The Spatiotemporal Effects of Speaking Rate on Gestural Coordination: an EPG study

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Abstract

Articulatory properties of the palatal(ized) consonants are investigated, using electropalatography, under changes in speaking rate. The results reveal that, while variations in speaking rate have different effects on the spatiotemporal properties, the timing patterns vary systematically with the phonological status of the consonants. This illustrates a phonological signature of the articulatory movements in the vocal tract.

1. Introduction

This study investigates the spatiotemporal properties of palatal and palatalized consonants in Japanese and explores the question of constancies in articulatory patterning as a function of speaking rate. Using electropalatography (EPG) the detailed analysis is conducted for [ɲ, ç, ɾ^j, k^j] in terms of intergestural coordination and timing between the primary articulatory gesture and the secondary dorsal gesture.

Previous studies have shown that palatal(ized) segments differ from language to language in the nature and extent of the involvement of the tongue dorsum raising gesture. In Japanese palatal(ized) consonants are allophonic in one context but are contrastive in another. They appear before the front vowel /i/ (called Ci syllables) and before non-front vowels /a, o, u/. The latter cases are phonologically contrastive, being analyzed as /Cj/ (called CjV syllables). When such a distribution is considered, it is reasonable to hypothesize that the dorsum raising gesture may roughly be categorized into two groups: [i]-like and [j]-like gestures.

Support for this hypothesis comes from Recasens (1984). In Catalan the dorsum raising gesture for the sequence [nj] is, surprisingly, smaller in degree and shorter in duration than that for [ɲ] or the sequence [ni]. This can be explained by the fact that the consonant [ɲ] has a phonemic status in the language. The data in Recasens (1984) reveals that, while the EPG patterns are almost identical, a three-way distinction is made in terms of the magnitude and timing of the dorsum raising gesture.

The current study extends the above approach to articulatory timing by examining consonantal articulations which differ in places and manners of articulation and in phonological status. Our hypothesis above, if supported, makes it more obvious that the time element must be treated explicitly at the phonological level. Furthermore, a language-specific part of phonetic knowledge will be sought in the stability of intergestural coordination and timing.

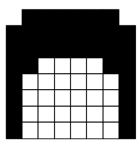
Another important factor in testing the language-specific timing constraints is the effect of changes in speaking rate. Since an increase in rate has been shown to affect the spatiotemporal properties of lingual gestures quantitatively, and palatal consonants involve articulatory antagonism, yielding a substantial degree of coarticulatory resistance, we can ask whether and how the differential patterns are achieved.

The purpose of the present experiment is twofold: (i) to determine whether the palatal(ized) consonants in the distinctive syllable types are characterized by different articulatory patterns and (ii) to examine how the phonological contrast and speech-rate contrast are related.

2. Experimental methodology

The speech items consisted of /a/CV2 disyllabic words where the consonants were [ɲ, ç, ɾ^j, k^j] and the changing V2s were /i, a, u/. All the target words were embedded in a carrier sentence /moo [word] bakarida/. Two native speakers of standard Japanese (MN, TM) repeated each sentence six times at normal speed, with the default accent pattern (i.e. low-high pattern) on the target word. And one speaker (MN) produced the same sentences at self-selected fast speed. Five repetitions were used for the analysis.

The Reading EPG artificial palate had 62 electrodes arranged in eight horizontal rows. Three major regions were identified sagittally: front, central and back.



R1	dentalveolar	Front (R1-4)	26/30=87%
R2	alveolar		
R3-4	postalveolar		
R5	prepalatal	Central (R5-7)	6/24=25%
R6-7	mediopalatal		
R8	postpalatal	→ Back (R8)	2/8=25%

Figure 1: EPG prototypical palatograms and three regions

The general articulatory properties were studied at the point of maximum linguopalatal constriction (MAX), the EPG frame showing the maximum number of on-electrodes. The degree of coarticulatory activities were inferred from the measurements made separately for the three regions.

For the analysis of the temporal properties, the EPG-contact trajectories were computed from the raw EPG data corresponding to the three regions. Thus, we characterize intergestural coordination and timing in terms of the interaction between the two particular EPG-trajectories relevant for the target consonant. The four temporal indices proposed by Byrd (1994: 28-29) were used with some modifications.

