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Coarticulation, assimilation and blending in Catalan consonant clusters

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Electropalatographic data on C-to-C coarticulatory effects were analyzed for consonant clusters composed of an extensive set of Catalan consonants, i.e., dentals (*t*), alveolars (*n*, dark *l*, *s*, trilled *r*), alveolopalatals (*ʃ*, *ʎ*, *ɲ*), palatals (*j*) and velars (*k*). Regarding tongue dorsum coarticulation, results show that consonantal effects in CC clusters are more prominent than vocalic effects in VCV sequences which is attributed to differences in articulatory control between consonants and vowels. Moreover, tongue dorsum lowering for the alveolar fricative and for the alveolar trill appears to be more coarticulation resistant than tongue dorsum raising and fronting for alveolopalatals. Data at the place of articulation show some interesting trends: on the one hand, sequences made of dentals (*t*), and fronter alveolars and alveolopalatals (i.e., *n*, *l*, *ʎ*, *ɲ*) yield articulatory blending; on the other hand, any of these consonants may assimilate to those alveolar and alveolopalatal consonants which exhibit a more retracted place of articulation (*s*, *r*, *ʃ*), but not *vice versa*. These findings are in agreement with the "degree of articulatory constraint" (DAC) model which relates coarticulatory and assimilatory effects to the degree of articulatory constraint involved in consonantal production, and predicts that fricatives and trills should be highly constrained both at the tongue front and at the tongue dorsum. Data on the relative strength of the anticipatory and carry-over effects reported in this paper are also to a large extent in agreement with predictions of the DAC model.

1. Introduction

It has been known for some time that consonantal gestures overlap in heterosyllabic consonantal sequences, i.e., in stop clusters and in clusters made up of a stop and a fricative (Hardcastle & Roach, 1979; Zsiga, 1994; Byrd, 1996), as well as in homosyllabic clusters (Hasegawa, Christensen, McCutcheon & Fletcher, 1979; Gibbon, Hardcastle & Nikolaidis, 1993). These studies are based, however, on a small number of consonantal combinations made mostly of bilabials, dentoalveolars and velars. A goal of

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the present study is to carry out a detailed articulatory analysis of clusters involving a more complete set of lingual gestures including consonants articulated at the palatal zone.

The paper focuses on three basic research topics in consonant cluster production. In the first place, tongue dorsum coarticulation in clusters is investigated for consonants specified for different degrees of coarticulatory resistance to effects from adjacent segments. The second research topic deals with C-to-C adaptation mechanisms taking place at the tongue front articulator. Finally, attention is paid to the relative prominence of the right-to-left and left-to-right directions of the C-to-C effects in the consonant clusters of interest regarding both tongue dorsum coarticulation and tongue front adaptation processes.

This investigation extends the predictions made by the degree of articulatory constraint (DAC) model to C-to-C effects in consonant clusters. In previous studies the model has been applied quite successfully to the study of V-to-C, C-to-V and V-to-V coarticulation in VCV sequences (see Recasens, Pallarès & Fontdevila (1997) and Recasens (1999) for a review; also Farnetani (1990), Fowler & Saltzman (1993) and Fowler & Brancazio (2000) for similar theoretical predictions). According to the DAC model, articulatory regions are specified for different degrees of articulatory constraint depending on their involvement in the performance of a closure or constriction. Thus, palatal consonants are more constrained at the tongue dorsum than dentoalveolars since this lingual region plays an active role in closure or constriction formation for the former consonantal class but not so for the latter. Coarticulatory sensitivity, i.e., the magnitude and temporal extent of the coarticulatory effects at a given articulator, should be inversely related to DAC degree: highly constrained phonetic segments are expected to be more resistant to coarticulation than phonetic segments specified for a lower DAC value and thus, less sensitive to coarticulatory influences from neighboring segments. Moreover, the model predicts that coarticulatory dominance ought to be positively related to DAC degree, i.e., phonetic segments which exhibit a high DAC value and are coarticulation resistant ought to exert prominent coarticulatory effects on adjacent phonetic segments. Tongue dorsum coarticulation data reveal indeed that, in comparison with dentoalveolar consonants, more highly constrained palatal consonants exert larger and longer coarticulatory effects on adjacent vowels while blocking vowel-dependent effects to a larger extent (Fowler & Saltzman, 1993). The first goal of the present study is to find out whether this scenario holds for C-to-C effects in CC sequences.

An important component of the DAC model is extended to consonant clusters in this investigation, namely, the relative weight of the anticipatory and carry-over coarticulatory directions. The model under discussion makes the direction of the consonantal coarticulatory effects dependent on the gestural requirements for the consonant. Thus, for example, the mechano-inertial properties involved in tongue dorsum raising for the production of palatal consonants account for more C-to-V carryover than C-to-V anticipation, and strict requirements on tongue dorsum anticipation for dark *l* explain why C-to-V anticipation exceeds C-to-V carry-over in this case. Furthermore, the prominence of the contextual effects on the target consonant along a particular coarticulatory direction ought to be inversely related to the strength of the consonantal effects on the adjacent phonetic segments along that specific direction. This principle justifies the fact that vocalic effects turn out to be more salient at the carry-over *vs.* anticipatory level in VCV sequences with palatals while the opposite pattern holds in VCV sequences with dark *l*.

The present research addresses another important theoretical aspect, namely, different C-to-C adaptation mechanisms at the tongue front in consonant cluster production. We try to elucidate whether consonantal overlap results in gradual approximation of the targets for the two adjacent consonants in the cluster or else into more categorical outcomes, i.e., blending *vs.* assimilation (see Section 1.2). It is believed that the adaptation mechanisms proposed so far in the literature may not be accurate enough to the extent that they are based on a limited subset of consonant classes. Also, while much research has been dedicated to the overlap of gestures on different tiers (e.g., the alveolar and labial gestures in the realization [mp] of /np/ in *seven plus*; Browman & Goldstein, 1989), much less is known about the articulatory outcomes generated through gestural overlap when the two meeting consonants involve the same or a close articulator. Our expectation is that a better understanding of the production mechanisms underlying these output realizations may be achieved on the basis of considerations about the degree of tongue front constraint during consonantal production.

In order to investigate these issues, data on spatial and temporal effects in tongue front and tongue dorsum contact are presented for heterosyllabic clusters made of 11 consonants from the Catalan language, i.e., *p*, *t*, *n*, *l*, *s*, *r*, *ʃ*, *ʎ*, *ɲ*, *j* and *k*. Some clarification about the articulatory properties of these Catalan consonants is needed: *t* is dental and thus, articulated with a dentoalveolar closure; among alveolar consonants, the apicoalveolar lateral consonant *l* is dark independent of word and syllable position, and across contextual conditions; the rhotic *r* is realized as an apicoalveolar trill in heterosyllabic clusters whether occurring postconsonantally or, less clearly so, preconsonantally; the fricative *ʃ*, the lateral *ʎ* and the nasal *ɲ* are produced with the tongue blade and predorsum at the alveolopalatal zone while the approximant *j* may be characterized as dorsopalatal (Recasens, 1990). Experimental evidence for the first two research topics, i.e., tongue dorsum coarticulation and tongue front adaptation mechanisms, will be obtained at C1 in view of the fact that syllable-final consonants should be more sensitive to coarticulation than consonants placed in syllable onset position (Ohala & Kawasaki, 1984; Byrd, 1996).

1.1. *Tongue dorsum coarticulation*

In order to test the predictive power of the DAC model, the following two hypotheses regarding consonant-dependent and vowel-dependent effects in tongue dorsum coarticulation are submitted to experimental analysis.

A first prediction is that differences in coarticulatory sensitivity at the tongue dorsum for consonants in CC clusters (i.e., the extent to which the tongue dorsum configuration for a given consonant adapts to that for other consonants) ought to resemble patterns of V-to-C coarticulation sensitivity in VCV sequences. If so, C-to-C effects should conform to consonant-dependent differences in V-to-C coarticulation reported in previous studies:

(a) Labials and velars should be highly sensitive to contextual effects. This should be so for labials since they are produced essentially with no lingual activity (Fowler & Brancazio, 2000), and for velars since they may be strongly coproduced with adjacent vowels (Wada, Yasumoto, Iteoka, Fujiki & Yoshinaga, 1970).

(b) Other consonants which are positively specified for dorsal activity, i.e., alveolopalatals and palatals, ought to be much more resistant (Recasens, 1984). It should also be the case for consonantal productions involving active predorsum lowering and more or less postdorsum retraction, i.e., dark *l* (Browman & Goldstein, 1995), lingual fricatives *s*, *ʃ* (Stone, Faber, Raphael & Shawker, 1992) and trilled *r* (Recasens, 1991; Recasens & Pallarès, 1999).

(c) An intermediate degree of tongue dorsum coarticulation is expected to apply to dentals and the alveolar *n* during the production of which apico-laminal activation may convey some automatic raising of the tongue dorsum (Kent & Moll, 1972).

An alternative prediction is that C-to-C coarticulatory effects should be more prominent than V-to-C effects. The rationale underlying this hypothesis is that consonants are specified for stricter articulatory requirements than vowels since they must achieve a closure or a constriction somewhere along the vocal tract.

When the two adjacent consonants in a cluster differ in degree of tongue dorsum constraint, gestural overlap may yield a similar scenario to that found in VCV sequences. Indeed, more C2-to-C1 overlap has been found in stop + stop sequences than in fricative + stop sequences and for front lingual consonants as a function of dorsal consonants than *vice versa* (Byrd, 1996).

A possible reason for the existence of more salient C-to-C than V-to-C effects may be gestural antagonism between consonants subjected to considerable articulatory demands. Indeed, while resisting the coarticulatory influence of more unconstrained consonants, highly constrained consonants may turn out to be quite sensitive to effects exerted by other highly constrained consonants produced with antagonistic articulatory gestures. Regarding tongue dorsum activity, gestural antagonism is at work between consonants requiring active tongue dorsum raising (alveolopalatals, velars) and those undergoing active tongue dorsum lowering (dark *l*, grooved *s*, trilled *r*). Experimental evidence obtained from languages opposing contrastively palatalized and velarized consonants indicates that the velarization gesture overrides the palatalization gesture when consonants of the two classes come into contact (Ní Chasaide & Fitzpatrick, 1995). In a similar fashion, C-to-V effects from dark *l* on *i* have been found to exceed effects from *i* on dark *l*, and a similar C-to-V and V-to-C behavior appears to hold when the consonant is pharyngealized (see Recasens, 1999 for a review).

If this is a universal trend, two patterns should occur for the present results. Regarding C-to-C coarticulation, tongue dorsum lowering effects from *l*, *s* and *r* on alveolopalatal *ʃ*, *ʎ* and *ɲ* ("depalatalizating" coarticulatory effects) are expected to exceed tongue dorsum raising effects from consonants of the latter group on those of the former group ("palatalizing" coarticulatory effects). For V-to-C coarticulation, effects of low vowels on palatalizing consonants (*ʃ*, *ʎ*, *ɲ*) should be more extensive than effects of high vowels on depalatalizing consonants (*l*, *s*, *r*). Moreover, assuming that there should be more gestural antagonism in CC clusters than in VCV sequences and that tongue dorsum lowering should override tongue dorsum raising, a central research goal of the present paper is to find the extent to which clusters allow more prominent effects in tongue dorsum height than VCV sequences and whether these differences in consonantal and vocalic coarticulation involve tongue dorsum lowering rather than tongue dorsum raising.

1.2. *Tongue front coarticulation*

1.2.1. *Blending and assimilation*

There is a good deal of literature on the adaptation strategies at the tongue front articulator during the production of consonantal sequences. Regarding the coproduction of gestures from different oral tiers, Articulatory Phonology (Browman & Goldstein, 1989) advocates the view that increasing degrees of overlap ought to induce articulatory reduction in the C1 gesture which may be eventually obscured. However, in addition to residual cases of the C1 alveolar gesture, studies on alveolar + velar sequences have reported instances of C1-to-C2 assimilation, i.e., a complete identification between C1 and C2 into a long segment, as for Catalan /t##k/ in *set cases* "seven houses" becoming [k:] in fast speech (Nolan, 1992; Kühnert, 1993; Ellis & Hardcastle, 1999). Moreover, it appears that nasals are more prone to assimilate than stops, e.g., /n##k/ > [ŋk] (Farnetani & Busà, 1994; Hardcastle, 1994).

On the other hand, Articulatory Phonology predicts that two more or less contiguous oral gestures on the same tier will yield blending and therefore will be realized at a single intermediate constriction location. Data on consonant clusters in the literature allow the identification of three possible blending scenarios:

(a) A sequence of a back dorsovelar and a following dorsopalatal. Blending is implemented through velar closure fronting in this case (e.g., /ki/, /gi/; Öhman, 1966).

