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An electropalatographic study of stop consonant clusters

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Abstract. This is an electropalatographic investigation of coarticulation for heterosyllabic stop consonant clusters in American English and Catalan VCCV sequences. The heterorganic clusters under analysis were [tk], [kt], [tp], [pt], [kp], [pk]. Evidence for gestural overlap between the two adjacent consonants in the cluster is found quite systematically about the closure midpoint and, less so, at C1 onset and at C2 offset. Overlap occurs between constrained and unconstrained lingual regions (e.g., [p] is produced with more alveolar contact than usual when preceded by [t]) and gives rise to blending between tongue front and tongue dorsum activity during the production of lingual clusters [kt] and [tk]. Clusters are equally sensitive to vowel-dependent effects at all moments in time during the closure period. Such effects are quite large for clusters involving lingual [t] or [k] and non-lingual [p] and quite small for clusters made of the two former lingual stop consonants. These data on consonant- and vowel-dependent coarticulatory effects suggest that stop clusters are produced as highly cohesive production units. A constraint for anticipatory vowel-dependent effects to occur at the cluster midpoint but not so at cluster onset can be taken in support of a time-locked model of coarticulation. Speaker-dependent trends were also observed.

Zusammenfassung. Dieser Artikel beschreibt eine elektro-palatografische Untersuchung der Mitartikulation bei Gruppen mit Mischsilben und Stopkonsonanten im amerikanischen Englisch und in VKKV Silben im Katalanischen. Die untersuchten, hetero-organischen Gruppen waren (tk), (kt), (tp), (pt), (kp), (pk). Es wurde eine systematische Überlappung der beiden aufeinander folgenden Konsonanten der Gruppe festgestellt, und zwar in der Mitte des Haltens und, nicht ganz so deutlich, am Anfang der Gruppe I und am Ende der Gruppe 2. Die Oberlappung tritt zwischen sprachlich erzwungenen und nicht erzwungenen Regionen auf (Z.B.: (p) wird durch einen stärkeren Hohlkontakt erzeugt, wenn (t) darvorsteht) und ergibt eine gemischte Aktivität zwischen der Zungenspitze und dem Zungenrücken während der Erzeugung der Gruppen (kt) und (tk). Die Konsonantengruppen werden in gleicher Weise während des Haltens durch die einschliessenden Vokale beeinflusst. Diese Auswirkungen sind ziemlich deutllch bei den mit der Zunge erzeugten Gruppen mit (t) oder (k) und bei der nicht mit der Zunge erzeugten Gruppe mit (p), sind aber ziemlich gering bei Gruppen, die (t) und (k) enthalten. Diese Daten über die Auswirkungen der Mitartikulation lassen vermuten, dass Stopkonsonanten wie stark zusammenhängende Einheiten erzeigt werden. Der Zwang der bewirkt dass die vorgreifenden Auswirkungen von den Vokalen abhängen treten nur in der Mitte der Konsonantengruppen auf und nicht am Anfang. So kann der Zwang als ein Element für ein zeitbegrenztes Modell der Mitartikulation betrachtet werden. Es wurden auch bestimmte vom Redner abhängige Tendenzen festgestellt.

Résumé. Cet article présente une étude électro-palatographique de la coarticulation dans des groupes hétéro-syllabiques de consonnes occlusives en anglais et dans des séquences VCCV en catalan. Les groupes hétéro-organiques étudiés sont [tk], [kt], [tp], [pt], [kp], [pk]. On trouve presque systématiquement la trace d'un recouvrement gestuel entre les 2 consonnes

adjacentes du groupe, au niveau du milieu de la tenue et, moins nettement, au début de Cl et à la fin de C2. Le recouvrement apparait entre des régions linguales contraintes et non contraintes (par exemple, [p] est produit avec un contact alvéolaire plus fort que la normale quand il est précédé de [t]) et donne lieu à un mélange d'activité du bout de la langue et du dos de la langue pendant la production des groupes [kt] et [tk]. Les groupes consonantiques sont influencés de la même manière, tout au long de la tenue, par les voyelles environnantes. Ces effets sont relativement larges pour les groupes comportant les linguales [t] ou [k] et la non-linguale [p] et sont relativement faibles pour les groupes comportant les 2 linguales occlusives [t] et [k]. Ces données sur les effets de co-articulation suggèrent que les consonnes occlusives sont produites comme des unités de production hautement cohésives. La contrainte imposant que les effets anticipatifs, dépendant des voyelles, n'apparaissent qu' au milieu du groupe consonantique et non à son début peut être considérée comme un élément en faveur d'un modèle de coarticulation "time-locked". Certaines tendances dépendantes du locuteur ont également été observées.

Keywords. Coarticulation; electropalatography; gestural blending; intergestural cohesiveness.

1. Introduction

The main theoretical goal of the research reported in this study is to gain more knowledge about the spatio-temporal mechanisms underlying lingual activity in speech production. We will investigate lingual coarticulation in VCCV sequences with vowels [i] and [a], and consonant clusters composed of oral stops of different place of articulation, i.e., [tk], [kt], [tp], [pt], [kp], [pk]. In order to achieve an integrated view of the articulatory organization of these VCCV sequences, separate analyses will be carried out for C-to-C effects (Section 3.2) and for vowel-dependent effects (Section 3.3) along the cluster.

1.1. Articulatory overlap between C_1 and C_2

Recent electropalatographic studies (Hardcastle and Roach, 1979; Marchal, 1988) show that bilabial, dentoalveolar and velar stops are to a large extent coproduced in heterorganic stop consonant clusters. For all C_1C_2 combinations the onset of C_2 may occur before the closure release of C_1 thus causing gestural overlap to occur. For example, there is anticipation of dorsopalatal closure at C_1 = [t] in the cluster [tk] and anticipation of dental or alveolar closure at C_1 = [k] in the cluster [kt].

As revealed by well accepted coarticulation studies (Öhman, 1966) and data on *C*-to-*C* effects reported above, overlap between the lingual gestures for the two consonants should affect those tongue regions uninvolved in the formation of a closure or constriction. Concerning the stop clusters investigated here coarticulatory effects ought to occur from [t] on [k] at the alveolar zone (since the tongue front is involved in the production of the former versus the latter), from [k] on [t] at the velopalatal zone (since the tongue dorsum intervenes in the formation of [k] but is highly inactive for [t]) and from [t] and [k] on [p] at the alveolar and velopalatal zone, respectively (since the production of bilabials does not require lingual activity). Effects should occur from a lingual consonant ([t], [k]) onto another lingual ([t], [k]) or a non-lingual ([p]) consonant.

Two questions remain largely unanswered concerning the nature of the coproduction mechanisms involved in the articulation of stop clusters, namely, articulatory overlap in the time domain and the spatial consequences at different temporal points along the cluster.

1.1.1. Articulatory overlap over time

In order to investigate the temporal extent of overlap we will measure coarticulatory effects in lingual activity from a given consonant at differents moments in time during the adjacent consonant in the cluster. We want to know whether effects associated with the C_2 articulatory gesture (i.e., anticipatory effects) and with the C_1 articulatory gesture (i.e., carryover effects) are evenly found at all moments in time during the cluster or decrease the more we depart from the target consonant. Thus, for example, the formation of a dental or alveolar closure for [kt] may be anticipated either in the vicinity of the cluster midpoint or about the onset of the cluster. Both outcomes have important theoretical implications.

A short span of anticipatory or carryover activity can be handled assuming considerable gestu-

ral dissociation between the two consonants involved. This is the view of Catford (1977) according to whom the duration of overlap between C_1 and C_2 is between 30% to 45% of the combined duration of the two consonants. This hypothesis is highly compatible with the notion of progressive articulatory adaptation in time within the cluster.

Large coarticulatory effects occurring at cluster midpoint, and at cluster onset (anticipatory effects) and at cluster offset (carryover effects) may be adduced in support of the notion that the two stop consonants are organized simultaneously at the production level. In these circumstances it can be claimed that the cluster is produced with a high level of articulatory cohesiveness. There is some electropalatographic evidence in the literature for simultaneous preparation of the lingual gesture for C_2 with that for C_1 (e.g., for C_2 = [t] with that for C_1 = [k] in the cluster [kt] (Marchal, 1988)); moreover, data for clusters composed of a lingual consonant and a labial consonant reported by Kozhevnikov and Chistovich (1965) indicate quite small delays in the preparation of the C_2 gesture after the C_1 closure has begun. Consistently with these findings, acoustic data reveal significant anticipatory effects of C_2 during the V_1 formant transitions in VCCV sequences with stop consonant clusters (Zsiga and Byrd, 1990).

It should be noted that articulatory superposition may be affected by several factors. One of them is the complexity involved in the transition from the gesture for C_1 to the gesture for C_2. Indeed, Hardcastle and Roach (1979) found differences in the mechanisms used by speakers during the production of [kt] versus [tk]; in particular, the interval between the onset of C_1 closure and the onset of C_2 closure was shorter in the latter versus former group. According to these authors this is so since, while the formation of C_2 = [k] after [t] in the cluster [tk] involves some tongue dorsum raising only, there is shifting forward and upwards (and thus, some repositioning) of the body of the tongue when traveling from [k] towards [t] along the cluster [kt]. A second factor could be the degree of flexibility of the articulator involved. Thus, there could be more anticipatory coarticulation upon a preceding consonant (e.g., [p]) for the tongue tip or blade (for [t]) than for the tongue dorsum (for [k]) since the former articulator is more flexible than the latter (Kuehn and Moll, 1976). Thirdly, constraints associated with language, speaker and speech rate may also play a role. Indeed, coarticulatory mechanisms may differ according to language and speaker, and the degree of intergestural overlap may increase with faster speech rates (see (Hardcastle, 1985) for some confirmation of this trend in the case of [kl] clusters).

