Articulatory strengthening at edges of prosodic domains

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In this paper it is shown that at the edges of prosodic domains, initial consonant and final vowels have more extreme (less reduced) lingual articulations, which are called articulatory strengthening. Linguopalatal contact for consonants and vowels in different prosodic positions was compared, using reiterant-speech versions of sentences with a variety of phrasings read by three speakers of American English. Four prosodic domains were considered: the phonological word, the phonological (or intermediate) phrase, the intonational phrase, and the utterance. Domain-initial consonants show more linguopalatal contact than domain-medial or domain-final consonants, at three prosodic levels. Most vowels, on the other hand, show less linguopalatal contact in domain-final syllables compared to domain-initial and domain-medial. As a result, the articulatory difference between segments is greater around a prosodic boundary, increasing the articulatory contrast between consonant and vowels, and prosodic domains are marked at both edges. Furthermore, the consonant initial strengthening is generally cumulative, i.e., the higher the prosodic domain, the more linguopalatal contact the consonant has. However, speakers differed in how many and which levels were distinguished in this way. It is suggested that this initial strengthening could provide an alternative account for previously observed supralaryngeal declination of consonants. Acoustic duration of the consonants is also affected by prosodic position, and this lengthening is cumulative like linguopalatal contact, but the two measures are only weakly correlated. © *1997 Acoustical Society of America.* [S0001-4966(97)04106-4]

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INTRODUCTION

It is by now well-established that prosody affects articulation. Beckman and Edwards (1994, p. 8) define prosody as ''the organizational framework that measures off chunks of speech into countable constituents of various sizes.'' These constituents are called prosodic domains, and their organization is called prosodic structure. Prosodic structure plays an important role in the realization of the ''content'' of speech sounds (Beckman and Edwards, 1994; Pierrehumbert and Beckman, 1988, p. 116; Fujimura, 1990b, p. 325). Beckman and Edwards distinguish two kinds of locations within prosodic domains that lead to differences in the articulation of content. One location is the head, or most prominent part, of a domain. For example, a nuclear accented syllable is the head of an intermediate phrase, and its vowel can have greater duration, lingual displacement towards the target, or velocity than other vowels (Beckman and Edwards, 1994; de Jong, 1995). The other location is next to the boundaries of the domain, the initial and final edge positions. For example, lengthening, a temporal change, has been found to occur at the initial and final edges of prosodic domains (e.g., Oller, 1973 for English; Byrd *et al.*, 1997 for Tamil). Our interest here is to add to the literature on domain edges, particularly the relatively small literature concerning spatial changes at edges.

For word edges, several studies have shown that articulations of the tongue, lips, velum, and glottis differ in magnitude in word-initial versus non-initial position (e.g., Fromkin, 1965; Vaissière, 1988; Krakow, 1989; Cooper, 1991; Browman and Goldstein, 1992; Farnetani and Vayra, 1996); for example, word-initial stops in English have more linguopalatal contact (Byrd, 1994, 1996). For phrase and sentence edges, similar articulatory variation has been found, though the number of studies is smaller: more linguopalatal contact for sentence-initial coronal stops (Keating, 1995), more lip rounding for sentence-initial rounded vowels (van Lieshout *et al.*, 1995). Fougeron and Keating (1996) found less nasal airflow (interpreted as higher velum), and more linguopalatal contact, for French /n/ when initial in a phrase. On the other hand, Byrd *et al.* (1997) found lengthening but no spatial changes at word and phrase edges in Tamil. Finally, acoustic records suggest that glottal articulations also are influenced by phrasal position (Pierrehumbert and Talkin, 1992; Jun, 1993; Dilley *et al.*, 1996).

Another effect on articulation has also been suggested: That articulations are more extreme earlier in utterances and decline[1] gradually over the course of utterances (e.g., Vaissière, 1986; Vayra and Fowler, 1992; Krakow *et al.*, 1994; Hinton, 1996). Vayra and Fowler described the articulatory variation they found for stressed Italian vowels as a ''supralaryngeal weakening'' and ''declination of supralaryngeal gestures'' (p. 49), ''a weakening of the entire mechanism, respiratory, laryngeal and supralaryngeal for stressing a vowel'' (p. 59). Most recently, Krakow *et al.* (1994) found that the height of the velum during the English /t/ depended on its position from early to late in a sentence. The velum was highest for the earliest /t/, intermediate for a middle /t/, and lowest for the latest /t/. They described ''supralaryngeal declination'' as ''a general 'winding down' in speech'' (p. 333).

