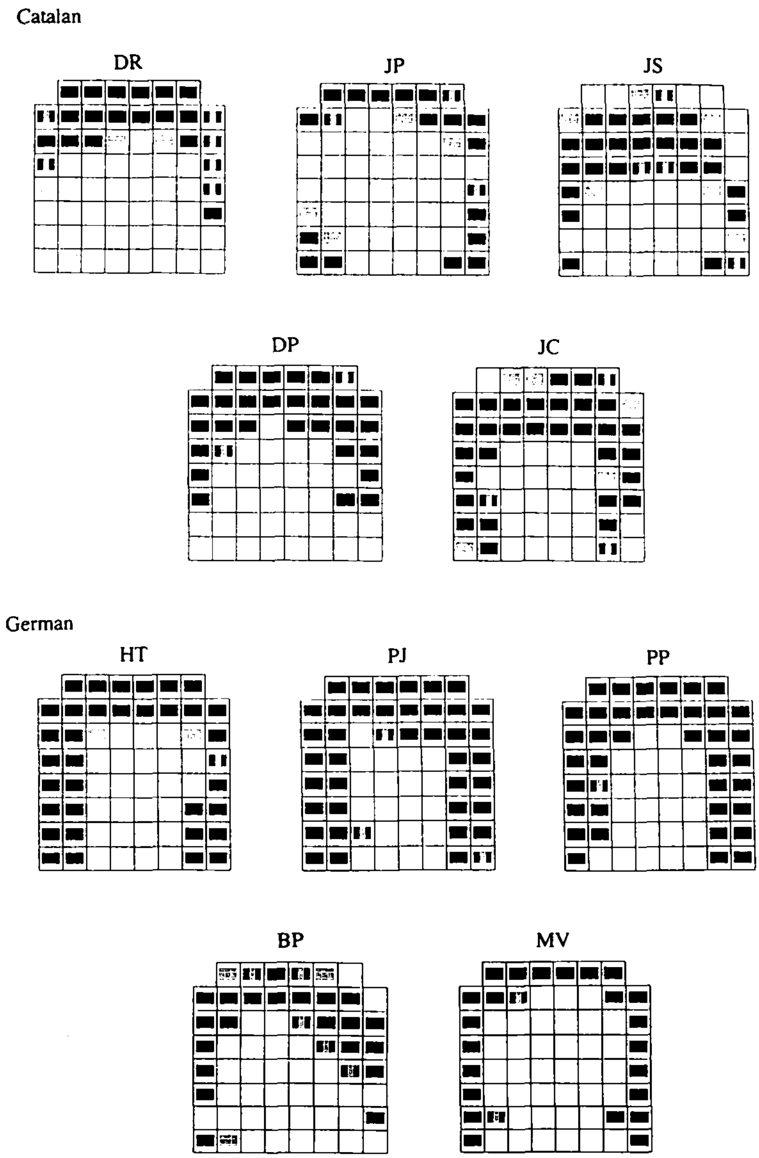

Figure 4. Linguopalatal contact configurations at the [l] closure midpoint in the sequence [ili] (Catalan and German speakers). Percentage of electrode activation: (■) 80–100; (▮▮) 60–80%; (░) 40–60%; (□) less than 40%.

that F_2 variability in German is due to speaker-dependent differences in dorsopalatal contact size rather than to speaker-related differences in vocal tract length.

3.4. *Coarticulatory resistance* (*acoustic data*)

The hypothesis that coarticulatory sensitivity is inversely related to the degree of consonantal velarization predicts that [l] should be more context-dependent in

German than in Catalan. In order to test this hypothesis we analyzed coarticulatory effects from [i] *vs.* [a] on [l] in symmetrical VCV sequences.

