Journal of Phonetics (2001) **29**, 109–135
doi.10.006/jpho.2000.0114
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Articulatory properties of initial segments in several prosodic constituents in French

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Received 19th August 1999, and accepted 18th August 2000

This study reports on how what is usually called "segmental" articulation may be affected by prosodic structure. Articulatory properties of segments of various types are compared in initial position of four prosodic constituents in French: an Intonational Phrase, an Accentual Phrase, a Word and a Syllable. Modification of linguopalatal contact, nasal flow, acoustic measures of glottal articulation, as well as durational properties of segments are examined depending on these prosodic positions. Results show that the articulation of initial segments varies according to the prosodic level of the constituent. Initial segments in higher prosodic domains tend to have more linguopalatal contact, somewhat less nasal flow for nasals, and vowels tend to be more frequently glottalized than in initial position in lower domains. The magnitude and the realization of the articulatory modification observed in these positions is found to depend on speakers, articulators, and segment types. However, the regular trend observed suggests that these articulatory properties can reflect the prosodic encoding of constituents of various levels within utterances.

1. Introduction

As early as 1901, the Abbé Rousselot noted in his *Principes de phonétique expérimentale* that the nature of morpho-syntactic phrases and their boundaries influences a segment's articulation. He concluded that one must consider "les nombreuses variétés auxquelles une même consonne est soumise en raison de sa place dans le mot ou dans la phrase" (the many forms a consonant can have because of its position in a word or a sentence, p. 601).

Since then, several studies have shown that the production of a sound can be influenced by the structure in which it is placed. Sometimes known as "articulatory prosody", this area of inquiry is concerned with the relationship between the segmental and suprasegmental (or prosodic) aspects of speech, and more particularly with the influence of the latter on the former. Most of the prosodically-conditioned segmental variation that has been reported so far is concerned either with the difference between accented and unaccented positions, or with the distinction between initial and final

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position in a syllable or a word (see Fougeron, 1999, for a review). It is more recently that studies have looked at whether traces of the higher level hierarchical prosodic organization of an utterance can be found in the articulation of the segments it contains. The study presented here shares this objective. It aims at determining whether articulatory variation reflects the prosodic encoding of utterances into constituents (domains) of various levels in French.

French is considered to be a "boundary language" rather than a "stress language", following Vaissière's (1983, 1992) expression, since *most* of its prosodic cues are associated with constituent boundaries. As a consequence, one can expect that if there is articulatory variation associated with the marking of prosodic structure, this should occur at constituent boundaries in such a language. Two positions around a boundary can be explored: the preboundary position which corresponds to the final position in a constituent, and the postboundary position which corresponds to the initial position in a constituent. Preboundary, or domain-final, position has been shown in several studies and in many languages to be the site of realization of prosodic markers, such as final lengthening and intonational boundary contour or tone (see among others, Delattre, 1965; Klatt, 1975; Vaissière, 1983; Wightman, Shattuck-Hufnagel, Ostendorf & Price, 1992). This study will focus on the mirror position, that is the domain-initial or postboundary position.

Evidence for the special status of domain-initial position has been widely documented at the syllable and word levels. Initial segments in these constituents show a particular behavior regarding synchronic and diachronic variants (e.g., Bell & Hooper, 1978; Ohala & Kawasaki, 1984): they are especially resistant to reduction or lenition processes. For example, in the sound changes from Latin to French, most of the syllable- and word-initial consonants have been maintained while medial or final ones have lenited or disappeared (Brunot & Bruneau, 1937; Bourciez & Bourciez, 1967). Initial segments have also been shown to have specific articulatory properties. Within a syllable or a word, the glottal and supraglottal articulations of a segment may vary depending on its position. Along with some well-known positional allophones, like the aspirated stops or the light form of /l/ occurring in initial position in English (e.g., Kahn, 1976; Lehiste, 1960), more subtle articulatory variations have been described in word- or syllable-initial position in many languages. For example, initial consonants can have, compared to final ones, a larger glottal opening (Cooper, 1991), a greater linguopalatal constriction (Rousselot, 1901; Byrd, 1994; Keating, Wright & Zhang, 1999) or a higher velum position for both nasal (Fujimura, 1977; Krakow, 1989) and oral segments (Benguerel, 1977; Vaissière, 1988).

This study is aimed at extending these results by looking at constituents higher than the syllable and the word. The hypothesis is that initial position is, along with final position, a site governed by a specific prosodic encoding which is linked to phrasal organization, that is the organization of utterances into constituents of various prosodic levels. In order to test this hypothesis, a comparison between initial and final segments is not sufficient. Initial positions in different prosodic domains have to be compared. A series of recent studies have indeed shown that articulatory variations such as those described for initial consonants at the syllable or word level, do reflect the hierarchical level of the constituent studied. The width of glottal opening as approximated by VOT (Pierrehumbert & Talkin, 1992 in English; Jun, 1993 and Cho & Keating, 2001 in Korean; Hsu & Jun, 1997 in Taiwanese), or the extent of linguopalatal contact (Fougeron & Keating, 1997 in English; Cho & Keating, 2001 in Korean), increases for segments that are initial in higher domains compared to segments that are initial in lower domains. Hence, as shown for final lengthening (e.g., Wightman *et al*., 1992), the progressive articulatory changes in initial position seem to reflect the hierarchical organization of prosodic constituents in distinguishing several levels of boundaries.

However, in most of these studies, it is noteworthy that the realization of these prosodically-dependent articulatory properties is quite variable. Table I summarizes some aspects of the studies that have reported articulatory variations in several domain-initial positions so far. It can be seen in the fourth column that not all the prosodic constituents studied are distinguished by articulatory variation. For example, Fougeron & Keating (1997) found in English that, out of the five prosodic constituents considered, three to four were distinguished by the amount of linguopalatal contact of their initial consonant (/n/). Furthermore, the three subjects studied did not distinguish the same constituents this way. For one subject, the amount of linguopalatal contact in the consonant was smaller in initial position of syllable and word, greater in initial position of what was called a phonological phrase (a phrasal constituent higher than the word, defined by at least one pitch accent and a phrase tone), and even greater in initial position of the highest constituent considered, an intonational phrase (a phrasal constituent defined by a complete intonational contour, including a final boundary tone). For another subject, there was a distinction between syllable-initial and word-initial /n/, but no distinction between phonological phrase- and intonational phrase-initial positions. A similar subject- and constituent-dependent variability was found by Cho & Keating

TABLE I. Summary of studies showing articulatory variation of segments in initial position of constituents of different prosodic levels. The language and the segments examined are given in columns 2 and 3. The last column shows the number of constituents distinguished by the articulatory measure out of all the constituents studied. The variability in this number indicates that the same distinctions are not made by all the speakers or for all the segments

Study	Language	Segments	No. of distinctions
Lingual articulation			
Byrd, Kaun, Narayanan & Saltzman (2000)	Tamil	/n/	2 out of 3
Hsu & Jun (1997)	Taiwanese	/t/	2 to 3 out of 3
Fougeron & Keating (1997)	English	/n/	3 to 4 out of 5
Cho & Keating (2001)	Korean	/t/, /t^h/, /t*/, /n/	3 to 5 out of 5
Nasal articulation			
Gordon (1996)	Estonian	/n/	2 to 3 out of 4
Glottal articulation: *VOT*			
Pierrehumbert & Talkin (1992)	English	/t^h/	2 out of 2
Jun (1993)	Korean	/p^h/	3 out of 3
Hsu & Jun (1997)	Taiwanese	/k^h/, /b/	3 out of 3
		/t/	0 out of 5
Cho & Keating (2001)	Korean	/n/, /t/, /t^h/, /t*/	3 to 5 out of 5
Glottal articulation: *vowel glottalization*			
Pierrehumbert & Talkin (1992)	English	/ɔ/ + divers	2 out of 2
Dilley, Shattuck-Hufnagel & Ostendorf (1996)	English	diverse	2 to 3 out of 3

(2001) in Korean. Thus, it appears that the observed phenomenon needs to be examined more deeply. If the articulatory variations observed in domain-initial position do reflect the prosodic organization of an utterance, one needs to understand why these variations are not always present and whether they are just a side effect of some other prosodic markers (intonational or durational, for example).

The work presented here aims at providing a better understanding of this effect by examining in a more comprehensive fashion its realization in French. The main objective is to uncover the nature of the variations undergone by the segments in initial position. From the third column of Table I, it appears that the influence of prosodic position on articulation has been studied mostly for stop consonants. It is only for glottal articulation that this effect has been extended to vowels (Pierrehumbert & Talkin, 1992; Dilley *et al.*, 1996). Hence, one must examine first if this effect generalizes to other types of segments. Second, the physiological mechanism governing these articulatory variations needs to be understood. In their study of lingual articulation, Fougeron & Keating (1997) have proposed to describe the increase in linguopalatal contact observed in domain-initial position as an *articulatory strengthening*. This term is meant to reflect that the articulation of a consonant is more extreme (with a greater constriction for stops) in initial position compared to medial, and more extreme at the beginning of higher level constituents than at the beginning of lower ones. Indeed this "strengthening" appears as a mirror modification of the "weakening" known to occur for final segments. In order to test this hypothesis, the nature (i.e., the directionality) of the articulatory variations in domain-initial position has to be examined in detail. In this study, the nature of these variations will be examined—within a single language, French—for several segments that differ in place and manner of articulation, and for three different articulatory subsystems (lingual, nasal, glottal).

