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A study of /ɾ/ and /r/ in the light of the "DAC" coarticulation model

Daniel Recasens* and Maria Dolors Pallarès

Laboratori de Fonètica, Institut d'Estudis Catalans, c/Carme 47, Barcelona 08001, Spain

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This is an electropalatographic and acoustic study of the production and coarticulatory characteristics of the alveolar tap /ɾ/ and the alveolar trill /r/ in Catalan VCV sequences. The finding that /r/ involves more closure retraction, more predorsum lowering and less apico-predorsal coupling than /ɾ/ suggests that the two consonants are realized by means of different lingual gestures. Moreover, in comparison with the tap, the trill exerts larger and longer effects on the adjacent vowels and is less sensitive to vocalic effects. This suggests that the tongue body is more constrained for /r/ than for /ɾ/. The finding that the lingual gesture for a consonant (/r/) overrides the lingual gesture for an adjacent vowel (/i/) when the two segments are highly constrained and antagonistic is supportive of a view that consonantal production is more precisely controlled than vowel production. The tap and the trill also differ with respect to the direction of VCV coarticulatory effects: on the one hand, in /VrV/ sequences, anticipatory consonant and vowel coarticulation is predominant; on the other, in /VɾV/ sequences, vocalic coarticulation is predominantly carryover, whereas consonantal coarticulation is mainly anticipatory. These patterns of coarticulatory behavior are accounted for in terms of gestural production mechanisms and biomechanical properties of the lingual articulators. Differences in articulation and coarticulation between /r/ and /ɾ/ suggest that the trill is not a geminate correlate of the tap.

1. Introduction

The goal of the present study is to better characterize the articulatory characteristics of the tap /ɾ/, which is articulated with a single brief central alveolar contact, and the trill /r/, which is articulated with several discontinuous rapid alveolar contacts. For this purpose, an experiment was conducted with Catalan speakers in which vocalic coarticulation (V-to-C effects) and consonantal coarticulation (C-to-V effects) were analyzed in symmetrical VCV sequences with the two consonants and the vowels /i/ and /a/. Measurements were taken from linguopalatal contact data collected by means of

*Also at Departament de Filologia Catalana, Universitat Autònoma de Barcelona, Bellaterra, Barcelona.

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electropalatography (EPG) and from formant frequency data for five speakers.[1] Several issues related to the production of the two rhotics are addressed in the present investigation and are discussed in detail below: tongue configuration, coarticulatory resistance and coarticulatory dominance, interarticulator coordination, coarticulatory direction and phonological status.

1.1. *Production constraints*

A first issue of interest is whether, in comparison with the tap, the trill is produced with more predorsum lowering and more postdorsum retraction (see X-ray and descriptive data for Spanish in Delattre (1971), Navarro Tomás (1972) and Quilis & Fernández (1972)) as well as with greater alveolar closure retraction (see EPG data for Catalan in Recasens, 1991). This articulatory maneuver would help to leave more room for the vertical movement of the tongue tip so that trilling is performed successfully (Solé, in press). It is also relevant to compare the lingual articulation for the two rhotics with that for other alveolar consonants (see Section 4). It is expected that greater apical involvement for the tap than for more laminal-like alveolars, such as /n/, should co-occur with more tongue dorsum retraction and a more concave predorsal shape (see Dart, 1991). Moreover, while the trill and dark /l/ should both involve much tongue predorsum lowering and tongue postdorsum retraction (which in the case of dark /l/ is associated with the formation of two places of lingual constriction: a primary apicoalveolar closure and a secondary dorsopharyngeal or dorsovelar approximation), it is an open issue whether the two consonants exhibit differences in tongue configuration.

Another topic investigated is coarticulatory resistance and coarticulatory dominance in symmetrical VCV sequences. A basic assumption underlying the hypotheses tested in this paper is that the trill is produced with a more constrained lingual configuration than the tap. Thus, trilling involves high articulatory control of aperture narrowing at the lingual constriction and of the adequate airflow through it, and depends on the intraoral pressure level behind the place of constriction being sufficiently high (McGowan, 1992; Ladefoged & Maddieson, 1996). More demanding lingual requirements for the trill than for the tap should have implications for V-to-C coarticulation, i.e., in comparison with the tap, the trill should be less sensitive to vowel-dependent effects.

Some evidence for the trill being less sensitive to vowel coarticulation than the tap is found in Recasens (1991): in comparison with /ɾ/, /r/ allows less change in closure fronting as a function of front *vs.* back vowels, and less dorsopalatal contact and a lower F2 as a function of /i/. Differing demands on the articulations for /r/ and /ɾ/ should also affect C-to-V coarticulation, i.e., the trill should exert more coarticulation on the adjacent vowels than the tap. A particularly interesting issue in this respect is the C-to-V outcome in the sequence /iri/ given that /i/ and /r/ are produced with antagonistic lingual gestures (the vowel involves tongue dorsum raising/fronting and the trill conveys tongue dorsum lowering/backing). Preliminary data show that C-to-V effects from /r/ and /i/ are more extensive than those exerted by /ɾ/ on the same vowel (Recasens, 1991). This

[1] The articulatory and coarticulatory analysis of /ɾ/ and /r/ presented in this paper is much more complete than that carried out in previous papers in respect of the issues which are raised, the methodological techniques and the number of speakers. Recasens (1987) reports F2 data on V-to-C and V-to-V coarticulation for only two speakers of Spanish and Catalan, and Recasens (1991) presents EPG and F2 data on C-to-V, V-to-C and V-to-V effects for a single Catalan speaker.

supports the hypothesis that a consonantal gesture overrides a vowel gesture when the two are antagonistic and that closure or constriction formation imposes higher demands on the trill than on the tap.

Interarticulator coordination is also investigated. Correlations between alveolar contact and palatal contact across vowel context conditions are performed in order to find out whether tongue front and tongue dorsum behave more independently for highly constrained /r/ than for less constrained /ɾ/. If both lingual regions behave interactively, an increase in dorsopalatal contact in the context of /i/ is expected to cause an increase in alveolar contact fronting, and a decrease in dorsopalatal contact in the context of /a/ ought to cause alveolar contact retraction; otherwise, if there is little interaction between apical activity and dorsal activity, variations in dorsopalatal contact should show little correlation with alveolar contact changes. Correlation data for rhotics were compared with correlation data for /n/ and dark /l/ as reported in previous papers (Recasens, Fontdevila & Pallarès, 1992, 1996) which demonstrated an inverse relationship between the number of alveolar–palatal contact correlations (for /n/ > dark /l/) and the degree of tongue dorsum constraint (for dark /l/ > /n/).

1.2. *Direction of coarticulation*

Dorsopalatal and F2 coarticulation data in VCV sequences with the tap and the trill allow a fourth issue to be addressed, direction of coarticulatory effects. Patterns of anticipatory and carryover coarticulation were studied within the framework of the Degree of Articulatory Constraint (DAC) model (see Recasens, Pallarès & Fontdevila (1997) for details).[2]

According to the DAC model, the direction of vocalic coarticulatory effects in V1CV2 sequences is strongly conditioned by whether the articulatory activity associated with the consonantal gesture is preferably anticipatory or carry-over. It predicts that the salience of V2-dependent anticipatory effects should vary inversely with the prominence of C-to-V2 carry-over effects since both coarticulatory effects "come across" one another over time. The same rationale predicts that the prominence of V1-dependent carry-over effects should be inversely related to the strength of consonantal anticipatory effects from C on V1. As shown in Recasens *et al.* (1997), this pattern of coarticulatory direction gives rise to two clear-cut scenarios: on the one hand, palatal consonants such as /ɲ/ with more extensive dorsal activity on V2 than on V1 block vocalic anticipatory effects to a larger extent than vocalic carry-over effects; on the other hand, consonants such as dark /l/, which exert much tongue dorsum anticipation during V1, block vocalic carry-over effects to a larger extent than vocalic anticipatory effects.

Within this theoretical framework, our prediction is that trends in coarticulatory direction for the trill /r/ should resemble those for dark /l/ since the two consonants exhibit similar production requirements (see Section 1.1). Thus, the trill should exert more C-to-V1 anticipation than C-to-V2 carry-over (mostly in the /i/ context condition) and thus allow more V2-dependent anticipation than V1-dependent carry-over. Preliminary coarticulation data for V-trill-V sequences (Recasens, 1987, 1991) indeed show prevalence of the anticipatory component over the carry-over component for the consonantal effects and essentially for the vocalic effects as well.

[2] Data for the DAC model were obtained initially from VCV sequences containing the vowels /i/ and /a/ and consonants other than /ɾ/ and /r/ (including dark /l/ and /n/).

Patterns of coarticulatory direction for the alveolar tap are expected to be in agreement with those for other alveolar consonants involving little tongue dorsum activity, e.g., /n/. According to Recasens *et al.* (1997), the direction of the coarticulatory effects in V1CV2 sequences with /n/ and fixed /i/ (in the sequence pairs /iCi/–/aCi/ and /iCi/–/iCa/) is analogous to that in V1CV2 sequences with palatal consonants in line with this vowel causing /n/ to be articulated with a raised tongue dorsum. Indeed, the fact that C-to-V2 carryover exceeds C-to-V1 anticipation in this case may account for the fact that vowel-dependent effects in tongue dorsum lowering associated with /a/ are more prominent at the carryover level than at the anticipatory level. If the tongue dorsum for /n/ is not particularly raised in the context of fixed /a/ (in the sequence pairs /aCa/–/aCi/ and /aCa/–/iCa/), C-to-V1 anticipatory effects turn out to be more prominent than C-to-V2 carry-over effects. This appears to be related to apical movement for the consonant being initiated much ahead of time. In these circumstances, a consonantal carry-over component of little prominence allows anticipatory tongue dorsum raising for V2 = /i/ to overlap freely with the preceding segments which explains why vocalic anticipation prevails over vocalic carry-over.

Previous studies (Recasens, 1987, 1991) reveal, however, that trends in coarticulatory direction in VCV sequences with /ɾ/ and /n/ are only in partial agreement. Vocalic effects associated with /i/ *vs.* /a/ in VCV sequences with the tap have been found to favor the carryover over the anticipatory component not only in the fixed /i/ condition (as for /n/) but also in the fixed /a/ condition. A possible interpretation for the prevalence of vocalic carryover over vocalic anticipation in the context of fixed /a/ is that the anticipatory apico-dorsal raising movement for /ɾ/ during V1 may be too rapid to block the carryover effects associated with tongue dorsum raising for V1 = /i/. The present investigation tests the validity of these trends in coarticulatory direction in VCV sequences with /ɾ/ using a more complete set of experimental conditions than in previous studies.