Coarticulatory effects have only been measured acoustically. These two vowels have been chosen since they represent two maxima along an articulatory dimension which is crucial for the velarization distinction, i.e., tongue dorsum raising-lowering. Contact data have not been taken into account since the presence of very little electrode activation for [l] in the sequence [ala] [see Fig. 5; mean Q_P value of 1.04 for Catalan (SD = 1.59) and of 1.75 for German (SD = 2.10)] is not representative of the real position of the tongue dorsum surface.

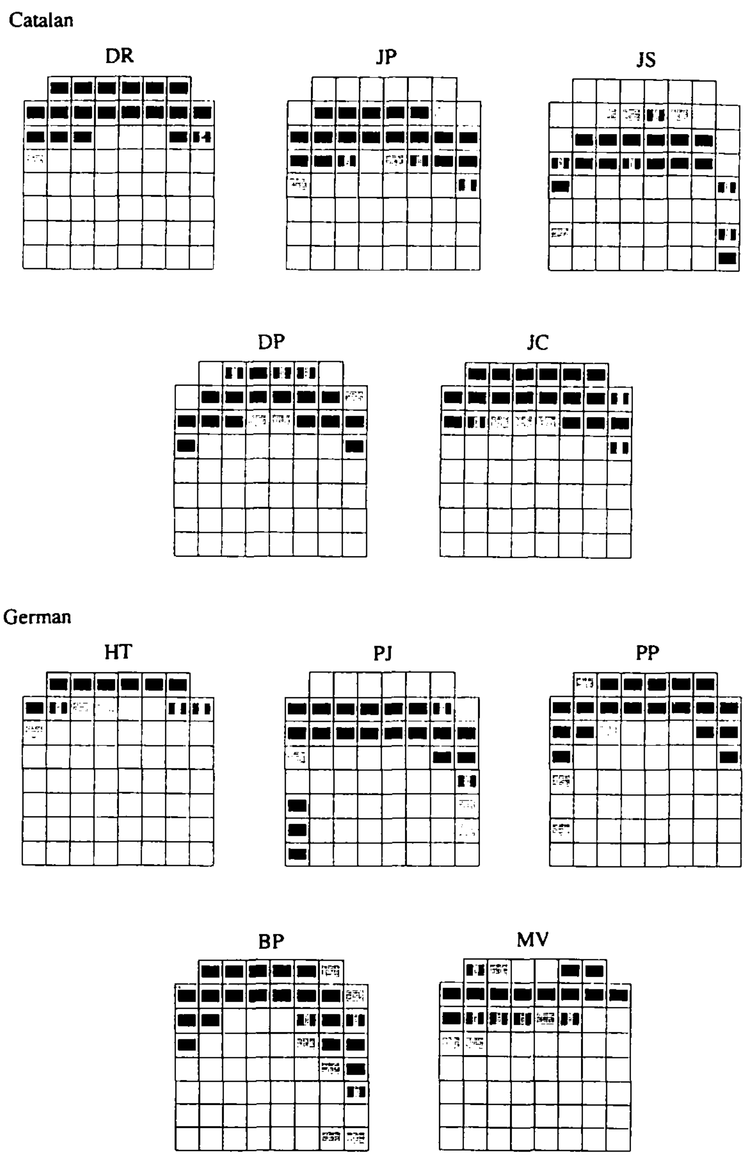

Figure 5. Linguopalatal contact configurations at the [l] closure midpoint in the sequence [ala] (Catalan and German speakers). Percentage of electrode activation: (■) 80–100%; (▮▮) 60–80%; (⁘) 40–60%; (□) less than 40%.

Table IV displays the mean F_2 values at the midpoint of [l] for [ili] and [ala] across male speakers in Catalan and German, as well as the MCD (mean coarticulatory distance) value in each language. MCD has been calculated using the procedure proposed by Bladon and Al-Bamerni (1976):

$$MCD = \frac{F_{2_{ili}} - F_{2_{ala}}}{2}$$

The MCD difference between German ($\bar{X} = 159.2$) and Catalan ($\bar{X} = 142.1$) across speakers is non-significant. Moreover, no significant correlation was found between MCD and F_2 nor between MCD and F_V for [ili] across speakers and languages. It can be concluded that the degree of coarticulation is not clearly related to the degree of velarization, thus refuting our initial hypothesis. As explained below this appears to be so since the mean MCD value for German was much smaller than expected.