1.1.2. Spatial consequences

An interesting case is the articulatory outcome of the superposition between a tongue front gesture (i.e., for [t]) and a tongue dorsum gesture (i.e., for [k]).

For large amounts of overlap, two successive consonantal gestures produced with the same articulator may blend (Browman and Goldstein, 1989b). Blending can be characterized as intergestural accomodation giving rise to a different articulatory configuration from that exhibited by either gesture alone. For example, in Catalan, the consonantal sequence t̪n̪ (e.g. in the word ètnic "ethnical") involving two apical stop gestures at the dental zone (i.e., t̪) and at the alveolar zone (i.e., n̪) is produced with a single apical gesture at the meeting point between the teeth and the alveolar ridge.

Even though the tongue tip and the tongue body may behave as different articulators in consonantal production, they may interact in blending processes. This is how, in Romance languages, clusters [nj] and [lj] composed of an apicoalveolar gesture and a dorsopalatal gesture evolved into consonants [ɲ] and [ʎ] produced with a single laminopredorso–alveoloprepalatal gesture. Indeed, in comparison to clusters [nj] and [lj], [ɲ] and [ʎ] are made with an intermediate articulator (i.e., the lamino-predorsal region of the tongue) at an intermediate place of articulation (i.e., the alveolo–prepalatal zone) (Recasens, 1990). Similar cases of blending between different lingual regions have been reported in the literature for the cluster [sj] becoming [ʃj] and for velar stops being realized as medio-postpalatal articulations before a palatal vowel (Browman and Goldstein, 1989a). In these instances blending may be said to occur because the two articula-

tors belong to the same articulatory structure, i.e. the tongue.

We want to know whether coproduction between consonants articulated with contiguous lingual regions in the clusters [tk] and [kt] results in mere gestural overlap or into some perturbation of the articulatory configurations for [t] and [k] (i.e. gestural blending). In the latter case, the lingual region subject to active control ought to be placed somewhere between the tongue front and the tongue dorsum (as for alveolopalatals).

1.2. Coarticulatory sensitivity along the cluster

The investigation of the coarticulatory influences exerted by vowels along the cluster is crucial to gain some understanding about the principles of articulatory organization in VCCV sequences. It should be recalled in this respect that, while there is a great deal of information about the effects of vowels on single consonants in VCV sequences (see (Farnetani, 1990) for review), little attention has been paid to vowel-dependent effects along consonant sequences. In our view, the analysis of vowel-dependent effects may throw light into two issues of general interest, namely, the degree of gestural cohesiveness within the cluster and the validity of a look-ahead versus a time-locked model of lingual coarticulation.

1.2.1. Degree of gestural cohesiveness

One hypothesis, i.e., temporal dissociation between the two consonants in the cluster, predicts that vowel-dependent effects should affect the adjacent consonant almost exclusively (i.e., C_1 for V_1-dependent coarticulation and C_2 for V_2-dependent coarticulation). Vowel-dependent effects would be rather individual consonant dependent than cluster dependent, and quite less obvious at the cluster midpoint than at the onset and offset of the cluster. They should be mostly related to the degree of articulatory compatibility between each vowel and its adjacent consonant in a given VCCV sequence. Thus, effects in contact fronting associated with [i] should be more pronounced at the onset of the cluster [kt] than of the cluster [tk] since the tongue front is involved in the production of [t] versus [k].

According to the alternative hypothesis stating that clusters involve a high degree of cohesiveness (i.e., a high degree of overlap between the two consonantal gestures), vowel-dependent effects should exhibit a comparable weight all along the cluster independently of its segmental composition. The amount of coarticulation at the cluster midpoint ought to be quite similar to that observed at cluster onset and offset, and should depend on the degree of constraint for the consonantal gestures involved: effects in lingual activity should be small for clusters with two lingual consonants (e.g., [tk]) and quite large for clusters with one lingual consonant only (e.g., [pk]).

These two alternative hypotheses have interesting implications for a theory of speech production. The finding that the vowels are linked to the adjacent consonant rather than to the entire cluster is in support of the notion that VCCV sequences are organized in VC and CV units at the production level. If so, there are reasons to believe that vowel-dependent effects on the adjacent consonant should be larger in VC than in CV sequences given that consonantal gestures are less defined in checked versus open syllables (Fowler, 1987). On the other hand, the finding that clusters allow similar degrees of vowel-dependent coarticulatlon at their midpoints than at their onsets and offsets implies that, analogously to homosyllabic consonant clusters (Kent and Moll, 1975; Borden and Gay, 1979; Günzburger, 1983), heterosyllabic clusters may be organized as unitary production entities.

1.2.2. Look-ahead versus time-locked model of lingual coarticulation

Concerning the experimental paradigm used in the present study, the look-ahead and the time-locked models make different predictions about the temporal extent of anticipatory coarticulation in tongue dorsum activity for [i] versus [a] along the cluster. As long as there are no antagonistic requirements involved, these vowel-related effects should be free to occur according to the former theory, but time locked to the target vowel gesture according to the latter (see (Bell-Berti and Harris, 1981) for discussion).

The presence of simultaneous tongue front and tongue dorsum activity in clusters [tk] and [kt] would be antagonistic to lingual effects from

the vowels. Thus, anticipatory effects from V_2 = [i] versus [a] at cluster offset would be quite small for a highly cohesive realization of [kt] since tongue dorsum activity for [k] would still be available at that temporal point.

Effects would be found at non-antagonistic articulatory dimensions (i.e., tongue front for [k], tongue dorsum for [t] and both regions for [p]) in clusters with two non-overlapping lingual consonants and in clusters with a labial consonant. The two coarticulation models would make different predictions concerning the onset of the vowel-related effects. The time-locked model would predict a highly fixed onset of coarticulation in all

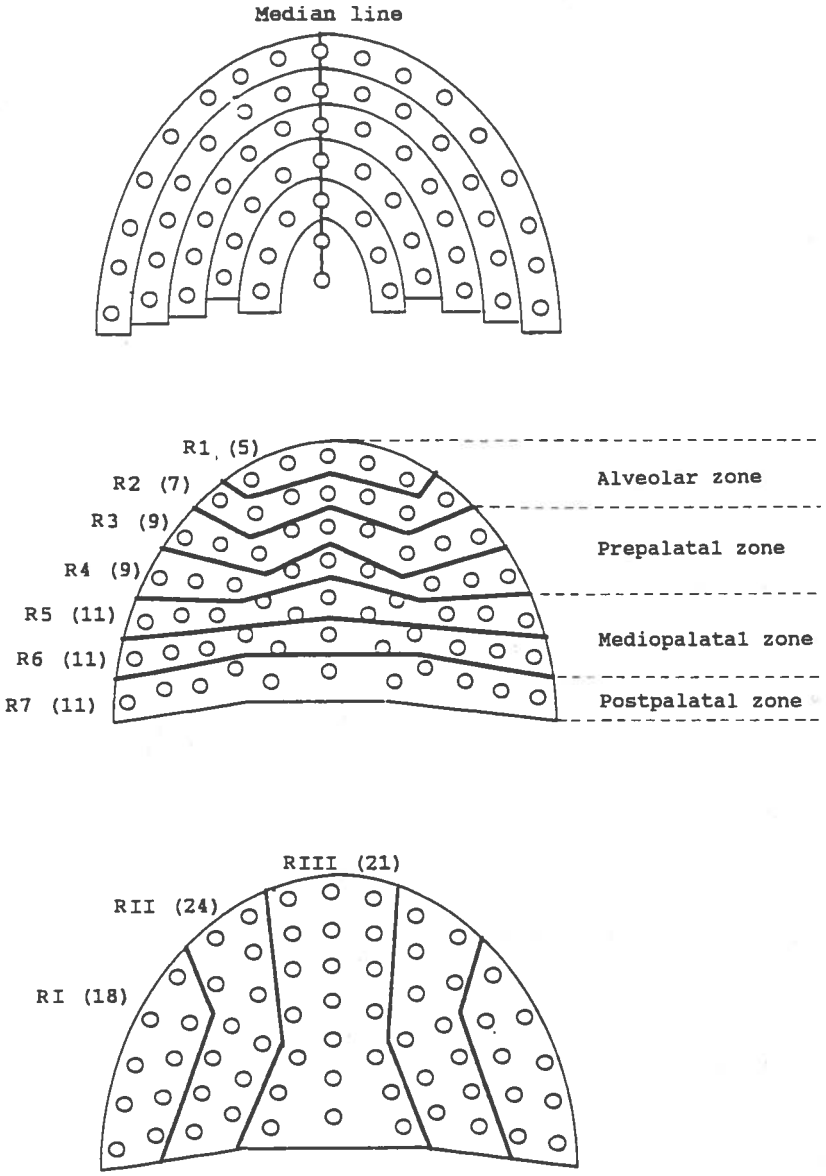

Fig. 1. (Top) Configuration of the artificial palate with division into five semicircular rows of electrodes. (Middle) Division into rows (7) and into articulatory zones along the sagittal dimension with number of electrodes within each row in parentheses. (Bottom) Division into regions (3) along the lateral-central dimension with number of electrodes within each region in parentheses.