(b) A sequence of an apicolaminal dental or alveolar and a following alveolopalatal or dorsopalatal. The two consonants yield an alveolo-prepalatal articulation through some contact retraction at closure location, as shown for /ntʃ/ (Italian, English; Farnetani & Busà, 1994; Solé & Estebas, 1995), and for the transformations /nj/ > [ɲ] (English *onion*, dialectal French *union*, *panier*, Argentinian Spanish *opinión*; Recasens, Fontdevila & Pallarès, 1995) and /sj/ > [ʃ] (Japanese, English *bless you*; Miyawaki, Kiritani, Tatsumi & Fujimura, 1974; Nakamura, 1999; Zsiga, 2000).

(c) A cluster composed of two apicolaminal articulations produced at the alveolar zone and at the dental zone. In this particular case, blending is implemented through contact fronting for the alveolar consonant or else through summation of the lingual contact areas at the two places of articulation. Supporting evidence has been adduced for /nθ/ (English *ten things*; Browman & Goldstein, 1990), /nt/ (Italian, Catalan; Farnetani & Busà, 1994; Solé & Estebas, 1995) and /ld/ (Spanish; Romero, 1996).

Data from other studies reveal, however, that blending is not a necessary strategy, and that complete assimilation and a sliding movement from C1 to C2 may also apply in cases (b) and (c) above. On the one hand, complete regressive assimilation has been reported both for /nʃ/ (Italian; Farnetani & Busà, 1994) and for /s##ʃ/ (Catalan, English; Badia, 1951; Recasens, 1993; Holst & Nolan, 1995); moreover, it has also been shown that laminal consonants (*s*, *ʃ*) do not adapt to apical consonants (*t*, *n*, *l*) but override them (British English; Bladon & Nolan, 1977). On the other hand, while approaching each other, the two contiguous front lingual gestures may still be realized sequentially in the clusters /sd/, /ʒd/ and /rd/ in Catalan and Spanish (Recasens, 1995; Romero, 1996) and /nʃ/ and /rn/ in Italian (Farnetani & Busá, 1994).

A fourth blending process may also take place in clusters composed of an alveolar and a velar and thus, of consonants articulated at two nonadjacent places of articulation (which calls for clarification as to whether the tongue front and the back dorsum should be considered to be on the same tier or on different tiers). Evidence for this particular example of blending is derived from sound changes such as /kl/ > [kʎ] > [ʎ] (Spanish [ʎaβe] from Latin CLAVE 'key') and /ngl/ > [ɲgʎ] > [ɲʎ] > [ɲ] (Spanish [uɲa] UNG(U)LA "nail"). Some EPG data in support of this blending type have been reported for /tk/ and /kt/ in the literature (Recasens, Fontdevila, Pallarès & Solanas, 1993).

1.2.2. *Research goals*

In light of these conflicting sources of evidence, the goal of our investigation is to test whether a better understanding of tongue front adaptation mechanisms can be achieved with reference to notions of articulatory constraint. In doing so, we exclude from analysis those clusters involving gestures on different tiers as well as other clusters which are known to undergo complete regressive assimilation in Catalan (see *Method* section). Our working hypotheses are based on the assumption that the tongue front exhibits different degrees of articulatory sensitivity from those operating at the tongue dorsum given that the two lingual regions are subjected to different articulatory requirements during consonantal production. The following predictions of tongue front coarticulatory sensitivity can be made:

(a) Nonfricative alveolopalatals (i.e., *ʎ*, *ɲ* but not *ʃ*), palatals and velars should be highly adaptable at the tongue front since the tongue tip stays lowered and inactive during their production, and the tongue blade only intervenes partly in alveolopalatal production. V-to-C coarticulation data in the literature (Hoole, Gfroerer & Tillmann, 1990) reveal indeed that velars are more sensitive than dentoalveolars at the tongue front.

(b) Among dentals and alveolars, available V-to-C coarticulation data for *n* and *l* confirm that these consonants are highly sensitive to contextual changes since their production involves mostly the tongue tip which is a nonmassive, flexible articulatory structure (Recasens, Fontdevila & Pallarès, 1992, 1996). Moreover, the latter paper reports more coarticulatory resistance at the tongue tip for dark *l* than for *n* presumably since velarization imposes higher demands on the apical articulator. Dental *t* offers an interesting case to the extent that, in contrast with alveolar *t*, the execution of a dental closure appears to prevent much vowel-dependent coarticulation at the tongue front from occurring (Farnetani, Hardcastle & Marchal, 1989).

(c) Conversely, lingual fricatives *s* and *ʃ* and trilled *r*, are expected to be highly resistant to tongue front adaptation in view of the high requirements on manner of articulation involved. Vocalic coarticulation data in the literature are in agreement with this prediction (Clark, Palethorpe & Hardcastle, 1982; Hoole *et al*., 1990; Recasens, 1991).

Considering these consonant-dependent differences in tongue front constraint, our initial hypothesis is that blending should affect sequences of consonants which are specified for low requirements on tongue front activity. While some evidence in favor of this principle has been reported for /nθ/, /nt/, /ld/, /ntʃ/, /nj/ and /sj/ in the literature (see Section 1.2.1), it remains to be seen whether blending is also at work in other consonantal sequences: alveolopalatal followed by a dental or an alveolar (as in the clusters [ɲt] and [ɲn]); alveolopalatal preceded or followed by a velar (e.g., [ɲk], [gʎ]); velar + dental or alveolar (e.g., [gd], [gn]).

Assimilation (instead of blending) is the expected outcome when two consecutive consonants are realized by means of tongue front gestures differing in degree of articulatory constraint. Therefore, unconstrained *t*, *n*, *l*, *ʎ* and *ɲ* are expected to assimilate to highly constrained *s*, *r* and *ʃ*, as suggested by data for the Italian cluster /nʃ/ reported above. Moreover, these three consonants should not assimilate to any following consonant specified for a lesser degree of constraint at the primary articulator which is in agreement with the presence of a sliding C1-to-C2 movement for /sd/, /ʒd/, /rd/ and /rn/

as mentioned in 1.2.1. Also, assuming that regressive assimilations are categorical changes, we predict that they should apply throughout the first consonant in the cluster.

The final scenario refers to clusters composed exclusively of consonants specified for a high degree of tongue front constraint, i.e., *s*, *r* and *ʃ* (which, as pointed out above, will only be investigated for the nonassimilating cases). The initial prediction that the degree of articulatory constraint should account for the final phonetic output appears to be borne out by the trill *vs.* the two lingual fricatives. On the one hand, the fact that *r* does not assimilate to following *s* and *ʃ* but *s* and *ʃ* assimilate to following *r* in Catalan is in accordance with the strong aerodynamic requirements on the performance of trills (Solé, 2000). On the other hand, the fact that /sʃ/ undergoes assimilation and /ʃs/ undergoes blending ([s^js^j]) in the same language may be related to differences in tongue body constraint between alveolopalatals and alveolars. Another conditioning factor may lie in the production mechanisms involved (Perkell, Boyce & Stevens, 1979; Nolan, Holst & Künhert, 1996): while the tongue dorsum activity for *ʃ* may be anticipated quite freely during preceding apical *s*, the production of /ʃs/ involves tongue repositioning, just as C1 and C2 may overlap more easily for /tk/ *vs.* /kt/ (English; Hardcastle & Roach, 1979; Byrd, 1996) and for /nk/ *vs.* /kn/ (Italian; Farnetani & Busà, 1994).

Another research issue explored in the present paper is the consonant-dependent coarticulatory effect on the size of the central lingual channel for the lingual fricatives *s* and *ʃ*. Assuming that *s* is mostly apical and *ʃ* is mostly laminal it remains to be seen whether the tongue tip for *s* adapts more easily to other consonants than the tongue blade or predorsum for *ʃ*, or *vice versa*.

In parallel to the tongue dorsum coarticulation data (Section 1.1), the present paper will investigate C2-dependent and vowel-dependent differences in coarticulation sensitivity at the tongue front during C1 production. The prediction here is that C-to-C effects should exceed V-to-C effects since vowels do not involve tongue front activation.

1.3. *Direction*

The predictive power of the DAC model will be used to estimate the relative prominence of the anticipatory and carry-over effects in tongue dorsum contact in consonantal sequences (Recasens *et al.*, 1997). Differences in C-to-C coarticulatory direction will be computed as a function of two consonantal groups, i.e., consonants known to exert more anticipatory than carry-over effects (i.e., highly constrained dark *l* and trilled *r*), and consonants which exert more extensive carry-over than anticipation (i.e., alveolopalatals) (see Recasens, 1999).

Differences in coarticulatory direction, i.e., between C-to-C anticipation and C-to-C carry-over, will be analyzed for a given consonant as a function of the same preceding and following consonants, respectively. Thus, for example, effects of *ʎ* on *n* will be measured in the sequence pair [nʎ] (anticipation)/[ʎn] (carry-over).

An evaluation of the relative weight of anticipatory and carry-over trends in consonantal clusters needs to take other factors into account. Syllable-position-dependent articulatory characteristics may play a role; generally speaking, anticipatory effects are expected to prevail over carry-over effects given that consonantal gestures are less prominent syllable finally than syllable initially (Ohala & Kawasaki, 1984). On the other hand, the alveolar lateral *l* could allow less coarticulation in syllable final position than in syllable onset position since it is known to be particularly dark syllable finally (Lehiste, 1964).

Assimilatory processes at the consonantal place of articulation may in principle be progressive (from C1 to C2) as well as regressive (from C2 to C1) though, as shown by the phonetic realization of the CC sequences mentioned in this section, regressive assimilations are known to occur much more frequently than progressive ones. In a production model based on degrees of articulatory constraint, highly constrained consonants are expected to exert regressive and progressive assimilations. In order to evaluate the relative strength of the two assimilatory types, tongue front contact patterns will be analyzed for several unconstrained consonants (*n*, *l*, *ʎ*) in a representative sample of CC clusters.

2. Method

2.1. *Data recording*

Electropalatographic (EPG) and audio recordings were obtained simultaneously for a set of consonantal clusters embedded in the string /aC##Ca/ where C1 and C2 were part of two meaningful Catalan words. Word sequences were read without pausing or assigning special emphasis to any of the two consecutive words. Three Catalan speakers DR, JP and JS recorded those clusters 5, 3 and 3 times each, respectively. Linguopalatal contact data were gathered every 5 ms with 62 electrode artificial palates using the Reading EPG system (Hardcastle, Jones, Knight, Trudgeon & Calder, 1989). As shown in Fig. 1 (top), the electrodes of the artificial palate are arranged in eight rows longitudinally (from R1 or most anterior row to R8 or most posterior one) and in eight columns sagitally (from C1 or most lateral column to C4 or most central column, both on the right and left sides of the palate surface). The graph also shows the grouping of rows in articulatory zones, i.e., alveolar and palatal; in view of the fact that the lingual closure for some of the consonants extended back to the 5th row of electrodes, the areal distribution of rows was chosen to be 5–3 instead of 4–4 which is the pattern commonly used in other studies. The bottom graph identifies the alveolar zone (a) and the three palatal subzones, i.e., prepalatal (b), mediopalatal (c) and postpalatal (d), which correspond roughly to rows of electrodes 6, 7 and 8, respectively. The bottom graph also shows the location of relevant articulatory regions on the tongue surface, i.e., tip and blade (e), predorsum (f), mediodorsum (g) and postdorsum (h). It may be seen that the front rows are distributed over a much smaller zone on the surface of the palate than the back rows.

The consonantal sequences selected for analysis are listed in Table I. The speech material was composed of consonantal clusters with *p*, *t*, *n*, *l*, *s*, *r*, *ʃ*, *ʎ*, *ɲ*, *j* and *k*. The consonants under study are represented in italics in this paper because stops and fricatives may be phonetically voiced or voiceless depending on the contextual conditions involved (see below).

Some indications should be given about the preparation of the corpus of consonant clusters. Bilabials were not included as C2 since they do not exert anticipatory lingual effects on the preceding consonant; moreover, *ɲ* and *r* only appear as C1 and C2, respectively, in line with restrictions on the frequency of occurrence of these consonants in Catalan lexical items. In order to match the other (voiced) consonants in the corpus, the stops *p*, *t*, and *k* and the fricative *s* were rendered voiced by being placed before a voiced stop or a voiced fricative; however, the palatal fricative had to be voiceless when acting as C1 (since /ʒ/ is realized as a palatal affricate word finally in Catalan) and voiced

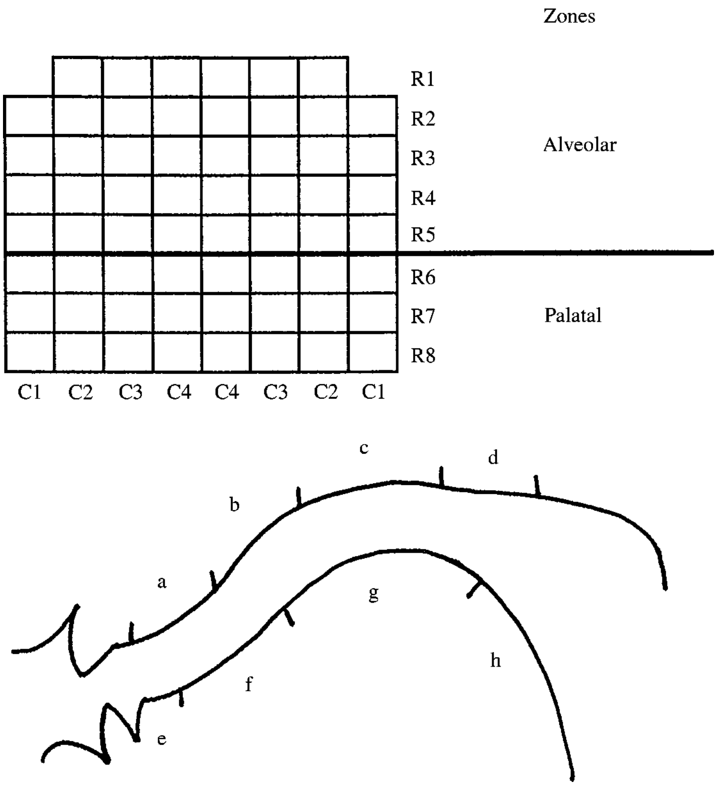

Figure 1. (Top) Diagram of the artificial palates used in the present study with subdivisions into rows (R1–R8), columns (C1–C4 on both palate sides) and articulatory zones (alveolar, palatal). (Bottom) Articulatory zones along the surface of the palate ((a)–(d)) and tongue regions along the tongue surface ((e)–(h)). See text for details.