An MCD value of 150 Hz in Catalan is the expected figure for a velarized consonant. In comparison to American English (with a MCD of 100 Hz according to data for the Southern California dialect reported in Chafcouloff, 1972), the F_2 frequency for the Catalan consonant is slightly higher in the sequence [ili] and quite similar in the sequence [ala]. On the other hand, in comparison to other languages with a non-velarized [l], German shows a smaller MCD value resulting from a lower F_2 for [ili] and a higher F_2 for [ala]. These languages are French and Spanish. Data correspond to Southern French (MCD = 244.67, with F_2 for [ili] = 1829.67 and F_2 for [ala] = 1340.33; Chafcouloff, 1985), Castilian Spanish (MCD = 489.63, with F_2 for [ili] = 2195.50 Hz and F_2 for [ala] = 1216 Hz; Recasens, 1987) and Argentinian Spanish (MCD = 225, with F_2 for [ili] = 1850 Hz and F_2 for [ala] = 1400 Hz; Chafcouloff, 1972). It should be pointed out that this comparison is somewhat risky since MCD differences could be due to language-dependent differences in vowel quality. Interestingly enough, however, they hold for all languages under investigation.

These data suggest that the MCD threshold separating the velarized from the non-velarized varieties of [l] occurs about 200 Hz. The MCD value for German reported in our study (which is consistent with an MCD value of 125 for the same language reported in Chafcouloff, 1972) is below this figure. Inspection of the MCD values for the individual speakers of German in Table IV reveals that, while PJ is the only speaker with a MCD value above 200, MV has a lower MCD value than all Catalan speakers. It can be thus concluded that, while being non-velarized, German [l] is highly resistant to coarticulatory effects from [i] *vs.* [a].

4. Discussion and conclusions

Data reported in this paper indicate that for the purposes of comparison between languages, the "clear"/"dark" distinction should be treated as a continuum proceeding in degrees of a given property, i.e., tongue dorsum lowering and backing. The precise consonantal realization along this continuum depends on several factors, i.e., speaker (German [l] is less "clear" for BP and MV than for the other three speakers), language ([l] shows a lower F_2 in some American English dialects *vs.* Catalan, and in German *vs.* Spanish, Italian, and French), vowel context (velarization is favoured by back *vs.* front vowels), and syllable position (syllable-final [l] is more velarized than syllable-initial [l]; see Introduction).

TABLE IV. Mean F_2 frequency values (in Hz) and MCD index for [ili] and [ala] in Catalan and German (male speakers only). Standard deviations have been included within parenthesis

Across speakers	Catalan	German	
F_2 [ili]	1349.04 (92.14)	1681.14 (211.88)	
F_2 [ala]	1064.80 (73.06)	1362.70 (212.86)	
MCD	142.1	159.2	
Individual speakers	**F_2 [ili]**	**F_2 [ala]**	**MCD**
Catalan			
DR	1274.00 (64.04)	994.80 (120.54)	139.6
JP	1282.00 (48.68)	1059.60 (20.56)	111.2
JS	1444.40 (46.92)	1149.40 (28.20)	147.5
DP	1289.80 (63.17)	992.20 (38.68)	148.8
JC	1455.00 (87.60)	1128.00 (24.97)	163.5
German			
HT	1914.20 (64.10)	1614.80 (37.89)	149.7
PJ	1795.00 (62.79)	1245.60 (36.22)	274.7
BP	1447.60 (92.84)	1137.80 (108.70)	154.9
MV	1567.75 (71.73)	1452.60 (34.13)	57.6

Evaluation of the articulatory and acoustic correlates of velarization presented in this paper indicates that this phonetic property may be accounted for more properly acoustically than articulatorily. Ladefoged (1971) makes a similar point about the nature of the classificatory features for vowels.