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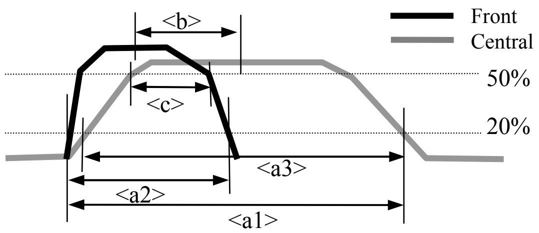

Figure 2: EPG-contact trajectories and four temporal indices

First, SEQUENCE DURATION <a1> is the total duration of linguopalatal contact for two regions. Secondly, REGION DURATION is the duration of a particular region, thus the intervals <a2> and <a3> are the duration of the front and central regions respectively. Both SEQUENCE and REGION durations are measured above the 20% cut-off point. Thirdly, PEAK INTERVAL <b> indicates the time between the peak contact in one region and that in the other. The peak point is calculated as the temporal center of the plateau of maximum contact. Finally, SEQUENCE OVERLAP <c> is the percentage of the total sequence duration during which contact occurred in both regions. A cut-off point was set at 50% of linguopalatal contact. This point was derived from visual inspection of the computation and demonstrated a near-maximum activation value in the central region during the target consonants.

The normal-rate productions were analyzed for the data given by the two speakers. The normal-fast comparison was made for the data collected from one speaker.

3. Results

3.1. Spatial characteristics

3.1.1. Tongue-palate contact pattern at MAX

EPG prototypical palatograms averaged over five repetitions are presented in Figure 3 below. There is no substantial divergence in the configuration of the tongue-palate contact for the target consonant across the vowel contexts. A large contact area over the surface of the palate is achieved by the extension of the side contact towards the mid-sagittal line: one exception is the palatalized tap [ɾʲ].

For the production of [ɲ], the posterior contact (rows 5-8) increases and the frontmost contact tends to be withdrawn. The closure is made by pressing the antero-dorsum of the tongue against postalveolar and palatal regions (rows 2-5), causing the tip to be directed downwards. These configurations characterize the consonant as an alveolopalatal nasal.

For the alveolopalatal fricative [ɕ], the maximum narrowing is formed at the rows 2 or 3-5. Notice here that, although both [ɲ̟] and [ɕ] are described with the same place label, the main constriction of the latter is formed slightly further back: we would identify [ɲ̟] as a palatalized alveolar and [ɕ] as an alveolarized palatal. For [ɕ] there are differences in the length of the constricted region between the speakers: the anterior end is row 3 for MN but is row 2 for TM. This idiosyncratic anterior realization must be related to the variability in the posterior end of the articulatory channel in TM: the narrowest region is regularly formed by pressing the blade at rows 2-3 and this is accompanied by the pre- (and presumably medio-) dorsum constriction (rows 4-5).

The palatalized tap [ɾʲ] is articulated with the tongue tip/blade against the alveolar region (rows 1 or 2-3). The palatalizing effects appear at the posterior region, the magnitude of which is less than for the other consonants. This characteristic is particularly attributed to the manner requirements. We shall return to this point later.

The palatalized velar [kʲ] shows another effect, namely fronting of the constriction place, where complete contact across the back of the palate (rows 7-8) is made and the side contacts extend further forward to the alveolar region (row 2). There are differences in the length of the complete occlusion: row 8 for MN and rows 7-8 for TM. This suggests that the constriction place is more fronted in the sense that the posterior part of the antero-dorsum, as well as the postero-dorsum, is pressed against the palate. Note in passing that the plain velar as in the /aka/ sequence in Japanese shows an incomplete occlusion at rows 7-8: the complete occlusion of the plain /k/ is formed further back in the soft palate.