The question arises, then, how supralaryngeal declination, apparently a global effect of serial position in a sentence, is related to the local effect of being at the edge of a prosodic domain. One idea has been that they are the same thing: That domain-final articulations are reduced relative to domain-initial ones precisely because they come later in the domain (Krakow 1989, p. 181). Yet existing data make clear that effects at word and phrase edges cannot be ascribed to simple sentence-level declination, because those effects do not depend on serial order. For example, in Byrd (1994), Jun (1993), and Pierrehumbert and Talkin (1992), the position of test segments in test sentences was controlled across comparisons. If edge effects and declination are to be related, then it must be in a more complicated way.

An important finding about domain-final lengthening is relevant here. Klatt (1975) and Wightman *et al.* (1992) showed that final lengthening is found at more than one domain level, and the lengthening is greater at the end of higher domains than of lower domains. That is, this edge effect operates hierarchically. Similarly, Jun (1993 p. 237) proposed that ''there is a hierarchy of strength of prosodic position'' to account for her finding that voice onset time (VOT) of a Korean consonant is greatest when phrase-initial, next greatest when word-initial but phrase-medial, and least when word- and phrase-medial. Supralaryngeal declination could also be hierarchically nested [as is $f0$ declination (Thorsen, 1985; Maeda, 1976)], and occur not only at the sentence level, but also at the word level, and at phrasal levels in between. Under this interpretation, then, declination would not depend strictly on serial position within a sentence, but instead on serial position within any given prosodic domain.

However, alternative hypotheses to declination are also potentially consistent with previous observations. Figure 1 shows a schematic of different possible patterns within a single prosodic domain, with three points highlighted in each pattern. Articulation varies along some arbitrary dimension on which lower, less extreme, values indicate articulatory reduction. We will refer to less extreme articulations as *weakened* (right panels) and more extreme articulations as *strengthened* (left panels). This is the same notion of weakening as that used by Vayra and Fowler (1992) and in historical linguistics (Straka, 1963). Figure 1(a) and (b) shows progressive trends in the two directions: *Progressive weakening*, corresponding to supralaryngeal declination, and *progressive strengthening*, a kind of reverse declination. In contrast, the other patterns represent more localized effects at domain edges, as has been shown to be the case for domain-final lengthening (Wightman *et al.*, 1992; Beckman *et al.*, 1992). Figure 1(d) shows a pattern that we will call *final weakening*, a local reduction or lenition only at the end of the domain. Figure 1(e) shows the converse, what we will call *initial strengthening*. Initial strengthening accords with

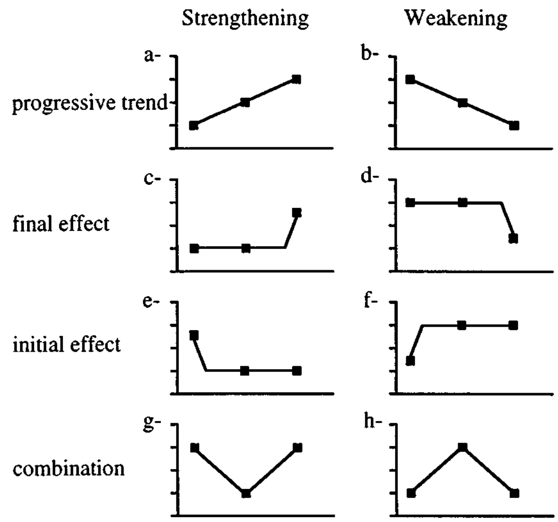

FIG. 1. A schematic of possible patterns of articulatory variation within a prosodic domain. The horizontal axis represents time; the vertical axis represents an arbitrary dimension of articulatory variation, in which lower values are a less extreme articulation. See text for explanation of individual panels.

Fujimura's suggestion (1990a, p. 232) that ''Syllable initial position, as well as word and phrase initial position, seems to be generally characterized by more 'forceful' articulatory gestures (...).'' Other possible local effects are given in Fig. 1(f) (*initial weakening*) and (c) (*final strengthening*), and combinations in (g) (V-shaped initial plus final strengthening) and (c) (initial plus final weakening).

Any of these patterns can be hierarchically nested. If some small number of datapoints is then sampled from the whole, then it is possible to obtain a set of three declining datapoints not only from nested progressive weakening, but also from nested initial strengthening or nested final weakening. All that is required is that the test utterance is produced with a certain kind of prosodic organization, in which the hierarchical levels decrease along with serial position in the sentence. That would be any prosodic structure in which the first datapoint is from a segment which is initial in a high prosodic domain (e.g., an utterance), the second segment is initial in some lower prosodic domain (e.g., a phrase), and the third segment is initial in an even lower prosodic domain (e.g., a word). There is thus a distinction between what can be observed in a set of datapoints versus the mechanisms that might underlie and produce that observation. The fact that some measure declines over an utterance does not by itself mean that speech involves a declination mechanism. Therefore our attention is focused on local effects as an alternative to declination.