1.3. *Phonological status*

A further goal of this study is to throw some light on whether the trill can be regarded as a long version of the tap. In languages such as Spanish, Portuguese or Catalan both sounds show the following basic distribution: they are in contrast in intervocalic position within morpheme boundaries (Spanish *pero*/*perro*); they are mutually exclusive word initially and after an heterosyllabic consonant (where only the trill appears; Spanish *rico*, *honrado*) and after a homosyllabic consonant (where only the tap shows up; Spanish *frío*); they are in free variation syllable finally (Spanish *mar*, *harto*). Several phonologists (Harris, 1969; Wheeler, 1979) have accounted for these facts either by deriving the trill from underlying geminate /ɾɾ/ intervocalically or postulating a rule that lengthens and tenses underlying /ɾ/ in all other cases. This phonological analysis suggests that the relationship between a tap and a trill is no different from that between simple and geminate consonants (Wheeler, 1979); according to this view, /r/ would be made of several successive taps and would thus be a long version of /ɾ/. However, as noted by Harris (1969), the fact that the trill is not split by a syllable boundary (i.e., Spanish *carro* syllabifies *ca-rro*) argues in favor of /ɾ/ and /r/ being different simple segments.

Articulatory and acoustic data presented in this paper should throw light upon the simple *vs.* geminate nature of the alveolar trill. If /r/ is to be treated as a geminate version of /ɾ/, the following predictions ought to hold:

(a) Both consonants should exhibit similar production characteristics besides differing in absolute duration. Italian geminate stops (Farnetani, 1990) and French double stops (Vaxellaire, 1995) share similar articulatory characteristics to their simple correlates with the former class involving an increase in contact area at the place of articulation either towards the back (for dentals) or towards the front (for velars); such contact differences can be viewed as compatible with differences in duration, i.e., longer geminates are produced with more extreme articulatory configurations than shorter non-geminates. In other cases, negligible differences in tongue configuration have been reported between both segmental classes, e.g., between simple and geminate /l/ in several languages (Delattre, 1971) and in Breton (Bothorel, 1971).

(b) The trill should be more resistant to coarticulation than the tap in line with differences in articulatory constraint. In agreement with this prediction, Farnetani (1990) has pointed out that the existence of a larger contact surface for geminate *vs.* simple dental stops in Italian may explain why the former class tends to be less sensitive to V-to-C coarticulation as a function of adjacent /i/ *vs.* /a/ than the latter.

(c) Both consonantal realizations should exhibit similar trends in coarticulatory direction in line with their involving essentially the same articulatory gesture. According to Farnetani's study, both Italian stop categories allow more salient vocalic carryover effects (i.e., effects from V1 = /i/ *vs.* /a/) than vocalic anticipatory effects (i.e., effects from V2 = /i/ *vs.* /a/).

Data on coarticulatory sensitivity for the two rhotics in the literature (see Section 1.1) are supportive of prediction (b) and thus could be reconciled with the geminate nature of /r/. However, articulatory differences between /r/ and /ɾ/ as well as trends in coarticulatory direction for the two consonants reported in Sections 1.1 and 1.2 are not in agreement with predictions (a) and (c), and suggest that the production of the trill and the tap involves two different basic gestures (see also Catford, 1977).

2. *Method*

2.1. *Recording and analysis procedure*

Linguopalatal contact and formant frequency data were collected for the sequences /iCi/, /aCa/, /iCa/ and /aCi/ with the consonants /ɾ/ and /r/ and stress on the first syllable. This speech material was read five times by each of five Catalan speakers (DR, JP, JS, DP, JC) giving (2 rhotics × 4 sequences × 5 repetitions × 5 speakers) 200 tokens for subsequent analysis. While stressed and unstressed /i/ had essentially the same vowel quality, the sequences /aɾa/ and /ara/ were not fully symmetrical (though we will refer to them as such throughout the paper) since unstressed V2 = /a/ is realized as [ə] systematically in Catalan. It is an open question whether this V2 realization reinforces the weight of the vocalic carry-over component in line with unreduced stressed vowels (i.e., V1 = [a]) generally exerting more coarticulation and allowing less coarticulation than reduced unstressed vowels (i.e., V2 = [ə]). This issue has not been explored in the present investigation.

Linguopalatal contact was gathered every 10 ms through each VCV sequence using artificial palates equipped with 62 electrodes (Reading EPG system; Hardcastle, Jones, Knight, Trudgeon & Calder, 1989). Figs 1 and 2 display average linguopalatal configurations for the tap and the trill obtained at the consonantal period in the symmetrical sequences /iCi/ and /aCa/. Electrodes are arranged in eight rows coronally and in eight columns sagitally. The four front rows on each EPG display belong to the alveolar zone which extends from the teeth to the alveolar ridge. The four back rows define the palatal zone which extends from the alveolar ridge back to the soft palate. The first two columns on each side of the artificial palate can be characterized as lateral and the four central columns can be designated central. The graphic representations in the figures do not capture the fact that the distance between adjacent rows is smaller at the alveolar zone than at the palatal zone.

The EPG data reported in this paper is expressed using two measures. Values for several lingual contact indices were calculated at the alveolar zone and at the palatal zone. CA (anteriority), CP (posteriority) and CC (centrality) indicate whether contact occurs more towards the front, towards the back or towards the median line respectively in the zone under analysis (the zone in question is identified by a subscript label—e.g., CA_{pal} refers to the anteriority contact index for the palatal zone). In addition, Q_{pal} or percentage of contact activation over the entire palatal zone will be used as an index of overall dorsal contact. All indices were computed using the four back rows of the artificial palate for the palatal zone and the four front ones for the alveolar zone since the consonantal place of articulation never occurs behind the fourth row of electrodes. The formula and rationale for these lingual contact indices have been discussed in Fontdevila, Pallarès & Recasens (1994).

The acoustic data were recorded with a Sennheiser MD44V microphone at a 20 kHz sampling rate. The frequency values F1, F2 and F3 were obtained at the same temporal intervals as the EPG data using LPC analysis (25 ms Hamming window, 12 coefficients) on a Kay CSL analysis system. Low-intensity formant structure was generally available during the contact periods for the trill which is consistent with partial opening of the vocal tract throughout the consonant and is in accordance with the frequent presence of alveolar openings on the linguopalatal contact patterns of Figs 1 and 2. The acoustical analysis was carried out in order to draw articulatory–acoustic correlations following well-known principles of the acoustic theory of speech production: F2 and F3 exhibit a positive correlation with dorsopalatal contact degree and, thus, with palatal constriction narrowing (Fant, 1960; Recasens & Pallarès, 1995). For typical configurations of /ɾ/ and /r/, F2 is largely back-cavity dependent, F3 is largely front-cavity dependent, and F1 should be positively correlated with an opening of the apical passage and with jaw opening and tongue lowering (see Ladefoged and Maddieson (1996) for trills, and Fant (1960) and Stevens (1998) for rhotics in general).

An EPG criterion was used to determine the consonantal boundaries. For both the tap and the trill, these boundaries were taken to extend from onset to offset of alveolar contact in the four central columns of electrodes. Onset occurred at the first temporal frame showing one or more "on" electrodes in the four central alveolar columns or, if no central contact was available, when one or more "on" electrodes on the two lateral alveolar columns started approaching the central alveolar area. Offset occurred at the temporal frame preceding the formation of a free channel at the central alveolar area or, when no central closure was available, at the first frame exhibiting a decrease in contact degree at the lateral alveolar columns. In a few VCV tokens for which there was no clear EPG signal for the trill, the consonantal boundaries were taken from spectrographic displays at temporal points showing significant changes towards a low-intensity steady-state F1 and F2 for the trill.

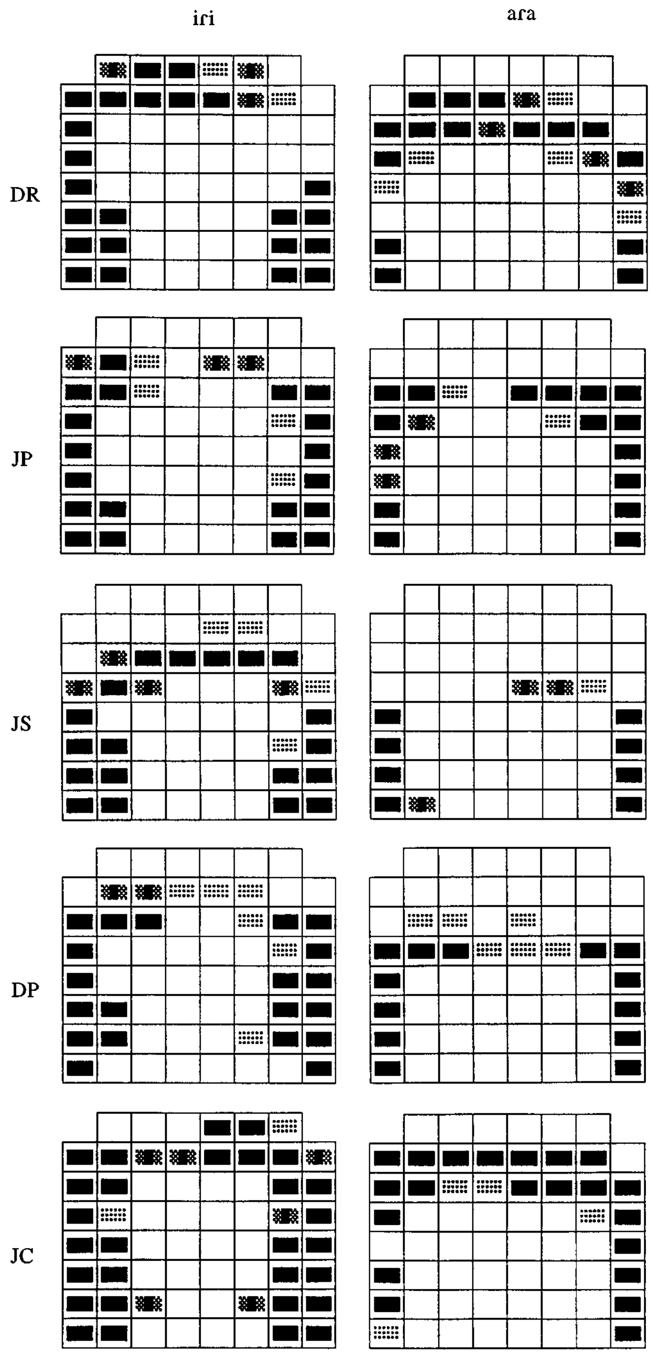

Figure 1. Linguopalatal contact patterns at consonantal midpoint for /iɾi/ and /aɾa/ for five Catalan speakers (DR, JP, JS, DP, JC). Electrode positions have been filled differently depending on the percentage of activation across repetitions, i.e., black (80–100%), striped (60–80%), stippled (40–60%), white (0–40%).