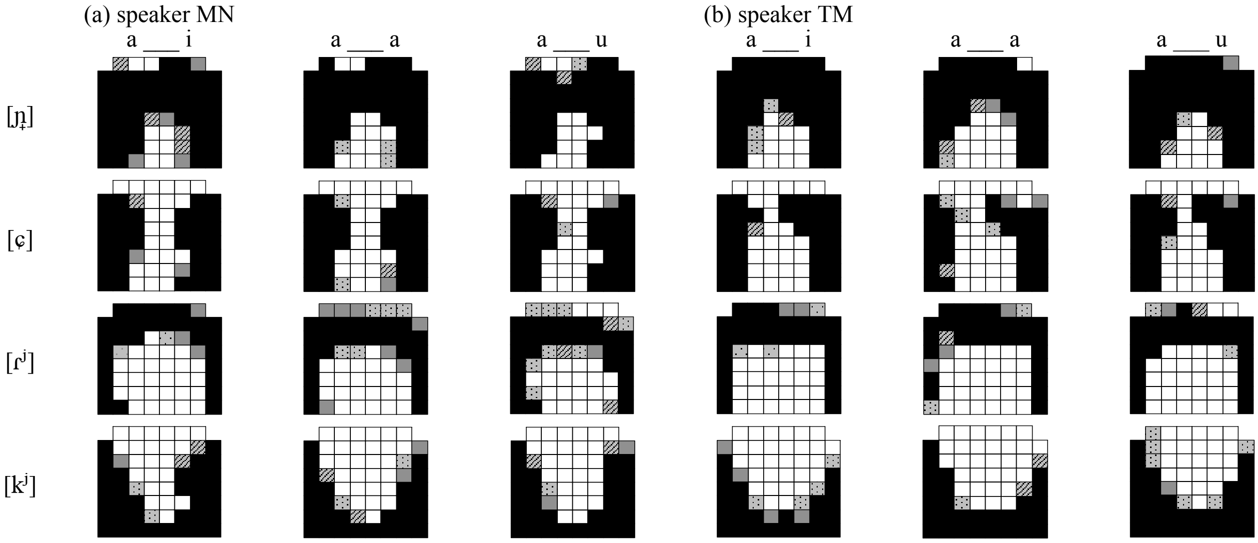

Figure 3: Linguopalatal configurations at the MAX point during the production of [ɲ̟, ɕ, ɾʲ, kʲ] at normal speaking rate
'black' 100-80%; 'grey' 79-60%; 'striped' 59-40%; 'dotted' 39-20%; 'white' 19-0%

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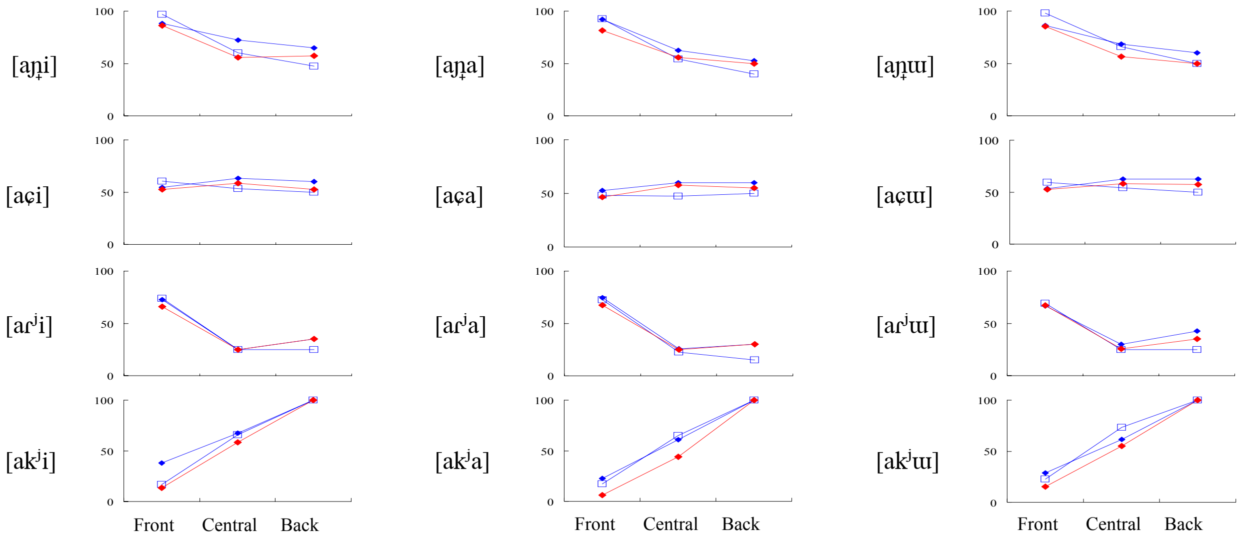

Figure 4: Mean percentage values of MAX contact in the three regions for [ɲ̟, ɕ, ɾʲ, kʲ] normal rate=■ (MN) and □ (TM); fast rate=■ (MN)

3.1.2. Coarticulation

Figure 4 above presents the mean percentage values of the MAX contact for [ɲ̟, ɕ, ɾʲ, kʲ] spoken at normal and fast rate. The values were calculated for the three regions separately and averaged over five repetitions. Figure 5 below shows the EPG contact patterns derived from the fast-rate productions. We shall develop our analysis with a particular emphasis on the tongue movement involved in the secondary palatal articulation, namely the contact pattern in the central region.

The analysis of the normal-rate tokens indicates that the amount of contact in the three regions varies significantly with the consonant type and that coarticulatory activities vary significantly with the two speakers. The results of a two-way (2 speakers×3V2s) ANOVA are summarized in Table 1.