The present experiment was designed with four goals. The first is to determine whether the articulation of a segment varies depending on its position in long sentences. The second is to determine if any such variation is due to a local strengthening or weakening at particular prosodic positions, or if it is due to a global progressive trend. To do this we compared consonants and vowels in a CV syllable in initial, medial, and final positions within each of four prosodic domains. The third goal is to test whether the articulatory varia-

TABLE I. Four types of models sentences for the reiterant speech with the syllable /no/.

Model sentences	
1. 89+89+89+89	=a lot.
2. (89+89)*(89+89)	=a lot.
3. 89*(89+89+89)	=a lot.
4. (89+89+89)*89	=a lot.

tion occurs at more than one prosodic level and is hierarchically cumulative. To do this we positioned test segments at different prosodic levels. The fourth goal is to test for acoustic correlates of these articulatory differences; here we will focus only on durational correlates.

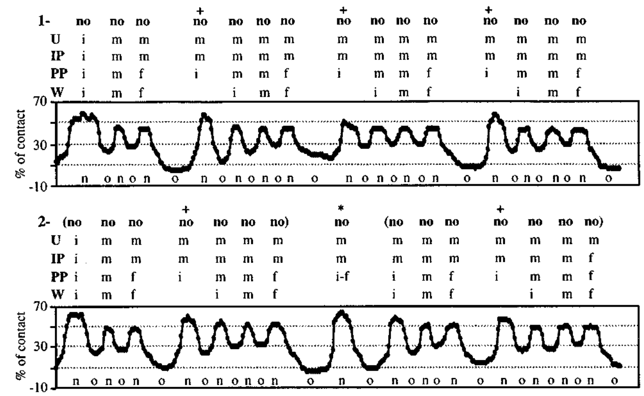

FIG. 2. EPG sample data: The line that moves up and down across the graph is the linguopalatal contact (as percent of electrodes contacted) over time for two samples of the reiterant sentences based on ''89+89+89+89=a lot'' and ''(89+89)*(89+89)=a lot,'' produced by speaker 1. At the top of each sample, reiterant syllables (/no/) aligned with percent-contact display, and arithmetic operators + and * indicated; below the percent-contact display, /n/ aligned with maximum contact and /o/ with minimum contact. Above the percent contact display, codings of the 15 test syllables as i(nitial), m(edial), or f(inal) in four prosodic domains: utterance (U), intonational phrase (IP), phonological phrase (PP), and word (W).

I. EXPERIMENT

A. Method

1. Electropalatography

The articulatory measure for consonants and vowels was linguopalatal contact, contact between the tongue blade/front and the hard palate. Variation in the amount of linguopalatal contact indicates differences in overall oral constriction. Linguopalatal contact was measured by electropalatography (EPG). The Kay Elemetrics Palatometer was used in this experiment; its custom-made pseudopalates have 96 electrodes covering the entire hard palate and the inside surfaces of the molars. Each sweep of the 96 electrodes takes 1.7 ms, and the sampling interval is 10 ms.

2. Test sentences and reiterant speech

To obtain different phrasings in our test stimuli, we used arithmetic statements in which the phrasing of the words would be crucial to conveying the meaning, shown in Table I. The last three test sentences require some prosodic disambiguation, while the first sentence is less constrained. As shown in Table I, these sentences were produced with the numeral ''89'' (eighty-nine), which usually has lexical stress on its final syllable. Because we were particularly interested in the behavior of the initial syllables, we wanted to avoid confounding stress and positional effects. To control for possible effects of lexical stress, lexical stress location was varied by using two additional trisyllabic numerals, ''70'' (seventy) with stress on its first syllable, and ''100'' (one-hundred) with stress on its second syllable.

The test sentences in Table I served as models for reiterant speech, in which each syllable of a model sentence is replaced by a single syllable (here, /no/), but intonation and other prosodic aspects of the model are meant to be preserved. The reiterant utterances used the syllable ''no'' (/no/), for all of the utterance before ''equals.'' For example, ''(89+89+89)*89=a lot'' was read as ''(nonono no nonono no nonono) no nonono equals a lot,'' giving 15 reiterant syllables. The vowel /o/ was chosen because it is one of the American vowels which occurs in both stressed and stressless syllables, yet is quite different from /n/ in its contact pattern, thus making clear the consonant to vowel difference.