2. Method

2.1. *Test segments and prosodic positions*

Five consonants varying in place and manner of articulation, /t, n, k, l, s/, and two vowels /i, ɑ̃/ were chosen for study. In order to examine their articulatory properties at different prosodic positions, these test segments were placed in initial position in four different prosodic constituents: an intonational phrase (IP), an accentual phrase (AP), a lexical word (W), a syllable (S). In order to reduce the size of the corpus, the stop /k/ and the vowels /i, ɑ̃/ were tested for only a subset of constituents: IP, AP and W. Carrier sentences were used in order to elicit a specific phrasing for each of the prosodic positions considered, and this phrasing was then controlled according to a set of criteria (see below). Table II gives an example of the sentences used for the test segment /n/. Each prosodic position will be henceforth named with an abbreviation, where "i" stands for "initial" and the capital letters before stand for the name of the constituent (e.g., "APi" = "Accentual-Phrase initial"). In all sentences used in experiment 1 (lingual articulation), the serial position of the test segment within the sentence was controlled so that the segments appeared at the onset of the fifth syllable in every prosodic position (see example in Table II(a)). This was done in order to avoid a possible articulatory declination that would modify the articulation of the segment because of its early-to-late position in the sentence (see Krakow, Bell-Berti & Wang (1994) but see Fougeron

TABLE II(a), (b). Examples of sentences used for the test segment /n/. The test segment, in bold, is placed at four different prosodic positions: Intonational Phrase-initial (IPi), Accentual Phrase-initial (APi), Word-initial (Wi), and Syllable-initial (Si). The sentences in (a) are used in experiment 1 (EPG) where the serial position of the test segment is constant (5th syllable), the sentences in (b) are used for experiment 2 (nasal flow) where the serial position (syllabic position) of /n/ varies

	(a)	(b)
IPi	Pauvre Tata, **N**adia et Paul n'arriveront que demain. *Poor Auntie, Nadia and Paul will arrive only tomorrow.*	La pauvre Tata, **N**adia et Paul n'arriveront que demain. *Poor Auntie, Nadia and Paul will arrive only tomorrow.*
APi	Tonton, Tata, **N**adia et Paul arriveront demain. *Uncle, Auntie, Nadia and Paul will arrive tomorrow.*	Tonton, Tata, **N**adia et Paul arriveront demain … *Uncle, Auntie, Nadia and Paul will arrive tomorrow …*
Wi	Paul et Tata **N**adia arriveront demain matin. *Paul and Auntie Nadia will arrive tomorrow morning.*	Tonton Paul et Tata **N**adia arriveront demain … *Uncle Paul and Auntie Nadia will arrive tomorrow …*
Si	Tonton et A**nn**abelle arriveront demain matin. *Uncle and Annabelle will arrive tomorrow morning.*	Tonton Paul et Tata A**nn**abelle arriveront demain … *Uncle Paul and Auntie Annabelle will arrive tomorrow …*

& Keating (1997) for counter-evidence against articulatory declination). In the corpus used in experiment 2 (nasal flow), the serial position of the test segment was not as well controlled, and the test segments could appear between the 5th and 8th syllable of the sentence (see Table II(b) for /n/). For all test segments, the surrounding segmental context was kept constant: /a_a/ for /n, l, s, k/, /ɔ̃_ɔ̃/ for /t/, /k_d/ for /ɑ̃/ and /p_p/ for /i/.

In several studies on the distinction between onsets and codas, the stimuli used were monosyllabic words (e.g., Byrd, 1994). Therefore, the difference observed between the positions cannot be attributed with certainty to an effect of position in the syllable or position in the word. Hence, it appears that in order to study the articulatory properties of segments at prosodic boundaries, one needs to control the hierarchical level of this boundary, i.e., the level of the constituents on both sides of the boundary. In this work, the Strict Layer Hypothesis (Selkirk, 1986), which states that constituents at the same hierarchical level cannot be nested, is adopted. It follows that a constituent of a level X^p can only be preceded by a constituent (if any) of the same level. Thus, a segment that is initial in a constituent is at the boundary between two constituents of the same hierarchical level.

In order to verify that the test segments were produced at intended prosodic position, a transcription of the sentences produced by the speakers was done *a posteriori* according to a set of prosodic criteria. These criteria define the prosodic level of the constituent preceding the test segment and, according to the Strict Layer Hypothesis, the level of the constituent in which the test segment is initial. Table III summarizes these criteria for the four prosodic positions studied. The criteria are: (1) presence (+) or absence (Ø) of a pause before the test segment; (2) final lengthening of the preceding vowel (lengthening: +, no lengthening: 0); (3) type of the tone preceding the test segment (major boundary tone (%%), minor boundary tone (%), no boundary one (Ø)). Pause detection was done

TABLE III. Criteria used for the definition of the prosodic position according to the presence (+) or absence (Ø) of pause before the test segment, the lengthening (+) or not (0) of the pre-boundary vowel and the type of tone preceding the test segment (%%: major boundary tone, %: minor boundary tone, Ø: none, L: low tone, H: high tone)

	Pause	Lengthening V1	Boundary tone
IPi	+	+	%% (L or H)
APi	Ø	+	% (H)
Wi	Ø	0	Ø (L or H)
Si	Ø	0	Ø (L)

visually from the acoustic signal. In the case of unvoiced stops (/t, k/) in Si, Wi and APi position, a visual control was made on the EPG frames to ensure that the linguopalatal closure filled the silent interval. Final lengthening of the vowels preceding AP- and IP-initial segments was measured acoustically and compared to the nonlengthened vowels preceding the S-initial segment, used here as a baseline. AP- and IP-final vowels were found to be longer than S-final vowels, while W-final vowels did not differ significantly from S-final vowels. Tonal transcription was done according to the model of French intonation developed by Jun & Fougeron (2000). A minor boundary tone corresponds to the final or primary accent in French. The Accentual Phrase is thus similar to what others have called "groupe accentuel", "mot prosodique" or "intonème mineur". The height of the tone preceding the test segment is also given in the table. In order to control for an effect of accent on the articulation of the test segments, it was verified that the test segments did not have an initial accent. In French, this accent is optional and, when present, is realized with a high tone. In this study, all the initial test syllables were realized with a low flat pitch contour. A handful of sentences that did not correspond to these criteria were eliminated—these were a set of sentences constructed for the APi position that had been produced by one of the speakers with a pause before the test segment (i.e., with a IP boundary). These sentences had to be re-recorded with the appropriate phrasing.

2.2. *Articulatory measures*

Two types of articulatory data were examined in this study. In experiment 1, an index of lingual articulation was obtained with electropalatography (EPG), which measures linguopalatal contact, that is, the contact of the tongue against the palate. Data were collected with the Kay Elemetrics Palatometer 6300. Figure 1 shows pictures of the custom-made pseudo-palates. The white circles indicate the placement of the 96 electrodes that cover the hard palate and the inner surface of the upper molars. In order to capture the dental contact of French /t/, and /n/, two electrodes were placed in the middle of the inner surface of the incisors. Each sweep of the 96 electrodes takes 1.7 ms and the sampling rate is 100 Hz. The audio signal was acquired in parallel at 12 800 Hz.

Variation in the lingual articulation of the consonants and the high vowel /i/ depending on their prosodic position was measured in terms of amount of linguopalatal contact. This was done by computing the percentage of electrodes contacted in the frame showing the largest amount of contact, that is, at the point of maximum constriction in the articulation of the segment. Most of the analyses describe the amount of contact over the whole palate (96 electrodes). Thus, 1% corresponds approximately to one electrode. For

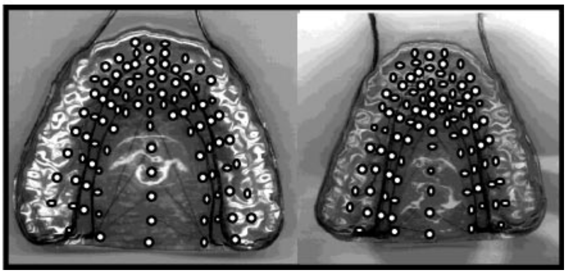

Figure 1. Picture of the pseudo-palates made for the two speakers. White circles represent the location of the 96 electrodes.

/s/ and /l/, some subregions of the palate have been defined to cover specific zones of articulation. These will be described in the appropriate sections.

In experiment 2, an indirect measure of articulation at the velum was obtained with aerodynamic data. The amount of nasal flow during the production of a nasal segment (/n/ and /ɑ̃/) has been considered to be an approximation of velopharyngeal opening and of velum height. It must be noted that the amount of nasal flow is also a function of the overall airflow through the glottis and of the oral impedance. These factors were not controlled and any change in nasal flow is interpreted here as resulting from a change in velopharyngeal aperture. Nasal flow, which was collected through a Rothenberg split mask, was filtered at 30 Hz and directly digitized, along with the audio signal, at a 1000 Hz sampling rate by a multichannel Kay Elemetrics CSL (model 4300B), and was then calibrated.