Significant differences for the central region, in particular, are related to consonant-specific co-production strategies for the palatalizing gesture and to idiosyncrasies in the consonant production. For [ɲ̟] and [ɕ], the antero-dorsum actively participates in the constriction formation, while the length of the constricted region was typical of each speaker. The same is true for [kʲ], yet fronting of the constriction place levels out the tongue height specific to the following V2.

In contrast, the palatalized tap reveals the smallest percentage value in the central region: [kʲ] 64%>[ɲ̟] 62%>[ɕ] 56%>[ɾʲ] 25% in the pooled-speaker context. As seen in Table 1, the effects of the following V2s are found to be non-significant. This implies that the raising gesture of the dorsum is tightly constrained in order for the tip/blade to make a distinctive flicking/transient movement: a consonant that is highly resistant to coarticulatory effects is also a strong influencer to the surrounding segments (e.g. Recasens 1990).

The two syllable-types have non-significant effects on the degree of the central region contact. One-way ANOVA results are [$F(1,28)=1.25$, $p=0.27$] for [ɲ̟]; [$F(1,28)=0.89$, $p=0.35$] for [ɕ]; [$F(1,28)=0.35$, $p=0.55$] for [ɾʲ]; and [$F(1,28)=0.36$, $p=0.55$] for [kʲ]: the spatial manifestation of the palatal gesture in Ci and CjV syllables is largely similar to each other.

The normal-fast comparison in Table 2 below was made by performing a two-way (2 styles×3V2s) ANOVA.

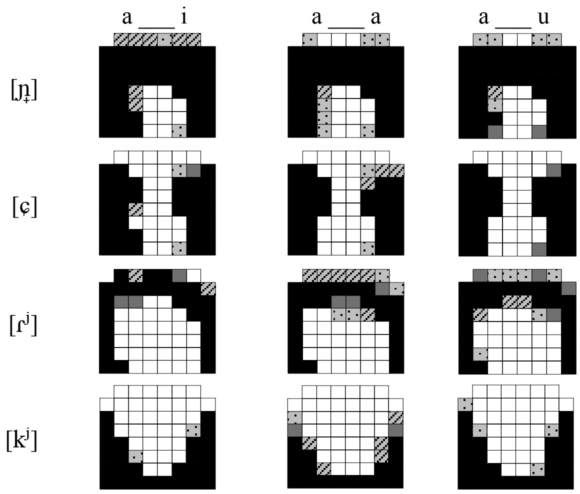

Figure 5: Linguopalatal configurations at the MAX point during the production of [ɲ̟, ɕ, ɾʲ, kʲ] at fast speaking rate

Table 1: Effects of two speakers and three changing V2s

			Front	Central	Back
[ɲ̟]	2 spkr	F(1,24)	19.88**	11.96**	34.13**
	3 V2s	F(2,24)	0.01	6.15**	7.60**
[ɕ]	2 spkr	F(1,24)	1.98	109.52**	37.55**
	3 V2s	F(2,24)	6.75**	9.68**	0.22
[ɾʲ]	2 spkr	F(1,24)	0.10	6.25*	38.53**
	3 V2s	F(2,24)	3.10	3.25	8.40**
[kʲ]	2 spkr	F(1,24)	27.91**	6.80*	n.s.
	3 V2s	F(2,24)	4.63*	2.42	n.s.

Table 2: Effects of two styles and three changing V2s

			Front	Central	Back
[ɲ̟]	Nor-fast	F(1,24)	2.84	23.52**	6.73*
	3 V2s	F(2,24)	0.09	1.49	5.15*
[ɕ]	Nor-fast	F(1,24)	5.28*	12.25**	5.76*
	3 V2s	F(2,24)	3.87*	1.31	0.82
[ɾʲ]	Nor-fast	F(1,24)	1.92	2.76	0.90
	3 V2s	F(2,24)	0.52	3.30	3.70*
[kʲ]	Nor-fast	F(1,24)	80.04**	39.50**	n.s.
	3 V2s	F(2,24)	10.75**	12.23**	n.s.

