

960

## AN ELECTROPALATOGRAPHIC STUDY OF ALVEOLAR AND PALATAL CONSONANTS IN CATALAN AND ITALIAN\*

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Electropalatographic data for Catalan and Italian reported in this paper reveal the existence of two categories of palatal consonants, namely, alveopalatals ([ɲ], [ʎ]) and palatals proper ([j]). All these consonants are produced with a single place of articulation and thus are not good candidates for complex segments involving a tongue front articulator and a tongue dorsum articulator. A higher degree of coupling between the primary articulator and other tongue regions for alveopalatals and palatals than for alveolar [n] accounts for a reduced sensitivity to coarticulatory effects for the former vs. the latter. Alveolar-palatal correlations reported in this study support the notion of relative independence between different tongue articulators for non-dorsal vs. dorsal consonants. Differences in articulation and coarticulation were found for Italian vs. Catalan. In comparison with their Catalan counterparts, Italian shows the following properties: Consonants are more anterior, [n] allows less coarticulation at the alveolar zone (in line with the laminal nature of the consonant), and long alveopalatals exhibit more contact and less coarticulation at the front palatal zone.

*Key words:* coarticulation, palatal consonants, electropalatography, Italian, Catalan

### INTRODUCTION

#### *Articulatory characterization of palatal consonants*

In order to design realistic speech production models we need to gather accurate information about the set of invariant, actively controlled mechanisms used by speakers to perform articulatory gestures.

The issue of tongue control during the articulation of palatal consonants has been given little attention in the literature (Fardell, 1967). This situation is in contrast with what we know about the production mechanisms for bilabial, dentoalveolar, and velar

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consonants. A common practice among phoneticians is to assume that all palatals (i.e., [ɲ], [ʎ], [ç], [ç̞], [j] ...) are realized at the same place of articulation (i.e., at the palatal zone) with the same articulator (i.e., the tongue dorsum) (I.P.A., 1974; Ladefoged, 1988). Recent proposals (Sagey, 1986; Keating, 1988; Recasens, 1990) suggest that traditional articulatory descriptions do not capture the complexity involved in the process of tongue control during the production of this set of speech sounds.

Palatal consonants usually show a large contact area over the surface of the hard palate. Patterns of linguopalatal configuration do not reveal whether the primary place of articulation extends over the entire contact area or is restricted to a specific location; therefore, it is not clear whether active control is exerted over a large or a rather small tongue region during the production of palatals.

Two alternative hypotheses have been proposed as to the articulatory specification of these consonantal segments. According to one proposal, palatals do not form a single category but need to be grouped into alveopalatals ([ɲ], [ʎ]) and "true" palatals ([j]) (Recasens, 1990; Recasens, Farnetani, and Ní Chasaide, 1991). Moreover, while all these sound classes require some tongue dorsum raising, articulatory control is presumably directed towards a single tongue region, namely, the predorsum (and presumably the back of the blade as well) for alveopalatals and the predorso-mediadorsum for "true" palatals. Another proposal argues that all those consonants (i.e., [ɲ], [ʎ], [j]) can be subsumed under the same articulatory class. According to this hypothesis they are complex segments involving simultaneous activation of two separate tongue regions, i.e., tongue blade and tongue dorsum (Keating, 1988). In summary, two questions remain unanswered regarding the characterization of consonants sharing a closure or constriction at the palatal zone: Whether articulatory control is directed towards a single articulator or towards different articulators at the same time, and whether palatals form a single articulatory class or not.

In this paper we will attempt to throw some light on the relative validity of these two alternative hypotheses by presenting electropalatographic data for [ɲ], [ʎ], and [j]. The articulatory manifestation of these consonants will be compared with that for alveolar [n] which, differently from [ɲ], is produced with the tongue front and is thus not suspect of involving tongue dorsum activation.

### *Articulatory control and coarticulation*

Realistic speech production models should also contain translation rules which account for the modifications of target gestures as a function of phonetic context, changes in speech rate, speaker, etc.

Data reported in the literature indicate that the degree of coarticulation (i.e., overlap of articulatory gestures along the time dimension) is often associated with the nature of the articulatory control mechanisms. In general terms, there appears to be an inverse relationship between the degree of involvement exhibited by a given articulator in the production of a particular gesture and the degree of sensitivity to coarticulatory effects. For example, speakers shape very accurately the width and location of the fricative channel during the production of [s], as indicated by the existence of little coarticulatory sensitivity to vowel-dependent effects at the tongue front (Recasens, Fontdevila, and

Pallarès, 1992). Large coarticulatory effects associated with the adjacent vowels occur at the palatal zone during the production of unaspirated [p] since the tongue dorsum is quite unconstrained in this case. In a classical study by Lubker and Gay (1982), Swedish rounded vowels appeared to be subject to higher control requirements than American English rounded vowels since they were articulated with more lip protrusion and allowed less variability.

Coarticulation may also be strongly affected by physico-mechanical constraints such as the degree of coupling between articulators. It has been shown that V-to-C effects on the tongue dorsum are larger for [n] than for [ɲ], since this articulator is somewhat involved in the formation of the latter consonant but not of the former (Recasens, 1984). Also, a larger degree of coupling between tongue front and tongue dorsum for English alveolar vs. Italian dental [t] may explain why the former is less resistant than the latter to closure backing and tongue blade raising effects associated with adjacent [i] (Farnetani, Hardcastle, and Marchal, 1989).

A given articulator may also be more or less sensitive to coarticulatory effects depending on its degree of flexibility. In this respect it is known that laminal articulations are more resistant to coarticulation than apical articulations (Bladon and Nolan, 1977).

One goal of the present study was to investigate the role of these factors (articulatory control, coupling, and articulator flexibility) in lingual coarticulation. Data on vowel-dependent coarticulatory trends for [n], [ɲ], [ɰ], and [j] were used to draw inferences about the degree of control exerted by speakers over different tongue regions during the production of those consonants.

A second question of interest concerned the role of consonantal duration. The consonants [ɲ] and [ɰ] are particularly long in Italian and may achieve in some cases a duration comparable to geminate consonants in the same language (Bladon and Carbonaro, 1978; Farnetani and Kori, 1986; Farnetani, 1990). If an increase in the duration of alveopalatals conveys an increase in linguopalatal contact, we could hypothesize that Italian alveopalatals should be more resistant to coarticulation than Catalan alveopalatals.

### *Interarticulatory coordination*

The study of interarticulatory coordination has received some attention in the case of different articulatory structures, namely, tongue and lip (Faber, 1989; Carney and Moll, 1971), and tongue and jaw (Gay, 1977). However, little is known about the interactive behaviour of different tongue regions in speech production.