Table 1
List of sequences analyzed in this study

TK	sitkis	KT	siktis
	sitkas		siktas
	satkis		saktis
	satkas		saktas
TP	sitpis	PT	siptis
	sitpas		siptas
	satpis		saptis
	satpas		saptas
KP	sikpis	PK	sipkis
	sikpas		sipkas
	sakpis		sapkis
	sakpas		sapkas

consonant clusters, probably not extending too much ahead of the cluster midpoint. The look-ahead model of coarticulation, on the other hand, would predict effects occurring back until cluster onset.

2. Method

2.1. General procedure

Electropalatographic data were collected for all possible symmetrical and asymmetrical [sVC-CVs] combinations with vowels [i] (as in English heed) and [a] (as in English father), and consonant clusters [tk], [kt], [tp], [pt], [kp] and [pk]. Nonsense items were chosen instead of real speech sequences in order to control the combinations of vowels and consonants as much as possible. The total number of sequences was 24 (see Table 1). The two vowels [i] and [a] were selected because they are produced with very different lingual configurations (i.e., high front [i] is articulated with contact at the sides of the palatal zone, and back low [a] may show some lateral contact at the very back of the artificial palate surface or no contact at all) and exert large coarticulatory effects on [p], [t] and [k] according to studies in the literature (see, for example, (Butcher, 1989)). Differently from [u], we can be confident that *V*-to-*C* coarticulatory effects in linguopalatal contact from [i] and [a] on [p] are highly independent of labial activity.

Subjects read the list of sequences six times each with the artificial palate in place after a period of adaptation. The electropalatographic system, RION Electropalatograph Model DP-01, was used in the experiment (Shibata et al., 1978). The artificial palate is a 2 mm thick rigid device made of acrylic resin, with a flexible film containing 63 gold electrodes arranged in five semicircular rows around the median line (see Figure 1, top). It allows displaying one pattern of contact every 15.6 ms. The artificial palate extends back to the postpalatal zone (see below) and all electrodes are distributed equidistantly.

Three speakers took part in the experimental sessions. One of the subjects was a speaker of Catalan, a Romance language spoken in Catalonia, Spain (speaker Re, the first author of this paper) and the other two were American English speakers (speakers Ra and Ha). They were trained phoneticians and had had previous experience with the artificial palate. Subjects were told to speak as naturally as possible at a comfortable rate, and to pronounce the two syllables with similar degrees of stress in order to avoid possible asymmetries in vowel-dependent coarticulation arising from one of the vowels becoming reduced; moreover, vowel reduction would also convey language-dependent differences in vowel coarticulation since unstressed /a/ is realized systematically as [ə] in Catalan versus English. Simultaneous recordings were made of the palatographic and the acoustic signal. The acoustical signal was digitized at a sampling rate of 10 kHz after pre-emphasis and low-pass filtering.

Language-dependent differences in stop production may affect the articulatory characteristics of the stop consonant clusters analyzed here. Concerning place of articulation [t] is dental in Catalan and alveolar in English, and [k] shows a front allophone (with adjacent front vowels) and a back allophone (with adjacent back vowels) in the two languages. Moreover, oral stops are unaspirated in Catalan and aspirated in English. Both languages could also differ with respect to the degree of overlap between the two stops in the cluster. Inspection of the acoustic signal suggests that this possible contrast is not related to the presence versus absence of an acoustic release for C_1: no C_1 release is available for clusters with C_2 = [p] in either language (also (Henderson and Repp, 1982)); moreover, the C_1

burst occurs systematically in the cluster [pk] for speaker Ra, and occasionally in the clusters [tk] (speakers Ra and Ha) and [pt] (speakers Re and Ha)

As shown in Figure 1 (middle and below), the following divisions have been performed on the artificial palate:

(a) Seven coronal rows of electrodes along the front-back dimension (R_1 = frontmost row; R_7 = backmost row) to calculate values for the contact anteriority and contact posteriority indices referred to below.

(b) Three sagittal electrode regions along the lateral-central dimension (R_I = lateral-most region; R_{III} = central-most region) to calculate values for the contact centrality index referred to below.

The correspondence between groups of coronal rows of electrodes and articulatory zones was analyzed separately for each speaker. All speakers show the same distribution of rows into articulatory zones, namely, alveolar zone (rows 1 and 2), prepalatal zone (rows 3 and 4), mediopalatal zone (rows 5 and 6), postpalatal zone (row 7) (see Figure 1, middle). We can thus be confident that the EPG data reported in this paper are comparable across speakers. As previously indicated in the literature, there also is a one-to-one relationship between tongue regions and those articulatory zones, namely, between tip and blade and alveolar zone, predorsum and prepalatal zone, mediodorsum and mediopalatal zone, and postdorsum and postpalatal zone (see (Catford, 1977)).

Two points in time were marked on the acoustic waveform for each sequence, at the onset of C_1 closure and at the offset of C_2 closure. Linguopalatal configurations were analyzed at the following EPG frames:

(a) At M_1 and M_3, namely, the second EPG frame after C_1 closure onset and before C_2 closure offset, respectively. This labelling criterion was based on the need to select a temporal point in which C_1 and C_2 were least influenced by the adjacent consonant in the cluster and most influenced by the adjacent vowel.

(b) At M_2, i.e., the EPG frame which was located half way between the onset and the offset of the complete closure period for the cluster. This labelling criterion was based on the need to measure articulatory overlap between the two adjacent consonants at a temporal point in which the cluster was least influenced by the surrounding vowels.

The location of M_2 was analyzed with reference to the period of contact overlap between C_1 closure and C_2 closure whenever visible on the EPG patterns. It can be ascertained that M_2 occurs mostly within that period and occasionally one EPG frame before it.

2.2. Indices of linguopalatal contact

The large number of data points for each EPG frame (i.e., 63) makes the analysis of the linguopalatal patterns extremely difficult. A new method of EPG data reduction, i.e., the contact index method, was used to attempt to solve this problem.

The EPG data were reduced with reference to three contact indices, namely, two indices along the anterior–posterior dimension (posteriority (CP) and anteriority (CA)) and one index along the lateral–central dimension (centrality (CC)). The anteriority and posteriority indices have been calculated on a row by row basis for the seven rows displayed in Figure 1, i.e., R_1 through R_7 (middle); the centrality index has been calculated for the three regions of electrodes represented in Figure 1, i.e., R_I through R_{III} (bottom). The value of an index increases as linguopalatal contact becomes either more posterior (CP) or more anterior (CA), or approaches the median line (CC). These three indices were chosen in order to achieve data reduction as well as to infer lingual activity along the most significant articulatory dimensions, namely, fronting (correlated with CA), backing (presumably correlated with CP) and raising (correlated with CC).

This method of EPG data reduction is explained in detail in Appendix A.

In order to measure coarticulatory effects, several analyses of variance were performed for all consonant clusters at M_1, M_2 and M_3 using SPSS (Nie et al., 1982). Data for each speaker were processed in separate ANOVAs ($p < 0.05$). Dependent variables were CP, CA and CC; indepen-

dent variables were vowel context and adjacent consonant in the cluster. Post-hoc analyses were carried out to elucidate significant coarticulatory effects associated with each pair of vowels and of adjacent consonants in all possible symmetrical and asymmetrical contextual combinations.

3. Results

3.1. General production characteristics

Before investigating the coarticulatory effects for the six stop clusters included in this study, we will carry out a general description of the two lingual consonants under study, i.e., [t] and [k]. It is believed that an understanding of the articulatory constraints involved in the production of these consonants should help predicting their coarticulatory behaviour.

Since no data for individual [t] and [k] are available (for example, in VCV sequences), clusters with [p] will be used to infer unaffected linguopalatal configurations for [t] (i.e., [tp], [pt]) and [k] (i.e., [kp], [pk]). This is so since [p] involves little or no lingual activity and should exert practically no coarticulation on [t] and [k]. Data