For both nasal segments, the amount of nasal flow in each prosodic position was taken at the point where nasal flow is maximum in the segment.

2.3. *Other measures of articulatory variation*

In order to approximate any change in glottal articulation depending on prosodic position, VOT was measured for the voiceless stops /t, k/. VOT was taken to be the time between the beginning of the burst and the onset of glottal vibrations in the acoustic waveform. For the vowel /i/, variation in glottal articulation was measured in terms of the occurrence of glottalization in each prosodic position. Presence of glottalization at the onset or during the vowel was determined visually from the acoustic signal either by the presence of isolated glottal pulses before the onset of regular voicing or by irregular glottal vibration in the initial part of the vowel (Dilley *et al.*, 1996).

Variation in the temporal properties of the initial segments was also measured. First, duration of the lingual closure of stop consonants was measured from the EPG data, as the time between the first frame showing a full lingual closure and the last frame before the lingual seal was broken. Second, acoustic duration of all segments was measured from the audio signal. In experiment 2 (nasal flow), even though the signal was filtered by the Rothenberg mask, its quality was sufficient for durational measurements. Segment boundaries were determined from both the waveform and a spectrogram. Consonant offset was determined by the onset of voicing and the appearance of F2 of the following vowel. Consonant onset was determined by the onset of frication noise in the spectrogram for /s/ and by the appearance of mid-frequency resonances and/or the onset of voicing for /l/ and /n/. For the voiceless stops /t/ and /k/, the closure duration (between onset of silence and burst) was measured only for positions where the stop was not preceded by a pause, that is for all prosodic positions except IPi. For vowels, segment boundaries were determined both by the onset/offset of voicing in the waveform and the presence of higher formants in the spectrogram.

2.4. *Speakers and procedure*

Four Parisian French subjects participated in this study. Speaker 1M (male) and speaker 2F (female, the author) were recorded for experiment 1 (EPG) and experiment 2 (nasal flow). Two additional female speakers (3F and 4F) participated in experiment 2 (nasal flow). All were between 20 and 30 years old and had spent from 1 to 5 years in the US at the time of the study.

Data were collected in the Phonetics Laboratory at UCLA in several recording sessions. The test sentences were presented to the subjects in blocks containing all four prosodic positions for each test segment (like in Table II). Subjects had to read each sentence 5–6 times and proceed to the next prosodic position. At the end of the block, they had to repeat the same sentences but in the reverse order (e.g., IPi, APi, Wi, Si then Si, Wi, APi, IPi) in order to avoid a list effect. Speakers were not told how to phrase the test sentences. In a few cases, when subjects were too monotonous, they were reminded to read in a more expressive style.

In general, 20 repetitions of each prosodic position were recorded except for /l/(10 rep.) and /k, i/ (15 rep.). In the nasal flow experiment, some recordings out of the 20 had to be eliminated from the data set mostly because of recording problems or because the subject had breathed during the pause (in IPi position) and the nasal flow had not come back to zero at the onset of the test segment. These correspond to about 15% of the data recorded.

For all the measures considered, the comparison between the prosodic positions was tested with a one factor (position) ANOVA and *post hoc* Fisher PLSD tests with a 95% significance level. A prosodic position was considered significantly different if it was different from *all* the other positions. For more details on the method and the measures, the reader is referred to Fougeron (1998).

3. Results

3.1. *Lingual articulation*

3.1.1. *Linguopalatal contact of stop consonants*

Statistical analysis shows that the lingual articulation of the three stops /t, n, k/ varies depending on prosodic position. The amount of linguopalatal contact of initial stops tends to increase progressively from the lowest constituent (S) to the highest constituent (IP). Fig. 2 illustrates this variation in the three stops for the two speakers. Table IV gives the statistical results of the comparisons for each segment and speaker.

For the nasal stop /n/, the increase in linguopalatal contact significantly distinguishes the four prosodic positions considered for the two speakers, with a progressive increase in contact from the lowest position (Si) to the highest (IPi). For /t/, only three positions

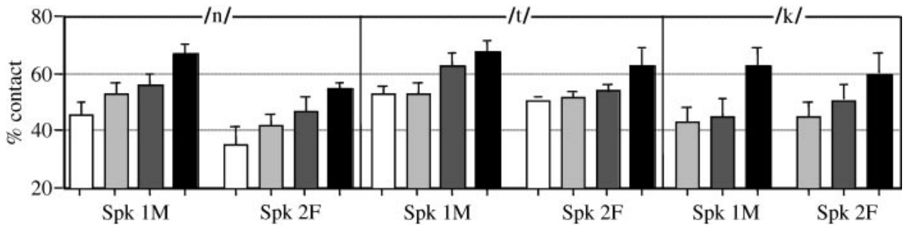

Figure 2. Amount of linguopalatal contact (mean and S.D.) for the stops /n/, /t/, and /k/ in the different prosodic positions examined, Si: Syllable-initial, Wi: Word-initial, APi: Accentual Phrase-initial, IPi: Intonational Phrase-initial: □ Si; ▒ Wi; ■ APi; ■ IPi.

TABLE IV. ANOVA results for lingual variation. Direction of the significant differences in the amount of palatal contact is indicated by " > " for more contact and " < " for less contact. When a prosodic position does not appear in the comparison, it is not significantly different from the surrounding positions (e.g., Wi for speaker 2F /t/ is not distinct from Si and APi). For /k/ and /i/, the position Si is not studied. Columns 3 and 5 show the number of positions distinguished by linguopalatal contact out of the number of positions studied. See text for further explanations

Segments	Speaker 1M		Speaker 2F	
/n/	$F(3,73) = 105.9$, $p = 0.0001$ Si < Wi < APi < IPi	4/4	$F(3,76) = 74.2$, $p = 0.0001$ Si < Wi < APi < IPi	4/4
/t/	$F(3,77) = 101.0$, $p = 0.0001$ Si, Wi < APi < IPi	3/4	$F(3,78) = 53.3$, $p = 0.0001$ Si < APi < IPi	3/4
/k/	$F(2,42) = 49.2$, $p = 0.0001$ Wi, APi < IPi	2/3	$F(2,44) = 25.9$, $p = 0.0001$ Wi < APi < IPi	3/3
/l/ front region	$F(3,35) = 23.4$, $p = 0.0001$ Si < Wi < APi < IPi	3/4	$F(3,36) = 23.4$, $p = 0.0001$ Si < Wi < APi, IPi	3/4
Asymmetry Index /l/	$F(3,35) = 37.7$, $p = 0.0001$ Si, Wi > APi > IPi	3/4	$F(3,36) = 7.7$, $p = 0.0004$ Si, Wi > APi, IPi	2/4
/s/ front region	$F(3,75) = 4.4$, $p = 0.006$ Wi < APi, IPi; Si < APi	2-3/4	$F(3,74) = 9.4$, $p = 0.0001$ Wi, APi < IPi, Si	2/4
/i/	$F(2,43) = 7.4$, $p = 0.002$ Wi < APi, IPi	2/3	$F(2,45) = 22.5$, $p = 0.0001$ Wi < APi, IPi	2/3

are distinguished by the progressive increase in contact. Speaker 1M does not show a distinction between the Syllable and Word levels, and for speaker 2F the Word level is not distinct from either the Syllable or AP level. Recall that for /k/, only Wi, APi and IPi positions were recorded. While for speaker 2F these three positions are distinguished by the amount of linguopalatal contact, speaker 1M produces only a two-way distinction between Wi/APi and IPi. The difference between Wi and APi follows the same trend with a greater amount of contact in APi but the difference is marginally significant ($p = 0.05$).

A closer look at the distribution of the linguopalatal contact shows that the increase in contact observed in higher constituents results from a widening of the lingual constriction against the palate. For the two front consonants, /n/ and /t/, the surface of occlusion extends more toward the center of the palate when the consonant is initial in a high-level constituent. This is illustrated in the examples of contact profiles given in Fig. 3(a). In

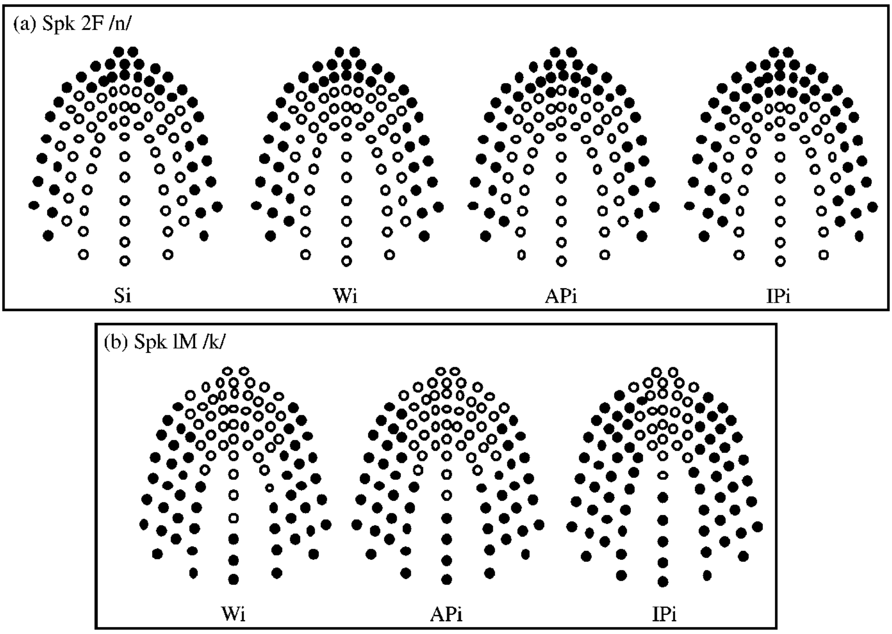

Figure 3. Example of contact profile for /n/ and /k/ produced by speaker 2F. Black circles represent the electrodes contacted by the tongue. Each profile is taken at the frame of maximum contact in the rendition.

these examples, the contact for /n/ in Si is maximal in the two front-most rows of electrodes and some electrodes are contacted on the third row. In IPi, the contact is maximal in the three front rows and extends to the fourth row. There is also an increase in electrodes contacted on the sides of the palate. This probably results from a better anchoring of the tongue against the palate in higher positions. For the back consonant /k/, the increase in contact in higher prosodic position appears as a widening of the back contact toward the middle of the palate, as illustrated in Fig. 3(b).