A third goal of this study, therefore, was to test whether speakers coordinate tongue front and tongue dorsum during the production of [n], [ɲ], [ɰ], and [j]. Lingual activity was inferred from linguopalatal contact data. Some aspects of interarticulatory coordination may be actively controlled; thus it may be that some speakers produce an alveolar stop closure at the back of the alveolar zone in order to facilitate tongue dorsum lowering effects caused by adjacent [a]. Other aspects may result from interarticulatory coupling effects. Although the tongue front is equally inactive during the production of palatals and velars, it may be freer to coarticulate for velars than for palatals because the former set of consonants is articulated with a more posterior place of dorsal articulation than the latter.

## METHOD

*Experimental paradigm and analysis criteria*

In order to study the theoretical issues discussed in the Introduction section we collected electropalatographic data for symmetrical VCV sequences with the vowels [i], [a], and [u], the consonants [ɲ], [ʎ], [j], and [n], and stress on the first vowel. This speech material was repeated five times by five native speakers of Catalan (five males – Eastern Catalan dialect), and by three native speakers of Italian (one male and two females – Northern variety of Standard Italian). Subjects were between 30 and 50 years of age and had grown up in their own native countries, i.e., Catalonia (Spain) and Italy. Sequences with [j] were not recorded for Italian; unstressed  $V_2 = /a/$  is always realized as [ə] in Catalan. Here are some words including [ɲ] and [ʎ] in both languages: (Catalan) *canya* ['kaɲə] 'cane', *balla* ['baʎə] 'he/she dances'; (Italian) *bagno* ['baɲo] 'bath', *battaglia* [ba'taʎa] 'battle'.

As shown in Figure 1 (top left), the artificial palate used in this study (Reading EPG system; Hardcastle, Jones, Knight, Trudgeon, and Calder, 1989) contains 62 electrodes divided into eight rows along the sagittal dimension (R1, . . . , R8) and four columns in each half of the surface of the electropalate (C1, . . . , C4). Arrows in the figure show that contact data for the rows are used to measure contact anteriority (CA) and contact posteriority (CP), while contact data for the columns indicate contact centrality (CC).

Figure 1 also represents the articulatory subdivisions on the artificial palate (top right) and on the palatal surface and tongue body (bottom). The four front rows of the electropalate correspond to the alveolar zone (until the very back of the alveolar ridge) and the four back rows form the palatal zone (behind the alveolar ridge); the alveolar zone is divided into two subzones (front alveolar and postalveolar) and the palatal zone into three subzones (prepalatal, mediopalatal, and postpalatal). Roughly speaking, there is a one-to-one correspondence between different tongue regions (Figure 1, bottom) and articulatory subzones: tip and front alveolar subzone; blade and postalveolar subzone; predorsum and prepalate; mediodorsum and mediopalate; postdorsum and postpalate. The terms central alveolar zone and central palatal zone are used in this paper as well; they refer to columns C3 and C4.

The general articulatory properties of the four consonants under study were measured at the point of maximum linguopalatal contact (PMC), namely, at the EPG frame showing the maximum number of "on" electrodes during the closure interval.<sup>1</sup> Contact configurations for the consonants under analysis were averaged across contextual conditions in order to study their articulatory characteristics (see below for details).

The degree of coarticulatory sensitivity was inferred from the number and size of the vowel-dependent coarticulatory effects allowed by each consonant at PMC. The contact index method described below was used to measure coarticulation. Contact index values

<sup>1</sup> In case that maximum contact lasts for 3, 5, 7 . . . frames, PMC is assumed to occur at the medial frame (i.e., frames 2, 3, 4 . . . , respectively); in case the maximum contact lasts for 2, 4, 6 . . . EPG frames, PMC is assumed to occur at the first of the two successive medial frames (i.e., frames 1, 2, 3 . . . , respectively).

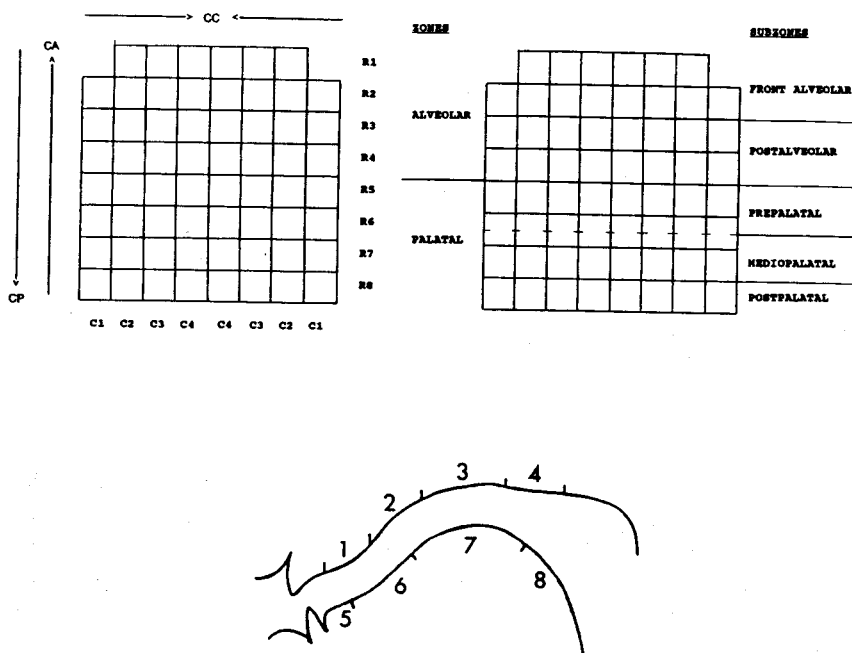


Fig. 1. Top, left: Distribution of rows R1 through R8 along the anteriority (CA) and posteriority (CP) dimensions, and of columns C1 through C4 along the centrality (CC) dimension on both sides of the electropalate. Top, right: Articulatory zones and subzones on the electropalate. Bottom: Vocal tract 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.

were applied to the alveolar and palatal zones independently. Vowel  $\times$  Language ANOVAs with repeated measures on the first factor were performed in order to find out whether a changing adjacent vowel (i.e., [i], [a], [u]) caused a significant difference in the contact index values, and whether significant effects were language dependent.

Correlations between contact indices at the alveolar and palatal zones for each consonant and speaker were also obtained. The purpose of this analysis was to examine speaker-dependent coordination mechanisms between tongue front and tongue dorsum in consonantal production.