**=p<0.01; *=p<0.05; unmarked=non-significant

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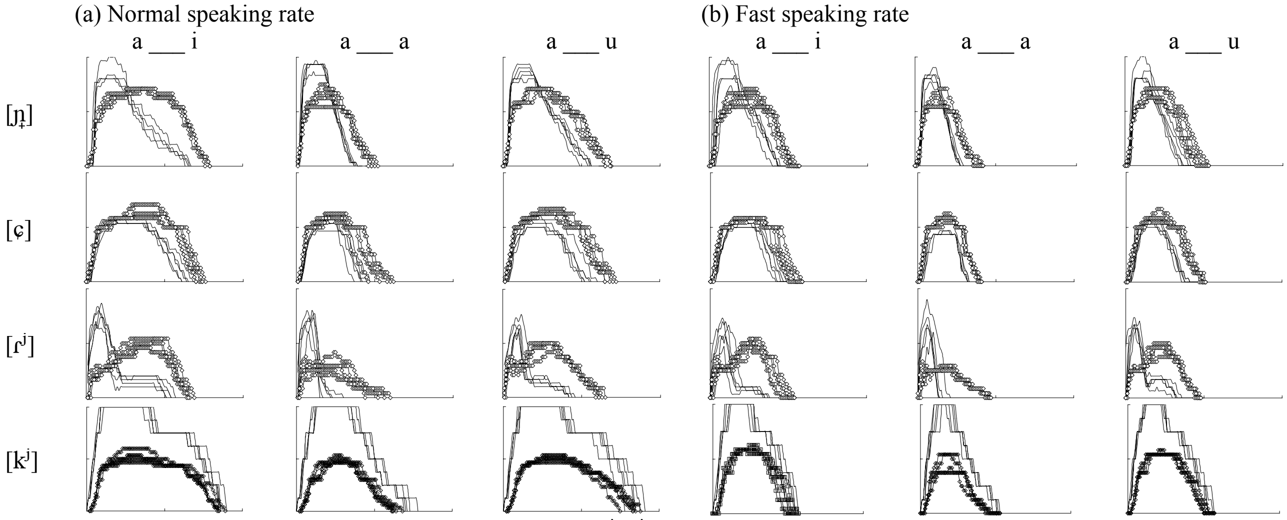

Figure 6: EPG-contact trajectories of the syllables with [ɲ̟, ɕ, ɾʲ, kʲ] (unblocked line=front (back for [k]); blocked line=central) X-axis=time in frames (0-100 frames); Y-axis=the percentage of contact (0-100%)

The general trend is that, as speaking rate increases, the amount of contact in the regions decreases, although the basic configuration specific to the given consonant is attained systematically. The significant effects in the central region suggest that the involvement or extension of the antero-dorsum is effectively reduced due to changes in speaking rate. One revealing exception, however, is [ɾʲ] which shows non-significant changes in the degree of the dorsum raising gesture: the tap is the most rate-resistant in the spatial domain. This unusual characteristic, together with the results of the normal-rate productions, implies that the dorsum raising gesture is highly antagonistic to a tapping gesture.

3.2. Temporal characteristics

Figure 6 above shows the trajectories for the target syllables spoken by one speaker (MN). Each panel contains five tokens: the EPG-contact trajectories of the front and central regions for [ɲ̟, ɕ, ɾʲ] and those of the central and back regions for [kʲ].

3.2.1. Sequence and region durations

Figure 7 below presents the mean values of region and sequence durations averaged over five repetitions. It is clear that the sequence duration (a1 and a2 in Figure 7) varies with the vowel contexts. One tendency common to both speakers is that the duration increases in the order of /a/</u/</i/. The two-way ANOVA results demonstrate significant differences for the consonant type, [$F(3,48)=226.88$, $p<0.01$] (MN) and [$F(3, 48)=216.33$, $p<0.01$] (TM); for the three flanking vowels, [$F(2,48)=247.76$, $p<0.01$] (MN) and [$F(3,48)=118.99$, $p<0.01$] (TM). Similar results are obtained for /i/ and /j/ in the /a, o, u/ symmetrical context (Nakamura 2001): the articulatory plateau of the vowel /i/ is longer and more stable than that of the approximant /j/. This characteristic can also be identified in the movement of the central trajectories in Figure 6.

The duration in the front (or back) and the central regions (b1-b2 and c1-c2 in Figure 7 respectively) is analyzed separately for the target consonants. The results of a one-way ANOVA are presented in Table 3 (next page).