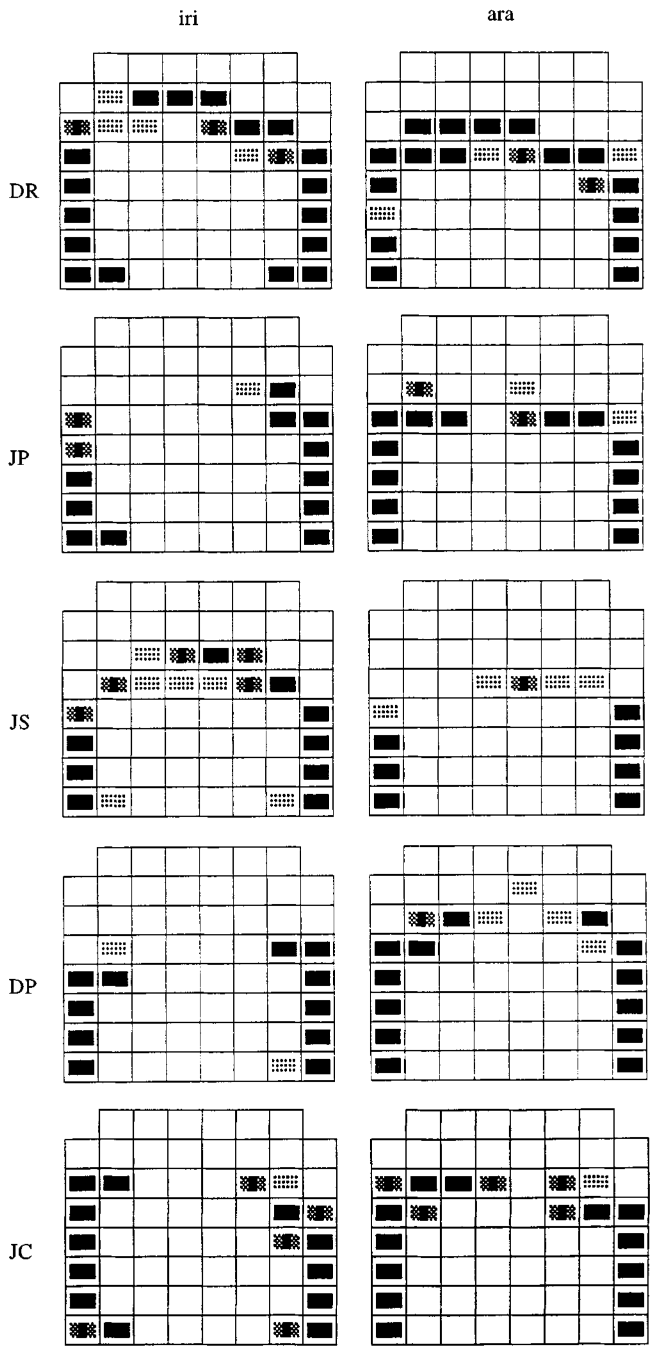

Figure 2. Linguopalatal contact patterns at the first central alveolar contact period or P1 for /iri/ and /ara/ for five Catalan speakers (DR, JP, JS, DP, JC). Electrode positions have been filled differently depending on the percentage of activation across repetitions, i.e., black (80–100%), striped (60–80%), stippled (40–60%), white (0–40%).

Measurements for the consonant were taken at closure for the tap and at three successive points (P1, P2, P3) for the trill. P1 was the first closure period and P3 was the last closure period in all cases. P2 was located between P1 and P3; its precise location depended on the number of contacts for the trill which varied mostly between 2 and 5 (see Section 1.1 of the Results), i.e., it was located at a contact period for a 3 or a 5 contact trill and at an opening period for a 2 or 4 contact trill. P1, P2 and P3 were identified at three equidistant points in a few cases where no alveolar contact changes were observed from onset to offset of /r/ and spectrographic patterns provided no useful information regarding the presence of contact periods presumably because the tongue tip was raised but did not reach the alveolar zone. Contact index and formant data (F2, F3, F1) were averaged across repetitions separately at the tap midpoint, and at P1, P2 and P3 for the trill. In order not to average across alveolar contact periods (e.g., in 3 or 5 contact trills) and opening periods (e.g., in 2 or 4 contact trills), alveolar contact index values were obtained at P1 and P3 but not at P2; however, palatal contact index and formant frequency values were calculated and averaged at the three periods.

2.2. *Criteria for measuring coarticulatory effects*

Coarticulatory effects for Q_{pal} and F2 were calculated in size and in temporal extent according to the measurement criteria described below. The methodological procedure for estimating the temporal span of coarticulation involved performing frame-by-frame comparisons between pairs of dorsopalatal and F2 trajectories. Trajectory differences at each temporal frame were submitted to statistical analysis. It was expected that sufficiently large differences would yield significant effects which could help to determine the extent of a given coarticulatory influence over time.

2.2.1. *C-to-V coarticulation*

The duration of the influence of the consonant on an adjacent vowel (C-to-V coarticulation) was equated with the period during which a significant consonant-related difference could be detected on that vowel. In order to estimate such effects, Q_{pal} and formant frequency values were first computed for all repetitions of /iCi/ and /aCa/ for each speaker in 10 ms steps starting at consonantal onset back to V1 onset, and at consonantal offset until V2 offset. The resulting values for a given symmetrical sequence were then compared separately with single measures of steady-state V1 and V2 for that same sequence using one-way repeated measures ANOVAs with 1 df between groups (since two population groups were compared) and 4 df within groups (since each group included data from five speakers). Steady-state V1 and V2 values for each symmetrical VCV sequence were established at the highest Q_{pal} or F2 for /i/ and at the lowest Q_{pal} or F2 for /a/ averaged across the five repetitions of that sequence; these values were identified during the first half of V1 and the last third of V2 since V2 was longer than V1 and the V2 steady state was located further away from the consonantal period than the V1 steady state. The last significant difference obtained in the statistical analysis procedure ($p < 0.05$) was taken to be the onset of C-to-V1 anticipatory coarticulation when the vowel being measured was V1 and the offset of C-to-V2 carry-over coarticulation when the vowel subject to measurement was V2. Onsets and offsets of the C-to-V effects for each VCV sequence type were separately averaged across

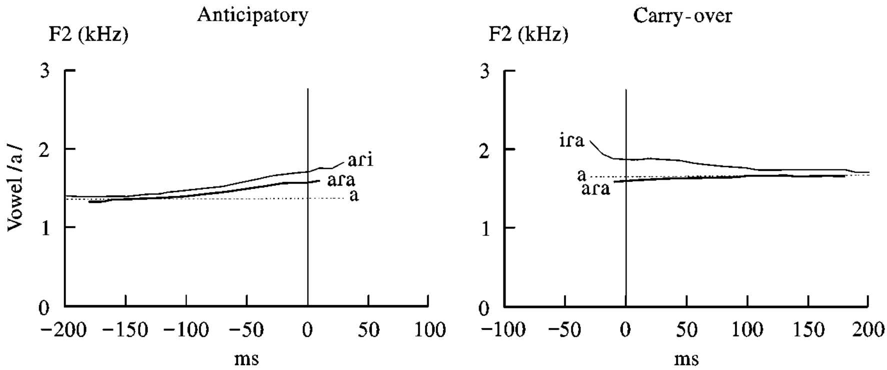

Figure 3. F2 trajectories showing anticipatory effects (left) and carry-over effects (right) in /VɾV/ sequences with contextual /a/. Data correspond to speaker JS. The 0 point on the x-axis occurs at /ɾ/ central closure onset for the anticipatory effects and at central closure offset for the carry-over effects. See text for details.

speakers and the resulting averages were used as an overall measure of C-to-V temporal coarticulation.[3]

Fig. 3 exemplifies the analysis method for the C-to-V temporal effects. The figure displays anticipatory (left) and carry-over (right) F2 effects exerted by the tap on /a/; VCV formant trajectories represent averages across five repetitions for speaker JS. A dotted line has been traced at the estimated F2 value for steady-state V1 = /a/ and V2 = /a/ in the same sequence /aɾa/. Statistical analyses comparing the entire trajectory for V1 = /a/ and steady-state V1 = /a/ (left) yielded a significant anticipatory difference starting at the 0 temporal point at consonantal onset and proceeding back to − 90 ms; significant carry-over differences between the trajectory for V2 = /a/ and steady-state V2 = /a/ (right) were absent, i.e., in this case, significant differences did not extend after 0 ms at consonantal offset.

The largest Q_{pal} or F2 difference between V1 and V2 in a symmetrical VCV sequence and the corresponding steady-state vowel value was taken to be the size of a C-to-V effect. This maximal difference usually occurs near-closure onset for C-to-V anticipation and near-closure offset for C-to-V carryover, and can be positive or negative depending on whether the consonant causes an increase or a decrease in Q_{pal} or F2. C-to-V size effects reported in this paper correspond to average values across repetitions and speakers for each symmetrical VCV sequence. Thus, for example, the size of the C-to-V anticipatory effect for V1 = /a/ in Fig. 3, i.e., the largest F2 difference between all values along V1 = /a/ and steady-state V1 = /a/ in the sequence /aɾa/ is 188 Hz meaning that the consonant contributes to an F2 raising during the vowel; on the other hand, the size of the C-to-V carry-over effect for V2 = /a/ is − 85 Hz.

Additional ANOVAs were applied to other mean differences for better evaluation of the size and temporal extent of directional differences in C-to-V coarticulation, i.e., to

[3] Both for the consonantal effects and for the vocalic effects (see Section 2.2.3), a comparison of the mean coarticulation data across speakers with those for the individual speakers revealed a few cases where an effect for one speaker deviated considerably from the same effect for the other four speakers. These outliers will be referred to explicitly in the results section.

differences between the anticipatory and carry-over C-to-V effects for each consonant in each vowel condition, and to differences between the C-to-V effects exerted by /ɾ/ and /r/ for each coarticulatory direction in each vowel condition.

2.2.2. *V-to-C coarticulation*

V-to-C effects reflect any vowel-dependent difference in Q_{pal} or in F2 frequency during the consonant and were measured in size only. They were taken to occur at the midpoint of the consonantal period for the tap and at P1, P2 and P3 for the trill.

Vowel-dependent articulatory and acoustic differences at the consonantal period in the symmetrical sequences were submitted to statistical analysis for /ɾ/ and /r/ independently (one-way repeated measures ANOVA). The same data and statistical procedure were used for the analysis of consonant-dependent differences in each symmetrical vowel context. Vowel-dependent contact index and formant frequency changes along the trill were also evaluated for all pairs of temporal points, i.e., P1 *vs.* P2, P2 *vs.* P3 and P1 *vs.* P3; other statistical comparisons involved the articulatory and acoustic differences between V1 = /i/ and V1 = /a/ at P1, and between V2 = /i/ and V2 = /a/ at P3, across symmetrical and asymmetrical sequences.

Data for all VCV sequences were included in correlation analyses of dorsopalatal contact degree and alveolar contact fronting (see Section 1.1). Correlations were calculated for the tap and for the trill at P1 which was the frame showing maximal contact at the trill closure location. In this analysis procedure, values for the alveolar contact indices CA_{alv} and CP_{alv} were correlated with values for the four palatal contact indices CA_{pal}, CP_{pal}, CC_{pal} and Q_{pal}. CC_{alv} data were not taken into account since this index does not provide information on variations in alveolar fronting.