#### *Contact index method*

The contact index method was developed by Fontdevila, Pallarès, and Recasens

(in press). Linguopalatal contact configurations were transformed into two contact index values along the sagittal dimension [posteriority (CP) and anteriority (CA)] and one contact index along the coronal dimension [centrality (CC)].

The CA and CP indices were calculated on a row by row basis, and the CC index on a column by column basis, separately for the alveolar zone (CAa) and for the palatal zone (CAp, Cpp, CCp). Contact at the alveolar zone was measured by CAa alone, since all consonants analyzed here are particularly sensitive to vowel-dependent effects in alveolar closure or constriction fronting; the choice of CAa is justified on the basis that this particular contact index is a much better indicator of variations in contact fronting than the CPa index (alveolar contact posteriority) or the CCa index (alveolar contact centrality). All three contact indices were computed at the palatal zone, since variations in dorsal contact may occur at the front palatal subzone or at the postpalatal subzone independently, and CCp is usually correlated with CAp and Cpp.

In view of the fact that closure location affects row R5 most of the time, this row was added to rows R1–R4 for the calculation of the CAa index; calculation of the palatal contact indices was based on the three backmost rows on the surface of the electropalate (R6–R8). The calculation of CCp was carried out for C1 through C4 on both sides of the surface of the artificial palate within the area delimited by R6 and R8. The value of the three indices increases as linguopalatal contact becomes either more anterior (CA) or more posterior (CP), or approaches the central zone on the surface of the artificial palate (CC). Each index varies between 0 and 1. For a detailed explanation, see the Appendix.

## RESULTS

### *Linguopalatal contact configurations and durational differences*

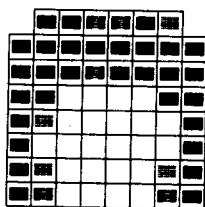
Figures 2, 3, 4, and 5 show average linguopalatal contact configurations at PMC for the consonants under study across vowel contexts in the two languages (all speakers). Electrode locations in the figures have been assigned three different grey shades at levels depending on the frequency of activation: (white) less than 40%; (dotted) 40–60%; (striped) 60–80%; (black) 80–100%. Darker electrodes delimit areas of contact stability, i.e., areas which are subject to less contact variability than lighter areas. It can thus be claimed that linguopalatal representations in the figures convey information about articulatory invariance for the consonants under study: Darker areas appear to be invariant to the extent that their activation is very much needed for a satisfactory production of the consonant.

*The consonant [n].* Closure for [n] occurs along the alveolar zone. Figure 2 suggests that this consonant is realized with the tongue tip, or with tongue tip and blade. Realizations which are mostly apical occupy a reduced area at the central alveolar zone which accords with the small magnitude of the tongue tip (speakers JP, JS, DP, JC, EF, MP); apicolaminar realizations show a larger contact area (speakers DR, GB). The presence of dotted electrodes at the place of articulation for some speakers suggests that alveolar closure fronting is quite variable. The figure shows that apical realizations

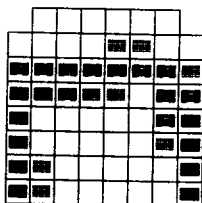
**n**

**CATALAN**

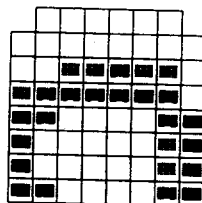
**DR**



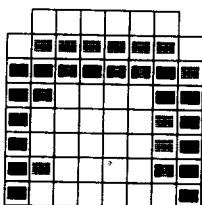
**JP**



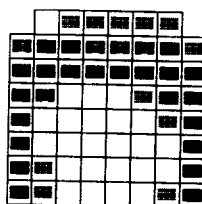
**JS**



**DP**

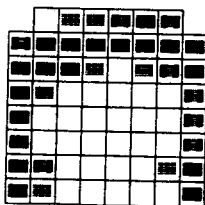


**JC**

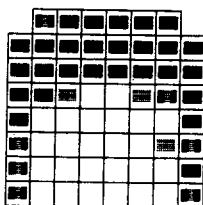


**ITALIAN**

**EF**



**GB**



**MP**

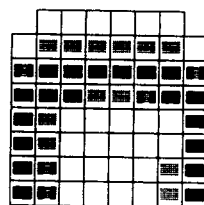
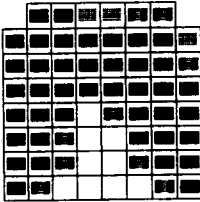


Fig. 2. Linguopalatal contact configurations at PMC for [n] across vowel contexts (all Catalan and Italian speakers). Percentages of electrode activation: (black) 80–100%; (striped) 60–80%; (dotted) 40–60%; (white) less than 40%.

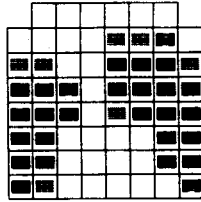
ʎ

**CATALAN**

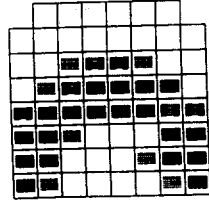
**DR**



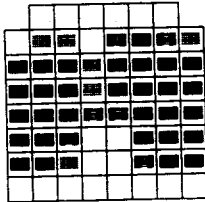
**JP**



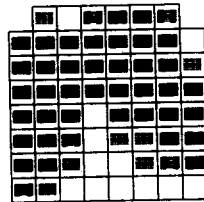
**JS**



**DP**

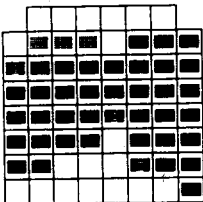


**JC**

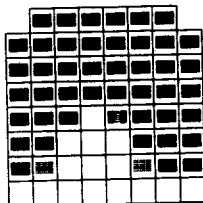


**ITALIAN**

**EF**



**GB**



**MP**

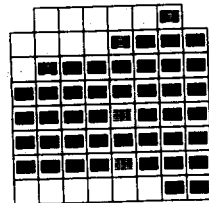


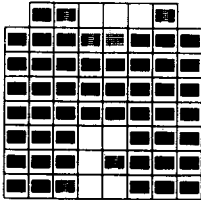
Fig. 3. Linguopalatal contact configurations at PMC for [ʎ] in Catalan and Italian.