3.1.2. *Linguopalatal contact of /l/*

For the lateral consonant, three regions have been defined on the palate. These are illustrated in Fig. 4. The front-central region contains 46 electrodes. It extends from the front-most part of the palate toward the prepalatal region and ends on the side after the premolars. The two lateral regions each contain 15 electrodes and cover the three most external lateral rows of electrodes.

Observation of the amount of contact over the front region shows that the lateral consonant follows a similar trend to that shown by the stops. The contact in the front region increases for initial /l/s in higher constituents. However, this increase in contact does not differentiate the same prosodic constituents as it does with the stops. For the two speakers, there is no distinction between the two highest levels: APi and IPi. Thus, as can be seen in Table IV and in Fig. 4(a), the two speakers make a three-way distinction between a sublexical level (Si), a lexical level (Wi) and a supra-lexical level (APi/IPi).

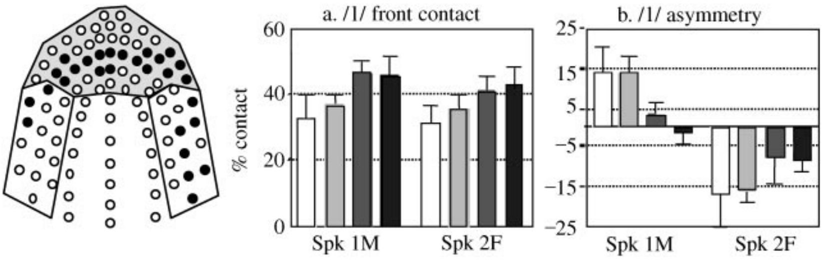

Figure 4. Amount of linguopalatal contact (mean and S.D.) for /l/ in the front region depending on prosodic position (a). Asymmetry in the lateral contact between the left and right regions depending on prosodic position (b). Asymmetry to the left appears as a positive index and asymmetry to the right as a negative index: □ Si; ■ Wi; ■ APi; ■ IPi.

In the lateral regions there is also a change in the amount of contact depending on prosodic position. This change is dependent on the location of the lateral channel, which varies for the two speakers (on the right for 1M and on the left for 2F). In the region of the lateral channel, the contact tends to increase when the /l/ is initial in higher constituents. This means that the opening of the lateral channel becomes smaller in this position. On the opposite side, i.e., the side of tongue anchoring, the contact tends to decrease slightly. As a consequence, there is a reduction of the contact asymmetry between the two lateral regions in initial position of higher domains. This is shown by a reduction of the asymmetry index computed as [(left contact − right contact)/total right & left contact], in Fig. 4(b) and Table IV.

In sum, for the two speakers, /l/ has a smaller asymmetry of tongue contact in initial position of higher constituents along with a widening of front central contact.

3.1.3. *Linguopalatal contact of /s/*

The articulation of the fricative /s/ is examined in the front region of the palate where the fricative groove is located. This region was defined as in Fig. 5. It includes 33 electrodes, extends towards the alveolar region, and ends on the side at the premolars. Variation in the amount of contact in this region is also illustrated in Fig. 5.

It can be seen that /s/ is less systematically affected by prosodic position compared to the other consonants studied (see discussion for the expected stability of /s/). For the two speakers, some variations are observed but the tendency is less clear than in the case of other consonants. Excluding the Si position, there is an increase in contact from Wi to APi/IPi for speaker 1M, and from Wi/APi to IPi for speaker 2F. Thus, even if the variation observed follows the same tendency as that of other consonants, i.e., an increase in contact in higher position, very few positions are distinguished this way for this consonant. Moreover, the lowest position Si does not follow this trend since a large amount of contact is observed there.

Closer examination of the characteristics of the fricative groove did not reveal any more effect of prosodic position on /s/. The width of the fricative groove, its area (length ∗ width) and the groove center location were measured following Fletcher's (1989) indices, but no clear trend was found among the speakers (see Fougeron (1998) for more details).

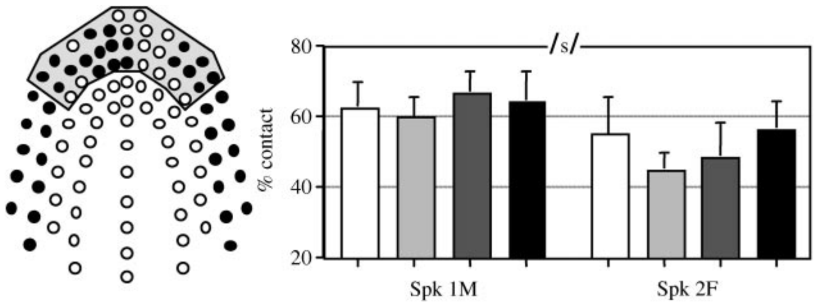

Figure 5. Amount of linguopalatal contact (mean and S.D.) for /s/ in the anterior depending on prosodic position: □ Si; ■ Wi; ■ APi; ■ IPi.

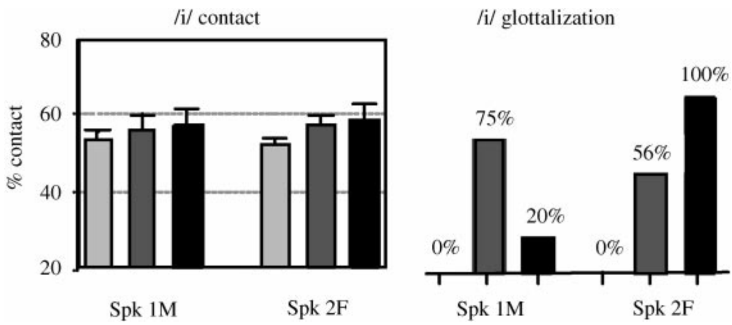

Figure 6. On the left, amount of linguopalatal contact (mean and S.D.) for /i/ depending on prosodic position. On the right, percent occurrence of glottalization for the vowel depending on prosodic position: ■ Wi; ■ APi; ■ IPi.

3.1.4. *Linguopalatal contact of the vowel /i/*

The amount of linguopalatal contact during the articulation of the close vowel /i/ was measured at the point of maximal contact, as was done for the consonants. Only three positions are compared: Wi, APi, IPi.

The left panel of Fig. 6 shows the amount of linguopalatal contact over the whole palate for the vowel. As observed for the consonants, there is an increase in contact in the vowel that follows the hierarchy of the positions. However, significant differences are only found between the lexical level (Wi) and the two phrasal levels (APi and IPi) for the two speakers (see Table IV).

3.2. *Nasal flow for nasals*

The amount of nasal flow depending on prosodic position was measured for the nasal consonant /n/ and the nasal vowel /ɑ̃/. For the nasal vowel, only three prosodic positions are studied: Wi, APi, IPi.