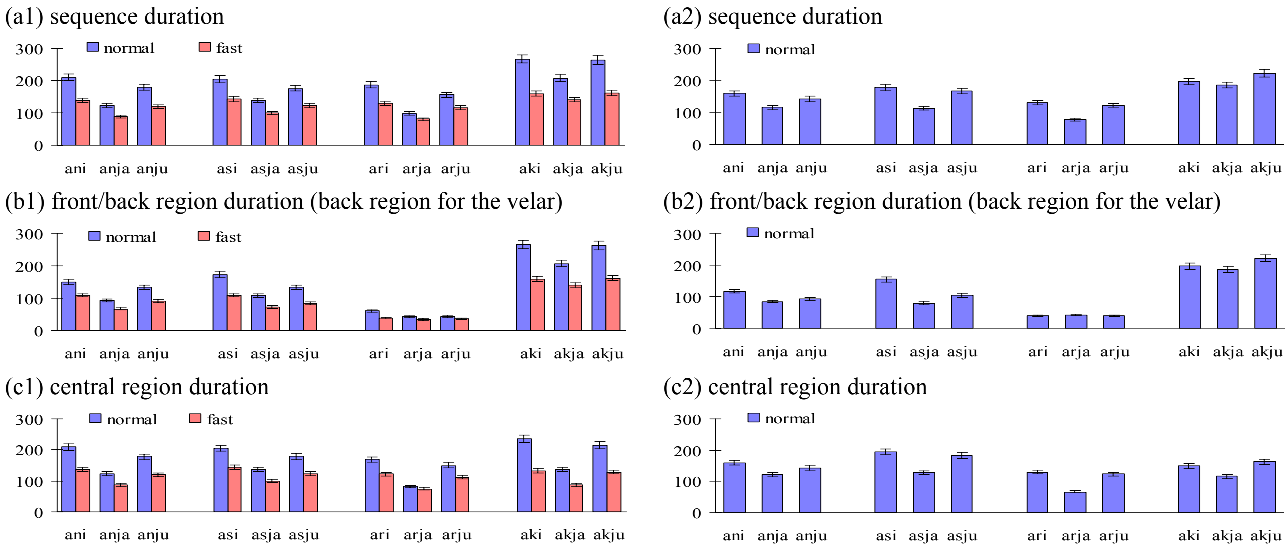

Figure 7: Mean values of sequence and region durations in millisecond
left three panels=MN; right three panels=TM; ‘n’ and ‘nj’=[ɲ̟]; ‘s’ and ‘sj’=[ɕ]; ‘r’ and ‘rj’=[ɾʲ]; and ‘k’ and ‘kj’=[kʲ]

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Table 3: Effects of three changing V2s on the front (or back) and central region duration (one-way ANOVA)

		(a) Front (or back) region duration				(b) Central region duration			
		ɲ̟	ɕ	ɾʲ	kʲ	ɲ̟	ɕ	ɾʲ	kʲ
MN	F(2,12)	56.45**	40.55**	10.04**	39.97**	182.24**	34.96**	39.57**	70.58**
	relation	i > u > a	i > u > a	i > u = a	i = u > a	i > u > a	i > u > a	i > a = u	i = u > a
TM	F(2,12)	16.71**	85.55**	0.36	8.68**	23.21**	122.57**	7.28**	4.21**
	relation	i > u = a	i > u > a	i = u = a	u > i = a	i > u > a	i > u > a	i = u > a	u = i > a

**=p<0.01; unmarked=non-significant. The relation between the particular pairs was assessed by the Scheffé post hoc analysis.

The general trend is that the anticipatory effects are significant for the differences in both the front (/back) and the central regions. For [ɲ̟, ɕ] the durational differences show a similar trend in both regions: /i/>/u/>/a/. This suggests that the alveolopalatals are sensitive to the height of the tongue dorsum for the following vowel. This is compatible with the spatial characteristics of the consonants.

The palatalized tap [ɾʲ] reveals remarkable characteristic: the following vowels cause little influence in the front region duration (except for MN's /i/). In contrast, the central region duration varies greatly across the vowel contexts and the speakers. Whereas the tip/blade activity is kept constant across the vowel contexts, the speakers may use different co-production strategies for the timing of the palatalizing gesture.

For the palatalized velar the raising gesture of the tongue dorsum is necessarily involved in the constriction formation. This clearly demonstrates the fact that the duration in the back region becomes shorter with the anticipation for the following low vowel, but is longer in the high vowel contexts.

Changes in speaking rate affected the region and sequence durations and they are consonant-specific. This is most clearly demonstrated by the analysis of the reduction ratios to the normal tokens. The mean values are given in Table 4 below.