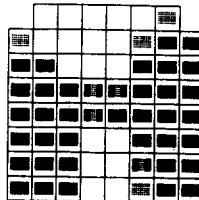
**ɲ**

**CATALAN**

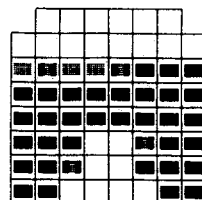
**DR**



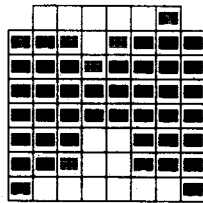
**JP**



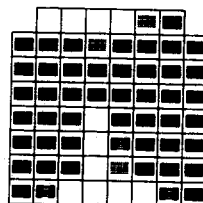
**JB**



**DP**

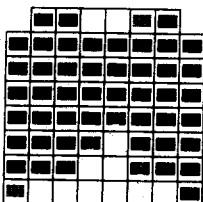


**JC**

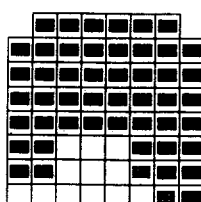


**ITALIAN**

**EF**



**GB**



**MP**

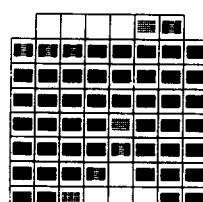


Fig. 4. Linguopalatal contact configurations at PMC for [ɲ] in Catalan and Italian.

TABLE 1

Mean durations (M) in msec and standard deviations (SD)  
for [ɲ] as a function of vowel context and language

Speakers	i		u		a	
	M	SD	M	SD	M	SD
C A T A L	DR	128 27.06	88 18.91	84 30.29	108 14.40	84 22.19
	JP	81 38.63	80 11.73	88 5.70	63 17.54	83 5.70
	JS	84 15.57	83 22.53	83 5.70	83 5.70	83 5.70
	DP	105 24.24	95 10.80	63 17.54	63 17.54	63 17.54
	JC	65 23.18	83 22.53	83 5.70	83 5.70	83 5.70
	TOTAL	92.6 24.38	85.6 5.79	85.2 16.02	85.2 16.02	85.2 16.02
I T A L I A N	EF	175 30.21	185 26.22	130 21.79	130 21.79	130 21.79
	GB	174 10.84	203 21.68	165 19.04	165 19.04	165 19.04
	MP	143 42.22	174 17.82	133 14.83	133 14.83	133 14.83
	TOTAL	164 18.19	187.3 14.64	142.7 19.40	142.7 19.40	142.7 19.40

of [ɲ] (like those for JP and JS) are more unstable than apicolaminal ones (for DR and GB) in this respect. Data in the literature support the view that the tongue tip is a more mobile articulator than the tongue blade (Bladon and Nolan, 1977).

The EPG configurations show only peripheral contact at the sides of the palatal zone, meaning that the tongue dorsum is quite low during the production of [ɲ].

*The consonants [ʎ] and [ɲ].* Closure location shows that [ʎ] (Figure 3) and [ɲ] (Figure 4) are alveopalatal (i.e., postalveolo-prepalatal) rather than palatal in both languages. These two consonants are always produced with complete contact at the postalveolar zone (row 4), usually extending to row 5 at the prepalatal zone, more so for the nasal stop than for the lateral. Occasionally lingual closure may spread further forward towards the front alveolar area (clearly so in the case of the Italian speaker GB) or further backward towards the mediopalate (as shown by the Italian speaker MP). The place of articulation for [ʎ] and [ɲ] in the figures suggests that both consonants are produced with the back of the blade and/or the predorsum.

In all cases alveopalatals involve a larger contact area at the sides of the palatal zone than the alveolar [n]. It can be argued that this difference is due to coupling effects

j

## CATALAN

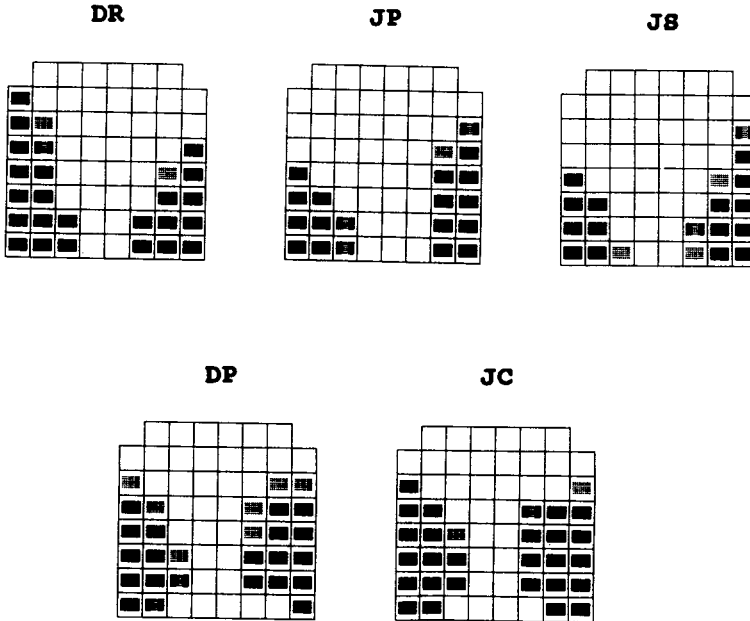


Fig. 5. Linguopalatal contact configurations at PMC for [j] in Catalan.

between tongue front and tongue dorsum: A more distributed and retracted place of articulation for [ɲ], [ʎ] vs. [ɲ] causes tongue dorsum raising.

There are differences between [ʎ] and [ɲ] which are probably associated with manner requirements. For most speakers, dorsal contact at the palatal zone occupies a smaller and more anterior area for [ʎ] than for [ɲ]. It appears that the tongue body must be placed in a more forward position for the lateral consonant so that airflow can escape through the sides of the postpalate or behind this articulatory subzone.