For both nasal segments, there is a tendency for nasal flow to decrease in initial position in higher constituents. However, the progressive nature of this trend is less striking than the increase observed for linguopalatal contact. As can be seen in Table V

TABLE V. ANOVA results for nasal flow variation. Direction of the difference in the amount of nasal flow is indicated by " > " for more flow and " < " for less flow. For /ɑ̃/, the position Si was not studied. Columns 3, 5, 7 and 9 show the number of positions distinguished by nasal flow out of the number of positions studied

	Speaker 1M		Speaker 2F		Speaker 3F		Speaker 4F	
/n/	$F(3,54) = 5.8$, $p = 0.002$ Si, Wi, APi > IPi	2/4	$F(3,70) = 5.2$, $p = 0.003$ Si, Wi, APi > IPi	2/4	$F(3,68) = 8.3$, $p < 0.001$ Wi, APi > IPi; Si < Wi	2-3/4	$F(3,59) = 6.6$, $p < 0.001$ Si, Wi, APi < IPi	2/4
/ɑ̃/	$F(2,24) = 9.4$, $p = 0.001$ Wi > APi, IPi	2/3	$F(2,27) = 0.3$, $p = 0.8$ ns.	0/3	$F(2,25) = 21.0$, $p < 0.001$ Wi > APi > IPi	3/3	$F(2,27) = 0.9$ $p = 0.4$ ns.	0/4

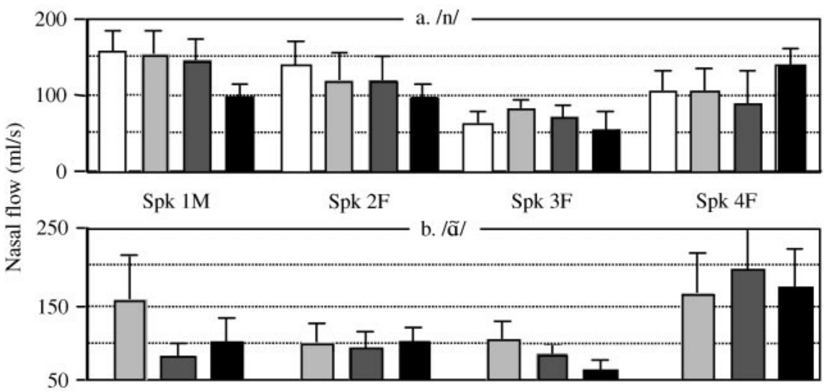

Figure 7. Amount of nasal flow at the point of maximum flow in /n/ (a) and in /ɑ̃/ (b) depending on prosodic position: □ Si; ■ Wi; ■ APi; ■ IPi.

and Fig. 7(a) the common pattern shown for three out of the four subjects is a diminution of nasal flow for initial /n/ in IP compared to initial /n/ in lower constituents. But for speaker 4F, the trend is the opposite. This speaker, who was the least expressive in her production, shows an increase in nasal flow in IPi position.

For /ɑ̃/, there is variation in nasal flow depending on prosodic position for two (1M, 3F) out of the four speakers and no variation for the others (see Table V and Fig. 7(b)). For these two speakers (1M and 3F), the trend is similar to the one shown for /n/: a diminution of nasal flow in higher positions. Speaker 3F presents a gradual decrease of nasal flow between the three positions studied (Wi > APi > IPi). Speaker 1M makes only a two-way distinction between the lexical level (Wi) and the phrasal levels (APi/IPi). Therefore, only the diminution from Wi to IPi is shared by these speakers.

3.3. *Glottal articulation*

3.3.1. *VOT of /t/ and /k/*

The comparisons of VOT depending on stop consonant position are given in the first two rows of Table VI. The VOT of /t/ shows little variation depending on the prosodic

TABLE VI. ANOVA results for durational variation. Direction of the duration difference is indicated by “ > ” for longer and “ < ” for shorter

Segments	Speaker 1M	Speaker 2F	Speaker 3F	Speaker 4F
		VOT duration		
/t/	Si, Wi < APi, IPi	Si < Wi, IPi		
/k/	ns.	ns.		
		Lingual seal duration		
/n/	Si < APi < IPi	Si, Wi < APi < IPi		
/t/	Si, Wi < APi < IPi	Si < Wi, APi < IPi		
/k/	Wi, APi < IPi	Wi, APi < IPi		
		Acoustic duration (comparison only for positions not preceded by a pause)		
/n/ exp. 1	Si < Wi < APi	Si < Wi < APi		
/n/ exp. 2	Si < Wi < APi	Si, Wi < APi	Si < Wi < APi	Si < Wi < APi
/t/ closure	Si < Wi < APi	Si < Wi < APi		
/k/ closure	Wi < APi	Wi < APi		
/l/	Si, Wi < APi	Si, Wi < APi		
/s/	Si, Wi < APi	Si < Wi < APi		
/i/	Wi < APi	ns.		
/ɑ̃/	Wi > APi	ns.	ns.	ns.

position of the consonant and the only common variation shown by the two speakers is that VOT is shorter in Syllable-initial position. For /k/ no difference is found in VOT duration depending on position.

3.3.2. *Occurrence of glottalization in /i/*

The percent occurrence of glottalization observed for the vowel /i/ in the different prosodic positions is illustrated in the right panel of Fig. 6 and in Table IV. Results show that, in this corpus, /i/ is never glottalized in Wi position, while it is more frequently glottalized in initial position of higher phrasal constituents. Depending on the speakers, the frequency of glottalization increases progressively from Wi to APi to IPi, as for speaker 2F, or is more frequent in AP-initial position, as for speaker 1M.

3.4. *Durational variation*

3.4.1. *Duration of articulatory events: lingual closure duration for stops*

Comparison between prosodic positions (Table VI) shows that the duration of the lingual closure (as captured in EPG data) varies in a similar way as the amount of linguopalatal contact: consonants initial in higher constituents have a larger amount of contact and also a longer lingual closure. However, fewer distinctions are made by the temporal measure (closure duration) than by the spatial measure (linguopalatal contact): speaker 2F loses the distinction between Si and Wi for /n/ and between Wi and APi for /k/; speaker 1M loses the distinction between Wi and both Si and APi for /n/.

In order to examine the relationship between the temporal and spatial properties of the lingual articulation, correlations were calculated between these two measures. These coefficients are given in the left part of Table VII. In (a) the correlations between the two

TABLE VII. Pearson correlation coefficients between (on the left) amount of linguopalatal contact and articulatory closure duration, and (on the right) amount of liguopalatal contact and acoustic duration. (a) Shows the results for all the prosodic positions (i.e., including IPi), (b) shows the results for all of the positions except IPi (i.e., all the positions not preceded by a pause)

		Articulatory closure duration			Acoustic duration					
		/n/ seal	/t/ seal	/k/ seal	/n/	/t/ closure	/k/ closure	/l/	/s/	/i/
(a)	Spk 1M	0.91 (*)	0.78 (*)	0.78 (*)	0.13 (ns)			0.44 (ns)	0.04 (ns)	0.30 (ns)
		$n = 75$	$n = 81$	$n = 45$	$n = 76$			$n = 38$	$n = 79$	$n = 46$
	Spk 2F	0.81 (*)	0.79 (*)	0.43 (*)	0.34 (*)			0.42 (ns)	0.34 (*)	0.17 (ns)
		$n = 77$	$n = 82$	$n = 46$	$n = 80$			$n = 40$	$n = 78$	$n = 48$
(b)	Spk 1M	0.80 (*)	0.77 (*)	0.05 (ns)	0.82 (*)	0.72 (*)	0.01 (ns)	0.84 (*)	0.19 (ns)	0.39 (ns)
		$n = 55$	$n = 60$	$n = 30$	$n = 57$	$n = 60$	$n = 30$	$n = 29$	$n = 60$	$n = 31$
	Spk 2F	0.81 (*)	0.59 (*)	0.01 (ns)	0.83 (*)	0.59 (*)	0.31 (ns)	0.82 (*)	0.35 (ns)	0.31 (ns)
		$n = 57$	$n = 62$	$n = 30$	$n = 60$	$n = 62$	$n = 31$	$n = 30$	$n = 59$	$n = 32$

* Indicates significant correlations at 0.05 (corrected after Bonferroni), and (ns) indicates non-significant correlations.

factors are computed for all positions. It can be seen that there is a strong relationship between the spatial and the temporal measures, with coefficients ranging from 0.43 to 0.91. The duration of the occlusion is usually very long in IPi position. In /n/, for example, examination of the successive EPG frames shows that the occlusion is initiated, and even achieved, well before the voicing starts, that is during the preceding pause. In order to avoid exaggerating the relationship between linguopalatal contact and closure duration by the characteristics of IPi position (large amount of contact and extra-long closure), the correlation was also computed only for the three positions not preceded by a pause: Si, Wi and APi. These results are shown in (b) in Table VII. As expected, the exclusion of IPi position somewhat reduces the correlation between the two variables (especially for /k/), with coefficients ranging from 0.01 to 0.81.

3.4.2. *Acoustic duration*

For all test segments, IPi position is characterized by large variability in acoustic duration, as shown by the large standard deviation in Fig. 8. While the segments can be quite long in this position, they are most often shorter than in other positions (especially shorter than APi). In IPi position, segments are preceded by a pause. It is known that the setting of appropriate aerodynamic conditions for voicing to occur may take some time after a pause, so that the acoustic duration of the segment may be shortened (e.g., Lisker & Abramson, 1964; Flege, 1982). Because of this large variability in IPi position, the discussion about segment duration will focus on the positions not preceded by a pause: Si, Wi, APi.

The last rows in Table VI summarize the differences observed in segment duration in these three positions. It can be seen in this table that the pattern shown by all consonants is a lengthening in APi position compared to initial position in lower constituents. In most cases, there is also a lengthening in Wi position compared to Si, thus a progressive lengthening from Si to Wi to APi.