TABLE I. Consonantal sequences selected for analysis

	C2								
C1	*t*	*n*	*l*	*s*	*r*	*ʃ*	*ʎ*	*j*	*k*
p	bd	—	bl	bz	br	bʒ	bʎ	bj	bg
t	—	—	—	dz	dr	dʒ	—	dj	—
n	nt	—	nl	ns	nr	nʒ	nʎ	nj	—
l	lt	ln	—	ls	lr	lʒ	lʎ	lj	lk
s	zð	zn	zl	—	—	—	zʎ	zj	zɣ
r	rt	rn	rl	rs	—	rʒ	rʎ	—	rk
ʃ	ʃt	ʒn	ʒl	ʃs	ʒr	—	ʒʎ	ʒj	ʃk
ʎ	ʎt	ʎn	ʎl	ʎs	ʎr	ʎʒ	—	ʎj	ʎk
ɲ	ɲt	ɲn	ɲl	ɲs	ɲr	ɲʒ	ɲʎ	ɲj	ɲk
k	gd	gn	gl	gz	gr	gʒ	gʎ	gj	—

when acting as C2 (since words beginning with /ʃ/ are rare in this language). Given these voicing conditions the sequences *sd* and *sg* were realized [zð] and [zɣ] according to the phonotactic rules of Catalan.

We excluded from analysis consonantal combinations yielding complete regressive assimilation either of manner and place or just of place of articulation: *t* before *n*, *l*, *ʎ* and *k* (which are usually realized as [nn], [ll], [ʎʎ], [kk]); *p* before *n* ([mn]); *s* before *r* and *ʃ* ([rr], [ʃʃ]); *n* before *k* ([ŋk]); *r* before *j* [ɾj]). These combinations appear as blanks in Table I. Moreover, data for a few sequences were analyzed only for two speakers ([bd] for DR and JP; [lʎ], [ɲj], [gz] and [gr] for DR and JS; [ʎs] for JP and JS), and the sequence [bʒ] was only available for the speaker DR.

Since one of the goals of the present study was to compare coarticulatory trends in consonantal clusters and in vocalic environments, EPG data were also collected for the same consonants and speakers in symmetrical VCV sequences, with *i*, *a* and *u*. Intervocalic stops and fricatives had to be voiceless since voiced stops become approximant in this contextual condition in Catalan.

2.2. *Segmentation*

In order to investigate C-to-C coarticulatory effects, C1 offset was identified applying several segmentation criteria which could vary with cluster and speaker.

C1 offset was identified at closure offset on the EPG record in sequences with C1 = *t*, *n*, *l*, *r*, *ʎ* and *ɲ*. Closure offset for *l* was characterized as a contact opening at the two central columns of electrodes at the alveolar zone. Closure offset for trilled *r* was taken to occur at the release of the only available alveolar contact period on the four central columns (the rhotic had two contacts when placed at C2 but only one contact when placed at C1).

An acoustic criterion for segmentation was applied to sequences in which C1 was a nasal, a lateral, *p*, *k*, or a fricative. This decision was based on the fact that nasals and laterals were often articulated with an incomplete lingual closure, labials involve no active linguopalatal contact, back closure for velars was not usually visible on the linguopalatal contact patterns, and fricatives show no central contact on the palatographic record. The temporal offset of nasals and laterals was fixed at the offset of formant structure associated with consonants of these two manners of articulation; this event often coincided with the onset of complete closure, fricative noise or formant structure for C2. In the case of sequences beginning with *p* and *k*, C1 offset was placed at the onset of C2-related formant structure when C2 was a nasal, a lateral, *j* or *r*, at the onset of C2-related noise when C2 was a fricative, and at the bilabial burst in the stop sequences [pt] and [pk]. Regarding sequences with a fricative C1, the boundary between C1 and C2 was fixed at the offset of the frication noise which often coincided with the onset of formant structure for a lateral or a nasal C2.

These segmentation criteria were also applied to several clusters made of a nasal, a stop, *r* or a lateral followed by a lingual fricative displaying a 5 or 10 ms epenthetic phonetic stop between C1 and C2 (a few repetitions of these combinations were excluded from analysis since the epenthetic stop was too long). In most [rC] sequences for speaker DR, C2 was taken to start after a mean 24 ms vocalic element following the alveolar contact period for *r*.

2.3. *Data analysis*

2.3.1. *Contact indices*

In order to carry out a numerical evaluation of the EPG data, the 62 data points of the linguopalatal contact patterns were transformed into several index values applying the contact index method (Fontdevila, Pallarès & Recasens, 1994). Three contact indices were calculated, namely, CAa or alveolar contact anteriority index, CCa or alveolar contact centrality index, and Qp or contact index at the palatal zone.

The CAa index reflects the degree of contact fronting at the five front rows of the artificial palate (i.e., from frontmost R1 to backmost R5) and is thus strongly correlated with place of articulation. The CAa formula is:

$$\mathrm{CAa} = [\log[[1(R5/8) + 9(R4/8) + 81(R3/8) + 729(R2/8) + 4921(R1/6)] + 1]]/[\log(5741 + 1)].$$

In the ratios within parentheses, the total number of electrodes on a given row (i.e., R5, R4, R3, etc.) is divided by the total number of electrodes on that row. Each ratio is multiplied by a coefficient number. These coefficients are chosen so that the activation of all electrodes at and behind a given row always yields a lower index value than the activation of a single electrode at more anterior rows.

Qp index values (Qp = quotient for the dorsopalatal contact) are averages of electrode activation at the palatal zone. Those averages are computed dividing the number of on-electrodes on the three back rows by the total number of 24 electrodes on those rows and are correlated with the degree of tongue dorsum raising.

The CCa index was measured applying the formula below to *s* and *ʃ*, and provides an estimate of changes in alveolar constriction width. The computation procedure of the CCa index is analogous to that of the CAa index, and takes into account the electrodes on a given column as well as those on the corresponding symmetrical column on the other half of the alveolar area of the artificial palate:

$$\mathrm{CCa} = [\log[[1(C1/8) + 11(C2/10) + 120(C3/10) + 1320(C4/10)] + 1]]/[\log(1452 + 1)].$$

2.3.2. *Analysis procedure*

C2-to-C1 coarticulation was measured in size and in temporal extent. Coarticulatory size effects were determined from the contact index values. For that purpose, all three contact indices were computed at the midpoint of the intervocalic consonants, and at −15 ms before C1 offset in the consonant clusters. In view of the short duration of [r], contact indices for this consonant were calculated at −10 ms instead of at −15 ms. Data were obtained for each speaker independently and averaged across speakers.

In order to measure the temporal extent of C2-to-C1 coarticulation, C2-dependent differences in Qp and CAa were evaluated statistically during C1 as long as the consonantal sequences being compared were represented by two or more repetitions. For that purpose, one-way ANOVAs ($p < 0.05$) were computed across C2 conditions for each C1 and for each speaker with contact index as the independent variable and C2 as the dependent variable. ANOVAs were performed, each for 5 ms, starting at C1 offset backwards, and the temporal extent of anticipatory coarticulation across C2 conditions was taken to occur at the last temporal frame exhibiting a significant difference along C1. In addition, *post hoc* Scheffé tests were carried out in 5 ms steps up to the last temporal frame yielding significant results in the ANOVAs; this procedure allowed us to determine which C2 comparisons were significant and the temporal extent of those significant comparisons.

In order to find out whether larger effects were also longer, correlation analyses between Qp coarticulation values in size and in temporal extent were performed only for those pairs of CC sequences showing significant temporal effects.

In order to estimate differences in coarticulatory direction between anticipatory C2-to-C1 effects and carry-over C1-to-C2 effects in dorsopalatal contact, Qp differences between identical C1 and C2 were submitted to statistical analysis in symmetrical CC pairs, i.e., for *n* in the sequence pair [ʎn]/[nʎ]. One-way ANOVAs ($p < 0.05$) were computed between Qp values at each (positive) 5 ms frame after C1 offset and at the same (negative) numerical frame before C1 offset, i.e., at $+5$ *vs.* -5 ms, at $+10$ *vs.* -10 ms… Qp differences usually exhibited the same sign at all significant temporal frames, namely, positive if Qp values for C2 were larger than Qp values for C1 or else negative if the opposite relationship was true. The last significant value obtained in this analysis procedure was taken to be the temporal extent of the prevalent coarticulatory direction; moreover, the largest Qp difference between C1 and C2 yielded a measure of size. The following effects were analyzed: from alveolopalatals (*ʃ*, *ʎ*) on several alveolars (*n*, *l*, *r*); from alveolars produced with active tongue dorsum lowering (*l*, *r*) on other alveolars (*n*, and *r* or *l*) and alveolopalatals (*ʃ*, *ʎ*).

Differences between C2-to-C1 anticipatory effects and C1-to-C2 carry-over effects at the place of articulation were analyzed for *n*, *l*, and *ʎ* in all possible CC combinations through an evaluation of CAa values at -15 ms and at $+15$ ms.

3. Results

3.1. *Size effects*

Size effects are reported in Table II and in Figs 2–5. Table II lists Qp, CAa and CCa values for C2-to-C1 anticipatory effects at -15 ms (for each C1 as a function of each C2) and for V-to-V effects (for each consonant as a function of *i*, *a*, and *u*); means across speakers and a variability measure across those means are presented in the table. Figs 2 and 3 plot Qp and CAa ranges for the consonantal effects (left) and for the vocalic effects for comparison (right). Figs 4 and 5 display linguopalatal configurations for C1 = *n* and for C1 = *ɲ* in all C2 conditions in order to illustrate the scenarios of articulatory adaptation at the alveolar and palatal zones.

3.1.1. *Qp* (*tongue dorsum coarticulation*)

(a) Qp ranges across C2 conditions provide an estimate of C1-dependent degrees of coarticulatory resistance at the palatal zone. According to Fig. 2 (left), consonants differ regarding the amount of C-to-C coarticulation in the progression *p*, *ɲ*, *k* > *t*, *n*, *l*, *ʃ*, *ʎ* > *s*, *r*. Moreover, *n* is somewhat more variable than the other consonants of the second group (*t*, *l*, *ʃ*, *ʎ*) while *s* is less resistant than *r*. Index values for the Qp ranges in the figure

TABLE II. Qp, CAa and CCa values at −15 ms for C1 (left) as a function of several C2 (top) and of several vowels. Data correspond to means across speakers. Standard deviations are also given