Some of the language-dependent differences for alveopalatals reported in this paper may be due to the fact that these consonants are longer in Italian than in Catalan (see Introduction). Table 1 displays closure durations for [ɲ] as a function of vowel context and language. As expected, Italian [ɲ] (range: 130–203 msec) is about twice as long

TABLE 2

Mean contact index values (M) and standard deviations (SD) for [n], [ɲ], [ɲ], and [j] as a function of vowel context. CAa: alveolar contact anteriority index; CAp: palatal contact anteriority index; CPp: palatal contact posteriority index; CCp: palatal contact centrality index. Brackets indicate significant vowel-dependent differences at the  $p < 0.05$  level according to Vowel X Language ANOVAs with repeated measures on the first factor

			CAa	CAp	CPp	CCp
n	i	M	0.94	0.86	0.80	0.45
		SD				
	u	M	0.61	0.73	0.79	0.26
		SD				
	a	M	0.72	0.63	0.63	0.11
		SD				
ɲ	i	M	0.78	0.94	0.71	0.66
		SD				
	u	M	0.76	0.92	0.74	0.62
		SD				
	a	M	0.79	0.89	0.56	0.46
		SD				
ɲ	i	M	0.83	0.95	0.82	0.70
		SD				
	u	M	0.83	0.95	0.86	0.65
		SD				
	a	M	0.82	0.93	0.75	0.61
		SD				
j	u	M	0.41	0.89	0.89	0.60
		SD				
	a	M	0.27	0.87	0.85	0.51
		SD				

as Catalan [ɲ] (range: 63–128 msec). This language-dependent difference was highly significant [ $F(1, 6) = 64.00, p < 0.001$ ]. The fact that both languages exhibit the same closure duration for [ɲ] (about 70 msec) reveals that duration differences for alveolo-palatals are phonological and independent of differences in speech rate between the two groups of speakers.

*The consonant [j]*. The consonant [j] (Figure 5) has a palatal articulation, with a constriction along the palatal zone produced with the tongue predorsum and mediodorsum. Lateral contact usually diminishes towards the front palate and may reach the edges of the postalveolar zone. The tongue tip and blade are mostly down during the production of this consonant.

#### *V-to-C coarticulation*

Table 2 presents mean contact index values for each consonant as a function of vowel context across the two languages under study. They were obtained from linguopalatal configurations such as those shown in Figures 6 and 7; these figures display palatograms at PMC for the consonants [ɲ] and [ɲ] in the context of [i], [a], and [u] for three of the Catalan speakers (DR, JP, JS). Contact index values were submitted to statistical analysis using Vowel  $\times$  Language ANOVAs with repeated measures on the first factor; the unequal number of speakers (five for Catalan, three for Italian) were handled using a unique variance approach. Brackets in the table indicate significant effects for specific vowel pairs according to *post-hoc* tests.

*The alveolar nasal [ɲ]*. The vowel effect was significant for all contact indices, i.e., CAa [ $F(2, 12) = 8.59, p < 0.01$ ], CAp [ $F(2, 12) = 18.21, p < 0.001$ ], CPp [ $F(2, 12) = 7.09, p < 0.01$ ], and CCp [ $F(2, 12) = 57.04, p < 0.001$ ]. While the language effect was nonsignificant, a Vowel  $\times$  Language interaction was obtained for CAa [ $F(2, 12) = 4.38, p < 0.05$ ].

As shown in Table 2 (also Figure 6), significant V-to-C effects in closure fronting (CAa) occur for front *vs.* back vowels; thus, [i] causes more alveolar contact fronting than [a] and [u]. The Vowel  $\times$  Language interaction is associated with a more anterior closure location with back vowels in Italian than in Catalan; indeed, a higher CAa index value was obtained in the former *vs.* the latter language, both for [u] (Italian:  $M = 0.84, SD = 0.16$ ; Catalan:  $M = 0.46, SD = 0.27$ ) and for [a] (Italian:  $M = 0.80, SD = 0.28$ ; Catalan:  $M = 0.66, SD = 0.25$ ). Inspection of data on significant vowel-dependent effects for individual speakers showed that alveolar articulations which are produced closer to the teeth (for Italian EF and GB, and for Catalan DR; see Figure 2) involve some laminal activity and are particularly resistant to retraction effects from adjacent back vowels. More apical-like realizations of the consonant (for Catalan JP, JS, DP, JC) may travel forward and backwards along the alveolar zone depending on the articulatory requirements for the adjacent vowel.

Concerning the palatal zone, the table shows significant differences in vowel fronting for CAp, in vowel height for CPp, and in both articulatory dimensions for CCp. Vowel-dependent effects in CAp and CPp can be traced in the contact configurations of Figure 6: While [i] involves more dorsal contact at the front palatal zone than [a] and [u] (see row 6), [a] is often produced with less contact than [i] and [u] at the back palate

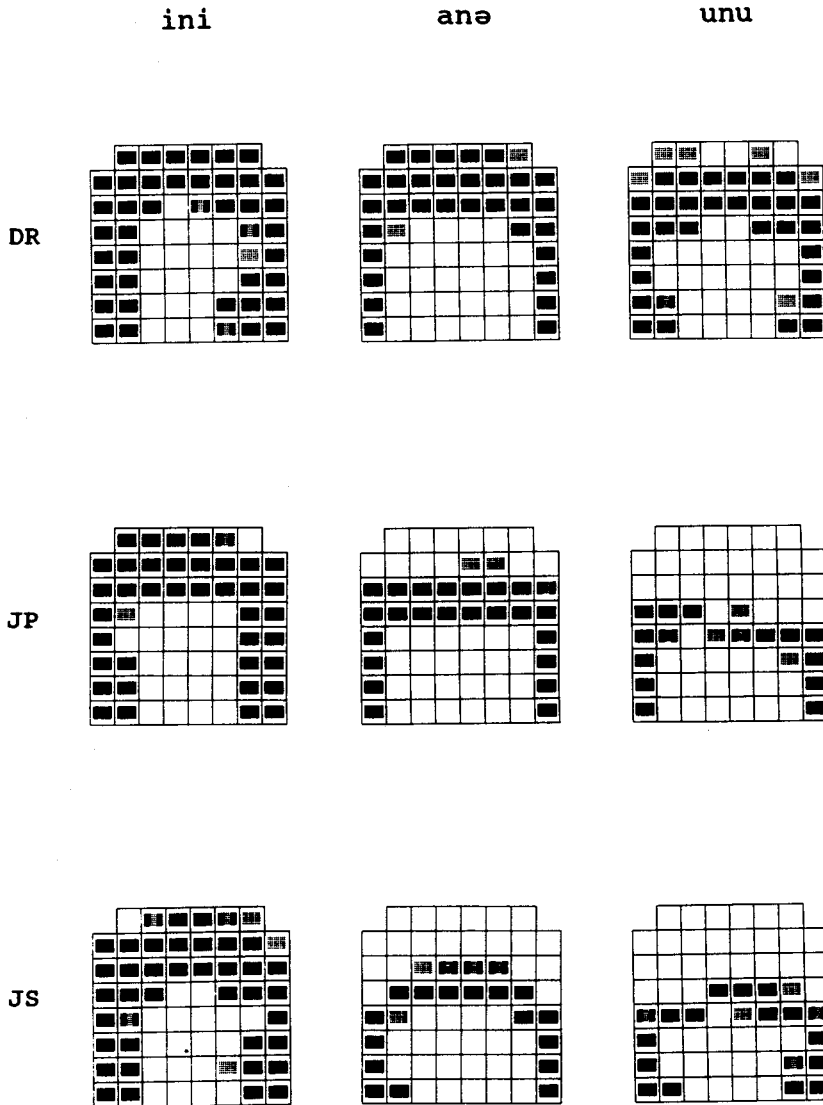


Fig. 6. Linguopalatal contact configurations at PMC for [n] in the symmetrical sequences [ini], [anə], and [unu] (Catalan speakers DR, JP, and JS).