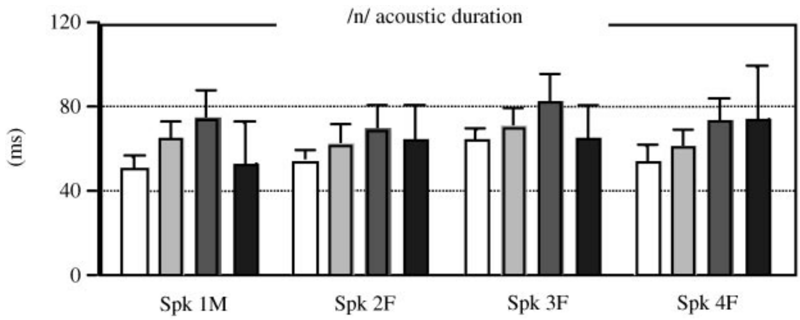

Figure 8. Acoustic duration of /n/ measured in experiment 2 (nasal flow) depending on prosodic position: □ Si; ■ Wi; ■ APi; ■ IPi.

The vowels exhibit variation in acoustic duration depending on prosodic position only for one speaker. Speaker 1M shows a significant lengthening in APi compared to Wi (and also IPi) for /i/ and a lengthening of /ɑ̃/ in Wi compared to APi (and IPi). However, it must be noted that initial vowels have been shown to be glottalized in higher constituents, and some of the glottalized portion may not have been included in the duration measurement.

Results of the correlation between the acoustic duration and the amount of linguopalatal contact of segments in experiments 1 (EPG) are given in the right part of Table VII. When the computation includes all of the position (in (a)), it can be seen that the acoustic and articulatory variables are only weakly correlated (with coefficients ranging from 0.04 to 0.44). On the contrary, when we look at the positions not preceded by a pause (in (b)), a positive correlation between the two variables appear clearly for /n/ and /l/, and /t/. For /n/ and /l/, the difference between the two types of computation (with or without IPi) results from the fact that in IP-initial position, these segments have a large amount of linguopalatal contact but a short acoustic duration (probably due to a delay of voicing onset after the pause as explained above). In the other positions, the increase in linguopalatal contact from lower to higher position is accompanied by a lengthening of these consonants. For the other segments (/k/, /s/ and /i/), the correlation between the two variables is weak in both types of computation.

4. Discussion

As previously shown for the word and syllable levels, this study demonstrates that segments placed in initial position in higher level constituents are characterized by specific articulatory properties in French. These properties are found to differentiate initial segments in higher domains from initial segments in lower domains as found in other languages (see Table I, for example). At the same time, the comparison between several domains showed that initial segments in the constituents studied are different from medial segments, since a segment that is initial in a lower constituent (e.g., a Word) is also medial in a higher constituent (e.g., an AP).

Thus, these results confirmed that for French the articulation of speech segments can be affected by the prosodic organization of the utterances in which they are produced.

For each of the articulatory properties considered, the magnitude of the variation observed between segments in initial position tends to follow the prosodic level of the constituents. For lingual articulation, for example, the magnitude of the increase in linguopalatal contact tends to be progressive from the lowest to the highest constituent studied. Hence, these articulatory properties in initial position do reflect the hierarchical organization of the prosodic constituents (i.e., of boundary strength).

4.1. *Variability in the realization of prosodically-driven articulatory properties*

This study also showed that there is a large amount of variability in the phenomenon observed. The realization of these prosodically-driven articulatory properties varies depending on the segment type (a), the articulator (b), the speaker (c) and the constituent (d) considered.

(a) As far as segment type is concerned, it was found that prosodic position clearly affects the articulation of the stops and the lateral, and to a smaller extent that of the vowels. Conversely, the lingual articulation of the fricative seems to be less affected by prosodic position. This finding is not surprising. In Byrd's comparison between onset and coda in English (1994), for example, /s/ also showed fewer positional differences. In fact, this consonant is known to be less subject to articulatory variation in general because it has fewer articulatory and acoustic degrees of freedom (e.g., Shadle & Scully, 1995). In the present study, it could also be the case that the variations taking place in initial position in higher domains consist of an increase in the upward force with which the tongue contacts the palate. This would affect the cross-sectional shape of the tongue (Stone, Faber, Raphael & Shawker, 1992, p. 266), but this modification could not be inferred from EPG alone since linguopalatal contact does not reflect the exact shape of the tongue.

(b) In experiment 2, it was found that the amount of nasal flow distinguishes at most three prosodic positions and in most cases, only a two-way distinction is made between IPi position and lower positions. Hence, variations in nasal flow show fewer distinctions than linguopalatal contact. This observation is hard to interpret since it could be due either to the type of articulator or to the type of articulatory data. Indeed, it is possible that velum height, especially for nasals, has fewer degrees of freedom (due to tongue raising, for example) than tongue position. It is also possible that aerodynamic data, which are an indirect measure of velopharyngeal aperture, do not reflect subtle differences in aperture between prosodic positions with enough precision.

(c) Another factor of variation is the speaker. Although all the speakers studied show some articulatory variations depending on prosodic position, they do not always realize the same distinctions. In the EPG experiment, it can be seen in Table IV that there are only three cases where the two speakers share exactly the same distinctions (for /n, l, i/). In the nasal flow experiment, there is even more variability: three out of the four speakers show a reduction of nasal flow in /n/ in IPi position while the other speaker shows an increase of nasal flow in that position. The difference remains to be explained. For /ɑ̃/, while two of the speakers show some variation in nasal flow depending on prosodic position, the other two speakers do not. As was noted in the introduction, comparable speaker variability was also observed in other related studies (see Table I). In their study of vowel glottalization in English, Dilley *et al.* (1996, p. 442) suggested that "… glottalization is one of a collection of strategies that speakers use to mark prosodic events, which together are rule-governed but which may individually vary with importance across speakers". A similar conclusion can be applied to the variations in supra-glottal articulation reported here.

(d) As noted above, all the speakers or all the segments do not show the same distinctions between prosodic positions. In other words, it is not the case that each constituent studied is consistently marked by variation in the articulation of its initial segment. As indicated in Tables IV and V, articulatory variations observed in initial positions differentiate at least two levels of constituents (linguopalatal contact for /s, i/ and nasal flow for /n/) and at the most four (out of 4) levels of constituents (linguopalatal contact for /n/). In general, the most robust distinctions observed are the ones made between the most extreme constituents of the hierarchy: the highest constituent IP and the lowest constituents S or W. Similar variability in the number and the nature of the constituents differentiated by articulatory variations was observed in other languages (e.g., Keating, Cho, Fougeron & Hsu, 1998). Lehiste (1964) also noted that positional allophones are not always produced in words and that their realization is more frequent in a "maximally differentiated style" of speech. This phenomenon needs therefore to be studied in a more casual style of speech and in spontaneous speech.

Interestingly, the word level does not appear to be consistently different from either the syllable or the accentual phrase level in the present data. This fact has to be interpreted with caution, since the definition of "word" in this corpus is lexical. It is possible that what was considered as a Wi position in a sequence like "Tata Nadia" does not correspond to an initial position in a prosodic word (which remains to be defined for French). Also the interaction with the presence or absence of an initial accent on the word preceding the test word (on the first /ta/ of "Tata Nadia") was not controlled. This needs to be explored further. Moreover, words in French are often preceded by a determiner. In the present corpus, the use of first names was meant to avoid having a determiner so that the word would be placed at the left edge of the constituents. Future studies will have to consider whether articulatory variation in initial position is purely an edge-effect. In that case, the articulation of the determiners should vary depending on the prosodic level of the constituents in which they are initial.

In sum, it appears that the realization of the prosodically-conditioned articulatory properties observed is *optional*. However, this fact does not reduce the interest of the phenomenon. As noted by Danes (1964) in his comments on Lehiste's (1964) results, what is interesting is the "potentiality" of these articulatory properties to occur: in some positions, but not in others, segments can be articulated in a different way. Then, it is the possibility *vs.* the impossibility of occurrence of these properties that makes the difference between the prosodic positions. This suggests that the initial position in a constituent is a particular site where these properties can be realized. Nonetheless, the optionality of the phenomenon leads to the fundamental question of whether these articulatory properties are intentionally produced by the speakers or whether they are side effects of other prosodic variations.

4.2. *Relationship with other prosodic variations*

The signaling of prosodic boundaries is multi-parametric. As noted earlier, particular intonational contour, the occurrence of pauses, or presence of final lengthening contribute to setting off constituents' boundaries. These markers were used here as criteria for defining the prosodic positions studied. It is therefore possible that the articulatory properties found in initial position of these constituents are only secondary effects of these other prosodic variations. The following arguments will show that it is not the case.

Articulatory variations in initial position do not seem to be conditioned by the occurrence of a pause, since they also occur in constituents not preceded by a pause (Si, Wi, APi). For nasal flow, the distinction between IPi position and the other positions may be influenced by the presence of a pause before the test segment that could induce a change in aerodynamic conditions. However, pausing cannot explain the few variations observed in positions that do not involve a pause (e.g., Wi *vs.* APi for /ɑ̃/).

The articulatory properties of initial segments do not appear to be a secondary effect of the type of intonation contour either. Recall that all the test segments are unaccented and produced with a low tone. Thus, the articulatory variations observed cannot be driven by the presence of a prominence on the segment. The nature and the height of the tone preceding the test segment vary since these are two of the criteria used to define prosodic positions. However, it is not possible to associate any articulatory variations with a specific intonational property: in APi and IPi segments show articulatory distinctions although they are both preceded by a final boundary tone (realized usually as a high tone and sometimes as a low boundary tone); in Wi and Si, segments also show articulatory distinctions although they are both preceded by a low f0 contour without a boundary tone.