In order to evaluate the direction of V-to-C coarticulation, differences were obtained for the sequence pairs /iCi/-/iCa/ and /aCa/–/aCi/ (anticipatory coarticulation) and for /iCi/-/aCi/ and /aCa/–/iCa/ (carry-over coarticulation), and averaged across repetitions for each speaker. They were computed when /i/ caused a higher Q_{pal} or F2 than /a/ and thus were always positive; negative values (e.g., when /a/ yielded a higher F2 value than /i/) were equated to zero in this averaging procedure. The resulting values for each VCV pair were submitted to one-way repeated measures ANOVAs with vowel context as independent variable (1 df between groups, 4 df within groups) and were considered to be significant at the $p < 0.05$ significance level.

2.2.3. *V-to-V coarticulation*

V-to-V temporal effects were taken to occur during the period along which a significant vowel-dependent difference extends into the fixed transconsonantal vowel. In order to single out such effects, Q_{pal} and F2 differences for /i/ > /a/ were calculated for the same VCV pairs described in Section 2.2.2; the analysis was performed every 10 ms starting at consonantal onset back to V1 onset and at consonantal offset until V2 offset. Those differences were submitted to one-way ANOVAs at each temporal point (1 df between groups, 4 df within groups). The last significant difference ($p < 0.05$) counting backwards during V1 was taken to be the onset of a V2-to-V1 anticipatory effect and the last one counting forwards during V2 was taken to be the offset of a V1-to-V2 carry-over effect. V-to-V temporal coarticulation data presented in this paper refer to the mean onset and offset times of the V-to-V effects for each VCV sequence pair averaged across speakers.

Fig. 3 illustrates the procedure for measuring V-to-V coarticulation. V2-to-V1 anticipatory effects occur when a significant difference between the F2 trajectories for /aɾi/ and /aɾa/ (left) is found before the 0 temporal point at central closure onset; in this particular case, significant differences extended back to − 120 ms. On the other hand, V1-to-V2 carry-over effects take place when a significant difference between the F2 trajectories for /iɾa/ and /aɾa/ (right) extends after the 0 temporal point at central closure offset; significant effects in the figure were found up to 100 ms after this point.

The size of a V-to-V effect was taken to be the largest significant Q_{pal} or F2 difference between /i/ and /a/ along the fixed transconsonantal vowel. It is always positive and usually occurs near closure onset for the anticipatory effects and near closure offset for the carry-over effects, or at the first temporal frame showing the expected coarticulatory difference when V-to-V effects were not significant. V-to-V size effects reported in this paper correspond to averages across speakers and repetitions. In Fig. 3, the size of the V-to-V anticipatory effects is 136 Hz (/aɾi/–/aɾa/) and that of the V-to-V carry-over effect amounts to 273 Hz (/iɾa/–/aɾa/).

Additional ANOVAs were applied to other mean differences in V-to-V coarticulation, i.e., to anticipatory *vs.* carry-over effects for each consonant in each vowel condition, and to effects across /ɾ/ *vs.* /r/ for each fixed vowel condition and coarticulatory direction.

3. Results

3.1. *Articulatory and coarticulatory characteristics*

3.1.1. *Phonetic differences between /ɾ/ and /r/*

Mean apicoalveolar contact duration for the alveolar tap across speakers was found to be very short; 18.4 ms in the case of /aɾa/ and 39.6 ms in the case of /iɾi/ (cf the average 20 ms long tap duration reported by Lindau (1985)). Barring the few tokens where there was no clear EPG signal, the trill was composed of a variable number of apical contacts (mostly 2 or 3 and, less often, 4 or 5) separated by short openings; its mean duration was 71.6 ms (/ara/) and 84 ms (/iri/) for a two-contact trill, 105.2 ms (/ara/) and 95 ms (/iri/) for a three-contact trill, and about 130 ms for a four-contact trill. These figures are roughly in agreement with descriptions in the literature stating that the frequency of alveolar trills is of the order of 30 cycles per second (Catford, 1977) and that their closed and open phases last about 25 ms each (Ladefoged & Maddieson, 1996).

Contact index and formant frequency differences between the tap and the trill in the symmetrical sequences /iCi/ and /aCa/ are reported in Appendix A and may be related to the linguopalatal contact patterns shown in Figs 1 and 2. For the alveolar contact indices, consonant-dependent differences reached significance only for CA_{alv} in the context of /i/ [$F(1,4) = 38.68$, $p < 0.003$] which is much higher for /ɾ/ than for /r/ in accordance with differences in alveolar fronting. The palatal contact indices CA_{pal}, CC_{pal} and Q_{pal} exhibited significantly higher values for /ɾ/ than for /r/ in the same vowel condition [$F(1,4) = 17.61$, $p < 0.014$; $F(1,4) = 51.64$, $p < 0.002$; $F(1,4) = 50.75$, $p < 0.002$, respectively] which accords with differences in dorsopalatal contact degree. More contact at the back palate than at the front palate for both /iri/ and /iɾi/ in Figs 1 and 2 suggests the existence of a concave lingual shape for /r/ and of some predorsum depression for /ɾ/. The small amount of dorsopalatal contact for the two consonants in the /a/ context yielded no significant consonant-dependent differences in any of the palatal contact index values.

F2 values were significantly higher for the tap than for the trill in the two vowel conditions /i/ and /a/ [$F(1,4) = 73.27$, $p < 0.001$; $F(1,4) = 9.18$, $p < 0.039$] which should be attributed to differences in tongue dorsum raising between the two consonants. In addition, F1 was found to be significantly higher for the trill than for the tap also in the context of /i/ and /a/ [$F(1,4) = 9.34$, $p < 0.038$; $F(1,4) = 38.26$, $p < 0.003$] suggesting that /r/ is produced with a more open jaw and a larger front cavity than /ɾ/. F3 differences between the two consonants were not significant.

3.1.2. *Coarticulatory sensitivity*

Fig. 4 plots contact index and formant frequency values for the tap and for the trill as a function of /i/ *vs.* /a/ in symmetrical VCV sequences.

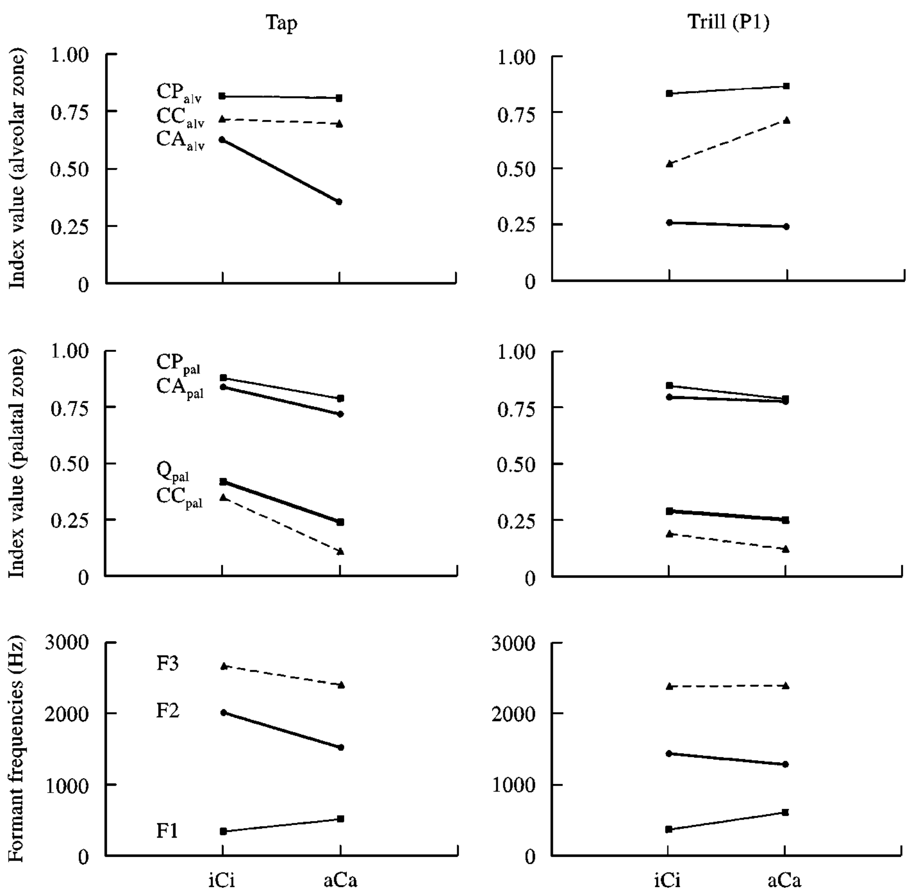

Figure 4. Cross-speaker values for the alveolar contact indices (top), the palatal contact indices (middle) and the formant frequencies (bottom) for the tap (left) and for the trill (right) in the VCV sequences /iCi/ and /aCa/. Data for the trill have been measured at P1. Q_{pal} values have been transformed into decimal numbers in order to make them comparable with the other three palatal contact index values.

Vowel-dependent alveolar contact differences (top row) reached significance only in the case of CA_{alv} for the tap [$F(1,4) = 38.3$, $p < 0.003$] which is articulated with more alveolar contact fronting when adjacent to /i/ *vs.* /a/ (Fig. 1). No significant vowel effects were found for /r/. Therefore, the tap appears to be more sensitive than the trill to vowel-related changes in alveolar contact fronting.

In agreement with linguopalatal contact configurations in Figs 1 and 2, most palatal contact index values (middle row) were significantly higher in the context of /i/ than in the context of /a/ for both /ɾ/ and /r/. Moreover, larger dorsopalatal contact differences for /ɾ/ than for /r/ as a function of /i/ *vs.* /a/ appear to be associated with /i/ causing more dorsopalatal contact during the tap than during the trill (see Section 3.1.1). These vowel-dependent differences reached significance in Q_{pal}, CC_{pal} and CP_{pal} both for the tap [$F(1,4) = 81.31$, $p < 0.001$; $F(1,4) = 45.22$, $p < 0.003$; $F(1,4) = 10.88$, $p < 0.003$] and for the trill [$F(1,4) = 14.83$, $p < 0.018$; $F(1,4) = 18.68$, $p < 0.012$; $F(1,4) = 12.56$, $p < 0.024$], but only for the tap in the case of CA_{pal} [$F(1,4) = 8.74$, $p < 0.042$]. Taken together these data indicate that the tap is equally sensitive to vocalic effects at the anterior palate and at the posterior palate while coarticulatory sensitivity for the trill is less at the front palate than at the back palate.