Velarized [l] requires a low tongue body position and exhibits a low F_2 frequency; while blocking tongue raising effects from [i], the lingual configuration for this consonantal variety is quite compatible with that for [a]. Non-velarized [l] in languages other than German does not involve much tongue dorsum constraint and thus, can be pulled to a larger extent in the direction of the adjacent vowel. Analogously to these languages, German [l] exhibits a higher F_2 and more dorsopalatal contact in the sequence [ili] than Catalan [l]. However, V-to-C coarticulatory effects in F_2 associated with [i] *vs.* [a] are as small for German non-velarized [l] as for Catalan velarized [l]. F_2 values for German [ili] and [ala] suggest that, while being non-velarized, German [l] is highly resistant to coarticulatory effects in tongue dorsum activity; indeed, its configuration appears to exert some blocking of the tongue dorsum lowering gesture for [a] and, possibly, some blocking of the tongue dorsum raising gesture for [i]. It can be hypothesized that a high target position needs to be attained by the dorsum of the tongue during the production of this consonant. It is also possible that coarticulatory resistance at the acoustic level follows not only from resistance in lingual activity but in labial or mandibular activity as well.

There are no clear explanations for why this should be so. It could be that the production of this and other phonetic segments requires less variable articulatory configurations in German than in French, Spanish and Italian. More constrainted articulations may be associated with vowel production (German distinguishes tense from lax vowels), consonantal production and/or prosodic structure (German is a stress-timed language). More experimental evidence is needed to investigate this issue.

In summary, the German case suggests that coarticulatory resistance for a particular vocalic or consonantal segment may not clearly depend on the articulatory constraints on gestural production. The articulatory explanation will no doubt account for why complex velarized [l] is not much affected by the surrounding segments. It will not however explain why, contrary to languages such as French, Spanish and Italian, German non-velarized [l] is also resistant to F_2 coarticulatory effects.

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Appendix

The contact index values were calculated with the following formula:

Palatal contact indices

$$CA_p = [\log[(R_8/8) + 9(R_7/8) + 81(R_6/8) + 729(R_5/8) + 1]]/\log(821)$$
$$CP_p = [\log[(R_5/8) + 9(R_6/8) + 81(R_7/8) + 729(R_8/8) + 1]]/\log(821)$$
$$CC_p = [\log[(C_1/8) + 9(C_2/8) + 81(C_3/8) + 729(C_4/8) + 1]]/\log(821)$$

In the ratios within parentheses, the number of activated electrodes on each row (i.e., R_5, R_6, R_7 . . .) or column (i.e., C_1, C_2, C_3 . . .) 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 will be explained below for the CA_p index.

A coefficient of 1 was arbitrarily assigned to the backmost row R_8. It follows from the contact index formula that the maximum CA_p value for this row when all eight electrodes are activated is 1:

(8 activated electrodes/8 electrodes available) × coefficient value of 1 = 1.

One "on" electrode on R_7 should contribute more to the CA_p index value than 1, which is the maximum CA index value for R_8, namely,

(1 activated electrode/8 electrodes available) × unknown coefficient value > 1.

It follows that the coefficient value for R_7 should be higher than 8, namely,

$$(8 \times 1) + 1 = 9.$$

To obtain the coefficient value for R_6, one "on" electrode on this row should contribute more to the CA_p index value than the previous rows R_7 and R_8. Since the addition of the maximum CA_p index value for R_7 and R_8 is 10, it follows that:

if (1 "on" electrode/8 electrodes available on R_6) × coefficient value > 10,

then the coefficient value for $R_6 = (8 \times 10) + 1 = 81$

The same operation was applied to the remaining indices. For the calculation of the CP_p index coefficients, rows were considered in the reverse order (thus, R_5 was assigned a coefficient of 1, R_6 a coefficient of 9, and so on). Coefficients for the CC_p 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_p, CP_p, and CC_p 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.