Final lengthening is also a criterion used for determining prosodic position. Consequently, articulatory variations do follow the pattern shown by final lengthening. For example, there is more linguopalatal contact in IPi where the test segment is preceded by a large final lengthening. However, for Si and Wi, it is not always the case that the vowel preceding a word-initial segment is lengthened more than the vowel preceding a syllable-initial segment. Nevertheless, some articulatory variation between Si and Wi was observed.

Lengthening of initial segments is also a factor found to vary with prosodic position in French. Initial lengthening was also reported at the word level (among others Oller, 1973; Vaissière, 1983) and for higher constituents (see Keating *et al.*, 1998) in several languages. Thus, it could be the case that the spatial modification of the articulation of initial segments is a consequence of their lengthening. As suggested by Fougeron & Keating (1997), following Lindblom's (1963) reasoning, it is possible that lengthened initial segments have more linguopalatal contact in higher constituents because the raising movement of the tongue has enough time to reach its target position, and even to overshoot it. Regarding the relationship between articulatory closure and amount of linguopalatal contact, it is obviously the case that the spatial dimension of the tongue movement is associated with its temporal dimension. However, when looking at the relationship between acoustic duration and amount of contact, it appears that the change in articulation in initial position is only partly associated with acoustic lengthening in French, especially when considering all the positions examined in this study (i.e., including IPi). Furthermore, for most of the segments, variations in linguopalatal contact distinguish a larger number of prosodic positions than the variation in initial lengthening does. In fact, initial lengthening appears to be mostly a characteristic of Accentual Phrase initial position in French. In English, Fougeron & Keating (1997) also found only a weak correlation between the amount of initial lengthening and the amount of linguopalatal contact for /n/. In Tamil, Byrd and colleagues (Byrd *et al.*, 2000) found a lengthening of the lingual occlusion of initial /n/ in higher constituents, but this lengthening was not associated with any change in the magnitude of the lingual gesture. Conversely, Cho & Keating (2001) found in Korean that the variations in linguopalatal contact show a larger positive correlation with initial lengthening. The relationship between the two factors could then be language-specific.

The cumulative nature of the articulatory variations observed suggests that these are associated with the prosodic phrasing of utterances: the articulatory properties found in initial segments reflect the hierarchical organization of the constituents. In that sense, *prosodic phrasing is realized in the articulation of the segments*. However, it is difficult at this point to conclude that these articulatory properties are perceptible prosodic markers or that they can be used by listeners for prosodic segmentation. Acoustic correlates of these articulatory properties first have to be found. In this study, we saw that initial lengthening often but not always accompanied these properties. An analysis of the acoustic energy of /n/ and /l/ depending on prosodic position (not reported here) has shown a trend for the energy distinction between the initial consonant and the following vowel to increase in IPi position (see Fougeron, 1998). However, this characteristic is not shared by all the speakers or by all the consonants, and it cannot distinguish other prosodic positions. Another interesting finding in Fougeron (1998) was that the spectral characteristics of initial /i/ are affected by the prosodic level of the constituents. From Wi to APi and to IPi, there is a significant progressive increase in F3. Since /i/ is surrounded by labial consonant in the corpus, this increase in F3 could be interpreted as a reduction of the contextual labialization of the vowel in initial position in a higher constituent. This would suggest that initial segments are more resistant to coarticulation in higher constituents, but this hypothesis has to be investigated further.

Whatever the linguistic function of these articulatory properties, it seems clear from this study and others that the variations in the articulation of initial segments appear as traces of the prosodic encoding of an utterance. These variations are not produced randomly, and although they may be optional, they are rule-governed: (1) they are cumulative and follow the prosodic hierarchy, and (2) they consist of subtle modifications of the articulation of the segment, a trend which is shared by all the segments studied. Hence, the issue now is to understand the nature of the physiological mechanism(s) responsible for the occurrence of these articulatory variations.

4.3. *On the nature of prosodically-conditioned articulatory variations*

4.3.1. *Comparison with articulatory variations found in other languages*

Lehiste (1964, p. 196) noted that "the manner in which boundaries are realized in a language constitutes an integral part of its structure, and has to be included in its phonological description". From the data reported so far on articulation at constituent boundaries, it is difficult to draw a comparison between languages since most of the studies have compared only a few types of segments or articulations, and the prosodic constituents studied are specific to each language. Nonetheless, it seems clear that the production of specific articulatory properties at initial boundaries is shared by several languages and that the nature of the variations is similar in the languages studied so far (see Table I).

As illustrated in Fig. 9, modifications in the articulation of initial segments found in French are comparable to the ones described in other studies, both in comparisons

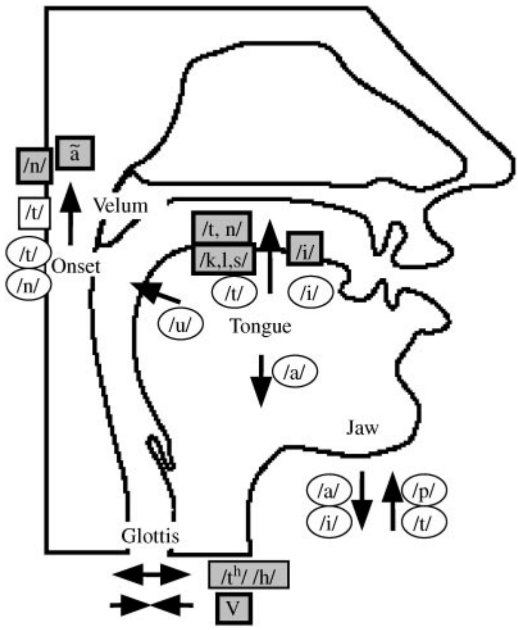

Figure 9. Schematic representation of the articulatory properties found to characterize initial segments. The direction of the arrows indicates the nature of the articulatory property for each articulator concerned. For example, the rising arrow for the tongue means that initial segments are characterized by a higher tongue position. Boxes indicate the properties found to characterize segments in initial position at the word or syllable level (compared to medial or final positions). In gray boxes are the segments for which these articulatory properties have been found to increase in magnitude for segments initial in higher prosodic constituents. Among these, the ones in bold boxes have been confirmed for French in this study. For comparison, circles show the articulatory properties reported to characterize segments in accented syllables.

between initial and noninitial segments at the word or syllable levels (white boxes), and in comparisons between initial positions in several prosodic constituents (gray boxes):

(1) For lingual articulation, initial segments in French show an increase in linguo-palatal contact and a widening of the constriction area in higher constituents. These properties were also found to characterize syllable/word-initial consonants in French by Rousselot (1901) and Straka (1963), and by others in several languages. This result also replicates the properties observed for initial stops in higher domains in English, in Korean and in Taiwanese (see Table I). The present study adds to these results by showing that the initial high vowel /i/ presents the same type of variation as consonants.

(2) For nasal articulation, initial nasal segments in French show some decrease of nasal flow. A similar observation was made by Gordon (1996) for Estonian /n/ in initial position of higher prosodic domains. Fujimura (1977) and Krakow (1989) observed that velum position is higher in word initial position compared to medial or final position for nasal consonants in English and Japanese. If we extend these observations made at the word level to our results, it is possible to interpret the observed decrease in nasal flow as a raising of the velum, which induces a reduction of velopharyngeal aperture in higher

position. Again, this study shows that nasal consonants and nasal vowels are affected by prosodic position in the same way (when they show variation).

(3) For glottal articulation, initial /i/ is more frequently glottalized in higher constituents than in Wi position in French. In other languages, vowel glottalization has been shown to characterize initial as opposed to medial or final vowels (e.g., Lehiste, 1964; Kohler, 1994). In French, processes like liaison or enchaînement reduce the likelihood of a word-initial vowel being glottalized. In the corpus used here, the test vowel was produced in the sequence "Philippe Ippine". It is probable that there was enchaînement between these two words, although this was not tested empirically. That initial vowels are more frequently glottalized in higher prosodic constituents in French corresponds to findings for English by Pierrehumbert & Talkin (1992) and Dilley *et al.* (1996): initial vowels are more frequently glottalized in Intonational Phrase compared to Word, and compared to Intermediate Phrase if the vowels are unaccented (Dilley *et al.*, 1996). As far as VOT is concerned, in Korean (Jun, 1993; Cho & Keating, 2001), in Taiwanese (Hsu & Jun, 1997) and in English (Pierrehumbert & Talkin, 1992), it has been found that the VOT of an aspirated voiceless consonant varies depending on its prosodic position. In Korean, for example, Jun (1993) showed a progressive lengthening of VOT of aspirated stops from Si to Wi to APi. In French, whose stops are unaspirated, this effect does not appear so clearly.

4.3.2. *Comparison with articulatory properties found in accented position*

As noted by Beckman & Edwards (1994, p. 8), the phrasing organization of an utterance "can be indicated by marking the edges or by marking the heads". It is therefore possible that articulatory variations in these two prosodically important positions (boundary position and accented position) are governed by the same mechanism. Indeed, the nature of the variations found in initial position of prosodic constituents is comparable to that observed in accented position as illustrated in Fig. 9 (circles).