		C2									V		
C1	Qp	*t*	*n*	*l*	*s*	*r*	*ʃ*	*ʎ*	*j*	*k*	*i*	*a*	*u*
p	X̄	**0.26**		**0.05**	**0.28**	**0.24**	**0.52**	**0.41**	**0.60**	**0.39**	**0.57**	**0.12**	**0.12**
	S.D.	*0.01*		*0.04*	*0.03*	*0.02*		*0.11*	*0.10*	*0.06*	*0.08*	*0.06*	*0.07*
t	X̄				**0.30**	**0.28**	**0.57**		**0.59**		**0.56**	**0.32**	**0.38**
	S.D.				*0.05*	*0.02*	*0.11*		*0.11*		*0.08*	*0.05*	*0.08*
n	X̄	**0.38**		**0.16**	**0.33**	**0.26**	**0.58**	**0.44**	**0.57**		**0.52**	**0.26**	**0.35**
	S.D.	*0.05*		*0.08*	*0.10*	*0.02*	*0.08*	*0.08*	*0.12*		*0.04*	*0.02*	*0.05*
l	X̄	**0.12**	**0.05**		**0.15**	**0.15**	**0.29**	**0.21**	**0.38**	**0.17**	**0.23**	**0.03**	**0.13**
	S.D.	*0.07*	*0.08*		*0.01*	*0.11*	*0.17*	*0.10*	*0.20*	*0.09*	*0.08*	*0.05*	*0.08*
s	X̄	**0.26**	**0.29**	**0.29**				**0.34**	**0.48**	**0.41**	**0.50**	**0.34**	**0.39**
	S.D.	*0.01*	*0.03*	*0.06*				*0.03*	*0.04*	*0.05*	*0.00*	*0.07*	*0.06*
r	X̄	**0.25**	**0.25**	**0.24**	**0.26**		**0.27**	**0.24**		**0.26**	**0.31**	**0.24**	**0.26**
	S.D.	*0.02*	*0.00*	*0.01*	*0.01*		*0.02*	*0.01*		*0.02*	*0.02*	*0.01*	*0.01*
ʃ	X̄	**0.47**	**0.50**	**0.29**	**0.47**	**0.28**		**0.47**	**0.55**	**0.61**	**0.63**	**0.52**	**0.60**
	S.D.	*0.04*	*0.02*	*0.02*	*0.08*	*0.03*		*0.05*	*0.02*	*0.03*	*0.04*	*0.03*	*0.08*
ʎ	X̄	**0.46**	**0.41**	**0.40**	**0.35**	**0.32**	**0.48**		**0.54**	**0.67**	**0.62**	**0.41**	**0.57**
	S.D.	*0.06*	*0.13*	*0.08*	*0.03*	*0.10*	*0.06*		*0.13*	*0.11*	*0.08*	*0.05*	*0.13*
ɲ	X̄	**0.70**	**0.56**	**0.45**	**0.50**	**0.34**	**0.66**	**0.65**	**0.74**	**0.87**	**0.73**	**0.64**	**0.75**
	S.D.	*0.11*	*0.15*	*0.11*	*0.01*	*0.09*	*0.07*	*0.09*	*0.01*	*0.05*	*0.04*	*0.13*	*0.05*
k	X̄	**0.59**	**0.57**	**0.37**	**0.63**	**0.33**	**0.79**	**0.70**	**0.76**		**0.70**	**0.54**	**0.35**
	S.D.	*0.04*	*0.01*	*0.10*	*0.02*	*0.03*	*0.08*	*0.08*	*0.04*		*0.08*	*0.06*	*0.06*
	CAa												
p	X̄	**0.51**		**0.87**	**0.49**	**0.33**	**0.81**	**0.86**	**0.76**	**0.01**	**0.52**	**0.14**	**0.00**
	S.D.	*0.70*		*0.15*	*0.35*	*0.22*		*0.13*	*0.03*	*0.01*	*0.30*	*0.24*	*0.00*
t	X̄				**0.72**	**0.70**	**0.65**		**1.00**		**0.99**	**1.00**	**0.99**
	S.D.				*0.22*	*0.22*	*0.21*		*0.01*		*0.01*	*0.00*	*0.01*
n	X̄	**1.00**		**0.83**	**0.60**	**0.42**	**0.62**	**0.95**	**0.92**		**0.96**	**0.63**	**0.41**
	S.D.	*0.00*		*0.11*	*0.18*	*0.20*	*0.20*	*0.04*	*0.09*		*0.04*	*0.33*	*0.36*
l	X̄	**1.00**	**1.00**		**0.76**	**0.58**	**0.79**	**0.98**	**0.97**	**0.92**	**0.94**	**0.78**	**0.80**
	S.D.	*0.00*	*0.00*		*0.16*	*0.30*	*0.07*	*0.02*	*0.04*	*0.12*	*0.09*	*0.21*	*0.17*
s	X̄	**0.64**	**0.62**	**0.64**				**0.66**	**0.60**	**0.55**	**0.56**	**0.46**	**0.41**
	S.D.	*0.36*	*0.23*	*0.37*				*0.22*	*0.27*	*0.22*	*0.27*	*0.24*	*0.23*
r	X̄	**0.43**	**0.33**	**0.42**	**0.46**		**0.45**	**0.36**		**0.47**	**0.50**	**0.35**	**0.41**
	S.D.	*0.17*	*0.20*	*0.09*	*0.32*		*0.33*	*0.27*		*0.18*	*0.21*	*0.11*	*0.22*
ʃ	X̄	**0.58**	**0.59**	**0.72**	**0.40**	**0.43**		**0.59**	**0.50**	**0.34**	**0.49**	**0.34**	**0.31**
	S.D.	*0.17*	*0.15*	*0.07*	*0.22*	*0.27*		*0.31*	*0.16*	*0.19*	*0.22*	*0.12*	*0.15*
ʎ	X̄	**0.95**	**0.94**	**0.98**	**0.57**	**0.72**	**0.61**		**0.72**	**0.77**	**0.68**	**0.67**	**0.64**
	S.D.	*0.07*	*0.04*	*0.01*	*0.30*	*0.26*	*0.36*		*0.16*	*0.16*	*0.25*	*0.31*	*0.29*
ɲ	X̄	**0.96**	**0.99**	**0.96**	**0.68**	**0.66**	**0.66**	**0.87**	**0.87**	**0.72**	**0.77**	**0.69**	**0.69**
	S.D.	*0.07*	*0.01*	*0.07*	*0.27*	*0.25*	*0.24*	*0.14*	*0.14*	*0.15*	*0.17*	*0.18*	*0.21*
k	X̄	**1.00**	**0.70**	**0.83**	**0.22**	**0.63**	**0.48**	**0.81**	**0.11**		**0.15**	**0.07**	**0.07**
	S.D.	*0.00*	*0.13*	*0.14*	*0.00*	*0.11*	*0.12*	*0.09*	*0.07*		*0.13*	*0.12*	*0.12*
	CCa												
s	X̄	**0.49**	**0.64**	**0.56**			**0.53**	**0.60**	**0.52**	**0.46**	**0.54**	**0.48**	**0.44**
	S.D.	*0.08*	*0.09*	*0.09*			*0.13*	*0.10*	*0.07*	*0.13*	*0.04*	*0.04*	*0.02*
ʃ	X̄	**0.69**	**0.67**	**0.64**	**0.44**	**0.20**	**0.76**		**0.52**	**0.46**	**0.61**	**0.51**	**0.55**
	S.D.	*0.10*	*0.05*	*0.21*	*0.08*	*0.19*	*0.08*		*0.04*	*0.03*	*0.03*	*0.04*	*0.09*

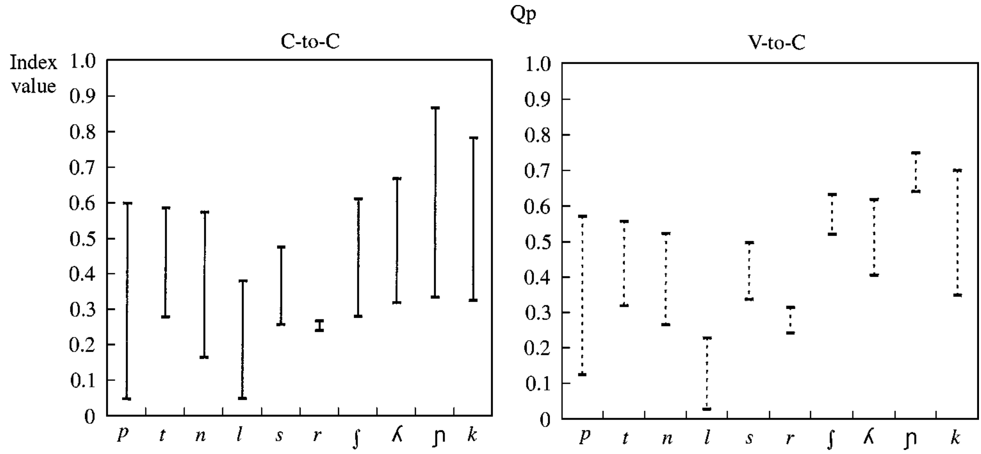

Figure 2. (Left) Ranges of Qp values for C1 across C2 sampled at −15 ms. (Right) Ranges of Qp values for the same consonants as a function of the vowels *i*, *a* and *u*.

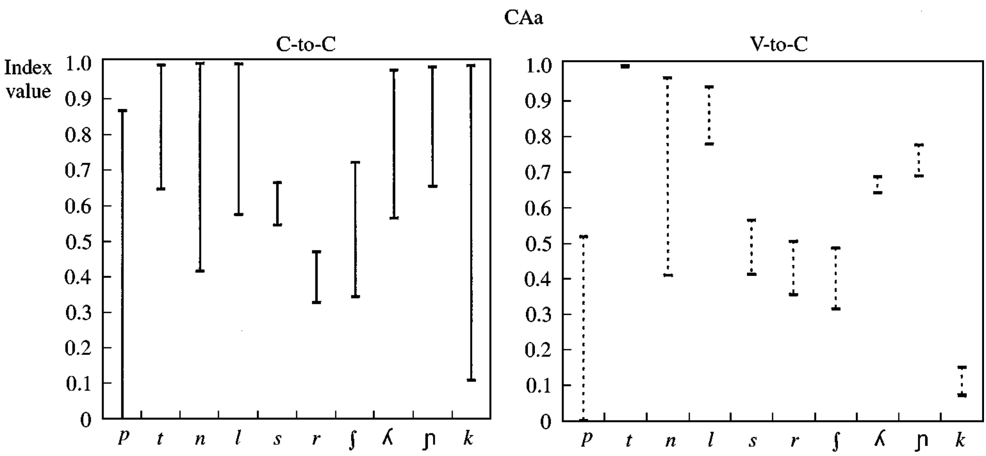

Figure 3. (Left) Ranges of CAa values for different C1 across C2 conditions and speakers sampled at −15 ms. (Right) Ranges of CAa values for the same consonants as a function of the vowels *i*, *a* and *u*.

also indicate the presence of minimal dorsopalatal contact for dark *l*, *r*, and, less so, *s*, and of maximal palatal contact for alveolopalatals and velars. The S.D. values in Table II reveal little speaker-dependent Qp variability for all consonants with the exception of *l* presumably due to differences in darkness across speakers.

A close look at the Qp data for each CC combination in Table II reveals highest Qp values (and thus maximal tongue dorsum raising effects) for bilabials, dentals and alveolars before consonants produced with a high tongue dorsum, i.e., alveolopalatals, palatal *j* and velar *k*. This happens to be more so in the case of sequences with C1 = *p*, *t*, and *n* than in the case of those with highly constrained C1 = *l*, *s* and *r*. Accordingly, linguopalatal configurations in Fig. 4 show considerable differences in palatal contact for

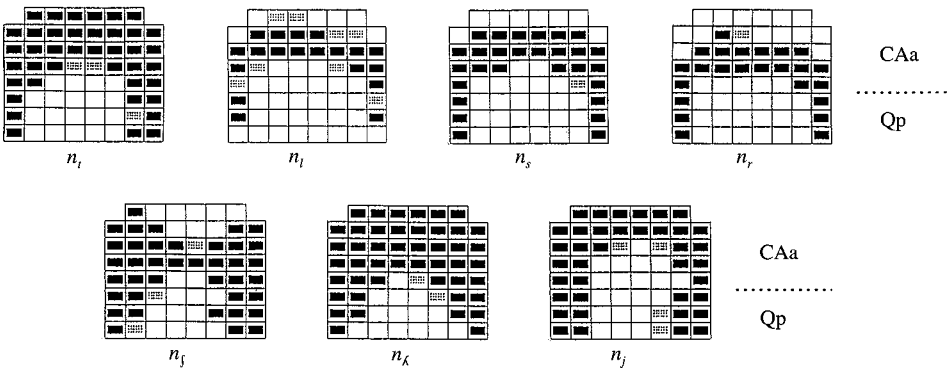

Figure 4. Linguopalatal configurations for *n* in all C2 context conditions (speaker DR).

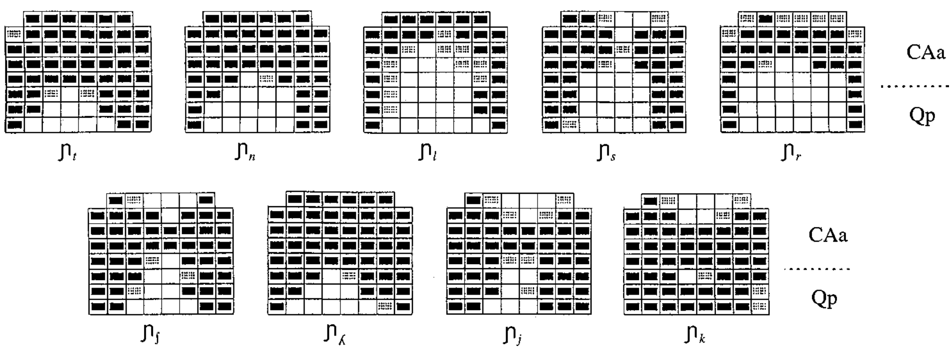

Figure 5. Linguopalatal configurations for *ɲ* in all C2 context conditions (speaker DR).

C1 = *n* before consonants produced with and without active tongue dorsum raising, i.e., *ʃ*, *ʎ*, *j* (bottom) *vs.* *t*, *l*, *s*, *r* (top). A partial exception is dental *t* which is produced with more laminal contact than the apicoalveolar consonants *l*, *s* and *r*, and thus causes some automatic elevation of the tongue dorsum to occur during preceding C1 = *n*.