Formant frequencies (bottom row) yielded significant results for F2 and F1 but not for F3. F2 for /ɾ/ was significantly higher in the context of /i/ *vs.* /a/ while F1 showed the opposite pattern [$F(1,4) = 413.91$, $p < 0.000$; $F(1,4) = 11.81$, $p < 0.026$]. These vocalic effects are indicative of the tongue dorsum for the tap being more lowered and retracted in the sequence /aɾa/ than in the sequence /iɾi/ (F2), and of /i/ causing less jaw opening for /ɾ/ to occur than /a/ (F1). The trill also showed a significantly higher F2 and a significantly lower F1 in the context of /i/ *vs.* /a/ [$F(1,4) = 47.04$, $p < 0.002$; $F(1,4) = 18.95$, $p < 0.012$]. Vowel-dependent differences in F2 frequency are, however, smaller for the trill (154 Hz) than for the tap (498 Hz) which is in accordance with differences in coarticulatory resistance at the palatal zone between the two consonants. On the other hand, the trill shows larger vowel-dependent differences in F1 frequency than the tap (225 *vs.* 176 Hz, respectively) suggesting that context-dependent F1 variability increases with jaw lowering for the consonant.

3.1.3. *Changes during the production of the trill*

According to Fig. 5 (numerical values in Appendix A), the alveolar contact index values during the trill generally lower from P1 to P3. This can be taken as an evidence for a decrease in alveolar contact during aerodynamic vibration after a targeted apical position at trill onset; such a decrease was found to be significant only in the case of CC_{alv} for /ara/ and /ari/ [$F(1,4) = 36.5$, $p < 0.004$; $F(1,4) = 12.14$, $p < 0.025$]. On the other hand, differences in CA_{alv}, CP_{alv} and CC_{alv} between /i/ and /a/ were found to be non-significant not only at P1 (see Section 3.1.2) but also at P3, meaning that the tongue tip is quite resistant to contextual effects during the production of the trill.

Changes throughout /r/ at the palatal zone can be studied from a statistical evaluation of the palatal contact index values (middle column) and of the F2 and F3 data (top and bottom graphs in the right column). Palatal contact index and F2 values for /iri/ lower from P1 to P2 and increase from P2 to P3; the former change reaches significance in the case of F2 [$F(1,4) = 18.48$, $p < 0.013$] while the latter becomes significant for CP_{pal}, CC_{pal} and Q_{pal} [$F(1,4) = 8.55$, $p < 0.043$; $F(1,4) = 9.96$, $p < 0.034$; $F(1,4) = 10.89$, $p < 0.030$]. Values for /ari/ rise significantly from trill onset at P1 through to trill offset at

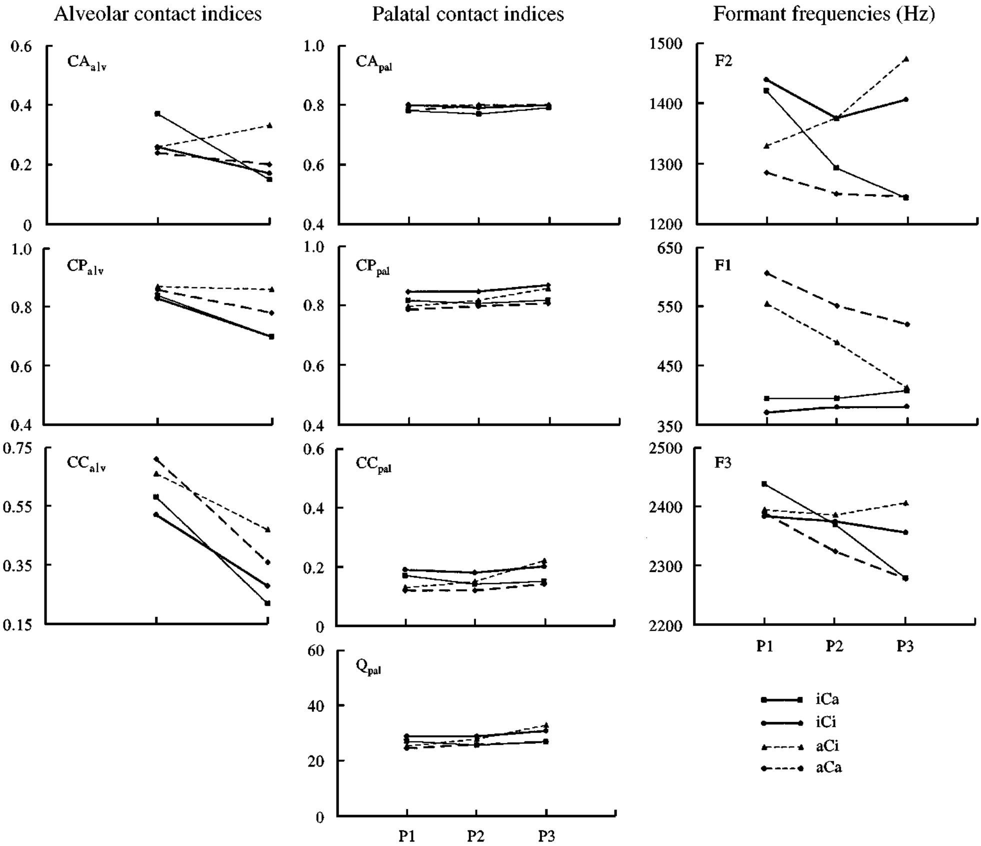

Figure 5. Cross-speaker values for the alveolar contact indices (left), the palatal contact indices (middle) and the formant frequencies (right) at the first closure period (P1), consonantal midpoint (P2) and final closure period (P3) during the trill. Data have been plotted separately for the VCV sequences /iCi/, /iCa/, /aCi/ and /aCa/.

P3 both for F2 [$F(1,4) = 15.71$, $p < 0.017$] and for CP_{pal} and CC_{pal} [$F(1,4) = 14.08$, $p < 0.020$; $F(1,4) = 8.25$, $p < 0.045$]. Regarding the sequences with V2 = /a/, no significant P1-to-P3 changes were found for /ara/ and there was a significant decrease in F2 and F3 from /r/ onset to /r/ offset for /ira/ [$F(1,4) = 48.47$, $p < 0.002$; $F(1,4) = 11.22$, $p < 0.029$]. These data suggest that the tongue dorsum must attain a consonant-dependent configuration in all /VrV/ sequences while adapting to the preceding vowel at trill onset and to the following vowel at trill offset. The coarticulatory reference of the adjacent vowels at the edges of the consonantal period is supported by statistical tests which reveal significant V1-dependent differences as a function of /i/ *vs.* /a/ in CC_{pal} and F2 at P1 (see Section 3.1.2) and significant V2-related differences in CP_{pal}, CC_{pal} and F2 at P3 [$F(1,4) = 9.07$, $p < 0.039$; $F(1,4) = 8.54$, $p < 0.043$; $F(1,4) = 20.90$, $p < 0.010$].

Significant F1 changes during the trill (middle graph on the right column) occur when V1 is produced with an open jaw (/a/) but not when V1 involves jaw closing (/i/); F1 was found to lower significantly from P1 to P3 in the case of sequences /ara/ [$F(1,4) = 17.67$, $p < 0.014$] and /ari/ [$F(1,4) = 11.06$, $p < 0.029$] while undergoing non-significant changes along the consonantal period in the sequences /ira/ and /iri/. Moreover, vowel-dependent differences in F1 frequency were found to be significant for V1 = /i/ *vs.* /a/ at P1 (Section 3.1.2) but not for V2 = /i/ *vs.* /a/ at P3. These F1 coarticulation data point to the conclusion that the trill is produced with more jaw lowering at onset than at offset when V1 = /a/ and that the presence of V1 = /i/ prevents jaw lowering at trill onset from occurring.

3.1.4. *Alveolar–palatal correlations*

A large number of high alveolar–palatal correlation values for /ɾ/ *vs.* /r/ in Table I is indicative of the tongue tip and the tongue dorsum behaving more interactively during the production of the tap than during the production of the trill.

For most speakers, the tap shows high positive correlations between CA_{alv}, and Q_{pal}, CC_{pal} and CP_{pal}, since an increase in medio-postpalatal contact for /i/ *vs.* /a/ causes the fronting of alveolar contact. High correlations between CP_{alv} and any palatal contact index are less numerous than those for CA_{alv}, meaning that, in comparison with front alveolar contact, back alveolar contact is less dependent on dorsopalatal contact changes; as expected, CP_{alv} correlations are mostly negative in line with a dorsopalatal contact decrease in the /a/ condition yielding an increase in back alveolar contact (see Fig. 1).

Alveolar–palatal interactions for the trill conform to a pattern similar to those obtained for the tap in the case of speaker DR only, i.e., high positive correlation values were found to hold between CA_{alv} and all palatal contact indices but for CA_{pal}. Negative interactions between CA_{alv} and the palatal contact index values for speaker DP may be due to his not succeeding in forming a complete alveolar closure for /r/ when the tongue dorsum is being raised in the context of /i/ (see Fig. 2). Analogous to the tap, both speakers show low negative *r* values between CP_{alv} and one or more palatal contact indices.

TABLE I. *r* correlation values about 0.7 or higher involving the alveolar contact indices (CA_{alv}, CP_{alv}) and the palatal contact indices (CA_{pal}, CP_{pal}, CC_{pal}, Q_{pal}) for the five speakers (DR, JP, JS, DP, JC). Data correspond to the consonantal midpoint for the tap and to the first closure (P1) for the trill. Asterisks indicate the presence of significant correlation values

		CA_{alv}					CP_{alv}				
		DR	JP	JS	DP	JC	DR	JP	JS	DP	JC
Tap	CA_{pal}		0.68			0.99*					
	CP_{pal}	0.96*	0.86*			0.91*	− 0.93*		0.87*		
	CC_{pal}	0.96*	0.86*		0.73	0.94*	− 0.90*				
	Q_{pal}	0.94*	0.87*	0.68	0.81*	0.97*	− 0.85*			− 0.70	
Trill	CA_{pal}				− 0.73				0.96*	− 0.78	
(P1)	CP_{pal}	0.80*					− 0.70				
	CC_{pal}	0.80*			− 0.85*					− 0.68	− 0.72
	Q_{pal}	0.85*			− 0.81*		− 0.70			− 0.67	

3.1.5. *VCV trajectories*

Average Q_{pal} (left) and F2 (right) trajectories for speaker DR in Fig. 6 provide representative information about the temporal implementation of the vocalic and consonantal lingual gestures during the production of all VCV sequences.

Trajectories for the symmetrical VCV sequences are displayed in the upper four graphs of the figure. Trajectories for /iri/ show that Q_{pal} and F2 lowering for the trill starts during V1 (before the 0 line-up point) and proceeds during V2 (after the vertical marks at the offset of the consonantal period). Interestingly enough, the Q_{pal} trajectory for /iɾi/ reveals that the tap also causes some decrease in dorsopalatal contact to occur during the preceding and following vowel /i/ which is in support of the production of this consonant involving some predorsum lowering. Q_{pal} and F2 trajectories for /aɾa/ and /ara/ exhibit no salient differences (some Q_{pal} increase from V1 to V2 may be related to the latter vowel being realized as [ə]).