For most of the articulators, modification in the articulation of segments under accent has been reported for vowels. For lingual articulation, several studies have shown that tongue position is more peripheral for vowels in accented compared to unaccented position (Rousselot (1901), Giot (1977), in French; Kent & Netsell (1971), in English; Farnetani & Vayra (1996), in Italian). For example, while /a/ is found to be more open in accented position, the tongue position for accented /i/ is higher and sometimes more front. This modification is thus similar to that showed by /i/ in initial position in higher constituents: more linguopalatal contact reflecting a higher and/or more advanced tongue position.

Accented consonants also show similar modifications to that found in initial position. For example, /t/ has a greater amount of linguopalatal contact in accented Italian syllables (Farnetani & Vayra, 1996). Vaissière (1988) showed that the velum is higher for nasal and oral consonants in accented syllables (but only in onset position).

Two main hypotheses have been advanced to explain articulatory variations conditioned by accent. Based on the observation of the jaw, Beckman and colleagues (Edwards & Beckman, 1988; Beckman, Edwards & Fletcher, 1992) proposed that the articulatory variations in accented position contribute to increasing the sonority distinction within a syllable: consonants with a higher jaw position are less sonorous while vowels with a lower jaw position are more sonorous. Straka (1964) made a similar hypothesis stating that it is the aperture distinction within the syllable that is increased under accent as well as in initial position. In these two hypotheses, it is the syntagmatic contrast in the syllable that is enhanced. However, de Jong (1995) has argued that the articulation of accent does not imply a sonority expansion mechanism. He showed that in English emphatic stress modifies not only the position of the jaw but also that of other articulators and that for some segments, the articulatory modifications go against a sonority expansion. For example, the elevation of the tongue for accented nonopen vowels reduces their sonority. Consequently, de Jong proposed that articulatory variations found in accented syllables result from a local hyper-articulation. Hence, the distinction between accented and unaccented position is made on the paradigmatic scale by an enhancement of the distinctive features of accented segments.

Considering the variations observed in domain-initial position in this study, neither of these two hypotheses can explain all the results. The increase in linguopalatal contact for initial /i/ in higher constituents does not result in an increase in the vowel's sonority or aperture. Moreover, measurement of the acoustic energy of sonorants (not presented here) showed that the modifications observed do not involve a systematic increase in acoustic distinction between the consonant and the following tautosyllabic vowel (see Fougeron, 1998). The hypothesis of an enhancement of distinctive features is in turn challenged by the variation observed for nasal segments. Initial nasal consonants and vowels show a decrease in nasal air flow in initial position of higher constituents. Neither their nasal feature nor their sonorant feature is therefore enhanced.

In fact, it appears that articulatory variations observed in initial position may contribute to enhancing syntagmatic as well as paradigmatic contrast (see for example, the lingual articulation of the consonants), but it seems that the underlying process governing these variations has to be found in a more physiological mechanism.

4.3.3. *A local and progressive articulatory strengthening in domain initial position*

Initial and accented positions have been traditionally described as "strong positions" in order to reflect the particular resistance of the segments in these positions to diachronic evolution. The notion of strength has also been used to describe the articulatory properties found in the segments placed in these two positions. For example, Vaissière (1986, 1988) posited a [+strong feature] for the word-initial and accented positions in English. She suggested that this feature is realized as an increased tension of the overall production mechanism. For Fujimura (1990, p. 233), initial positions in syllables, words and phrases are characterized by more "forceful" articulatory gestures along with a reinforced source intensity.

The notions of "strength", "strengthening", "articulatory force" have also been widely used in the literature to characterize the articulation of particular segments: strong consonants along a strength scale and fortis (*vs.* lenis) consonants (e.g., Delattre, 1940; Malmberg, 1943; Straka, 1964 for French). Straka (1963) also used this notion to characterize a particular style of speech, "la parole renforcée" (strengthened speech), which he described as involving a more "energetic or more forceful" articulation. Interestingly, the segmental articulatory properties, allegedly explained by an increase in articulatory force, present striking similarities with the properties found to vary in initial position in prosodic constituents. For example, an increase in linguopalatal contact and a widening of the occlusion surface was found to distinguish strong (voiceless) consonants from weak (voiced and nasal) consonants (e.g., Rousselot, 1901; Simon, 1967; Marchal, 1979 for French). Similar properties were found for /t, k, s, l/ in "parole renforcée" compared to normal pronunciation by Straka (1963). Strong voiceless stops have also been shown to have a closer tightening of the velum against the velopharyngeal wall compared to voiced stops (Simon, 1967). Moreover, Straka found that in "parole renforcée" velum position is higher for both oral and nasal segments.

Nonetheless, the notion of "articulatory force" (or "articulatory strengthening") has been strongly debated in the literature, mostly because of its intuitive use, its lack of physiological definition and other difficulties in quantifying it (see e.g., Debrock, 1977). However, if one considers the definition given by Straka (1963), it seems that articulatory strengthening could be the mechanism involved in initial position. For him, articulatory force is "rien d'autre que la force de contraction des muscles entrant en action pour l'articulation donnée" (nothing but the contraction strength of the muscles involved in a given articulation, p. 91). What must be underlined in this definition is that it is only the muscles involved in the positioning of the articulators for the given articulation that are affected by this increased contraction. For Straka, articulatory strengthening is thus an increase in the "force of the articulatory movements" but not an increase in the overall "muscular effort" (including the phonatory and expiratory forces) involved in articulation.

With this definition, articulatory strengthening could be appropriate for explaining the modification observed in the lingual, nasal and glottal articulation of segments in initial positions:

(1) Given the approximation in inferring lingual movements from EPG traces, the larger amount of linguopalatal contact and the widening of the occlusion surface could reflect a greater elevation of the tongue in initial position (and maybe also some backing/fronting depending on the consonant's place of articulation). For consonants, this elevation could result from an increased contraction of the elevator muscles of the tongue (genioglossus, palatoglossus and styloglossus). For the close vowel /i/, it depends on which muscles are considered to be mainly involved in its production. Straka considered that all vowel articulations were essentially governed by the activity of the lowering muscles. However, since then, it has been empirically shown that elevator muscles (particularly the posterior genioglossus) are mainly responsible for the protrusion of the tongue to the front of the mouth (e.g., Honda, Hirai & Kusakawa, 1995; Payan & Perrier, 1996). An increased contraction of this muscle would therefore increase the tongue protrusion, which, in turn, could result in an increase in linguopalatal contact.

(2) The decrease in nasal flow observed for nasals in initial position of higher constituents in this study, as well as the higher position of the velum for word-initial oral and nasal consonants observed in the literature (see introduction), could also be explained by an articulatory strengthening. The elevation and the lowering of the velum position seem to be mainly governed by the activity of the levator palatini, its contraction and its relaxation, respectively (see Bell-Berti, 1993). An articulatory strengthening for non-nasals in initial position would thus increase the levator palatini contraction, resulting in a higher velum position. Conversely, for nasals, this strengthening would reduce the relaxation of the levator-palatini, resulting in a smaller lowering of the velum (see also Straka, 1963; Fujimura, 1990).

(3) Vowel glottalization observed in initial position in higher constituents could also result from articulatory strengthening if an increase in contraction of the laryngeal muscles affects the constriction of the arytenoids, resulting in a perturbation of vocal fold vibration.

Even though the definition adopted here remains to be tested empirically, articulatory strengthening appears as a possible unifying physiological mechanism to account for the articulatory modifications observed for various segments in domain-initial position. Articulatory strengthening seems here to be applied locally to the initial position of a constituent, and to be a function of the height of that constituent. Therefore, the distinction between prosodic boundaries seems to consist of a gradual increase in articulatory strengthening from lowest to highest prosodic constituents. In that sense, it is conceivable that articulatory strengthening is one of the physiological correlates of the prosodic phrasing of an utterance. However, considering the variability observed in the realization of the articulatory properties in each of the domain-initial position studied, it seems that, at this point, articulatory strengthening should be considered mainly as a trace of the prosodic encoding of utterances rather than an intended cue to phrasal organization.

5. Conclusion

While the segmental and suprasegmental aspects of speech have been most often studied separately, it becomes more and more obvious that these two aspects are closely connected. The signaling of prosodic boundaries is undoubtedly multi-parametric. Final lengthening and melodic contours may be the most robust and the most important acoustic cues for the perception of phrasing. However, this study of French confirms the fact that the prosodic phrasing of an utterance is also reflected in the articulation of initial segments. The relevance of this finding for perception, as well as its linguistic function, remain to be explored. Nonetheless, these results suggest that some articulatory properties often defined as segmental characteristics should be considered as one of the suprasegmental characteristics of speech.

I would like to thank my three subjects, and particularly Laurent Girard, for participating in these experiments. I am grateful to Pat Keating and Jaqueline Vaissière for their help and motivating spirit and to all the members of the UCLA Phonetics Lab for comments on various presentations of this work. I also wish to thank F. Bell-Berti, J. Fletcher and an anonymous reviewer for helpful comments. This work was supported by a Research Allocation from the French Research Ministry and by NSF grant SBR-9511118 to P. Keating. The author is currently funded by grant 1113-049698.96 from the Fond National de Recherche Suisse.

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