3. Subjects and procedure

There were three female American English speakers in the experiment, all phoneticians in the UCLA Phonetics Laboratory. Speaker 1 was the second author. Speakers 2 and 3 were graduate students who had participated in one previous EPG study (Byrd, 1994) but were naive about the present study.

Each test sentence was repeated six times. Speaker 1 read all combinations of the three numerals and four sentence types, for a total of 72 sentences. Speakers 2 and 3 produced all the numerals only in the first sentence type, and the other sentence types only with ''89,'' for a total of 36 sentences per speaker. Subjects were not told how to phrase each sentence, but instead were simply asked to speak moderately fast and to convey the mathematical meanings indicated, which they all said they understood. Subjects practiced first with the real words, then reiterantly a few times. The audio signal was recorded along with the EPG signal, using an ordinary tabletop microphone in an open laboratory room. Both the audio (12.8-kHz sampling rate, 16-bit resolution) and the EPG signal (100-Hz sampling rate) were recorded digitally in Kay Elemetrics's Computerized Speech Lab (CSL).

4. Measurements

Linguopalatal contact was measured for each /n/ and /o/. EPG data were analyzed outside CSL by computing the percent of the 96 electrodes contacted in each data frame (Byrd *et al.*, 1995). Each percentage point, then, is about equal to one electrode contacted. Figure 2 shows data for sample tokens by speaker 1, for the first two sentence types, using the number ''89'' as the model. Notice that in both sample sentences the first /n/ has noticeably greater contact that does the second /n/, while the third /o/ has noticeably less contact than does either of the first two /o/'s.

For each segment (stop or vowel) contact was measured in a single frame, the one showing the extreme contact for that segment. This extreme was defined differently for the /n/ and the /o/, because their articulatory targets are in opposite directions. Because a canonical stop /n/ is characterized by a linguopalatal closure, the target of its articulatory movement was considered to be a maximum contact. Because a canonical vowel /o/ is characterized by a lingual lowering and backing, the target of its articulatory movement was considered to be a minimum contact. With two segments per /no/ syllable, 15 syllables per utterance, and 144 utterances, there was a total of 4320 contact measurements.

In addition, acoustic durations of /n/'s and /o/'s were measured from computer-displayed spectrograms. Segmentation was based on the presence of energy in the region of the higher formants.

Finally, a tonal transcription was made of each token with the help of a trained transcriber who listened to the audio signal and looked at the $f0$ contour, the segmental durations, and any pauses. Phrase tones and boundary tones were transcribed using the tonal part of the ToBI system (Silverman *et al.*, 1992).

Statistical analyses were performed on the coded data using StatView (Abacus Concepts, 1992). The tests used are described in each results section below. We note here only that, because the speakers selected their own phrasings, and because the categories form a hierarchy, the sample sizes of the different prosodic categories varied widely, but were never smaller than 25 per cell.

5. Prosodic coding

In order to compare different prosodic positions, each segment was coded according to its position in a prosodic structure derived from prosodic hierarchy theory (see Wightman *et al.*, 1992 or Shattuck-Hufnagel and Turk, 1996 for reviews). (1) Our highest level is an utterance (henceforth utterance or U). An utterance here corresponds to a complete sentence. Although not all researchers agree on the existence of the utterance as a distinct prosodic domain, it seems possible that the very beginning of an utterance (in a pretheoretical sense, meaning simply when a speaker begins talking) could have some special status with respect to articulation. (2) This utterance domain contains one or more intonational phrases [henceforth IP, also called Full Intonational Phrases by Beckman and Pierrehumbert (1986)]. An IP is defined by a complete intonational contour, including a final boundary tone. (3) Our intermediate level is a smaller phrasal domain, defined by at least one pitch accent and a phrase tone. It is the Intermediate Phrase of Beckman and Pierrehumbert (1986), and is roughly equivalent to the phonological phrase of other authors. For clarity of abbreviation we will refer to it here as the phonological phrase (henceforth PP). (4) The phonological word (henceforth word or W) in this study corresponds to a numeral like ''eighty-nine.'' While the subparts of ''89'' and ''100'' (''eighty,'' ''nine,'' ''one,'' ''hundred'') are themselves lexical words, ''89'' and ''100,'' like other compounds, function as single prosodic as well as morphosyntactic words. (5) We considered a domain lower than the word, the syllable (henceforth syllable, syll, or S) solely in our across-domain comparisons.