(see row 8). Thus, a contact increase is obtained for high front vowels all over the palatal zone and for high back vowels at the back of the palatal zone only. Some nonsignificant language-dependent differences were observed: Contact index values for [n] with adjacent [a] were lower in Italian than in Catalan, both for CAp (Italian:  $M = 0.52$ ,  $SD = 0.24$ ; Catalan:  $M = 0.70$ ,  $SD = 0.00$ ) and for CPp (Italian:  $M = 0.48$ ,  $SD = 0.35$ ; Catalan:  $M = 0.72$ ,  $SD = 0.04$ ). Significance was not achieved in this case presumably because of the large variability involved in Italian. To a large extent this finding should be attributed to differences in vowel production between the two languages. Indeed, linguopalatal contact patterns at the steady-state vowel period of  $V_1 = [a]$  for the speakers of this study reveal that this vowel is considerably lower in Italian than in Catalan (in many cases the vowel was produced with some contact at the sides of the palatal zone in Catalan and no contact at all in Italian).

*The alveolopalatals: Nasal [ɲ] and lateral [ʎ].* The vowel effect was nonsignificant for CAa but significant for the palatal contact indices, i.e., CAp for [ʎ] [ $F(2, 12) = 8.70$ ,  $p < 0.01$ ] and [ɲ] [ $F(2, 12) = 4.39$ ,  $p < 0.05$ ], CPp for [ʎ] [ $F(2, 12) = 13.30$ ,  $p < 0.001$ ] and [ɲ] [ $F(2, 12) = 13.97$ ,  $p < 0.001$ ], and CCp for [ʎ] only [ $F(2, 12) = 10.28$ ,  $p < 0.05$ ]. The language effect was nonsignificant, and there was a Vowel  $\times$  Language interaction for CAp in the case of [ʎ] [ $F(2, 12) = 6.15$ ,  $p < 0.05$ ].

The absence of significant vowel-dependent differences in CAa for [ʎ] and [ɲ] indicates that these consonants are more resistant to tongue front coarticulation than [n] (which shows effects in vowel fronting at the alveolar zone). If we assume that the back of the blade and the front predorsum are actively involved in the formation of the consonantal closure for alveolopalatals, coupling effects may explain why the front blade (the tongue tip is probably down) is highly constrained, thus allowing for no vowel-dependent variability. Some non-significant language-dependent differences in CAa occur for alveolopalatals; indeed analogously to [n], CAa mean values indicate the presence of more closure fronting for Italian [ʎ] ([i] = 0.82, [u] = 0.85, [a] = 0.89) than for Catalan [ʎ] ([i] = 0.75, [u] = 0.70, [a] = 0.73), and for Italian [ɲ] ([i] = 0.88, [u] = 0.96, [a] = 0.93) than for Catalan [ɲ] ([i] = 0.80, [u] = 0.75, [a] = 0.75). Significance may not have been achieved in this case since the Catalan realizations were more variable (range of SD values: 0.13–0.26) than the Italian ones (range of SD values: 0.05–0.16).

Data at the palatal zone reveal a similar number of significant differences for [ʎ] as for [n], and a smaller amount of significant differences for [ɲ] than for the other two consonants. Differences between means in CAp and in CCp across vowel contexts decrease in the progression [n] > [ʎ] > [ɲ]; it appears that the degree of coarticulatory sensitivity at the front palatal zone increases with closure fronting and thus with a decrease in the coupling effects between the tongue dorsum and the tongue front. Although all consonants allow significant vowel-dependent effects in CPp at the back palatal zone, differences between means are smaller for [ɲ] than for [n] and [ʎ] (see also Figure 7); this finding suggests that large coupling effects for [ɲ] extend until the postpalate, thus preventing much coarticulation from occurring at this articulatory subzone.

Significant differences for alveolopalatals occur for high [i] and [u] (more contact)