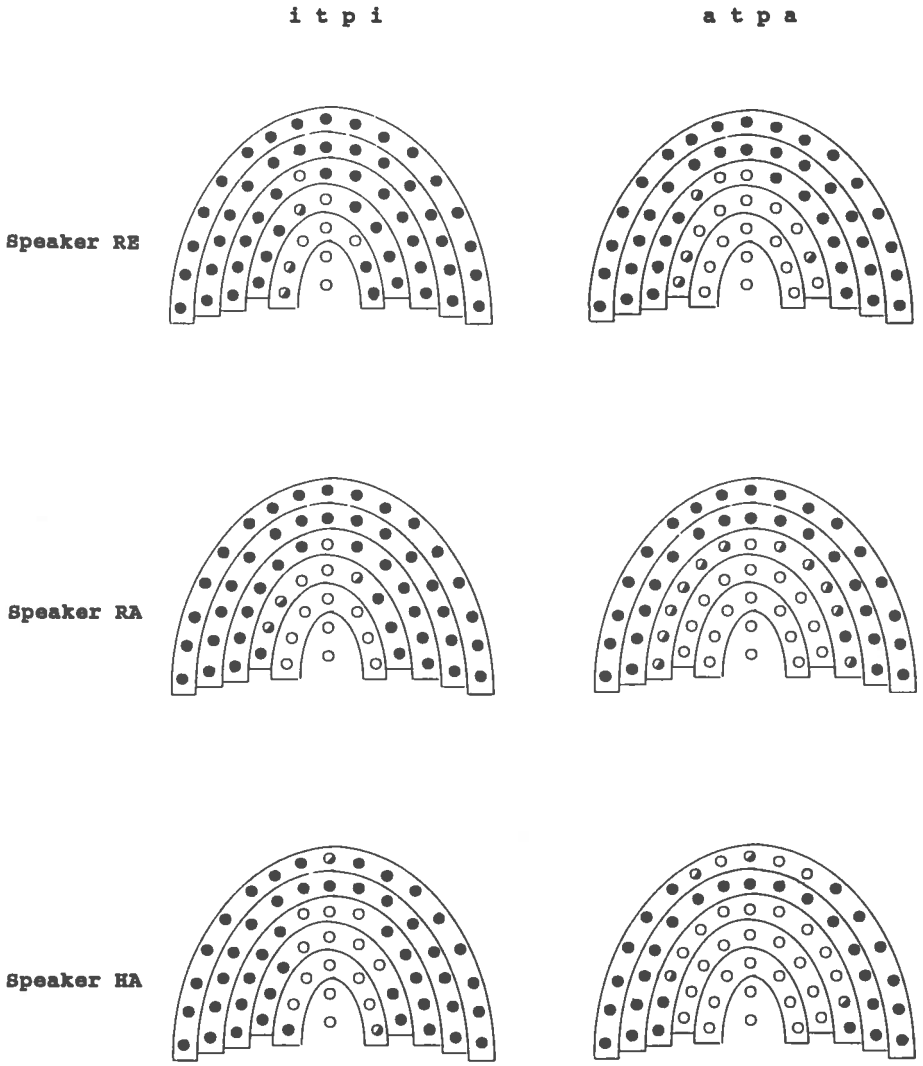

Fig. 2. Linguopalatal contact configurations for [t] in clusters [itpi] and [atpa] (all speakers).

for [t] and [k] at M_1 in the symmetrical sequences [iCpi] and [aCpa] have been chosen to characterize the two stop consonants (Figures 2 and 3).

Consonant [t] (Figure 2) is produced with full alveolar contact for speakers Re and Ra and some closure retraction within that zone for speaker Ha. It also involves dorsal contact at the sides of the palatal zone, more so for speaker Re than for speaker Ra and less so for speaker Ha than for the other speakers.

Consonant [k] (see Figure 3) shows no complete closure in the example presented here (but does so at the postpalate for clusters involving [t] and [k]). The most plausible explanation for this finding is that closure location occurs further back when [k] is adjacent to [p]; since the artificial palate does not extend into the velar zone it may not be effective in signalling velar closures in this contextual condition. According to Figure 3 the presence of [i] causes an overall contact increase all over the palatal surface which reflects a tongue dorsum raising gesture; analogously to [t], speaker Re shows some more contact towards the front and towards the center than speakers Ra

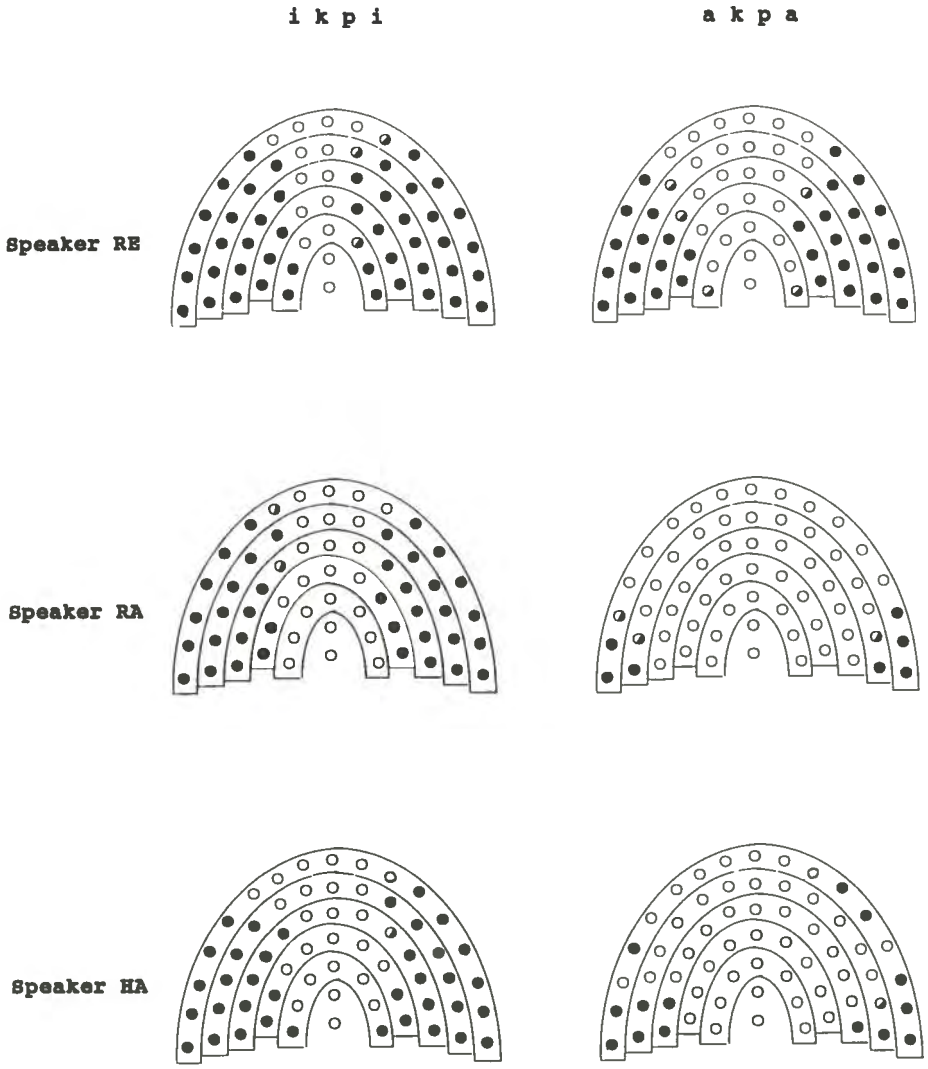

Fig. 3. Linguopalatal contact configurations for [k] in clusters [ikpi] and [akpa] (all speakers).

and Ha. Speaker-dependent differences are quite larger when [k] is adjacent to [a]; thus, in contrast with [ikpi], the American English speakers show much more contact retraction towards the back and the sides of the palatal surface than the Catalan speaker. This contrast is apparently related to more tongue dorsum lowering associated with the vowel [a] in American English versus Catalan, as confirmed by the EPG data at V_2 and at V_1; a lower realization of [a] in the former language versus the latter causes a more retracted back velar allophone to occur.

3.2. Consonant-dependent effects

Table 2 indicates the occurrence of significant differences in CA, CC and CP resulting from a preceding or a following changing consonant upon a fixed consonant in the cluster. Results are presented at M_1 and M_2 for C_1, and at M_2 and M_3 for C_2, in all vowel contexts. Thus, for example, the pair of clusters [tk]–[tp] allows measuring anticipatory coarticulatory effects from [k] versus [p] on [t] at M_1 (i.e., during C_1) and also at M_2 (since it is assumed that there may be traces of C_1 at the cluster midpoint). For speaker Re, these effects are shown at the upper left cell (M_1) and at the central cell (M_2) of Table 2. Significant effects occur mostly in contact posteriority (i.e., CP) and in contact centrality (i.e., CC) for the sequences [itka] versus [itpa] (2), [atki] versus [atpi] (3) and [atka] versus [atpa] (4). Thus, in the referred contextual conditions the dorsum of the tongue is making some more palatal contact during the production of [t] in anticipation of [k] versus [p] as revealed by index values capturing contact differences at the palatal zone. Moreover these contact differences turn out to be significant generally back to M_1.

3.2.1. Linguopalatal contact configurations at M_2

The number of significant effects in Table 2 shows that differences in linguopalatal contact between cluster pairs are expressed more at M_2 than at either M_1 or M_3 for all contact indices and speakers. The percentage of effects amounts

Table 2
Significant consonant-dependent differences in contact anteriority (CA), contact posteriority (CP) and contact centrality (CC) at M_1, M_2 and M_3 at the $p < 0.05$ level of significance. Each vowel combination is represented by a numerical code (iCCi = 1, iCCa = 2, aCCi = 3, aCCa = 4) and the presence of a number in the cell indicates that a significant difference was found for that vowel combination

		Speaker RE											
		M_1				M_2				M_3			
tk–tp	CA	–	–	–	4	–	–	–	–				
	CP	–	2	3	4	–	2	3	4				
	CC	–	–	3	4	–	2	3	4				
kt–pt	CA					1	2	–	4	1	2	3	4
	CP					1	2	3	4	1	2	3	4
	CC					1	2	3	4	1	2	3	–
kt–kp	CA	–	–	–	4	1	2	3	4				
	CP	–	2	–	–	–	2	3	4				
	CC	–	2	–	4	1	2	3	4				
tk–pk	CA					1	2	3	4	–	2	–	4
	CP					–	–	3	4	–	–	–	4
	CC					1	2	3	4	1	–	3	4
pt–pk	CA	–	2	3	4	1	2	3	4				
	CP	1	–	3	4	1	2	3	4				
	CC	–	–	–	–	–	2	3	4				
tp–kp	CA					1	2	3	4	–	–	3	4
	CP					1	2	3	4	1	–	3	–
	CC					1	2	3	4	1	–	3	–

to 85% (M_2) versus 44% (M_1) and 64% (M_3) for speaker Re, 74% (M_2) versus 19% (M_1) and 58% (M_3) for speaker Ra, and 79% (M_2) versus 17% (M_1) and 53% (M_3) for speaker Ha. These differences in coarticulatory sensitivity occur because contact configurations at M_2 are simultaneously conditioned by C_1 and C_2, while contact configurations at M_1 and M_3 are mostly dependent upon either C_1 (at M_1) or C_2 (at M_3). It thus appears that intergestural coproduction is particularly achieved at the cluster midpoint.