Consonants produced with tongue dorsum raising, i.e., alveolopalatals (*ʃ*, *ʎ*, *ɲ*) and velars (*k*), show low Qp values and thus major tongue dorsum lowering effects before *l* and *r* and, less so, before *s*. Their Qp values are high before other dorsal consonants (i.e., before alveolopalatals and palatal *j* and, even more so, before velars) and intermediate before dental *t* and *n*. Palatographic displays in Fig. 5 show differences in degree of palatal contact for *ɲ* as a function of these three groups of consonants. While a velar consonant is known to blend with a following high front vowel (see *Introduction*), high Qp values in sequences made of an alveolopalatal and a velar do not correspond to a blending situation. Indeed, the linguopalatal configuration for C1 in the sequence [*ɲ*k] in Fig. 5 shows that temporal overlap between the alveolopalatal gesture and the velar gesture does not result in a single place of articulation at the palatal zone but in two separate closure locations. Data for other clusters with a velar and a dentoalveolar or alveolopalatal articulation ([gd], [gn], [gʒ], [gʎ]) also show gestural overlap but no blending.

(b) Qp ranges of C-to-C coarticulation agree to a large extent with Qp ranges of V-to-C coarticulation (Fig. 2, right): in both cases, contextual variability is high for labials and velars, and low for the trill and *s*; dental *t* and alveolars *n* and *l* are somewhat less sensitive to V-to-C coarticulation than to C-to-C effects, vocalic effects being less obvious for *l* than for *t* and *n*. It thus appears that consonants involving demanding manner requirements (and little dorsopalatal contact) block consonantal and vocalic effects at the palatal zone, i.e., apical vibration for *r*, frication for *s* and, less so, laterality and the formation of a secondary lingual constriction for dark *l*. Dark *l* appears to undergo more palatalization as a function of contextual *j* than of adjacent *i* (Table II).

Differences in coarticulatory sensitivity between the V-to-C and C-to-C scenarios are most striking for consonants produced with maximal palatal contact, i.e., alveolopalatals happen to be much more variable in the latter contextual condition than in the former (more so for *ɲ* and *ʃ* than for *ʎ*). Those differences are mostly related to contextual conditions contributing to dorsopalatal contact lowering. Indeed, as shown in Table II, Qp for C1 = *ʃ* and *ɲ* decreases much more dramatically as a function of C2 = *l*, *s*, and *r* (down to a value of about 0.25–0.40) than of the vowel *a* (down to about 0.5–0.6); analogous but smaller differences are obtained for C1 = *ʎ*. It may be thus concluded that antagonistic consonants requiring active tongue dorsum lowering and backing may exert a stronger depalatalizing effect on alveolopalatal consonants than low vowels.

According to the table, vocalic effects occur as a function of front *vs.* nonfront vowels in the case of labials, dentals and alveolars (i.e., $i > u$, a) and of high *vs.* low vowels in the case of alveolopalatals (i.e., $i, u > a$). As expected, vocalic effects for velars vary in the progression $i > a > u$ which reflects the existence of three vowel-dependent tongue dorsum positions.

3.1.2. *CAa* (*tongue front adaptation*)

(a) Differences in consonantal closure or constriction fronting (as inferred from CAa index values) need to be identified in order to account for tongue front adaptation mechanisms in consonant clusters. Vowel-dependent differences in CAa will serve this purpose since it is known that vowels exert minimal effects on the place of articulation for most consonants.

Among dentals, alveolars and alveolopalatals, CAa values were found to be high for *t*, *n*, *l*, *ʎ* and *ɲ*, and low for *s*, *r*, and *ʃ* (Fig. 3, left). Demanding manner requirements, i.e., frication and apical vibration, require some closure or constriction retraction which explains why *s*, *r* and *ʃ* are produced with a back lingual constriction at the alveolar zone. In light of these different places of articulation, alveolar and alveolopalatal consonants will be subdivided into four groups throughout this paper whenever necessary: front alveolars (*n*, *l*), back alveolars (*s*, *r*), front alveolopalatals (*ʎ*, *ɲ*) and back alveolopalatals (*ʃ*).

(b) Consonant-dependent variability in CAa is maximal for labials and velars (Fig. 3, left) since these consonants involve no tongue front activation. Gestural overlap explains why CAa values for C1 = *p* and *k* are usually higher before dentals, front alveolars and alveolopalatals than before back alveolars, palatals and velars (Table II). At the other end, highly constrained alveolars *s* and *r* exhibit less variability than any other C1 and are thus maximally resistant to alveolar contact fronting as a function of following dentals, front alveolars and front alveolopalatals.

Dentals (*t*), front alveolars (*n*, *l*) and alveolopalatals (*ʃ*, *ʎ*, *ɲ*) show a good deal of C2-dependent CAa variability and thus, appear to adapt to the place of articulation of the following consonant. This is so presumably since the tongue front is down during alveolopalatal production, and *t*, *n*, and *l* are produced with the tongue tip and are specified for less demanding manner requirements than fricatives and trills. The most noticeable C-to-C coarticulatory effects in this case involve closure retraction for dentals, front alveolars and front alveolopalatals (*t*, *n*, *l*, *ʎ*, *ɲ*) before the back alveolars *s* and *r* and the back alveolopalatal *ʃ*, in agreement with phonetic descriptions stating that /t/ becomes alveolar in those three contextual conditions in Catalan (Recasens, 1993). Indeed, as shown in Table II, those C1 exhibit low CAa values before the back C2 of interest. Linguopalatal contact patterns in Figs 4 and 5 also reveal that *n* and *ɲ* are articulated exclusively at the back alveolar subzone when placed before *s* and *r* which suggests that C1 assimilates to C2 in these circumstances. This adaptation pattern may be facilitated by the strong apical nature of *l* and *n* and indicates that the transition from C1 to C2 in sequences such as [ns] and [nr] does not require changes in place of articulation but just in the manner of articulation (i.e., the velum must be raised for the production of C2 in both clusters). CAa values for *ʎ* and *ɲ* before palatal *j* and velar *k* tend to be as low as those before back alveolars (Table II).

CAa values for *n*, *l*, *ʎ* and *ɲ* are high before front alveolars (*t*, *n*, *l*) and front alveolopalatals (*ʎ*), which is in accordance with /n/ and /l/ becoming dental before a dental stop in Catalan (Recasens, 1993). Moreover, contact patterns for [nt] and [nʎ] (Fig. 4) and for [ɲt] and [ɲn] (Fig. 5) suggest that speakers use a blending strategy which is actualized through some contact expansion and may encompass the dental zone as well. Thus, blending processes may be argued to involve the addition of the tongue contact characteristics at the places of articulation for the two consecutive consonants in the cluster. High CAa values for *t*, *n* and *l* before *j* (sequences [tj], [nj], [lj]) and little increase in alveolar contact towards the back for [nj] in Fig. 4 suggests that dentals and front alveolars do not undergo blending with following *j* in the present study. Strict requirements on frication explain why C1 = *ʃ* is not very sensitive to C2-dependent fronting effects (see low CAa values for this consonant in Fig. 3) and therefore may not undergo articulatory blending with the following consonant.

(c) Vocalic effects (Fig. 3, right) resemble consonantal effects in being large for *p* (for $i > a$, *u*; see Table II), and small for *s* and *r*. Small vowel-dependent CAa differences for velars and related to the absence of contact on the sides of the alveolar zone; indeed, for all speakers, velar closure occurs on row 8 for [iki] and behind this row for [aka] and [uku], and lateral contact may extend along two or three (and exceptionally four) rows of electrodes.

While being highly sensitive to coarticulatory effects in consonant clusters, dentals, front alveolars and alveolopalatals allow little vowel-dependent coarticulation (for $i > a$, *u*) except for *n*. The finding that CAa for intervocalic *t* does not vary at all as a function of the adjacent vowels in consistent with dentals being articulated fixedly at the teeth and exhibiting considerable alveolar contact (see *Introduction*). Little vowel-dependent variability in CAa for dark *l*, and for the alveolopalatals *ʃ*, *ʎ* and *ɲ*, should be related to the high articulatory constraints involved in the production of complex consonantal segments (dark *l*) and of consonants articulated with the dorsum of the tongue (alveolopalatals). These consonants exhibit more prominent consonant-dependent *vs.* vowel-dependent effects which are mainly associated with alveolar closure retraction for *t* before *s*, *r* and *ʃ*, and for *l* before *r*, and with alveolar contact fronting for *ʃ*, *ʎ* and *ɲ* before dentals and front alveolars.

3.1.3. *CCa* (*constriction width*)

CCa values for *s* show little context-dependent variability as a function of adjacent consonants and vowels and little speaker-dependent variability as well (see Table II). CCa values are higher before some front consonants (e.g., *n*, *l*) and in the adjacency of the vowel *i* than before some back consonants (e.g., *j*, *k*) and in the adjacency of back vowels meaning that the lingual constriction is narrower in the former context condition than in the latter.

In comparison with *s*, CCa values for *ʃ* are more variable across contextual consonants and equally variable across contextual vowels and speakers (Table II). Context index values for the alveolopalatal fricative are lower before back alveolars, palatals and velars (*s*, *r*, *j*, *k*) than before fronter consonants (*t*, *n*, *l*, *ʎ*), and in the context of *u*, *a vs. i*. The finding that *s* allows less consonant-dependent coarticulation than *ʃ* (not only in CCa but also in Qp and CAa) is in agreement with differences in articulatory control between these two lingual fricatives.

3.2. *Effects in temporal extent*

Data on the temporal extent of C2-to-C1 coarticulation should accord with the size effects reported in Section 3.1. In order to evaluate this relationship, Fig. 6 plots the duration of those temporal effects which were found to reach significance beyond 20 ms before C1 offset according to *post hoc* statistical tests. These significant temporal effects will be discussed in the light of results obtained in correlation analyses between the size and the temporal extent of C2-to-C1 coarticulation (see *Section* 2) and will be illustrated with a representative sample of Qp temporal trajectories for clusters with C1 = *n* and with C1 = *ɲ* for speaker DR (Figs 7 and 8).

3.2.1 *Qp*

Significant Qp temporal effects are represented in two separate panels depending on whether C1 does (*ʃ*, *ʎ*, *ɲ*, *k*; middle panel) or does not (*p*, *t*, *n*; top panel) involve active tongue dorsum raising. Effects are plotted as a function of the relevant C2 pairs on the abscissa axis. For each C2 pair, some consonants exert a stronger coarticulatory influence than others, i.e., palatalizing C2 = *ʃ*, *ʎ*, *j*, *k* on nondorsal C1 (top), and depalatalizing C2 = *l*, *s*, *r* on dorsal C1 (middle).

Size by time correlations for C1 unspecified for tongue dorsum activity (*p*, *t*, *n*) yielded high *r* values in the case of *p* (speaker DR = 0.75; speaker JP = 0.93; speaker JS = 0.82) and *n* (0.78; 0.70; 0.72). Indeed, as shown in the top panel of Fig. 6, longest effects in tongue dorsum contact during those C1 occur mostly when the C2-dependent differences are particularly large, i.e., when C2 = *ʃ*, *ʎ*, *j* or *k* is paired with a consonant involving tongue dorsum lowering (*l*, *s*, *r*). In agreement with these data, Qp trajectories for clusters with C1 = *n* in Fig. 7 (upper graph) exhibit large and long anticipatory differences during C1 when a palatalizing C2 (i.e., *ʃ*, *ʎ*, *j* for which Qp reaches about 0.6 during C2) is compared with a depalatalizing C2 (i.e., *l*, *s*, *r* which show a Qp value about or below 0.2).

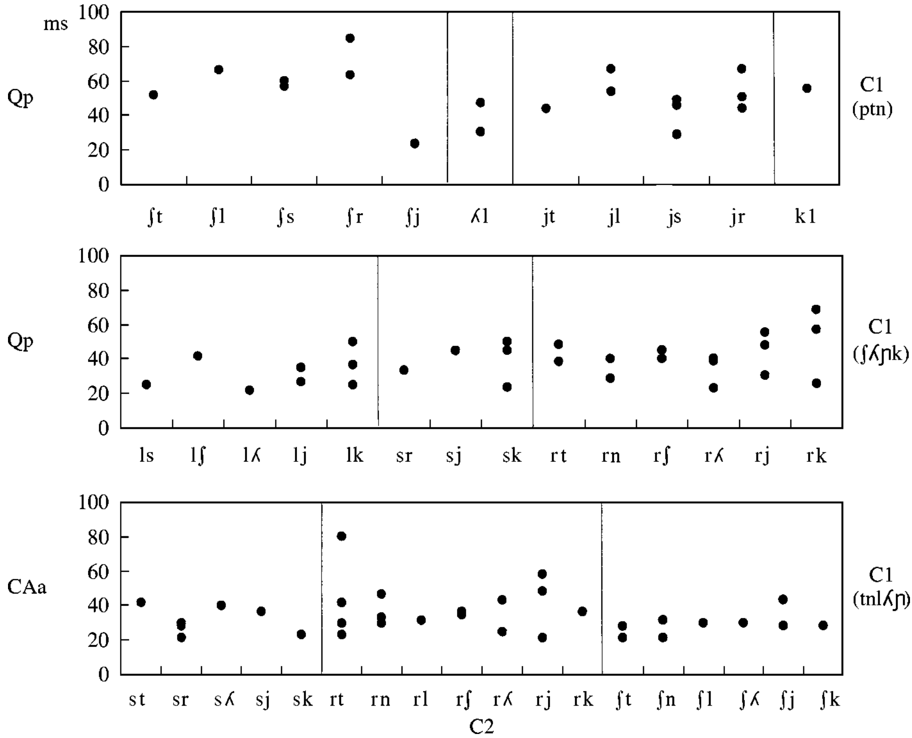

Figure 6. Significant C2-to-C1 temporal effects in Qp and CAa exceeding 20 ms before C1 offset. Data are plotted for nondorsal (Qp, upper panel), dorsal (Qp, central panel) and front (CAa) consonants as a function of those C2 pairs yielding significant coarticulatory effects. In each C2 pair the phonetic symbol on the left corresponds to the consonant exerting maximal coarticulation.