Trajectories for the asymmetrical VCV sequences are represented in the lower four graphs. As with the symmetrical trajectories, Q_{pal} and F2 trajectories for /ira/ show an earlier onset of Q_{pal} and F2 lowering than those for /iɾa/; this Q_{pal} and F2 lowering motion may be said to end at a similar time in both sequences /iɾa/ and /ira/ relative to consonant onset due to the longer duration of the trill than the tap. Also, as for the symmetrical trajectories, there are no apparent differences between /ari/ and /aɾi/ at V1, i.e., raising of Q_{pal} and F2 appears to start at a similar moment in time for both sequences; however, the offset of this raising movement takes place at a later temporal point for /r/ than for /ɾ/ which is in support of the trill being more compatible with /a/ than with /i/.

3.2. *Coarticulatory direction*

3.2.1. *C-to-V effects*

Fig. 7 presents data on the magnitude and temporal extent of anticipatory and carry-over effects exerted by /ɾ/ and /r/ on both adjacent vowels and allows us to observe trends in C-to-V coarticulatory direction. Numerical values and the positive or negative sign of the magnitude (size) effects are reported in Appendix B; negative values in the table were converted to positive values in the figure since the goal was to compare the degree of coarticulation across the two coarticulatory directions.

C-to-V effects for the tap tend to favor the carry-over direction in the context of /i/ and the anticipatory direction in the context of /a/ (black bars often exceed grey bars in the /i/ vowel context condition while the reverse pattern holds in the /a/ condition). These differences in coarticulatory direction were found to be significant for the F2 temporal effects in the case of /i/ and for the Q_{pal} size effects in the case of /a/ [$F(1,4) = 10.65$, $p < 0.031$; $F(1,4) = 12.27$, $p < 0.025$]. Turning to C-to-V coarticulation for the trill, Q_{pal} gives preference to anticipation and F2 favors carry-over independently of the contextual vowel; direction differences were found to be significant for Q_{pal} size in the context of /i/ and /a/ [$F(1,4) = 9.75$, $p < 0.035$; $F(1,4) = 17.53$, $p < 0.014$], and for F2 in the context of /a/ both in size and in temporal extent [$F(1,4) = 8.49$, $p < 0.043$; $F(1,4) = 9.85$, $p < 0.035$].

A comparison between C-to-V effects for the tap and those for the trill reveals the following scenario. Effects of size and temporal extent are more prominent for the trill than for the tap in the /i/ condition; indeed, grey and black bars are consistently higher

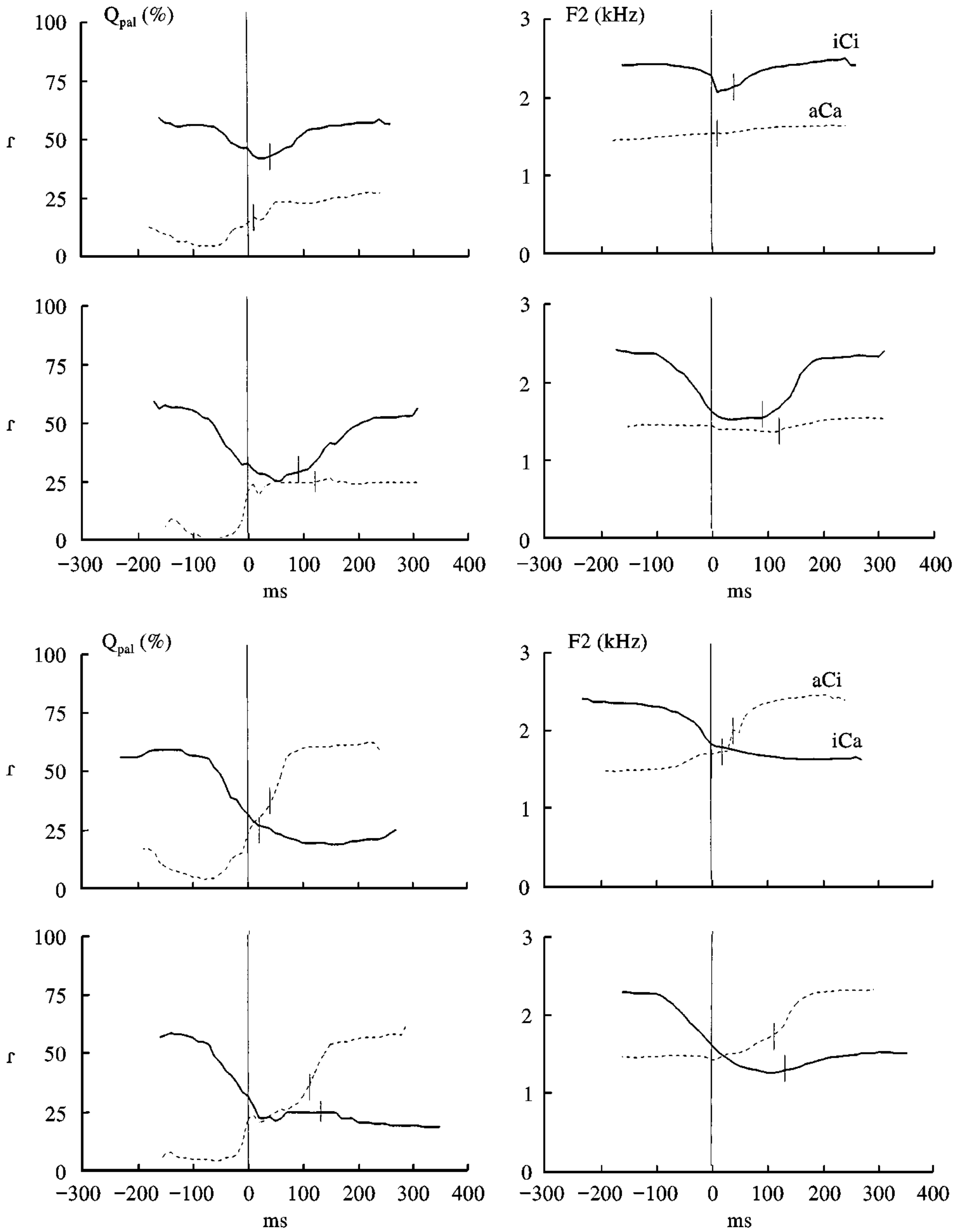

Figure 6. Q_{pal} trajectories (left) and F2 trajectories (right) for symmetrical (above) and asymmetrical (below) VCV sequences with a tap and a trill. Trajectories for /iCi/ and /iCa/ (continuous lines) and for /aCi/ and /aCa/ (dashed lines) have been lined up at the onset of the consonantal period (0 ms value along the temporal axis). Short vertical marks crossing the Q_{pal} and F2 trajectories have been inserted at the start of the consonant interval. Data correspond to a single speaker (DR).

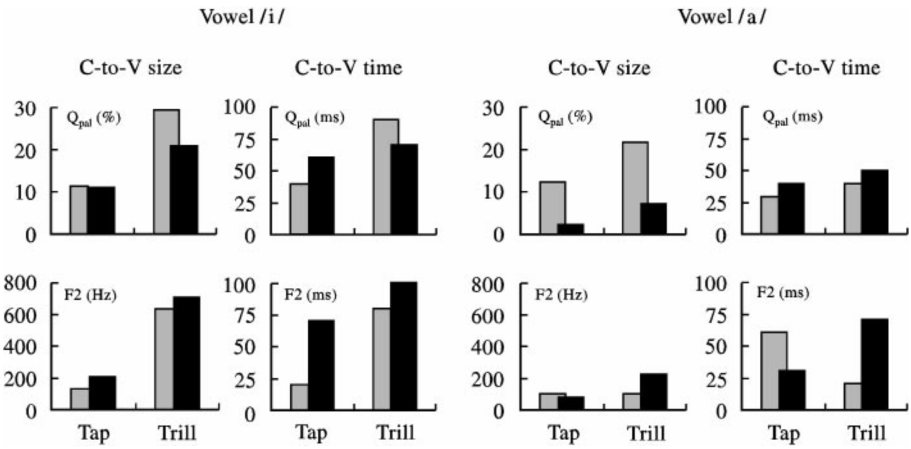

Figure 7. Cross-speaker C-to-V effects in size and temporal extent for the tap and for the trill in the /i/ (left) and /a/ (right) context conditions. Data have been plotted separately for Q_{pal} (above) and F2 (below), and for the anticipatory direction (grey bars) and the carry-over direction (black bars).

for /r/ than for /ɾ/ in this vowel context. There were significant anticipatory consonant dependent differences for Q_{pal} size and temporal extent [$F(1,4) = 21.08$, $p < 0.010$; $F(1,4) = 11.45$, $p < 0.028$] as well as for F2 size and temporal extent [$F(1,4) = 82.36$, $p < 0.001$; $F(1,4) = 27.69$, $p < 0.006$]. There were significant carryover differences for Q_{pal} size and temporal extent [$F(1,4) = 21.71$, $p < 0.010$; $F(1,4) = 54.97$, $p < 0.002$] but not so for F2. It thus appears that, while both consonants exert some tongue dorsum lowering and retraction on /i/ (size effects from /r/ and /ɾ/ on /i/ are always negative; see Appendix B), this becomes more so in respect of anticipatory effects for /r/. C-to-V effects on /a/ are also often more prominent for the trill than for the tap but only reach statistical significance in anticipatory Q_{pal} size [$F(1,4) = 14.34$, $p < 0.019$] and in carry-over effects on F2 temporal extent [$F(1,4) = 12.25$, $p < 0.025$].

3.2.2. *V-to-C coarticulation*

Coarticulatory direction for the vocalic effects during the consonantal period are shown in Fig. 8 which shows anticipatory and carry-over V-to-C size effects for the tap and at P1, P2 and P3 for the trill in both fixed vowel conditions (numerical values are presented in Appendix C).

Vocalic effects on the tap were found to be significant in most cases. Q_{pal} showed significant anticipatory and carry-over effects in the context of /i/ [$F(1,4) = 23.9$, $p < 0.008$; $F(1,4) = 65.45$, $p < 0.001$] and only significant carry-over effects in the context of /a/ [$F(1,4) = 94.32$, $p < 0.001$]. On the other hand, F2 showed significant anticipatory and carry-over effects in the context of /i/ [$F(1,4) = 55.7$, $p < 0.002$; $F(1,4) = 467.38$, $p < 0.000$] and in the context of /a/ [$F(1,4) = 91.21$, $p < 0.001$; $F = 110.54$, $p < 0.000$]. Moreover, there was a clear trend for carry-over effects (back bars) to exceed anticipatory effects (grey bars) which happened to be significant in the case of F2 in both vowel contexts [$F(1,4) = 18.7$, $p < 0.012$] but not so in the case of Q_{pal}.