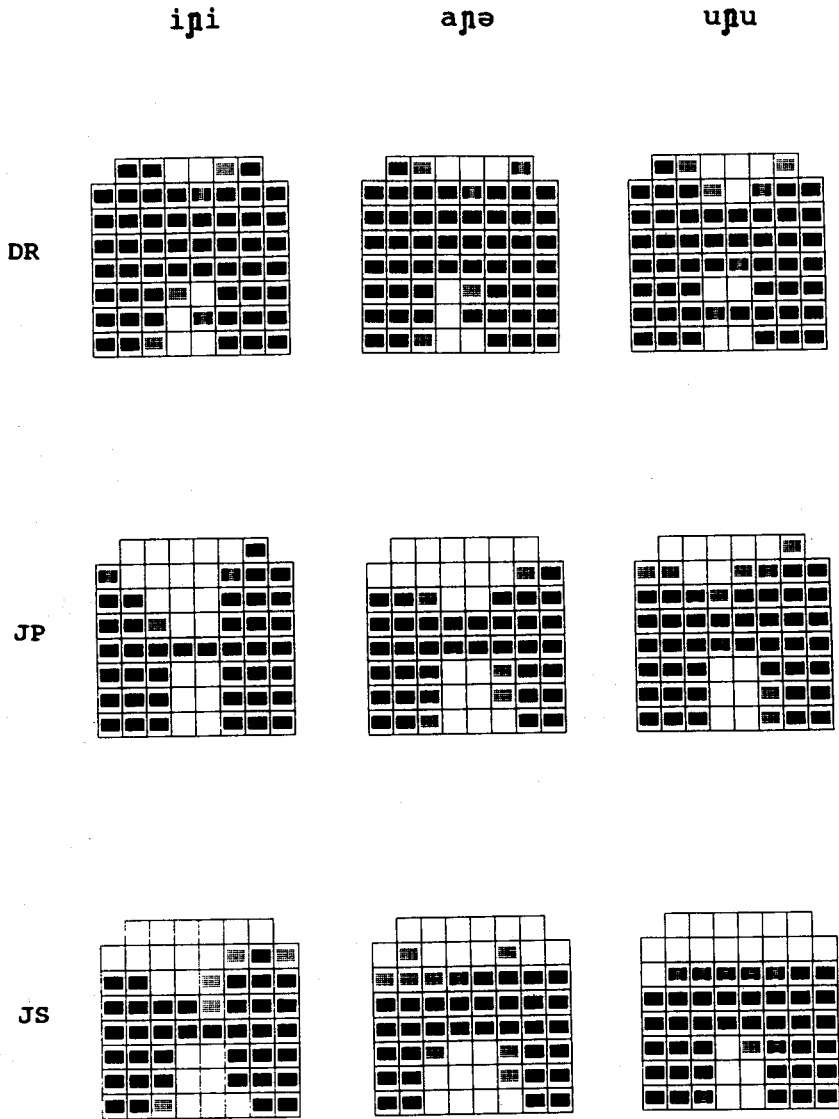


Fig. 7. Linguopalatal contact configurations at PMC for [ɲ] in the symmetrical sequences [ipi], [aɲə], and [upu] (Catalan speakers DR, JP, and JS).



vs. low [a] (less contact). The fact that coarticulation favors effects from vowels differing in height rather than in fronting may be due to constraints associated with tongue positioning for alveopalatals in general: Given that these consonants are produced with a large lamino-predorsal closure, there is little room for horizontal displacement in tongue dorsum activity as a function of [u] vs. [i] but some room for vertical displacement as a function of [a] vs. [i], [u]. Larger mean differences in CPp (at the back palatal zone) than in CAp (at the front palatal zone) suggest that coarticulatory sensitivity at the tongue dorsum increases with distance from the place of articulation.

Differences in linguopalatal contact and in coarticulatory sensitivity as a function of duration for alveopalatals (long in Italian, short in Catalan) was one of the research topics of this paper. CAp index values with adjacent back vowels are highly stable across languages (range of SD values: 0.02–0.06), and their means show a trend for Italian long [ɰ] ([u] : 0.95, [a] : 0.94) and [ɲ] ([u] : 0.96, [a] : 0.94) to be produced with more predorsal contact than Catalan [ɰ] ([u] : 0.91, [a] : 0.86) and [ɲ] ([u] : 0.95, [a] : 0.92). This trend can be also observed in Figures 3 and 4, and was confirmed by analogous non-significant language-dependent differences in CCp. The Vowel × Language interaction in CAp for [ɰ] reported above suggests that long alveopalatals require more control at the place of articulation (at least for the lateral consonant), thus allowing less coarticulation in tongue predorsum lowering from adjacent vowels. On the other hand, although non-significant, Catalan shows higher CPp values than Italian and thus more contact at the back palatal zone (see Figures 3 and 4).

*The palatal approximant [j].* Data for this consonant were obtained for the group of Catalan speakers only. A one-way ANOVA with repeated measures yielded a significant vowel effect for CAa [ $F(1, 4) = 14.7, p < 0.05$ ] but no significant effect for the three palatal contact indices (i.e., CAp, CPp, CCp).

Coarticulation at the alveolar zone could in principle occur quite freely since the tongue front is not involved in the production of [j]; CAa values in Table 2 show indeed that alveolar contact was significantly less with adjacent [a] than with adjacent [u]. The absence of significant differences from adjacent vowels at the palatal zone suggests that the size of the constriction passage for [j] is highly controlled and thus resistant to context-dependent modifications. At least for speaker DP (see also mean values in Table 2), high [u] causes some more narrowing of the central passage at the palatal zone than low [a]. In this case, the tongue body moves as a whole during the production of [j]; thus, some tongue dorsum lowering for [j] with adjacent [a] involves considerable tongue blade lowering as well.

#### *Alveolar-palatal correlations*

As pointed out in the Introduction section, a study of the correlations between CAa and the palatal contact indices across vowel contexts is useful to understand whether tongue front and tongue dorsum behave either in a coordinated fashion or independently.

Three Catalan speakers and one Italian show significant correlations for [ɲ] (range of  $r$  values: 0.64–0.86), with higher correlations between CAa and CAp than between CAa and CPp or CCp. For the three Catalan speakers (JP, JS, and DP) these correlations result from the fact that differences in alveolar contact fronting as a function of front

[i] vs. back [a] and [u] co-occur with differences in dorsal contact at the palatal zone. Correlations for the Italian speaker (MP) reflect simultaneous differences in alveolar contact fronting and in dorsal contact for high [i] and [u] vs. low [a]. Most speakers showing no correlations (DR, EF, GB) present a front alveolar allophone of [n] and allow little closure retraction as a function of adjacent back vowels.

Alveopalatals [ɲ] and [ʎ] show no significant alveolar-palatal correlations for any of the speakers analyzed in this study. This is so because the tongue front remains highly fixed independently of vowel context (see Table 2). In these circumstances, coarticulatory effects in tongue dorsum contact cannot correlate with vowel-dependent changes at the alveolar zone.

Significant correlations for [j] (range of *r* values: 0.77–0.91) are obtained for three of the five Catalan speakers (DR, JP, DP), mostly with CCp. For some speakers, differences in contact anteriority at the alveolar zone are directly correlated with differences in contact centrality at the palatal zone. As pointed out earlier, the tongue front for [j] is not subject to active requirements and may covary with changes at the place of dorsal articulation.

## DISCUSSION

An important issue addressed in this study is the articulatory characterization of palatal consonants. The data reveal that [ɲ] and [ʎ] are alveopalatal, and that only [j] is palatal. Therefore, a clear differentiation needs to be made between alveopalatals and palatals: Consonants such as [ɲ], [ʎ], and [j] cannot be subsumed under the same place of articulation category.

Even though the purpose of this paper was not to test articulatory complexity in alveopalatals, the fact that their place of articulation is highly specific suggests that these consonants are not complex segments but are produced at one place of articulation only (postalveolo-prepalatal) with a single articulator ((lamino)-predorsal). The extent of linguopalatal contact cannot be taken as an indicator of articulatory complexity either. In comparison to Catalan alveopalatals, an increase in front alveolar and/or mediodorsal contact for Italian long alveopalatals may be attributed to coupling effects between different lingual zones as lingual pressure increases presumably at the place of articulation. In our view alveopalatals may have been mistakenly interpreted as complex segments for the following reasons: (a) Their place of articulation takes place along two traditional articulatory zones (i.e., alveolar and palatal); (b) The lamino-predorsal articulator involves two traditional articulatory regions (i.e., blade and dorsum); (c) A cluster composed of [n] + [j] may give rise to [ɲ] (palatalization process) and *vice versa* (depalatalization process). In our opinion, neither process accounts for the existence of a [j] component during the production of alveopalatals. Palatalization simply requires the loss of the temporal lag between the two gestures of the cluster [ɲj]; the outcome of this process is a new consonant produced with one articulator at a single place of articulation. On the other hand, depalatalization may just imply the assignment of independent status by listeners to the articulatory configuration

at the release of alveolopalatal [ɲ].