Large C2-dependent effects on dorsal C1 (*ʃ*, *ʎ*, *ɲ*, *k*) tend to be long as well. Size × time correlation analyses often yielded high *r* values for C1 = *ʃ* (0.89; 0.77; 0.75), *ʎ* (0.48; 0.80; 0.68), *ɲ* (0.87; 0.92; 0.80) and *k* (0.68; 0.53; 0.80). As shown in Fig. 6 (central panel), longest effects were obtained for C2 pairs in which depalatalizing *l*, *r*, or less so, *s* was paired with an alveolopalatal (*ʎ*), a palatal (*j*) or a velar (*k*). This finding is consistent with the trend for dark *l* and trilled *r* to involve strong anticipatory lingual activity during a preceding antagonistic dorsal consonant (see *Section* 1). Moreover, the fact that extensive anticipation is also related to the presence of an alveolopalatal, palatal or velar C2 in this case may be associated with articulatory overshoot and thus, with an intensification of the tongue dorsum raising gesture during a preceding alveolopalatal or velar C1. All these observations are consistent with Qp trajectories for C1 = *ɲ* in Fig. 7 (lower graph) showing large and long Qp differences as a function of a palatalizing C2 (i.e., *ʃ*, *ʎ*, *j*, *k* with Qp values between 0.6 and 0.9) *vs.* a depalatalizing C2 (i.e., *l*, *s*, *r* with Qp values between 0.2 and 0.4).

C2-dependent temporal effects in Qp on highly resistant alveolar C1 produced with active tongue predorsum lowering, i.e., *l*, *s*, and *r*, are not shown in Fig. 6 since they barely exceeded 20 ms. High size by time correlation values were found to hold only for C1 = *l*, i.e., 0.69 (speaker DR), 0.80 (JP), 0.86 (JS).

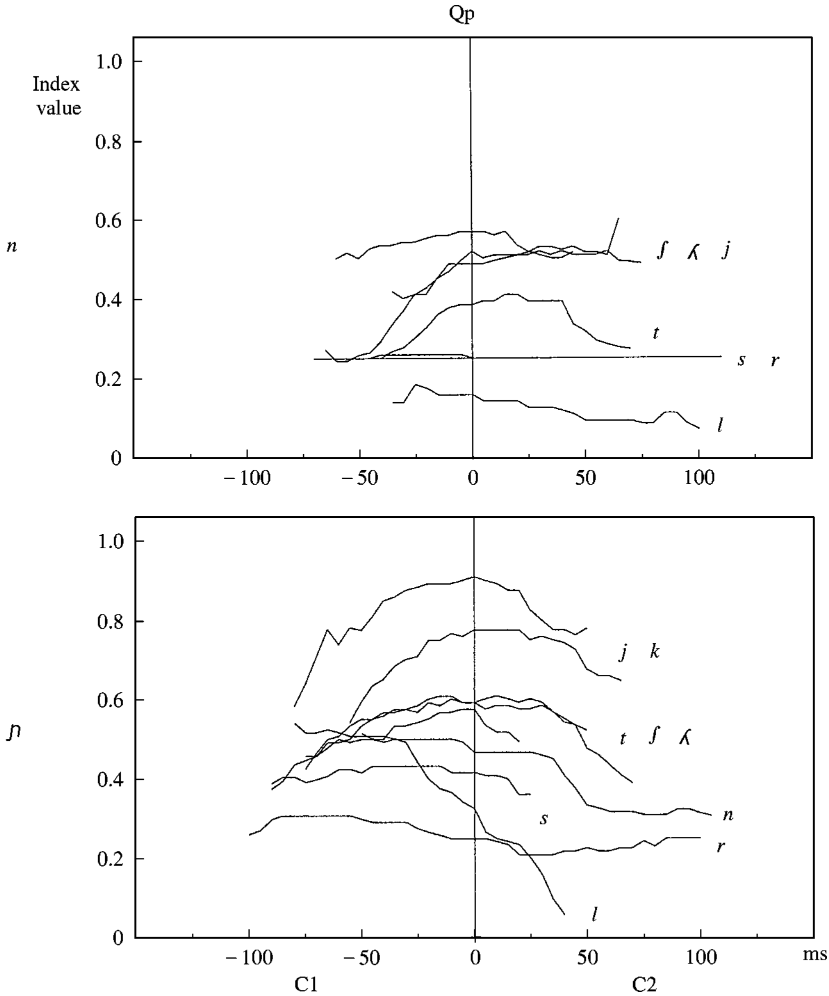

Figure 7. Qp temporal trajectories for *n* and for *ɲ* in all C2 conditions (speaker DR).

3.2.2. *CAa*

Significant CAa temporal effects in articulatory retraction have been displayed on the bottom panel of Fig. 6 for front consonants *t*, *n*, *l*, *ʎ* and *ɲ* as a function of C2 pairs with highly constrained back *s*, *r*, and *ʃ*. In agreement with size effects in Section 3.1.2, those effects become especially prominent when the other member of the consonantal pair does not prevent alveolar contact fronting from occurring (i.e., *t*, *n*, *l*, *ʎ*, *j*, *k*). CAa trajectories for clusters with C1 = *n* and *ɲ* in Fig. 8 indicate that these anticipatory effects in alveolar retraction may extend back to C1 onset which is in agreement with their being assimilatory rather than just coarticulatory (see also Section 3.1.2). The same observation may apply to instances of articulatory blending (e.g., [nt], [nʎ], [ɲt], [ɲn]; see Figs 4 and 5).

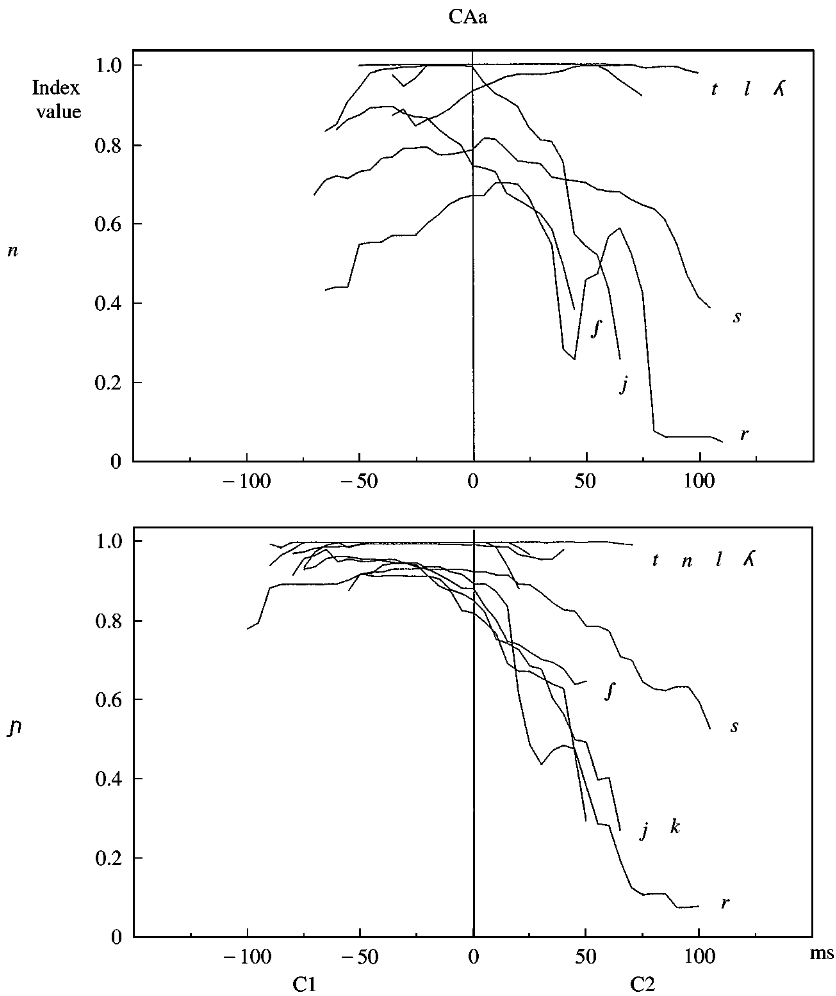

Figure 8. CAa temporal trajectories for *n* and for *ɲ* in all C2 conditions (speaker DR).

Anticipatory fronting effects from dentals and front alveolars on back alveolars and back alveolopalatals did not go over 20 ms which explains why they have not been displayed in Fig. 6.

3.3. *Direction*

3.3.1. *Qp*

Figs 9 and 10 allow a study of C-to-C effects in tongue dorsum raising and in tongue dorsum lowering as a function of coarticulatory direction. Fig. 9 represents tongue dorsum raising effects on the alveolars *n*, *l* and *r* as a function of the alveolopalatals *ʃ* and *ʎ*, and Fig. 10 plots tongue dorsum lowering effects from the depalatalizing alveolars *l* and *r* on other alveolar consonants *n* and *l* or *r* and on the alveolopalatals *ʃ* and *ʎ*.

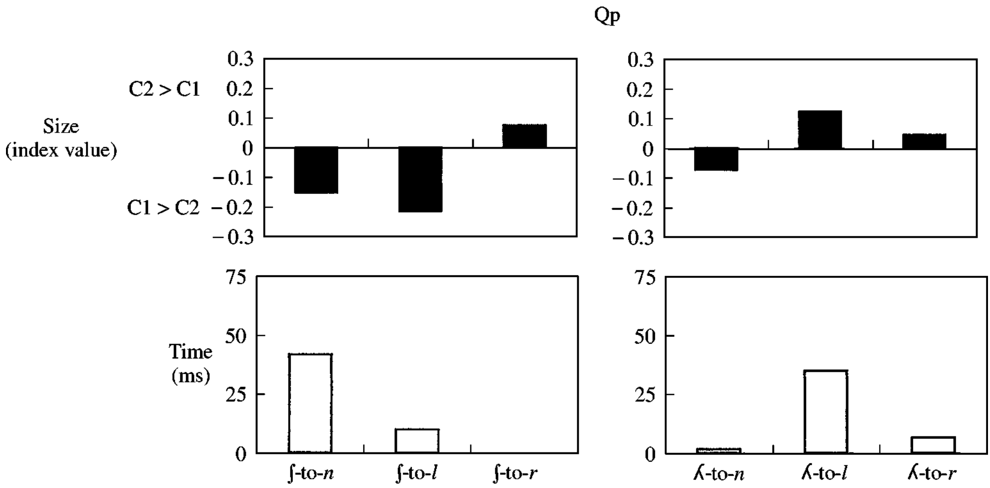

Figure 9. Size and temporal C2–C1 differences in Qp for several alveolars as a function of alveolopalatals *ʃ* (left) and *ʎ* (right). Size effects (top) may be positive or negative depending on whether Qp differences are more prominent when the alveolar consonant is placed at C2 or at C1, respectively.

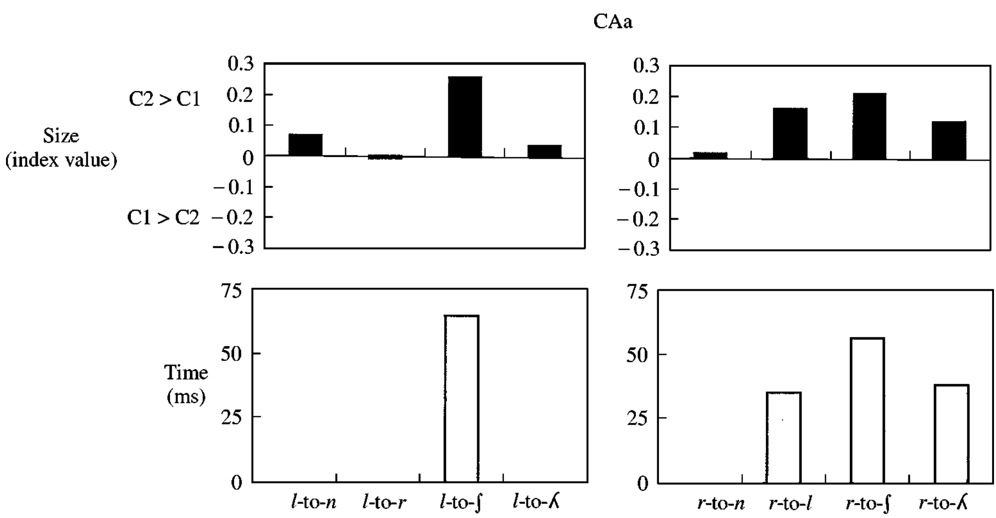

Figure 10. Size and temporal C2–C1 differences in Qp for several alveolars and alveolopalatals as a function of *l* (left) and *r* (right). See Fig. 9 caption for details.