As commented below, coarticulatory effects from one lingual consonant on another lingual or labial consonant occur at those tongue regions which are not directly involved in the closure making process.

(a) Dentoalveolar [t] shows more dorsopalatal contact as a function of [k] versus [p] (see, for example, clusters [kt] and [pt] in Figure 4, top; speaker Re). According to Table 2 significant differences at M_2 from velar [k] versus bilabial [p] upon the fixed dentoalveolar [t] (cluster pairs [tk]–[tp] and [kt]–[pt]) are more obvious for the posteriority and centrality indices than for the anteriority index for all speakers. Large effects in CP and CC reflect the existence of more tongue dorsum raising in the case of adjacent [k] than of adjacent [p]; the presence of a front closure at M_2 for the two clusters prevents to a large extent effects in CA from taking place.

(b) Effects from [t] versus [p] on velar [k] (Figure 4, middle; speaker Re) are mostly associated with the presence (in clusters with [t]) versus absence (in clusters with [p]) of a front complete closure. According to Table 2, significant differences associated with changing [t] versus [p] upon fixed [k] at M_2 (cluster pairs [kt]–[kp] and [tk]–[pk]) occur mostly in CA and CC for all speakers. These coarticulatory trends reflect the presence of more tongue front raising in the case of adjacent [t] than of adjacent [p]; the presence of a back closure or constriction at M_2 for the two clusters prevents to a large extent effects in CP from taking place.

(c) Effects from [t] versus [k] on bilabial [p] at M_2 occur both at the alveolar zone and at the

Speaker RA												Speaker HA											
M_1				M_2				M_3				M_1				M_2				M_3			
–	–	–	4	1	–	–	–					1	–	–	–	1	2	–	4				
–	–	3	4	1	2	3	4					–	–	3	4	1	2	3	4				
–	–	–	4	–	–	–	4					–	–	–	–	–	2	3	4				
				–	–	–	–	–	–	3	–					–	–	3	4	–	–	3	–
				1	2	3	4	1	2	3	4					1	2	3	4	–	2	–	–
				–	2	–	–	–	2	3	–					1	2	3	4	–	–	–	4
–	–	–	–	1	2	3	4					–	–	3	4	1	2	–	–				
1	–	–	–	1	2	3	4					–	–	–	–	–	2	3	4				
1	–	–	–	1	2	3	4					–	–	–	–	1	2	3	4				
				1	2	3	4	–	2	–	4					1	2	3	4	–	2	3	4
				–	2	3	4	–	2	3	4					–	–	–	4	–	2	–	4
				1	2	3	4	–	2	3	4					1	2	3	4	–	2	–	4
–	–	–	–	1	2	3	4					–	2	–	–	1	2	3	4				
–	2	–	–	1	–	3	4					–	–	–	–	–	–	3	–				
–	–	–	–	1	2	3	4					–	–	–	–	1	2	3	4				
				1	2	3	4	1	–	3	–					1	2	3	4	1	2	3	–
				–	–	–	–	–	–	–	4					1	2	–	–	1	2	3	–
				1	2	3	4	1	–	3	4					1	2	3	4	1	2	3	–

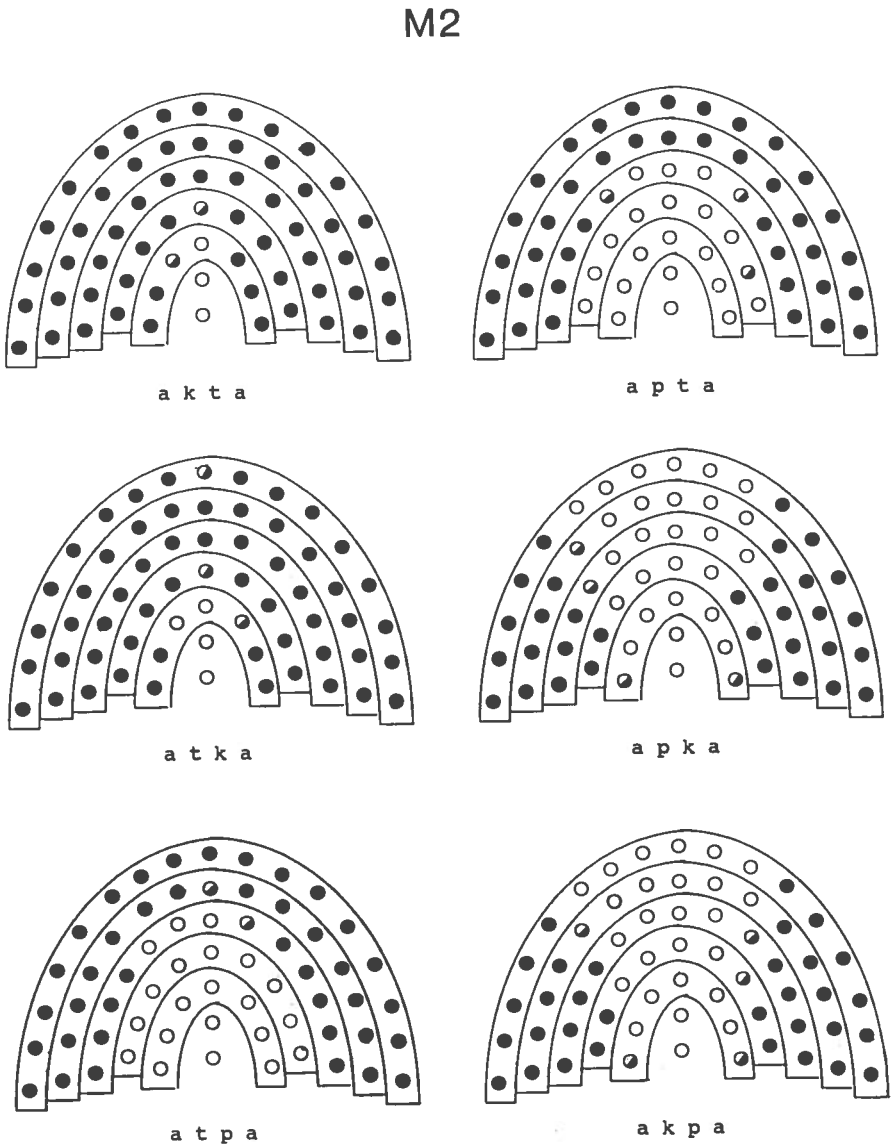

Fig. 4. Linguopalatal contact configuration at M_2 for the pairs of clusters [akta]/[apta], [atka]/[apka] and [atpa]/[akpa] (speaker Re).

palatal zone: clusters with [t] show a complete alveolar closure at the former, while clusters with [k] show a partial or complete palatal closure at the latter (Figure 4, bottom; speaker Re). According to the general hypothesis, data for speaker Re on Table 2 show large significant effects from [t] versus [k] on [p] at M_2 (cluster pairs [pt]–[pk] and [tp]–[kp]) in the three dimensions, CA, CP and CC. However, speakers Ra and Ha show less coarticulatory effects in CP than in CA and CC. This finding is presumably related to the absence of central contact at the back palate during the production of [k] for the two American English speakers, mostly when adjacent to the back vowel [a] (see Section 3.1).

3.2.2. Linguopalatal configuration for [tk] and [kt] at M_2

Notice that the amount of contact for clusters [kt] and [tk] at M_2 in Figure 4 is not a mere

addition of the linguopalatal configurations for [t] and [k]. In comparison to the contact patterns for uncoarticulated [t] (in clusters [tp] and [pt]) and for uncoarticulated [k] (in clusters [pk] and [kp]) shown in the same figure, the clusters [kt] and [tk] convey additional contact at the front and at the back palate. Indeed, the front closure in these clusters is larger and more retracted than for singleton [t] since it extends into the prepalatal zone on rows 3 and 4; also, there is more dorsopalatal contact than for [k].