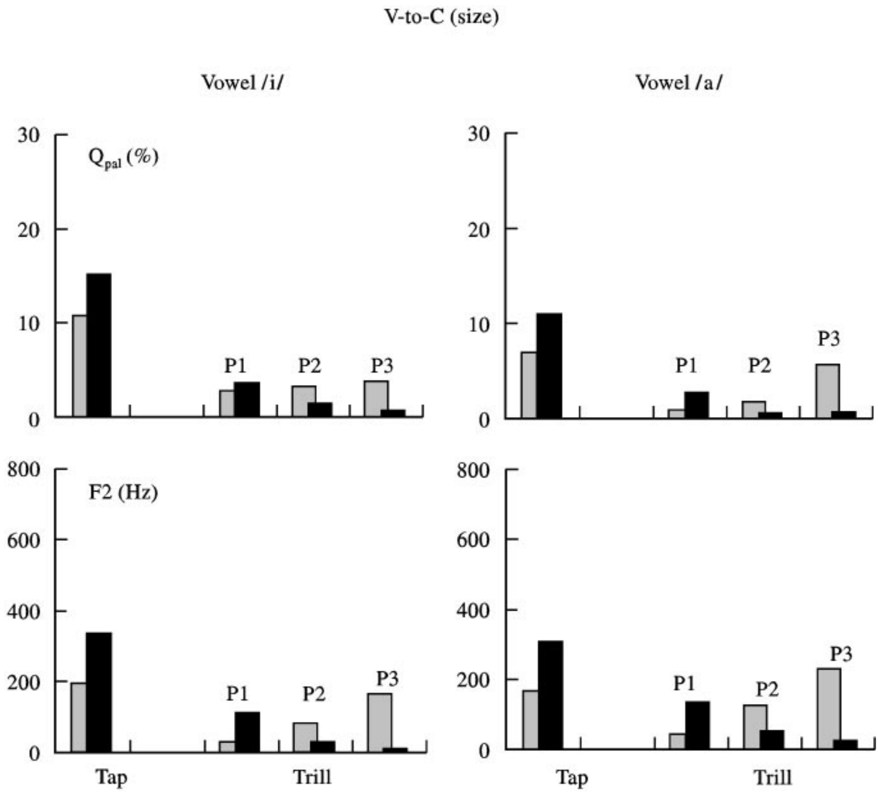

Figure 8. Cross-speaker V-to-C size effects at consonantal midpoint for /ɾ/ and at P1, P2 and P3 for /r/ in the /i/ and /a/ context conditions. Data have been plotted separately for Q_{pal} (above) and F2 (below), and for the anticipatory direction (grey bars) and the carry-over direction (black bars).

Anticipatory and carry-over vocalic effects during the trill were more often significant in the context of /i/ than in the context of /a/. In the former vowel context, vocalic carry-over effects reached significance at P1 for Q_{pal} and F2 [$F(1,4) = 9.62$, $p < 0.036$; $F(1,4) = 184.41$, $p < 0.000$] and significant vocalic anticipatory effects occurred at P2 and at P3 also for Q_{pal} [$F(1,4) = 10.34$, $p < 0.032$; $F(1,4) = 9.17$, $p < 0.039$] and for F2 [$F(1,4) = 13.31$, $p < 0.022$; $F(1,4) = 22.95$, $p < 0.009$]. The same trend was found to hold in the context of /a/ for F2 only, i.e., significance was reached by vocalic carry-over effects at P1 [$F(1,4) = 23.30$, $p < 0.008$] and by vocalic anticipatory effects at P2 [$F(1,4) = 17.56$, $p < 0.014$] and at P3 [$F(1,4) = 14.23$, $p < 0.020$]. Differences between V-to-C anticipation and carry-over were found to be most robust for F2 both at P1, where vocalic carry-over effects exceeded significantly vocalic anticipatory effects in the context of /i/ and /a/ [$F(1,4) = 20.77$, $p < 0.010$; $F(1,4) = 16.15$, $p < 0.016$], and at P3, where vocalic anticipatory effects turned out to be significantly larger than vocalic carry-over effects in both vowel context conditions [$F(1,4) = 17.43$, $p < 0.014$; $F(1,4) = 14.93$, $p < 0.018$]. In summary, judging from the coarticulatory situation at P2 (i.e., at trill midpoint), there appears to be a trend to favor vocalic anticipation throughout /r/; as expected, P1 is mostly sensitive to V1-dependent carry-over coarticulation and P3 and V2-dependent anticipatory effects.

3.2.3. *V-to-V coarticulation*

V-to-V coarticulation values across the tap and the trill are reported in Appendix D. Overall, the size and temporal V-to-V effects are larger and longer for the tap than for the trill in both fixed vowel contexts with only one exception, i.e., short V-to-V temporal effects in Q_{pal} happen to be quite similar across the two consonants.

Coarticulatory effects across the tap show no preference for either direction in the /i/ context condition (except for the F2 temporal effects which show a non-significant tendency towards favoring carry-over coarticulation). On the other hand, carry-over effects across /ɾ/ in the fixed /a/ condition were found to be more prominent than anticipatory effects, and reached significance in F2 size [$F(1,4) = 25.83$, $p < 0.007$]. The trill shows some more evidence of V-to-V anticipation over V-to-V carry-over in most cases, whether in the context of /i/ or in the context of /a/, though these differences turned out to be non-significant.

4. Discussion and Conclusions

The data reported above, in conjunction with previous findings for other alveolar consonants (Recasens, Fontdevila & Pallarès, 1992, 1995; Recasens, Farnetani, Fontdevila & Pallarès, 1993), give a clear account of the lingual gestures for /r/ and /ɾ/, and of the way in which these consonants coarticulate with adjacent vowels. The data also shed light on the phonological status of the rhotic consonants.

4.1. *Production characteristics*

The tap is articulated with a restricted short apicoalveolar closure and more predorsum lowering than other alveolars. In comparison with /n/, /ɾ/ involves less apico-predorsal coupling and exhibits larger dorsopalatal and F2 troughs in the sequence /iCi/.

The execution of several successive alveolar contacts leads to the trill being produced with a more retracted apicoalveolar closure than the tap, as well as with more tongue predorsum lowering, particularly in the context of /i/ and with more jaw opening, particularly in the context of /a/. VCV articulatory and acoustic trajectories also indicate that, in comparison with the tap, the articulatory configuration for /r/ is more antagonistic to that for a high front vowel and more compatible with that for a low vowel. Evidence has been provided of little variation in alveolar closure fronting as a function of vowel-dependent changes in tongue dorsum raising which suggests that /r/ involves a high degree of tongue body constraint. This is supported by the achievement of an invariant articulatory target during the consonantal period in all VCV sequences. Differences between /r/ and dark /l/ (which also involves active tongue body lowering and backing) should be pointed out: the alveolar closure is more retracted for the trill than for dark /l/ and little vocalic coarticulation occurs in either case. Furthermore in comparison with /r/, dark /l/ exhibits less dorsal contact at the sides of the palatal zone and a lower F2 presumably since it is produced with more tongue dorsum lowering when adjacent to both /i/ and /a/.

4.2. *General coarticulatory trends*

Differences in articulatory constraint between /ɾ/ and /r/ account for patterns of coarticulatory sensitivity and coarticulatory dominance. The tap has been found to allow some vowel-dependent effects in alveolar closure fronting and substantial vocalic coarticulation all over the palatal zone, meaning that the tongue dorsum is relatively free to adapt to the adjacent phonetic segments. The trill however shows a more fixed apico-alveolar closure and is less sensitive to tongue predorsum variations both at onset and offset (/i/ causes an increase in dorsal contact at the mediopostpalate but not so at the prepalate). F1 coarticulation data suggest that the trill is more sensitive than the tap to vowel-dependent changes in oral opening degree.

The lingual gesture for /r/ is highly constrained and antagonistic with respect to that for /i/. Thus, in comparison with /ɾ/, the trill is more resistant to effects from /i/ and exerts more prominent C-to-V effects on this vowel (mostly in an anticipatory direction). On the other hand, C-to-V effects on /a/ are similar for both consonants though still somewhat more prominent for /r/ than for /ɾ/. The coarticulatory scenario for /iri/ is comparable to that for /ili/ (with dark /l/) and is in support of the notion that C-to-V effects prevail over V-to-C effects when the vowel and the consonant are produced with highly constrained and antagonistic lingual gestures; it is as if the speaker had to make sure that the consonantal closure or constriction is achieved satisfactorily in these circumstances. Though /r/ is articulated with less tongue dorsum lowering than dark /l/, the trill exerts more prominent effects on /i/ than the alveolar lateral (i.e., longer C-to-V effects in Q_{pal} and F2) which may be related to manner requirements on trilling performance. Moreover, in comparison with dark /l/, anticipatory C-to-V effects in F2 from /r/ on /a/ are shorter and smaller, but carry-over effects are longer and slightly larger.

4.3. *Direction of coarticulation*

As pointed out in the Introduction, the DAC model defines the relationship between the direction of vocalic coarticulation and that of consonantal coarticulation. Interactions between both coarticulation types reported in the present paper are essentially in agreement with predictions from the DAC model and with the findings of previous studies.

Data for the tap will be summarized first. In the fixed /i/ context condition, consonantal and vocalic coarticulation were found to favor carry-over effects (in the sequence pair /iɾi/–/aɾi/) over the anticipatory effects (/iɾi/–/iɾa/) which is analogous to the situation for /n/ and accords with predictions from the DAC model. Indeed it has been argued in Section 1.2 that inertial constraints associated with vowel-related tongue dorsum raising during the consonant account for C-to-V effects on /i/ being mostly carry-over which contributes to blocking of the V2-dependent anticipatory effects. The scenario in the fixed /a/ context condition differs from that reported in VCV sequences with /n/ in previous studies. As with /n/, C-to-V effects from /ɾ/ on /a/ tend to be more salient at the anticipatory level (/aɾa/–/aɾi/) than at the carry-over level (/aɾa/–/iɾa/) in agreement with apical activity for alveolar consonants being anticipated freely during a preceding low vowel. However, the C-to-V anticipatory component appears to be stronger for the alveolar nasal than for the alveolar tap (perhaps since apical raising proceeds more slowly for /n/ than for /ɾ/) which may account for why there is more vocalic anticipation than vocalic carry-over in VCV sequences with /n/, while vocalic carry-over effects are more prominent than vocalic anticipatory effects in VCV sequences with /ɾ/. This partial disagreement between the coarticulatory behavior for /ɾ/ and for /n/ in the context of /a/ suggests that information about speed of gestural movements may have to be incorporated into the DAC model. Indeed, differences in velocity of articulatory displacement may explain why apico-laminal consonants favoring C-to-V anticipation may allow more vocalic anticipation (as in /n/) or else more vocalic carry-over (as in /ɾ/).

Analogous to dark /l/, the trill gives more weight to C-to-V anticipation over C-to-V carry-over in the /i/ context condition (clearly so for Q_{pal}) since the lingual gesture for /r/ is initiated quite early in this antagonistic vowel environment. As for vocalic coarticulation, anticipatory effects have been found to prevail over carry-over effects at P2 or trill midpoint which is analogous to the scenario for dark /l/ and should be attributed to consonantal anticipation blocking, to a large extent, the vocalic carry-over effects associated with V1. In the /a/ context condition, while C-to-V effects for /r/ do not give priority to any coarticulatory direction (Q_{pal} size effects favor anticipation over carry-over while F2 temporal effects favor the opposite pattern), there is again a trend for anticipatory vocalic coarticulation to be more prominent than carry-over effects at trill midpoint (P2); this picture is analogous to that for dark /l/ which favors the anticipatory direction both for the consonantal effects and for the vocalic effects. This scenario for the trill is in accordance with predictions from the DAC model in conforming to the principle that consonantal gestures requiring much anticipation (such as those for dark /l/) allow more vocalic anticipation than vocalic carry-over.