We hypothesized that articulatory constraints on the production of alveolars, alveolopalatals, and palatals ought to be related to V-to-C coarticulatory effects and to alveolar-palatal correlations.

Coarticulatory effects for [ɲ] are quite large and occur for all contact indices at the two articulatory zones. Large effects at the palatal zone are associated with the fact that the tongue dorsum is not strongly coupled with the primary apico-laminal articulator; large effects at the alveolar zone agree with the high flexibility of the apico-laminal articulator. Considerable alveolar-palatal correlations for [ɲ] reflect the fact that the tongue front and the tongue dorsum may adapt to vowel context in a synergistic fashion: Closure fronting co-occurs with tongue dorsum raising, while closure backing co-occurs with tongue dorsum lowering.

The absence of alveolar-palatal correlations in the case of alveolopalatals indicates that either the tongue front (for [ɰ]) or the entire tongue body (mostly for [ɲ]) is quite constrained and thus resistant to coarticulation. Coarticulatory resistance at the palatal zone for [ɲ] occurs because the tongue dorsum is strongly coupled with the lamino-predorsal articulator; vowel-dependent effects for the two consonants occur preferably towards the back palatal zone. Coarticulatory resistance at the alveolar zone for alveolopalatals is due to coupling effects between tongue front and the primary dorsal articulator.

Palatal [j] allows larger coarticulatory effects at the tongue front than at the tongue dorsum. Variations in dorsal constriction size (i.e., in tongue dorsum height) co-occur with variations in alveolar contact fronting (i.e., in tongue blade height).

Language-dependent trends were found for alveolars and alveolopalatals. Contact index data at the alveolar zone and at the palatal zone for those consonants reveal a tendency to place the whole tongue body in a more forward position in Italian than in Catalan. On the other hand, differences in duration between Italian and Catalan alveolopalatals appear to be correlated with differences in contact size at the alveolo-prepalatal zone; moreover, an increase in contact conveys lesser sensitivity to coarticulatory effects from vowels.

As stated in the Introduction section, lingual coarticulation is conditioned by a complex array of factors.

Interarticulatory coupling effects explain coarticulatory trends for alveolopalatals and palatals at articulatory zones which are not primarily controlled. Alveolar-palatal coupling effects for consonants involving a dorsopalatal closure or constriction cause the tongue front to remain fixed; in the case of [j], the tongue front may adapt to vowel context along with the palatal zone. Coarticulation for alveolar [ɲ] is not ruled out by the primary articulator. Conversely, changes at the alveolar zone occur as a function of changes at the articulatory zone which is not actively involved in the production of the consonant. Presumably, they occur not because of inertial constraints but because of the need to facilitate consonantal production in a given phonetic environment. This is particularly clear in the case of [ɲ] with adjacent [a]: Tongue dorsum lowering for [ɲ] is compatible with the presence of a front and a back alveolar closure, and speakers differ with regard to whether they choose the former option or the latter.

Differences in articulatory flexibility may explain why laminal-like varieties of [n] block vowel-dependent effects at the alveolar zone to a larger extent than apical-like allophones of the consonant.

Finally, linguistic factors affect coarticulation. Concerning Italian and Catalan, coarticulatory trends appear to be conditioned by constraints on the production of the consonants (language-dependent differences in tongue body fronting, and in segmental duration and degree of contact) as well as on the production of the adjacent vowels (language-dependent differences in tongue height for [a]).

In view of these observations it appears that a theory of coarticulation must integrate linguistic aspects subject to active control with mechanico-inertial ones, such as coupling effects between articulators and articulatory flexibility.

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## APPENDIX

The following mathematical formulae were developed for the calculation of the index values:

*Alveolar contact index:*

$$CAa = [\log [ [(R5/8) + 9(R4/8) + 81(R3/8) + 729(R2/8) + 4921(R1/6) ] + 1 ] ] / [\log (5742)]$$

*Palatal contact indices:*

$$CAp = [\log [ [(R8/8) + 9(R7/8) + 81(R6/8) ] + 1 ] ] / [\log (92)]$$

$$CPp = [\log [ [(R6/8) + 9(R7/8) + 81(R8/8) ] + 1 ] ] / [\log (92)]$$

$$CCp = [\log [ [(C1/6) + 7(C2/6) + 49(C3/6) + 343(C4/6) ] + 1 ] ] / [\log (401)].$$

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 will be 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 CA value for this row is 1 when all eight electrodes are activated:

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

One “on” electrode on R7 should contribute more to the CA 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 CA index value than the previous rows R7 and R8. Since the addition of the maximum CA index value for R7 and R8 is 10, it follows that:

if  $(1 \text{ "on" electrode} / 8 \text{ electrodes available on R6}) \times \text{coefficient value} > 10$ ,  
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 C<sub>Pp</sub> index coefficients, rows were considered in the reverse order (thus, R6 was assigned a coefficient of 1, R7 a coefficient of 9, and so on). Coefficients for the C<sub>Cp</sub> 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 to each contact index so that a range from 0 to 1 is obtained.

The contact index method will be illustrated with a comparison between index values at the alveolar zone for [n] in the sequences [ini], [anə], and [unu] for speaker DR (see Figure 6, top). Lingual contact in the figure is represented by filled electrodes. The placement of the alveolar central closure is more anterior with adjacent [i] and [a] (at R1, R2, and R3) than with adjacent [u] (at R2 and R3). CA<sub>a</sub> index values capture this difference: CA<sub>a</sub> is higher for [ini] (1.00) and [anə] (0.98) than for [unu] (0.82). Differences in contact index values at the palatal zone can also be illustrated. Contact differences at the prepalatal subzone in the progression [i] > [u], [a] are captured by the CA<sub>p</sub> index values ([ini] : 0.85; [anə] : 0.70; [unu] : 0.71); vowel-dependent differences at the postpalatal subzone for [i] > [u] > [a] yield different C<sub>Pp</sub> index values ([ini] : 0.87; [anə] : 0.70; [unu] : 0.84). Given those CA<sub>p</sub> and C<sub>Pp</sub> index values, the degree of central contact at the entire palatal zone varies in the expected progression, i.e., [ini] (0.50) > [unu] (0.28) > [anə] (0.11).