These data can be interpreted as follows. During the production of [tk] and [kt], simultaneous raising of the tongue front for [t] and of the tongue dorsum for [k] causes the raising of the intermediate tongue surface portion. During a period of the cluster closure event (i.e., at M_2), the outcome of this process is blending between

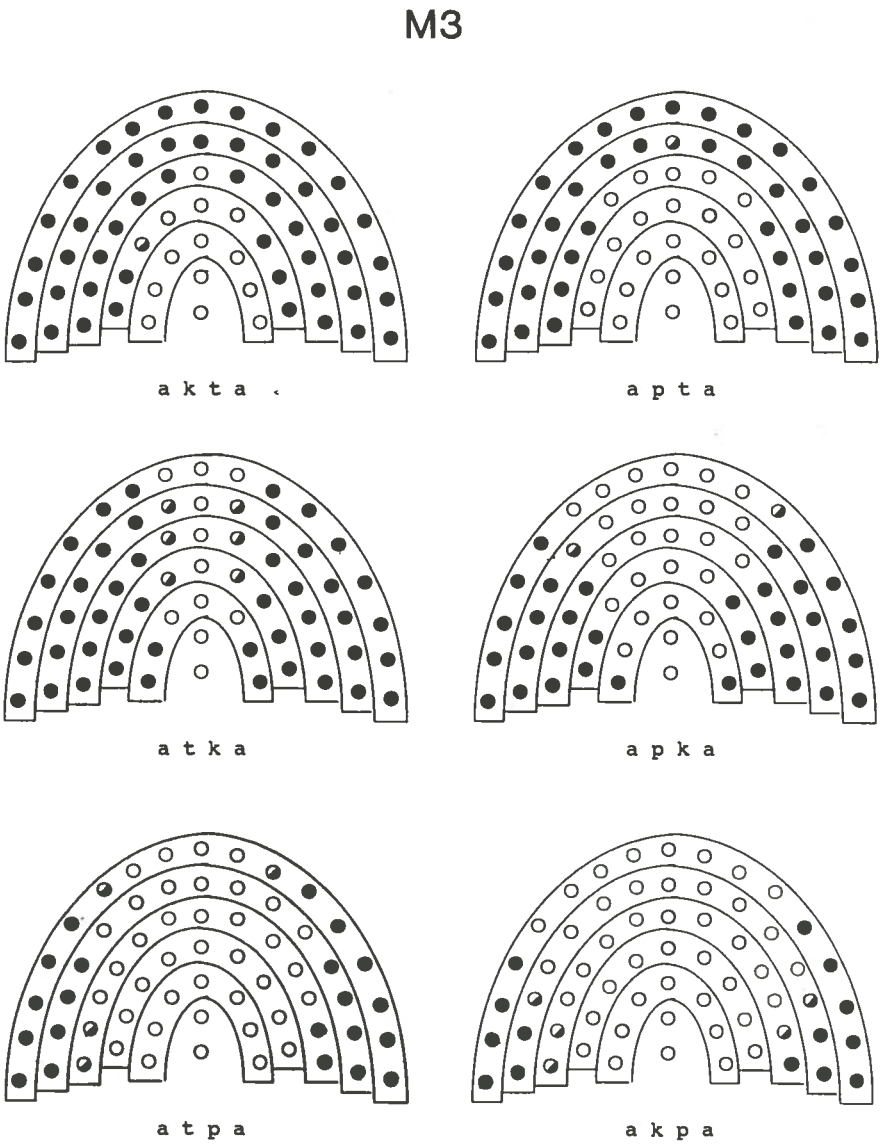

Fig. 5. Linguopalatal contact configuration at M_3 for the pairs of clusters [akta]/[apta], [atka]/[apka] and [atpa]/[akpa] (speaker Re).

two lingual gestures into a single gesture involving an intermediate primary articulator, i.e., the predorsum. As expected, blending conveys a shift in place of articulation (i.e., prepalatal instead of alveolar or velopalatal) and an increase in degree of dorsopalatal contact (which is larger than for dorsal [k]).

3.2.3. Linguopalatal contact configurations at M_1 and M_3

Table 2 also provides information about coarticulatory effects from a changing consonant upon a fixed consonant at the onset of the cluster (i.e., M_1) and at the offset of the cluster (i.e., M_3). It is expected that linguopalatal contact configurations at those two points in time reflect quite accurately the production characteristics of C_1 and C_2, respectively. However, while there are fewer coarticulatory effects at M_1 (from C_2) and at M_3 (from C_1) than at M_2, their number is in no way negligiable. As stated above, they exceed 50% at M_3 for all speakers and are quite high at M_1 for speaker Re (44%). Since consonant-dependent effects at these two moments in time can be quite large (more so at the carryover level than at the anticipatory level), it can be concluded that the degree of articulatory cohesiveness for the stop clusters analyzed in this paper is quite high.

Coarticulatory effects are analogous to those observed at M_2. Figure 5 illustrates the nature of these effects in some pairs of VCCV sequences for speaker Re. Data correspond to M_3 and are also valid for M_1.

(a) Dentoalveolar [t] shows some more tongue dorsum contact as a function of [k] versus [p] (Figure 5, top). A comparison between the EPG data for the same cluster [kt] at M_3 and M_2 (see top pairs in Figures 5 and 4) proves that [k] causes less dorsopalatal contact to occur in the former versus latter location. Therefore, the amount of coarticulation decreases the more we depart from the changing consonant.

Table 3
Significant effects from [i] versus [a] in contact anteriority (CA), contact posteriority (CP) and contact centrality (CC) at M_1, M_2 and M_3 at the $p < 0.05$ level of significance. Effects are given for symmetrical VCCV sequences (S), and for changing V_1 (carryover; C) and changing V_2 (anticipatory; A). The quality of the transconsonantal vowel is indicated for significant effects in asymmetrical sequences. Data are represented for each speaker independently. See the text for the characterization of long-range and short-range coarticulatory effects

		Speaker RE								
		M_1			M_2			M_3		
		C	S	A	C	S	A	C	S	A
tk	CA	–	–	–	–	–	–	–	–	–
	CP	–	–	–	–	–	–	–	–	i
	CC	–	–	–	–	–	–	–	–	i
kt	CA	–	–	–	–	–	–	–	–	–
	CP	–	–	–	–	–	–	–	*	i/a
	CC	a	–	–	–	–	–	–	*	i/a
tp	CA	–	–	a	–	–	–	–	–	–
	CP	i/a	*	–	i/a	*	i/a	i	*	i/a
	CC	i/a	*	–	i	*	–	i	*	i
pt	CA	–	–	–	–	*	–	–	*	i/a
	CP	i/a	*	–	i/a	*	a	i	*	i/a
	CC	i/a	*	–	i	*	–	i	*	i
kp	CA	–	–	–	i	*	i	i	*	i/a
	CP	a	*	a	a	*	a	–	*	i/a
	CC	i/a	*	a	i/a	*	i/a	–	*	i/a
pk	CA	i	*	i	i	*	i	–	–	–
	CP	i/a	*	–	–	*	–	–	*	a
	CC	i	*	–	i	*	i	–	*	i/a

(b) Velar [k] undergoes more tongue fronting as a function of [t] versus [p] (Figure 5, middle). Coarticulatory effects associated with [t] are not strong enough to cause the presence of a complete alveolar closure in the adjacent consonant [k] at M_1 or M_3. Since a complete alveolar closure was achieved at M_2 (see linguopalatal configuration for [tk] in Figure 4, middle) we can be confident that the amount of coarticulation is less at M_1 or M_3 than at the midpoint of the cluster.

(c) Bilabial [p] conveys some alveolar contact fronting associated with [t] and some dorsopalatal contact associated with [k] (Figure 5, bottom). Coarticulation at M_1 and M_3 is less than at M_2: [t] causes less alveolar contact fronting at M_1 or M_3 than at M_2 (as shown by [tp] at M_3 and M_2; see Figures 5 and 4, bottom); [k] causes less dorsopalatal contact at M_1 or M_3 than at M_2 (as shown by [kp] at M_3 and M_2; see Figures 5 and 4, bottom).

3.3. Vowel-dependent effects

Table 3 indicates the occurrence of significant vowel-dependent coarticulatory effects in CA, CP and CC for each cluster at each moment in time (i.e., M_1, M_2 and M_3). In other words, results in the table show whether vowel-dependent variations in contact index values achieve statistical significance. The results are displayed separately for each speaker. Effects in symmetrical sequences have been indicated with an asterisk (e.g., [ipti] versus [apta], [ikti] versus [akta],...). Effects in asymmetrical sequences have been indicated with reference to the fixed vowel in the pair of sequences under analysis (e.g., a refers to significant effects from [i] versus [a] when the transconsonantal vowel is [a]).

The table contains information about the directionality of coarticulation, namely, about whether coarticulatory effects in asymmetrical se-

Speaker RA									Speaker HA								
M_1			M_2			M_3			M_1			M_2			M_3		
C	S	A	C	S	A	C	S	A	C	S	A	C	S	A	C	S	A
–	–	–	–	–	–	–	–	a	a	–	i	–	–	i	a	–	–
–	*	–	–	–	–	–	*	i/a	i/a	*	–	i/a	*	–	a	*	a
–	–	–	–	–	–	i	–	a	a	*	–	a	*	–	a	*	a
i/a	*	–	–	–	–	–	–	–	i/a	*	–	i/a	*	–	i/a	*	i
i/a	*	–	i/a	*	–	–	*	–	i/a	*	–	i/a	*	–	i/a	*	–
i/a	*	–	–	*	–	–	*	–	i/a	*	–	i/a	*	–	–	–	–
–	–	–	–	–	–	–	*	i/a	a	*	–	i/a	*	–	i	*	i
i/a	*	–	–	*	i/a	–	*	i/a	i/a	*	–	i/a	*	i/a	–	*	i/a
–	–	–	–	–	–	–	*	i/a	i/a	*	–	i/a	*	i	i	*	i
i/a	*	–	–	–	–	–	–	–	a	*	–	i/a	*	–	i/a	*	–
i/a	*	–	i/a	*	i	i	*	i/a	i/a	*	–	i/a	*	–	–	*	–
i	*	i	i	–	–	–	–	i	a	*	–	i/a	*	–	i/a	*	–
i	*	–	i	*	i	–	–	–	i/a	*	–	–	–	–	–	*	i
i/a	*	–	a	*	a	a	*	i/a	i/a	*	–	i/a	*	–	i	*	i/a
–	–	–	i	*	i	–	*	i/a	i/a	*	–	i/a	*	i	i	*	i/a
i	*	–	i	*	i	–	–	a	i/a	*	–	i	*	–	i	*	i
i/a	*	a	i/a	*	i/a	–	*	i/a	i/a	*	–	i/a	*	i/a	a	*	i/a
i	*	i	i	*	i	–	*	i/a	i/a	*	–	i/a	*	i	i	*	i/a

quences are either anticipatory (associated with V_2 = [i] versus [a] when V_1 is kept constant; e.g., [ipti] versus [ipta], [akti] versus [akta],...) or carryover (associated with V_1 = [i] versus [a] when V_2 is kept constant; e.g., [ipti] versus [apti], [ikta] versus [akta],...). Since significant effects associated with V_1 and V_2 have been analyzed at all moments in time, it is possible to distinguish between short-range coarticulatory effects from adjacent vowels (i.e., carryover effects at M_1 and anticipatory effects at M_3) and long-range coarticulatory effects from distant vowels (i.e., carryover effects at M_2 and M_3, and anticipatory effects at M_2 and M_1). Let us illustrate these expressions with vowel-dependent coarticulatory effects in CP for the cluster [tp] according to speaker Re (3rd row of Table 3).