Trends summarized in Sections 4.2 and 4.3 suggest that systematicities in V-to-C and V-to-V coarticulatory behavior may be related to a large extent to the temporal activation and the biomechanical properties of the lingual articulators for the performance of specific consonantal gestures. The principle that the V-to-V mode of coarticulation is much dependent on the C-to-V mode has been shown to account for patterns of coarticulatory sensitivity and coarticulatory dominance as well as for patterns of coarticulatory direction.

4.4. *Phonological status*

It was proposed in the Introduction that /ɾ/ and /r/ ought to exhibit similar production mechanisms and similar patterns of coarticulatory direction if the trill is to be considered a geminate version of the tap. Data reported in this paper suggest that the two consonants are articulated with different lingual gestures (see Section 4.1), i.e., /r/ involves more apical retraction and more predorsum lowering than /ɾ/. General coarticulation effects appear to be in support of this notion: the lingual gesture for the trill is highly resistant to effects from /i/ and exerts maximal coarticulation on this vowel while C-to-V effects for the tap are especially salient in vowel contexts facilitating apical raising (i.e., /a/). Moreover, patterns in coarticulatory direction in VCV sequences summarized in Section 4.3 are also consonant-dependent and thus more in line with the two-gestural account: VCV sequences with the trill favor anticipatory *vs.* carry-over direction both for the C-to-V effects and for the vocalic effects; on the other hand, the tap gives priority to the carry-over direction for C-to-V effects on /i/ and for all vocalic effects, and to the anticipatory direction for C-to-V effects on /a/.

While many phonological systems could advocate treating /r/ as the geminate correlate of /ɾ/, we feel that the distributional evidence supporting such analysis is weak. Thus, it is not clear how this solution could account for why a trill cannot be split by a syllable boundary (see Section 1.3). This weakness coupled with evidence of qualitative distinct gestural properties suggests that trills are probably not geminate taps at any level of phonological representation.

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Appendix A

Mean contact index values and formant frequency values (in Hz) for the tap and the trill in the four VCV sequences under analysis. Data have been measured at the midpoint of the consonant interval for the tap, and at the first and last closure periods (P1, P3) and at the consonantal midpoint (P2) for the trill. Standard error values (S.E.) are also given

		Tap				Trill											
						P1				P2				P3			
		iCi	iCa	aCi	aCa	iCi	iCa	aCi	aCa	iCi	iCa	aCi	aCa	iCi	iCa	aCi	aCa
Ca_{alv}	$\bar{X}$	0.63	0.34	0.46	0.36	0.26	0.37	0.26	0.24					0.17	0.15	0.33	0.20
	S.E.	*0.10*	*0.08*	*0.13*	*0.12*	*0.10*	*0.09*	*0.06*	*0.05*					*0.04*	*0.05*	*0.05*	*0.04*
CP_{alv}	$\bar{X}$	0.82	0.70	0.91	0.81	0.83	0.84	0.87	0.86					0.70	0.70	0.86	0.78
	S.E.	*0.03*	*0.07*	*0.02*	*0.08*	*0.01*	*0.02*	*0.04*	*0.05*					*0.14*	*0.14*	*0.01*	*0.09*
CC_{alv}	$\bar{X}$	0.73	0.46	0.86	0.70	0.52	0.58	0.66	0.71					0.28	0.22	0.47	0.36
	S.E.	*0.05*	*0.07*	*0.01*	*0.08*	*0.13*	*0.13*	*0.05*	*0.04*					*0.04*	*0.08*	*0.06*	*0.04*
CA_{pal}	$\bar{X}$	0.84	0.80	0.80	0.72	0.80	0.78	0.80	0.78	0.79	0.77	0.80	0.80	0.80	0.80	0.80	0.80
	S.E.	*0.02*	*0.01*	*0.00*	*0.04*	*0.02*	*0.01*	*0.02*	*0.02*	*0.02*	*0.02*	*0.01*	*0.01*	*0.01*	*0.02*	*0.01*	*0.00*
CP_{pal}	$\bar{X}$	0.88	0.84	0.82	0.79	0.85	0.82	0.80	0.79	0.85	0.81	0.82	0.81	0.87	0.82	0.86	0.81
	S.E.	*0.02*	*0.02*	*0.03*	*0.01*	*0.01*	*0.03*	*0.00*	*0.01*	*0.01*	*0.00*	*0.01*	*0.01*	*0.01*	*0.01*	*0.02*	*0.02*
CC_{pal}	$\bar{X}$	0.35	0.23	0.18	0.11	0.19	0.17	0.13	0.12	0.18	0.14	0.15	0.12	0.20	0.15	0.22	0.14
	S.E.	*0.03*	*0.03*	*0.03*	*0.02*	*0.02*	*0.02*	*0.01*	*0.01*	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*	*0.04*	*0.03*
Q_{pal}	$\bar{X}$	41.8	33.0	26.8	23.9	29.0	27.1	25.5	24.7	28.8	25.6	27.8	25.9	30.8	26.9	32.8	26.9
	S.E.	*0.61*	*2.02*	*1.6*	*1.9*	*1.1*	*1.2*	*0.87*	*0.68*	*1.62*	*1.1*	*1.4*	*0.8*	*1.9*	*1.1*	*3.1*	*1.5*
F2	$\bar{X}$	2024	1833	1693	1527	1440	1421	1330	1286	1375	1293	1375	1250	1405	1243	1474	1245
	S.E.	*37.1*	*46.0*	*23.7*	*31.4*	*82.6*	*98.1*	*76.5*	*77.2*	*87.4*	*83.6*	*97.7*	*85.0*	*88.1*	*87.2*	*104.7*	*86.6*
F1	$\bar{X}$	340	376	436	516	370	394	555	606	379	394	489	551	380	407	412	519
	S.E.	*8.21*	*15.3*	*44.7*	*50.3*	*13.3*	*16.6*	*48.3*	*46.6*	*4.8*	*13.1*	*37.2*	*37.9*	*13.1*	*18.0*	*15.2*	*35.1*
F3	$\bar{X}$	2679	2629	2523	2410	2383	2437	2394	2389	2374	2369	2385	2324	2355	2279	2405	2278
	S.E.	*31.2*	*10.2*	*47.8*	*139.4*	*133.2*	*90.1*	*69.5*	*83.6*	*150.5*	*102.2*	*37.1*	*61.8*	*142.8*	*88.8*	*39.2*	*71.8*

Appendix B

C-to-V effects in size (in % of electrode activation and in Hz) and in temporal extent (in ms) for the tap and the trill in the /i/ and /a/ context conditions across speakers. Data correspond to Q_{pal} and F2, and to the anticipatory and carry-over directions. Standard error values are also given

			Size				Time			
			Anticipatory		Carry-over		Anticipatory		Carry-over	
			Tap	Trill	Tap	Trill	Tap	Trill	Tap	Trill
i	Q_{pal}	$\bar{X}$	− 11.4	− 29.4	− 11.3	− 20.8	40	90	60	70
		S.E.	*2.07*	*3.06*	*1.97*	*2.65*	*6.78*	*8.12*	*13.04*	*17.15*
	F2	$\bar{X}$	− 130	− 634	− 209	− 710	20	80	70	100
		S.E.	*26.73*	*73.73*	*45.25*	*49.88*	*2.45*	*13.27*	*17.44*	*13.27*
a	Q_{pal}	$\bar{X}$	12.4	21.5	2.3	7.3	30	40	40	50
		S.E.	*1.14*	*2.24*	*2.95*	*2.48*	*5.10*	*7.35*	*6.78*	*22.27*
	F2	$\bar{X}$	104	− 103	− 83	− 229	60	20	30	70
		S.E.	*43.40*	*46.23*	*25.35*	*72.52*	*16.85*	*6.78*	*15.30*	*19.49*

Appendix C

V-to-C size effects (in % of electrode activation and in Hz) for the tap and the trill in the /i/ and /a/ context conditions across speakers. Data correspond to Q_{pal} and F2, and to the anticipatory and carry-over directions. Standard error values are also given. Asterisks indicate significant effects

					Trill					
			Tap		P1		P2		P3	
			Ant	Carr	Ant	Carr	Ant	Carr	Ant	Carr
i	Q_{pal}	$\bar{X}$	10.6*	15.0*	2.8	3.5*	3.2*	1.4	3.8*	0.6
		S.E.	*2.23*	*1.93*	*1.27*	*1.13*	*0.99*	*0.61*	*1.27*	*0.63*
	F2	$\bar{X}$	191*	331*	26	110*	82*	24	162*	6
		S.E.	*25.58*	*15.33*	*13.57*	*8.11*	*22.48*	*14.91*	*33.82*	*6.40*
a	Q_{pal}	$\bar{X}$	7.0	10.9*	0.9	2.8	1.8	0.6	5.8	0.8
		S.E.	*2.66*	*2.04*	*0.56*	*1.64*	*0.88*	*0.48*	*2.94*	*0.61*
	F2	$\bar{X}$	166*	306*	44	135*	125*	53	229*	24
		S.E.	*17.38*	*29.14*	*18.64*	*27.91*	*29.93*	*26.01*	*60.74*	*19.84*

Appendix D

V-to-V effects in size (in % of electrode activation and in Hz) and in temporal extent (in ms) for the tap and the trill in the /i/ and /a/ context conditions across speakers. Data correspond to Q_{pal} and F2, and to the anticipatory and carry-over directions. Standard error values are also given

			Size				Time			
			Anticipatory		Carry-over		Anticipatory		Carry-over	
			Tap	Trill	Tap	Trill	Tap	Trill	Tap	Trill
i	Q_{pal}	$\bar{X}$	8.5	3.2	8.4	0.4	10	20	10	20
		S.E.	*2.41*	*1.85*	*1.71*	*0.38*	*7.75*	*22.00*	*5.83*	*16.00*
	F2	$\bar{X}$	148	42	138	1	30	20	50	0
		S.E.	*78.95*	*34.09*	*34.05*	*0.80*	*26.76*	*16.00*	*30.72*	*0.00*
a	Q_{pal}	$\bar{X}$	5.1	2.7	8.0	0.9	10	20	20	0
		S.E.	*1.86*	*1.38*	*2.07*	*0.73*	*7.48*	*22.00*	*10.68*	*0.00*
	F2	$\bar{X}$	150	26	261	14	80	0	100	0
		S.E.	*12.50*	*14.18*	*18.19*	*7.34*	*12.88*	*0.00*	*11.22*	*2.00*