Table 4: Mean reduction ratios of 3 duration categories (sd)

	ɲ̟	ɕ	ɾʲ	kʲ	relation
Front /back	0.70 (0.35)	0.64 (0.78)	0.79 (0.20)	0.63 (0.04)	ɾʲ > ɕ = ɲ̟ = kʲ
Cen-tral	0.67 (0.49)	0.70 (0.69)	0.80 (0.18)	0.59 (0.60)	ɾʲ = ɕ > ɲ̟ = kʲ
Seq.	0.69 (0.04)	0.67 (0.06)	0.80 (0.12)	0.61 (0.05)	ɾʲ > ɕ = ɲ̟ = kʲ

A two-way repeated-measures ANOVA for the region durations indicated a significant effect for the consonant type [F(3,112)=2.68, p<0.001] but not for the three duration categories [F(1,112)=3.29, p=0.79]. The Scheffé post hoc test indicated the hierarchical relation: [ɾʲ] was the most rate-resistant; the stronger resistance in the central region duration distinguished [ɾʲ, ɕ] on the one hand from [ɲ̟, kʲ] on the other. The syllable type turned out to be non-significant (one-way ANOVA [F(1,58)=2.82, p=0.09]): the mean reduction ratio of CV syllables was 0.65 and that of CjV syllables was 0.71.

3.2.2. Peak Interval

Analysis of the peak interval illustrates the timing of the palatal gesture with respect to the primary constriction. The average peak intervals for each consonant are given in Figure 8(a1-2). The results of a two-way (3V2s×2syllable-types) ANOVA, summarized in Table 5 (a), showed the significant main effects for all the consonants. There is a significant temporal lag between the peak of the tip/blade (or postero-dorsum) activity and that of the antero-dorsum activity in CV syllables, but this time interval is shortened in CjV syllables. The mean ratio of the CV-syllable interval to the CjV-syllable was 2.23 in the pooled-speaker-vowel context.

Such a lengthening or shortening of the peak interval is less clear in [ɾʲ]. In fact, the same pattern of peak interval observed for [ɾʲ] is essentially attained by the durational nature of the palatalizing gesture. As shown in Figure 6, the shorter peak interval is not comparable with the synchronization between the two components of the tongue: the tip/blade gesture strongly resists the palatalizing effects by the dorsum.

The difference in timing was consistently maintained in the fast-rate productions. Although the interval became shorter by about 40%, the significant main effects, similar to the normal-rate productions, were obtained (see Table 6 (a)). The mean CV/CjV ratio was 1.88 in the pooled-consonant context. These results suggest that the speakers make a meaningful distinction in timing control of the dorsum raising gesture.

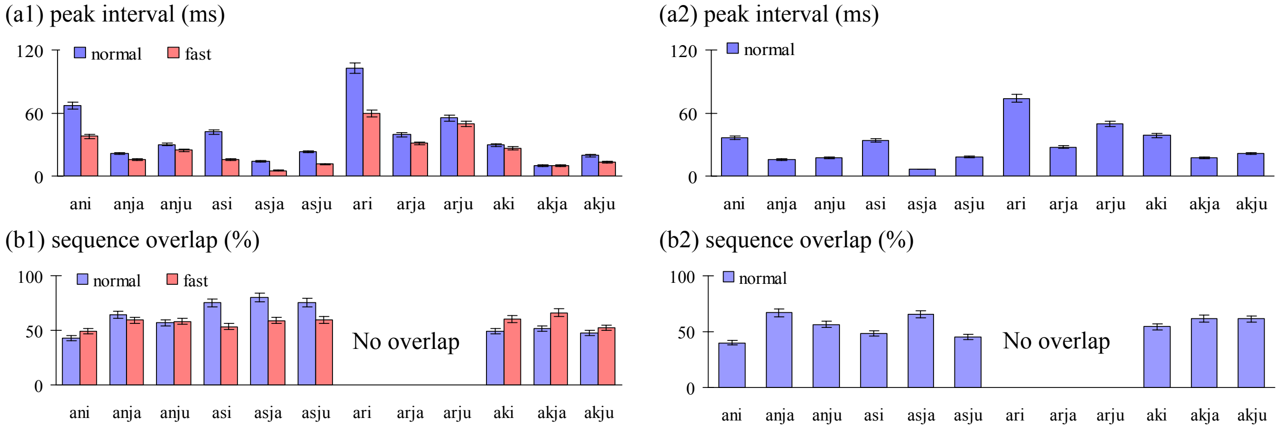

Figure 8: Mean values of peak interval and sequence overlap (left two panels=MN; right two panels=TM)

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Table 5: Effects of three changing V2s and syllable type on peak interval and sequence overlap (two-way ANOVA)