The presence of asterisks at the cells for M_1, M_2 and M_3 indicate that significant effects in symmetrical sequences (i.e., [itpi] and [atpa]) occur at the three moments in time. Short-range carryover effects from V_1 = [i] versus [a] at M_1 occur in asymmetrical sequences with V_2 = [i] and V_2 = [a] (as indicated by the symbols i/a); short-range V_2-dependent anticipatory effects at M_3 also occur when V_1 = [i] and V_1 = [a]. This cluster allows long-range coarticulatory effects. Significant long-range carryover effects are found at M_2 (when V_2 = [i] and V_2 = [a]) and at M_3 (when V_2 = [i]); significant long-range anticipatory effects take place at M_2 (when V_1 = [i] and V_1 = [a]) but not at M_1.

3.3.1. Coarticulation and intergestural cohesiveness

Percentages of significant effects for each moment in time across cluster conditions in Table 3 indicate similar amounts of vowel-related coarticulation at M_1, M_2 and M_3. In comparison with the number of significant effects at M_1 and M_3, coarticulation at M_2 is slightly less for speaker Ra (44% at M_2 versus 50% at M_1 and 50% at M_3), slightly more for speaker Ha (54% at M_2 versus 50% at M_1 and 50% at M_3) and somewhere in between for speaker Re (44% at M_2 versus 40% at M_1 and 55% at M_3). Therefore, effects at the midpoint of the cluster are roughly equal to those observed at the onset and offset of the cluster. Overall, clusters analyzed in this paper appear to behave quite homogeneously with respect to effects from the adjacent vowels. This finding is in agreement with the notion of intergestural cohesiveness rather than with that of dissociation between the gestures of the consonants in the cluster.

Table 3 shows differences in number of significant effects depending on the segmental composition of the cluster. Percentages of significant effects for each cluster and its symmetrical counterpart across moments in time reveal a consistent trend for coarticulation with vowels to decrease in the progression [kp], [pk] > [tp], [pt] > [tk], [kt]. This trend occurs for all speakers, i.e., speaker Re (53% > 49% > 10%), speaker Ra (53% > 38% > 24%) and speaker Ha (63% > 58% > 50%).

It can be concluded that the degree of vowel-dependent coarticulation during a given stop cluster decreases with the lingual involvement in the making of palatal contact. A high degree of resistance to coarticulation for [tk] and [kt] follows from the fact that the tongue front and the tongue dorsum are highly constrained because they participate in the formation of the two consonants. Relatively unalterable articulatory requirements on the production of the cluster block vowel-dependent effects. In the case of clusters [tp] and [pt], coarticulation for [t] occurs mostly in CP and CC since adjacent [p] involves no tongue dorsum raising and leaves the tongue dorsum free to coarticulate during the production of the dentoalveolar consonant. There is a trend for vowel-dependent coarticulation to affect all contact indices during the production of clusters [kp] and [pk]; this is so since [p] involves no place of lingual articulation, and a front and a back allophones ought to be distinguished in the case of [k].

3.3.2. Extent and directionality of the coarticulatory effects

Short-range coarticulatory effects (from adjacent vowels at M_1 and M_3) and long-range coarticulatory effects (at M_2) across cluster pairs in symmetrical sequences gave similar percentages. This was the case for speaker Re (M_1 = 50%, M_2 = 61%, M_3 = 67%), speaker Ra (M_1 = 72% M_2 = 55%, M_3 = 61%) and speaker Ha (M_1 = 94%, M_2 = 89%, M_3 = 89%).

For speakers Re and Ra, carryover and anticipatory effects associated with V_1 and V_2 across cluster pairs in asymmetrical sequences decrease as we depart from the adjacent consonant in the cluster. In the case of speaker Re, V_1-dependent carryover effects amount to 44% (M_1), 33% (M_2) and 14% (M_3) and V_2-dependent anticipatory effects amount to 64% (M_3), 25% (M_2) and 11% (M_1); for speaker Ra, carryover effects reach 56% (M_1), 33% (M_2) and 8% (M_3), and anticipatory effects achieve 61% (M_3), 28% (M_2) and 8% (M_1). These percentages show indeed smaller long-range effects at M_2 than short-range effects from adjacent vowels at M_1 and M_3. Moreover carryover effects at M_2 are slightly larger than anticipatory effects in spite of the fact that short-range effects at M_1 and M_3 were larger at the anticipatory level than at the carryover level. Long-range effects into the distant consonant in the cluster (i.e., effects from V_1 at M_3 and from V_2 at M_1) are very small and do not exceed 15% for any of the two speakers and coarticulatory directions. In summary, vowel-dependent effects last until the midpoint of the cluster and favour carryover directionality.

Speaker Ha uses a different coarticulation strategy in asymmetrical sequences from the other two speakers. Calculation of the total number of coarticulatory effects across contact indices, vowel contexts and moments in time show that this speaker allows much more coarticulation than speakers Re and Ra (speaker Re: 37%, speaker Ra: 39%, speaker Ha: 57%) Moreover, carryover effects are much larger than anticipatory effects and are found at all moments in time (carryover: $M_1 = 86\%$, $M_2 = 83\%$, $M_3 = 50\%$; anticipatory: $M_1 = 3\%$, $M_2 = 22\%$, $M_3 = 47\%$).

4. Discussion

4.1. Articulatory overlap between consonants

Significant *C*-to-*C* effects reported in this paper occur from a lingual consonant (either [t] or [k]) onto another lingual consonant or onto a labial consonant (i.e., [p]). Effects are particularly large at the cluster midpoint and, less so, at onset for speaker Re and at offset for all speakers. This finding is in support of the notion of cohesiveness (i.e., degree of overlap) between the consonants in the cluster and suggests that they are planned to a certain extent as a homogeneous production event.

Overlap between the two stop consonants at the midpoint of all clusters analyzed in this paper was obtained since articulatory conflict is not involved (see (Bell-Berti and Harris, 1981)). Tongue front closure and tongue dorsum closure cooccur in the case of clusters composed of [t] and [k]; the absence of lingual activity for [p] allows alveolar closure when the adjacent consonant is [t] and dorsal closure when the adjacent consonant is [k]. These processes of articulatory overlap are consistent with coproduction models of coarticulation (Kent, 1983).

Coproduction between [t] and [k] in the sequences [tk] and [kt] leads to intergestural blending about the cluster midpoint. Blending affects a tongue front gesture and a tongue dorsum gesture, and involves a shift in primary articulator and in place of articulation with respect to the two lingual consonants alone. The articulatory outcome of this blending process is comparable to a single gesture. This new articulation could be characterized as laminopredorso–alveoloprepalatal (see Section 1.1.2 for definition), and exhibits more extensive medio–postpalatal contact than a velar consonant. The case presented in this paper indicates that blending involving the same articulatory structure (i.e. the tongue) may take place between two semi-independent articulators.

The number of significant effects decreases as we depart from the target lingual consonant. Therefore, C_2-dependent anticipatory effects decrease in the progression $M_3 > M_2 > M_1$ and C_1-dependent carryover effects decrease in the opposite progression, i.e., $M_1 > M_2 > M_3$. While coarticulatory effects at M_2 result from complete overlap between two lingual consonants or a lingual and a labial consonant, linguopalatal configurations at M_1 and M_3 ought to be rather characterized as cases of partial overlap. Thus, for example, while complete dentoalveolar closure for [t] is hold at M_2 in all clusters, effects from [t] on [p] and [k] at M_1 or M_3 convey some alveolar contact fronting but no complete closure.

Fewer anticipatory and carryover effects at cluster onset and offset than at cluster midpoint indicate that the degree of fusion between the two gestures of a stop consonant cluster is less than that found in doubly articulated stops (e.g., labial-velar [k͡p], [g͡b] in African languages). In support of this statement it is known that clusters show longer durations than double articulations and that the two gestures involved in the production of the latter set of sounds exhibit nearly synchronous articulatory activity (Maddieson and Ladefoged, 1989).

4.2. Vowel coarticulation

The number of vowel-related effects at M_2 was not smaller than that found at M_1 and M_3. As indicated in the Introduction, this finding suggests that the entire cluster is produced with a good deal of articulatory coherence, thus allowing a similar degree of vowel-dependent coarticulation at all temporal points. On the one hand, asymmetrical clusters specified for a high degree of tongue body constraint ([tk] and [kt] for speakers Re and Ra) allow little coarticulation not only at M_2 but also at M_1 and M_3. On the other hand, asymmetrical clusters with a labial consonant allow long-range vowel-dependent effects until M_2. Effects in symmetrical sequences occur at all temporal points as well.