Size values (top graphs) correspond to maximal C2–C1 differences in Qp for those consonants along which coarticulatory effects were measured. Bars are positive if the consonant of interest was produced with more palatal contact when acting as C2 than when acting as C1; they are negative in case more dorsopalatal contact was obtained in C1 *vs.* C2 position. Temporal values (bottom graphs) indicate the duration of those positive or negative differences according to results obtained from statistical analyses.

Let us take, for example, effects from *ʃ* on *n*, *l* and *r* on the upper and lower left graphs of Fig. 9. Negative bars for the *ʃ*-to-*n* and *ʃ*-to-*l* conditions in the upper graph mean that *n* and *l* are produced with more dorsopalatal contact when acting as C1 in the sequences [nʃ] and [lʃ] than as C2 in the sequences [ʃn] and [ʃl]; conversely, a positive bar for the *ʃ*-to-*r* condition indicates that the rhotic involves more palatal contact in the cluster [ʃr] than in the cluster [rʃ]. Temporal data for the *ʃ*-to-*n*, *ʃ*-to-*r* conditions on the lower graph indicate that those negative or positive C2–C1 differences in palatal contact become significant during 30 ms for *n* and 10 ms for *l*, but do not reach significance for *r*.

(a) Regarding the action of contextual alveolopalatals (Fig. 9), it was expected that C-to-C effects would yield more dorsopalatal contact along C2 than along C1. This ought to be so since, as pointed out in *Section* 1, alveolopalatals ought to exert more carry-over than anticipatory coarticulation and thus, should cause more dorsopalatal contact to occur on a following alveolar than on a preceding alveolar. According to these expectations, all bars reporting size effects in Fig. 9 should be positive.

Trends in coarticulatory direction for C-to-C effects on alveolars requiring active tongue predorsum lowering, i.e., *l* and *r*, are partially in agreement with our initial hypothesis. As expected, the two alveolar consonants may show more dorsopalatal contact when acting as C2 than when acting as C1, i.e., *r* in the context of *ʃ* and *ʎ*, and *l* in the context of *ʎ*. These data are also consistent with the possibility that dark *l* and *r* involve more tongue dorsum lowering syllable finally than syllable initially.

Bars reporting effects on the more unconstrained alveolar nasal stop *n* are not positive but negative meaning that this consonant is produced with more dorsopalatal contact in syllable final position than in syllable initial position when adjacent to a contextual alveolopalatal. This unexpected outcome may be attributed to the conditions on consonantal production in syllable coda position. If *n* is programmed to be articulated with less tongue dorsum raising syllable-finally than syllable-initially, syllable final *n* could indeed be more easily coproduced with an adjacent alveolopalatal than syllable initial *n*. This scenario should not apply to dark *l* and *r* which are highly constrained and thus ought to block anticipatory antagonistic palatalization effects. Another interpretation is based on the sequencing of articulatory maneuvers needed to produce two consecutive consonantal lingual gestures: while anticipatory tongue dorsum raising may be facilitated by an increase in laminoalveolar contact in sequences such as [nʃ] or [nʎ], the transition from an alveolopalatal to following *n* may be a much more complex task to the extent that it involves some tongue repositioning. A similar rationale may be put forth in order to account for the fact that /sʃ/ but not /ʃs/ undergoes complete assimilation (see *Section* 1).

(b) The DAC model predicts that consonants requiring active predorsum lowering (*l* and *r*) should exert more tongue dorsum lowering at the anticipatory level than at the carry-over level. According to this hypothesis, bars in Fig. 10 ought to be positive meaning that an alveolar or alveolopalatal consonant should exhibit more dorsopalatal contact syllable initially than syllable finally when adjacent to *l* and *r*. Size and temporal effects in the figure conform to our predictions most of the time.

Other concomitant factors may account for the prevalence of C-to-C anticipation over C-to-C carry-over in some of these CC scenarios. The fact that trills are subjected to higher manner requirements in syllable onset position than in syllable offset position may help to explain why consonants preceding *r* present less dorsopalatal contact than those following the trill. Moreover, C2–C1 differences in degree of dorsopalatal contact for the consonants *l*, *ʃ* and *ʎ* may be related to syllable position differences in their articulatory implementation, i.e., the alveolar lateral should be darker syllable finally than syllable initially and alveolopalatals could involve less dorsopalatal contact in syllable final *vs.* syllable initial position.

3.3.2. *CAa*

CAa values in Fig. 11 allow a study of the relative salience of the anticipatory effects (unfilled bars) and carry-over effects (filled bars) at the place of articulation for the front alveolars *n* and *l* and for the front alveolopalatal *ʎ*. Bars represent CAa ranges across all following consonants at − 15 ms and across all preceding consonants at + 15 ms.

The figure shows a larger dispersion of CAa values for C1 than for C2. It thus appears that the assimilatory influence on closure location for *n*, *l* and *ʎ* is regressive rather than progressive. According to Table II and Section 3.2.2, CAa differences occur mostly as a function of front *vs.* back alveolars and alveolopalatals (*t*, *l*, *ʎ*, *ɲ*, *vs.* *s*, *r*, *ʃ*).

4. Discussion

4.1. *Coarticulatory variability*

Contextual variability for consonants was found to be generally larger as a function of adjacent consonants than of adjacent vowels, mostly so in Qp and CAa for alveolopalatals, and in CAa for the remaining consonants but for back alveolars *s* and *r*. CCa values for *ʃ* were also found to vary more considerably as a function of consonants than of vowels.

Within the framework of the DAC model, those differences in CAa variability accord with differences in tongue front involvement in the formation of a closure or constriction for the production of consonants *vs.* vowels. On the other hand, differences in Qp variability are in agreement with the notion that the tongue dorsum is subjected to

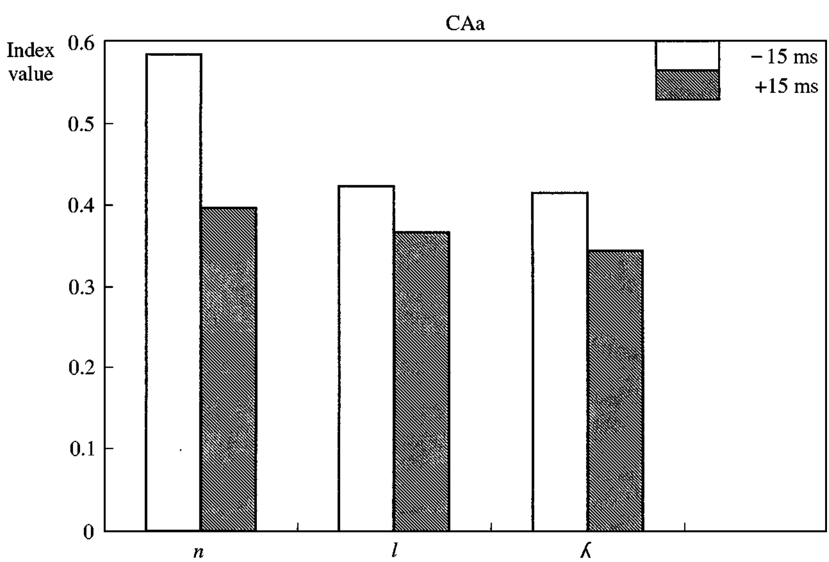

Figure 11. Ranges of CAa values for *n*, *l*, and *ʎ* as a function of several C2 at − 15 ms (unfilled bars) and of several C1 at + 15 ms (filled bars).

higher competing requirements in consonant clusters than in VCV sequences. Several findings were consistent with the latter claim: more robust depalatalizing effects on alveolopalatals as a function of consonants than of low vowels; more extensive effects in alveolar contact fronting for *t* and *l* as a function of back alveolars and back alveolo-palatals than of back vowels, and for alveolopalatals as a function of dentals and front alveolars than of front vowels.

4.2. *Gestural antagonism*

According to the present investigation, highly constrained alveolar consonants *s* and *r* undergo less coarticulation than dentals, other alveolars and alveolopalatals presumably because of the manner requirements involved. Indeed, these consonants are highly resistant to contextual palatalization and fronting, thus being produced with a relatively context-independent low predorsum configuration and a retracted tongue front at constriction location. This finding is quite surprising in the case of *r* given the short duration of rhotics syllable finally. Coarticulatory data show that dark *l* also resists effects in tongue dorsum raising to a large extent in line with demanding requirements on the implementation of laterality and on the formation of a back secondary constriction. It was also found that *s* is more resistant than *ʃ* to opening effects at the central constriction location which may be taken in support of consonant-dependent differences in tongue front control between the two lingual fricatives.

On the other hand, dentals and front alveolars undergo much palatalization as a function of following dorsal consonants while alveolopalatals are especially sensitive to depalatalizating effects exerted by *l*, *s* and *r*. Temporal coarticulation effects are in agreement with size effects in assigning a special relevance to the depalatalization of alveolopalatals and perhaps of velars before *l* and *r*, and to the palatalization of more unconstrained dental *t* and alveolar *n*. Articulatory overshoot may account for the presence of an additional degree of dorsopalatal contact in sequences of two consecutive dorsal consonants and perhaps of an additional degree of tongue dorsum lowering for *t* and *n* before *l* and *r*.

In summary, it may be concluded that the tongue dorsum lowering and retraction gesture overrides the tongue dorsum raising and fronting gesture when the two come into contact. An obvious reason for this finding may be that the former articulatory mechanism is conditioned by manner requirements. It appears, however, that the same difference in coarticulatory behavior applies to palatalized and velarized consonants of the same manner of articulation in languages in which both consonantal classes have phonological status.

This general finding is consistent with other results reported in the present investigation. Effects of high vowels on some depalatalizing consonants (*r*) were found to be less extensive than effects of low vowels on palatalizing consonants, and there were no substantial differences between palatalization effects on *l*, *s*, and *r* as a function of high dorsal consonants and of high vowels.

4.3. *Blending and assimilation*

Articulatory adaptation strategies at constriction location appear to be largely consistent with considerations on articulatory constraint at the primary articulator. Size and temporal effects found here support the conclusion that consonants which are essentially unconstrained at the tongue front, i.e., dentals and front alveolars (*t*, *n*, *l*) and front alveolopalatals (*ʎ*, *ɲ*), are subjected to blending and assimilation at the place of articulation: on the one hand, they appear to undergo blending in CC sequences where they combine among themselves; on the other, they assimilate to highly constrained back alveolars (*s*, *r*, *ʃ*). Consonants of the latter group do not undergo either assimilation or blending but exert a clear assimilatory action on more unconstrained dentals, front alveolars and front alveolopalatals.

(a) In contrast to *s* and *r*, dentals, front alveolars and alveolopalatals are subjected to much context-dependent variability in front alveolar contact. This finding has been attributed to low manner requirements and to the involvement either of the tongue tip or of no tongue front region in their production.

The palatalization of dentals and front alveolars (*t*, *n*, *l*) before alveolopalatals results in back contact expansion at closure location and thus blending of the alveolar contact characteristics of two adjacent consonants. Overlap but no blending has been reported to hold for those consonants before palatal *j* in the present investigation. Front alveolopalatals appear to blend before *t*, *n* and *l* as well, i.e., a significant front contact expansion at closure location was indeed obtained before a dental or a front alveolar consonant mostly when in contrast with C2 $=$ *r* which causes a considerable reduction in alveolar contact area. The back alveolopalatal *ʃ* does not blend with dentals and front alveolars but causes them to undergo regressive place assimilation.

Consonantal sequences composed exclusively of *t*, *n* and *l* may yield blending as well. Thus, there is presumably blending through front contact expansion in sequences made of *n* and *l* before *t* which is consistent with dental stops being produced with considerable alveolar contact.

It has also been found that labials and velars overlap with lingual consonants in general, and that velars blend before *i* and *j* but not so in the adjacency of an alveolopalatal or dentoalveolar consonant. Experimental and sound change data in the literature reveal that blending may be obtained in the latter consonantal sequences as well (see *Section* 1).

(b) Assimilatory closure retraction is exerted by the highly constrained postalveolars *s*, *r*, and *ʃ* on dentals, front alveolars and front alveolopalatals. This is confirmed by CAa changes for C1 $=$ *l*, *n*, *ʎ* and *ɲ* as a function of C2 $=$ *t*, *n* $>$ *s*, *r*, *ʃ*. Long CAa temporal effects in alveolar contact retraction have been found to hold for dentals, front alveolars and front alveolopalatals mostly as a function of following *r* when in contrast with a nonbacking C2.