			(a) Peak interval				(b) Sequence overlap		
			ɲ	ç	ɾʲ	kʲ	ɲ	ç	kʲ
MN	3V2s	F(2,12)	119.87**	10.54**	49.77**	12.03**	37.03**	2.41	0.38
		relation	i > a = u	i > a = u	i > a = u	i = u >a	i < u < a	i = u = a	i = a = u
	Syllable type	F(1,12)	232.09**	19.00**	93.74**	18.25**	65.32**	0.25	0.97
TM	3V2s	F(2,12)	7.98**	12.74**	26.09**	52.19**	155.46**	9.60**	8.15**
		relation	i > a = u	i > a = u	i > u > a	i > a = u	i < u < a	i = u < a	i < a = u
	Syllable type	F(1,12)	15.89**	21.24**	40.60**	100.65**	265.65**	2.83	16.26**

**=p<0.01; unmarked=non-significant. The relation between the particular pairs was assessed by the Scheffé post hoc analysis.

Table 6: Effects of two styles, three changing V2s, and syllable type on peak interval and sequence overlap (three-way ANOVA)

		(a) Peak interval				(b) Sequence overlap		
		ɲ	ç	ɾʲ	kʲ	ɲ	ç	kʲ
Normal-fast	F(1,24)	57.57**	31.06**	38.37**	2.47	0.27	65.67**	35.51**
3V2s	F(2,24)	129.04**	15.81**	76.18**	2.47**	37.79**	1.56	7.18**
	relation	i > u >a	i > a = u	i > u >a	i > u >a	i < a = u	i = a = u	i = a > u
Syllable type	F(1,24)	242.39**	26.94**	131.32**	50.53**	70.61**	2.65	0.06

**=p<0.01; unmarked=non-significant. The relation between the particular pairs was assessed by the Scheffé post hoc analysis.

3.2.3. Sequence overlap

Sequence overlap specifies the degree of co-production in the front-central regions for [ɲ, ç, ɾʲ] and in the central-back regions for [kʲ]. The results of a two-way (3V2s×2 syllable-types) ANOVA are given in Table 5(b). The significant main effects were found for [ɲ]: the two regions were more blended in CjV syllables than in CV syllables. This pattern was not obtained for [ç]. This tendency comes from the strong coupling effect between the two components of the tongue. For [kʲ] the two speakers provide contrasting results, which are due to idiosyncratic co-production strategies: for MN the forward extension came before the complete closure, but the order was reversed for TM. The tap [ɾʲ] reveals an uncommon characteristic, no overlap. Rigid timing of the tip/blade gesture, as shown before, suppresses the overlap between the two gestures. Consequently, they are altered in timing and degree.

The analysis of the fast-rate productions in Table 6 (b) reveals that the sequence overlap of [ɲ,] is not affected by an increase in speaking rate and that the distinction between the syllable types is maintained. The significance of [ç] and [kʲ] is related to the considerable reduction in the front region contact for [ç] and in the central region contact for [kʲ] (see Figure 4). Because of this, the usual cut-off point was unworkable. To capture the activities in those regions, the cut-off point was adjusted at the near-maximum activation value, 40%. Thus, a possible interpretation would be that the two regions, similar to the results of the normal tokens, overlap completely, rather than blending more in fast-rate speech.

4. Discussion

The primary question we addressed in this paper was how the secondary dorsal articulation is spatiotemporally coordinated with the primary articulation during the production of [ɲ, ç, ɾʲ, kʲ]. The EPG experiment indicates that the spatial configurations, similar between the palatal(ized) consonants in CV and CjV syllables, are derived from the different temporal coordination between the two components of the tongue. Despite the consonant-specific implementation of the palatalizing gesture (blending for [ɲ, ç], fronting for [kʲ], and sequencing for [ɾʲ]), the temporal intervals are stable and closely linked to the syllable types. This stability of the different timings for the dorsum raising gesture is independent of large spatiotemporal variations under changes in speaking rate. In contrast, the spatial overlap turns out to be a weaker indicator and is not a necessary concomitant in manipulating the contrastive pattern of intergestural coordination. These articulatory and coarticulatory effects are explained by the temporal mechanism involved in the raising gesture of the tongue dorsum during the production of the palatal(ized) consonants. One important implication is that one aspect of language-specific timing constraints can be sought in the stability in relational aspects of articulatory coordination patterns: the contrastive timing of the dorsum raising gesture relative to the primary gesture functions as a language-specific timing constraint for the palatal(ized) consonant articulations in Ci and CjV syllables in Japanese.

5. Conclusions

Articulatory evidence for language-specific timing constraints has been presented for the palatal(ized) consonant articulations under changes in speaking rate. The findings suggest that the stability of the relative timing maintains phonological integrity and is one of the linguistic signatures of the articulatory movements in the vocal tract.

6. Acknowledgements

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