It is thus the case that coarticulation is cluster dependent rather than consonant dependent. Overall, coarticulatory sensitivity varies in the progression [pk], [kp] > [tp], [pt] > [tk], [kt]. Clusters involving two lingual consonants (i.e., the tongue front and the tongue dorsum) are more resistant than those with one lingual consonant only; among the latter, clusters with a dentoalveolar consonant are more resistant than those with a velar consonant which accords with [k] showing as many places of articulation as adjacent vowels. Vowel-related coarticulation occurs at those tongue regions which are not actively involved in the primary articulation (i.e., tongue dorsum in clusters [tp], [pt]; tongue front in clusters [pk], [kp]).

The fact that vowel-dependent anticipatory effects in asymmetrical clusters with labial [p] are usually found at M_2 but rarely at M_1 can be taken in support of a time-locked model of coarticulation rather than of a look-ahead model. For example, clusters [tp] and [pt] ought to allow the onset of V_2-dependent coarticulation to occur at M_1 since neither of the two consonants are positively specified for tongue dorsum activity. Instead, while some effects are found at the cluster midpoint, no effects are found at the onset of the cluster. There appears to be a constraint for the initiation of the activity of the sluggish tongue dorsum not to take place at C_1 onset across C_2. Additional evidence for the time-locked hypothesis should be adduced in future research using data on more points in time along the entire CC closure period than just M_1, M_2 and M_3.

4.3. Speaker-dependent trends

Consonant-dependent coarticulatory effects at M_1 (from C_2) and at M_3 (from C_1) were generally more numerous for carryover than for anticipation. This trend was more noticeable for the two English speakers than for the Catalan speaker; in fact, the two English subjects showed very few anticipatory effects from C_2 upon C_1 at M_1 (e.g., in tongue fronting, from [t] upon preceding [p] and [k]). These speaker-dependent trends may be due to a language-related characteristic to favour more anticipation of the C_2 lingual gesture in the cluster in Catalan than in American English. This explanation is however not too plausibe in view of the small number of speakers used in this study (which renders impossible the detection of language-dependent trends) as well as some evidence showing that American English clusters are produced with more frequent C_1 stop bursts than Catalan clusters (see the Introduction).

The causal factor may be differences in speech rate among speakers. The hypothesis underlying this rationale is that larger amounts of articulatory overlap at the anticipatory level ought to occur at faster versus slower speech rates (see (Gay, 1981)). Differences in degree of articulatory overlap as a function of speech rate have been reported for the cluster [kl] in the literature (Hardcastle, 1985). In line with variations in anticipatory effects, speech rate was faster for the

Catalan speaker Re (mean VCCV durations = 143.5 ms) than for the American English speakers Ra ($\bar{X}$ = 177.8 ms) and Ha ($\bar{X}$ = 179.4 ms). It can be claimed that, under slower speech rate conditions such as those used by speakers Ra and Ha, mechanical carryover effects were favoured over effects associated with articulatory anticipation.

Judging from the data for speakers Re and Ra, differences in speech rate affected inversely the amount of anticipatory C_2-to-C_1 coarticulation but did not affect the amount of anticipatory V_2-to-C coarticulation. Indeed, while the number of C_2-dependent significant effects at M_1 is quite smaller for speaker Ra (19%) than for speaker Re (44%), the two speakers allow practically the same number of V_2-dependent significant effects at M_3, M_2 and M_1 in asymmetrical sequences (61%, 28% and 8% for speaker Ra; 64%, 25% and 11% for speaker Re). The fact that faster speech rates convey more C-to-C coarticulation than V-to-C effects appears to be also in support of the existence of articulatory cohesiveness between the two consonantal elements of the cluster.

Another interesting finding reported in this paper is that speakers may use very different coarticulatory mechanisms. Many coarticulatory phenomena observed for speakers Re and Ra did not operate in the case of speaker Ha. For speaker Ha, carryover effects from V_1 = [i] versus [a] occurred all through the cluster independently of the place of articulation of the two sequential consonants. The degree of coarticulatory resistance at M_1 and M_3 may also depend on speaker and language. Thus, data for speaker Ra reveal that [t] is particularly resistant to effects from adjacent [i] versus [a]. In comparison to the Catalan speaker, the two American English speakers allow more vowel coarticulation for [k] and [p], presumably because [a] is produced with a lower tongue configuration in the latter versus former language.

Appendix A

The following mathematical formula were developed to measure the CP, CA and CC indices:

$$\begin{aligned}\mathrm{CA} = [&(r_7/11) \times 1 + (r_6/11) \times 12 \\ &+ (r_5/11) \times 144 + (r_4/9) \times 1414 \\ &+ (r_3/9) \times 14140 + (r_2/7) \times 109978 \\ &+ (r_1/5) \times 628446]/754135.\end{aligned}$$

$$\begin{aligned}\mathrm{CP} = [&(r_1/5) \times 1 + (r_2/7) \times 8 + (r_3/9) \times 82 \\ &+ (r_4/9) \times 820 + (r_5/11) \times 10022 \\ &+ (r_6/11) \times 120264 \\ &+ (r_7/11) \times 1443168]/1574365.\end{aligned}$$

$$\begin{aligned}\mathrm{CC} = [&(r_1/18) \times 1 + (r_{II}/24) \times 25 \\ &+ (r_{III}/21) \times 547]/573.\end{aligned}$$

In each formula, each ratio within parentheses contains the number of activated electrodes on each row (for rows 1 through 7) or region (for regions I, II and III), divided by the total number of electrodes in that row or region. This normalization procedure ensures that rows or regions containing different number of electrodes contribute the same to the contact index values. In other words, two rows (or regions) should not contribute a different amount to an index value due to their differing in the absolute number of electrodes, but only because of their relative location along the artificial palate. The ratios within parentheses are each multiplied by a coefficient. Each row and region is assigned a different coefficient value according to the following principle: the contribution of a given electrode to the value of indices CP or CA exceeds the contribution of all the electrodes located on the previous front (CP index) or back (CA index) rows; the contribution of a given electrode to the CC index value exceeds the contribution of all the electrodes located on more lateral regions. The calculation method of the coefficient values is illustrated below for the CA index.

A coefficient of 1 was assigned arbitrarily to the backmost row (R_7). When applied to the ratio for this row in the CA formula (i.e., $[r_7/11] \times 1$), a maximum CA index value of 1 is obtained:

$$\frac{\text{11 "on" electrodes}}{\text{11 electrodes available on } R_7} \times 1 = 1.$$

The coefficient for the next row (i.e., R_6) is calculated as follows. One "on" electrode on this

row should be assigned a higher CA weight than 1 which is the maximum CA value for R_7. According to the ratio for this row in the formula,

$$\frac{1 \text{ "on" electrode}}{11 \text{ electrodes available on } R_6} \times \text{coefficient} > 1.$$

It follows that the coefficient value for R_6 should be higher than 11, namely, $(11 \times 1) + 1 = 12$.

To obtain the coefficient value for the next front row (i.e., R_5), the contribution of one activated electrode on that row to the CA index should be more than the maximum CA value for the two previous rows (i.e., a value of 13 since the maximum CA value for R_6 is 12 and that for R_7 is 1). It follows that

$$\text{if } \frac{1 \text{ "on" electrode}}{11 \text{ electrodes available on } R_5} \times \text{coefficient} > 13, \quad \text{then the coefficient value for } R_5 \text{ is } (11 \times 13) + 1 = 144.$$

The same operation is applied to find out the CA index coefficients for more anterior rows. The contributions from each row or region were summed in the numerator of the expression. The resulting CA index was divided by its maximum possible value (i.e., 754135 for CA in the denominator) so that a range from 0 to 1 is obtained, with 0 indicating the least contact and 1 the most.

The ordering of the mathematical expressions for each row in the case of the CP index is just the reverse of that representing the CA index. Therefore the rows of electrodes were considered in reverse order for the calculation of the CP index coefficients, i.e., R_1 was assigned coefficient 1, a coefficient value of 8 was obtained for $R_2, \ldots$ The CC index coefficients were calculated with reference to the number of electrodes for each region on both sides of the median line (i.e., 18 for R_I, 24 for R_{II} and 24 for R_{III}; see Figure 1, bottom).

Index values were calculated for all clusters across repetitions at points in time M_1, M_2 and M_3. The goal of these calculations was to find out whether a significant difference in the values of the CA, CP and CC indices at those temporal points could be attributed to a changing adjacent consonant in the cluster ([t] versus [k] versus [p]) or to an adjacent or a transconsonantal vowel ([i] versus [a]).

The validity of the contact index method will be illustrated with the conversion into index values of the linguopalatal patterns for [akta], [apta] and [apka] at M_2 according to speaker Re (Figure 4). The CA index value for [akta] (0.999) is highly similar to that for [apta] (0.991) since both clusters are produced with practically complete contact at the alveolar zone. In comparison with the CA index values for [akta] and [apta], the CA index value for [apka] is quite low (0.033); this is the expected outcome given that [pk] in [apka] is articulated with practically no alveolar contact. The CP index value is correlated with lingual contact at the back rows. According to the figure, [akta] is produced with more mediopalatal and postpalatal contact than [apta], [apka] falling in between; accordingly, CP index values decrease in the progression [akta] (0.908) > [apka] (0.838) > [apta] (0.548). The CC index value is much higher for [akta] (0.818) than for [apta] (0.321) in line with differences in degree of dorsopalatal contact towards the median line between the two clusters; [apka] shows the lowest CC index value (0.105) since there is almost no contact anywhere along R_{III} in this case.

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