A joint consideration of coarticulatory effects at the tongue front and at the tongue dorsum indicates that tongue dorsum raising and tongue dorsum lowering may covary with an enlargement of the alveolar contact area and with some place of articulation retraction, respectively, but that this is not necessarily the case. Indeed, while front alveolopalatals cause palatalization and an increase in alveolar contact size, contextual *ʃ* exerts simultaneous palatalization and closure retraction; on the other hand, depalatalization effects as a function of *s* and trilled *r* co-occur with closure retraction while dark *l* exerts depalatalization but no closure retraction.

4.3. *Direction*

Syllable-position differences in dorsopalatal contact for a given consonant as a function of *l* and *r* were found to be in agreement with predictions from the DAC model. Less contact was obtained at syllable coda than at syllable onset independent of whether the target consonant is antagonistic (*ʃ*, *ʎ*) or not (*n*, *l*) with respect to tongue dorsum lowering and backing effects. This finding is in accordance with the salience of the anticipatory effects associated with active tongue dorsum lowering and retraction in consonantal production.

Predictions of coarticulatory direction by the DAC model were partly confirmed by the action of alveolopalatals on other consonants. Thus, the carry-over direction was found to prevail over the anticipatory direction when the target consonant is antagonistic (*l*, *r*) but not so when this is not the case (*n*). More extensive anticipatory than carry-over effects from alveolopalatals on *n* were accounted for in terms of the articulatory properties of coda consonants and of coordinative strategies in the production of consonant clusters.

Highly constrained consonants *s*, *r*, and *ʃ* were found to exert a progressive assimilation on more unconstrained front alveolars and front alveolopalatals though this influence happened to be somewhat less robust than the corresponding regressive assimilatory action.

5. Conclusion

A model based on articulatory constraints has been shown to account quite coherently for several basic C-to-C adaptation processes in consonant clusters. The most significant findings of the present investigation improve our understanding of gestural coordination mechanisms and phonological assimilatory processes. Data at the palatal zone reveal the presence of a higher degree of coarticulatory dominance and coarticulatory resistance for phonetic segments involving tongue dorsum lowering and retraction than for those produced with tongue dorsum raising and fronting. Data at the front place of constriction, on the other hand, indicate that blending (and thus mutual adaptation between consecutive consonants) is favored by the presence of unconstrained C1 and C2, assimilation (and thus unilateral adaptation) takes place when C2 is more highly constrained than C1, and that sequencing (and thus no adaptation) is the natural output for clusters composed of a highly constrained C1 and an unconstrained C2. Progressive assimilations may also occur in the last scenario and specific mechanisms of gestural coordination are at work (e.g., *rd* does not yield blending but C1-to-C2 sliding in view of the mobility of the tongue tip). In summary, the three production strategies are possible and may be predicted from gestural requirements. Assimilatory processes involving two neighboring articulatory regions could be viewed as the cognitive extension of adaptation effects between gestures specified for different degrees of articulatory constraint.

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References

Badia, A. M. (1951) *Gramática histórica catalana.* Barcelona: Noguer.

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

Browman, C. P. & Goldstein, L. (1989) Articulatory gestures as phonological units. *Phonology*, **6,** 201–251.
Browman, C. P. & Goldstein, L. (1990) Tiers in articulatory phonology, with some implications for casual speech. In *Papers in laboratory phonology I: between the grammar and physics of speech* (J. Kingston & M. E. Beckman, editors), pp. 341–376. Cambridge: Cambridge University Press.
Browman, C. P. & Goldstein, L. (1995) Gestural syllable position effects in American English. In *Producing speech: contemporary issues for Katherine Safford Harris* (F. Bell-Berti & L. J. Raphael, editors), pp. 19–33. New York: American Institute of Physics.
Byrd, D. (1996) Influences on articulatory timing in consonantal sequences, *Journal of Phonetics*, **4,** 59–74.
Clark, J. E., Palethorpe, S. & Hardcastle, W. J. (1982) Analysis of English lingual fricatives: multi-modal data using stepwise regression methods, *Working Papers of the Speech and Language Research Centre, Maquarie University*, **3,** 1–90.
Ellis, L. & Hardcastle, W. J. (1999) An instrumental study of alveolar to velar assimilation in careful and fast speech. In *Proceedings of the XIVth International Congress of the Phonetic Sciences* (J. J. Ohala, Y. Hasegawa, M. Ohala, D. Granville & A. C. Bailey, editors), Vol. 3, pp. 2425–2428. San Francisco: American Institute of Physics.
Farnetani, E. (1990) V-C-V lingual coarticulation and its spatiotemporal domain. In *Speech production and speech modelling* (W. J. Hardcastle & A. Marchal, editors), pp. 93–130. Dordrecht: Kluwer Academic Publishers.
Farnetani, E. & Busà, M. G. (1994) Italian clusters in continuous speech. In *Proceedings of the 3rd International Conference on Spoken Language Processing*, Yokohama, Vol. 1, pp. 359–362.
Farnetani, E., Hardcastle, W. J. & Marchal, A. (1989) Cross-language investigation of lingual coarticulatory processes using EPG. In *Eurospeech 1989. European conference on speech communication and technology* (J. P. Tubach & J. J. Mariani, editors), pp. 429–432.
Fontdevila, J., Pallarès, M. D. & Recasens, D. (1994) The contact index method of EPG data reduction. *Journal of Phonetics*, **22,** 141–154.
Fowler, C. A. & Brancazio, L. (2000) Coarticulatory resistance of American English consonants and its effects on transconsonantal vowel-to-vowel coarticulation, *Language and Speech*, **43,** 1–41.
Fowler, C. A. & Saltzman, E. (1993) Coordination and coarticulation in speech production, *Language and Speech*, **36,** 171–195.
Gibbon, F., Hardcastle, W. J. & Nikolaidis, K. (1993) Temporal and spatial coordination in /kl/ sequences: a cross-linguistic investigation, *Language and Speech*, **36,** 261–277.
Hardcastle, W. J. (1994) Assimilation of alveolar stops and nasals in connected speech. In: *Studies in general and English phonetics in honor of Professor J. D. O'Connor* (J. Windsor Lewis, editor), pp. 49–67. London: Routledge.
Hardcastle, W. J., Jones, W., Knight, C., Trudgeon, A. & Calder, G. (1989) New developments in electropalatography: a state-of-the-art report, *Clinical Linguistics and Phonetics*, **3,** 1–38.
Hardcastle, W. J. & Roach, P. (1979). An instrumental investigation of coarticulation in stop consonant sequences. In *Current issues in the phonetic sciences* (H. Hollien & P. Hollien, editors), pp. 531–540. Amsterdam: John Benjamins.
Hasegawa, A., Christensen, J. M., McCutcheon, M. J. & Fletcher, S. G. (1979) Articulatory properties of /s/ in selected consonant clusters. In *Speech communication papers presented at the 97th ASA meeting* (J. J. Wolf & D. H. Klatt, editors), pp. 115–118. New York: ASA.
Holst, T. & Nolan, F. (1995) The influence of syntactic structure on [s] to [ʃ] assimilation. In *Phonology and phonetic evidence. Papers in Laboratory Phonology IV* (B. Connell & A. Arvaniti, editors), pp. 315–333. Cambridge: Cambridge University Press.
Hoole, P., Gfroerer, S. & Tillmann, H. G. (1990) Electromagnetic articulography as a tool in the study of coarticulation, *Forschungsberichte des Instituts für Phonetik, Munich*, **28,** 107–122.
Kent, R. D. & Moll, K. L. (1972) Cinefluorographic analyses of selected lingual consonants, *Journal of Speech and Hearing Research*, **15,** 453–473.
Kühnert, B. (1993) Some kinematic aspects of alveolar-velar assimilations. *Forschungsberichte des Instituts für Phonetik und Sprachliche Kommunikation, München*, **31,** 263–272.
Lehiste, I. (1964) *Some acoustic characteristics of selected English consonants*, Vol. 34. Research Center in Anthropology, Folklore and Linguistics, Indiana University.
Miyawaki, K., Kiritani, S., Tatsumi, I. F. & Fujimura, O. (1974) Palatographic observation of VCV articulations in Japanese. *Annual Bulletin, Research Institute of Logopedics and Phoniatrics, University of Tokyo*, **8,** 51–57.
Nakamura, M. (1999) Two kinds of palatalisation in Japanese: an electropalatographic study. In *Proceedings of the XIVth International Congress of the Phonetic Sciences* (J. J. Ohala, Y. Hasegawa, M. Ohala, D. Granville & A. C. Bailey, editors), Vol. 1, pp. 57–60. San Francisco: American Institute of Physics.
Ní Chasaide, A. & Fitzpatrick, L. (1995) Assimilation of Irish velarised and palatalised stops. In *Proceedings of the XIIIth International Congress of Phonetic Sciences* (K. Elenius & P. Branderud, editors), Vol. 1, pp. 334–337. Stockholm: Arne Strömbergs Grafiska

Nolan, F. (1992) The descriptive role of segments: evidence from assimilation. In *Papers in Laboratory Phonology II* (G. J. Docherty & D. R. Ladd, editors), pp. 261–280. Cambridge: Cambridge University Press.

Nolan, F., Holst, T. & Kühnert, B. (1996) Modelling [s] to [ʃ] accomodation in English, *Journal of Phonetics*, **24,** 113–138.

Ohala, J. & Kawasaki, H. (1984) Prosodic phonology and phonetics. *Phonology Yearbook*, **1,** 113–128.

Öhman, S. (1966) Coarticulation in VCV sequences, *Journal of the Acoustical Society of America*, **39,** 151–168.

Perkell, J. S., Boyce, S. & Stevens, K. N. (1979) Articulatory and acoustic correlates of the [s-ʃ] distinction. In *Speech communication papers presented at the 97th ASA meeting* (J. J. Wolf & D. H. Klatt, editors), pp. 109–113. New York: ASA.

Recasens, D. (1984) V-to-C coarticulation in Catalan VCV sequences, *Journal of Phonetics*, **12,** 61–73.

Recasens, D. (1990) The articulatory characteristics of palatal consonants, *Journal of Phonetics*, **18,** 267–280.

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

Recasens, D. (1993) *Fonètica i fonologia*. Barcelona: Enciclopèdia Catalana.

Recasens, D. (1995) Coarticulació i assimilació en fonologia. Dades de moviment lingual sobre els grups consonàntics amb C2 = /d/ en català, *Caplletra*, **19,** 11–26.

Recasens, D. (1999) Lingual coarticulation. In *Coarticulation* (W. J. Hardcastle & N. Hewlett, editors), pp. 80–104. Cambridge: Cambridge University Press.

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

Recasens, D., Fontdevila, J. & Pallarès, M. D. (1995) A production and perceptual account of palatalization. In *Phonology and Phonetic Evidence. Papers in Laboratory Phonology IV* (B. Connell & A. Arvaniti, editors), pp. 265–281. Cambridge: Cambridge University Press.

Recasens, D., Fontdevila, J. & Pallarès, M. D. (1996) Linguopalatal coarticulation and alveolar–palatal correlations for velarized and non velarized /l/, *Journal of Phonetics*, **24,** 165–185.

Recasens, D., Fontdevila, J., Pallarès, M. D. & Solanas, A. (1993) An electropalatographic study of stop consonant clusters, *Speech Communication*, **12,** 335–356.

Recasens, D. & Pallarès, M. D. (1999) A study of /ɾ/ and /r/ in the light of the 'DAC' coarticulation model, *Journal of Phonetics*, **27,** 143–170.

Recasens, D., Pallarès, M. D. & Fontdevila, J. (1997) A model of lingual coarticulation based on articulatory constraints. *Journal of the Acoustical Society of America*, **102,** 544–561.

Romero, J. (1996) Articulatory blending of lingual gestures, *Journal of Phonetics*, **24,** 99–112.

Solé, M. J. (2000) Assimilatory models and aerodynamic factors. *Proceedings of the 5th Seminar on Speech Production: Models and Data*, pp. 109–112. University of Munich.

Solé, M. J. & Estebas, E. (1995) Connected speech processes: a cross-linguistic study. In *Proceedings of the 4th European Conference on Speech Communication and Technology* (J. M. Pardo, E. Enríquez, J. Ortega, J. Ferreiros, J. Macías & F. J. Valverde, editors). Vol. 3, pp. 2239–2242. Madrid: UPC.

Stone, M., Faber, A., Raphael, L. J. & Shawker, T. H. (1992) Cross-sectional tongue shape and linguopalatal contact patterns in [s], [ʃ] and [l], *Journal of Phonetics*, **20,** 253–270.

Wada, T., Yasumoto, M., Iteoka, N., Fujiki, Y. & Yoshinaga, R. (1970) An approach to the cinefluorographic study of articulatory movements, *Cleft Palate Journal*, **7,** 506–522.

Zsiga, L. (1994) Acoustic evidence for gestural overlap in consonant sequences, *Journal of Phonetics*, **22,** 121–140.

Zsiga, L. (2000) Phonetic alignment constraints: consonant overlap and palatalization in English and Russian, *Journal of Phonetics*, **28,** 69–102.