Given the strictly hierarchical relation of these levels, every syllable in every token could be coded according to its position in each domain. Figure 2 shows the coding of the syllables in the two sample tokens. In every case the entire sentence was taken to be a single utterance. This means that the first syllable in each token was coded as U-initial, and all other test syllables in each token were coded as U-medial. There were no U-final test syllables, because the ''equals a lot'' portion of the tokens was not analyzed. Each numeral was a phonological word, and the initial, medial, and final syllables of the numerals were coded as word-initial, word-medial, and word-final, respectively. For the cross-domain analysis the W-medial syllables were recoded as syll-initial. The arithmetic operators ''plus'' and ''times'' were not used as words, since their single syllables are both W-initial and W-final, but they were coded for all higher levels.

Figure 2 also shows codings for the two intermediate prosodic levels used in this study, IP and PP. For these two levels, there was inter- and intra-speaker variation in phrasing (as in Fujimura, 1990a), so that the coding depended on the tonal transcription of each token. Consider first the IP level. Because the prosodic domains are taken to be strictly layered, the first syllable of each token is necessarily initial in an IP. The end of the IP is defined by the presence of a boundary tone. Any syllable after an IP-final syllable is IP-initial; all other syllables are IP-medial. Some tokens, like sample No. 1, had no syllables coded as IP-final, meaning that the first IP continued past the last test syllable into the ''equals a lot.'' In general, there was a tendency for parentheses to delimit IPs, though not in either of the examples shown here. Finally, consider the PP level. The first syllable of a token is necessarily PP-initial. The end of a PP is defined by an intermediate break, and any following syllable is PP-initial. The PPs seen in Fig. 2 comprise either single numerals, or a ''plus'' and a following numeral, or a ''times'' alone. Although these are the general tendencies, other phrasings occurred as well. Both operators and numerals were coded for position in these two domains (as well as in the utterance). If an operator formed a PP or IP by itself, it was coded as both initial and final, as with the ''PPi-f'' in sample No. 2, and was excluded from all further analyses. Although some prosodic domains are consistently longer than others here (an utterance always contains more than 15 syllables and a word only three syllables), PPs and IPs have variable length. Also word-, PP-, and IP- initial syllables can occur in various position in the utterance, so it is not the case that syllables which are initial in a higher level come earlier in the utterance than syllables which are initial in a lower domain. The consonant and vowel of each syllable are coded the same as the syllable as a whole. To avoid potential confusion with absolute positions in a CV, /o/ in a domain-initial CV syllable will be referred to as ''initial-syllable /o/'' and /n/ in a domain-final CV syllable will be referred to as ''final-syllable /n/.'' Finally, syllables in numerals were coded as stressed or unstressed based on auditory impressions of each speaker's pronunciation.[2]

B. Results for linguopalatal contact

1. Within-domain comparisons

We tested for variation in linguopalatal contact of /n/ and /o/ within each prosodic domain in order to determine which, if any, of the mechanisms presented in Fig. 1 is at work in our data (especially, a local effect at domain edges or a global trend). Recall that the dependent variable, the measure of articulatory variation, is the extreme value of linguopalatal contact. For /n/, for which the extreme of contact is the maximum value, strengthening would correspond to an increase in contact. In contrast, for /o/, for which the extreme of contact is the minimum value, strengthening would be a decrease in contact. Weakening will show the reverse patterns. A decrease of contact for /o/ can result from a backing or lowering of the tongue, but to simplify here we will describe it as ''opening.''

a. Tests for domain initial effects: initial versus medial and final syllables. In this analysis we compare the initial syllable with the medial and final syllables in each prosodic domain to test for local effects in domain-initial position. First, U-initial segments were compared to U-medial segments, i.e., all other segments (recall that there are no U-final test segments). Second, IP-initial segments which were not also U-initial were compared to IP-medial and IP-final segments. Third, PP-initial segments which were not also IP-initial or U-initial were compared to PP-medial and PP-final segments. Finally, W-initial segments which were not also PP-initial, IP-initial, or U-initial were compared to W-medial and W-final segments. Therefore, in these analyses, ''IP-initial,'' for example, means ''the highest domain in which this syllable is initial is the IP.'' This limitation to ''exclusive'' coding was necessary to ensure that initial segments in some smaller domain would not have greater average contact than the medials or finals because some initials were also initial in a larger domain. With three speakers, there were thus a total of 12 comparisons.

Figure 3 shows the average values for each speaker of these linguopalatal contact measures for the /n/'s and the /o/'s in initial, medial, and final positions within each prosodic domain. For this analysis, all data from the three subjects were used. Table II gives the results of statistical comparisons by one-factor analysis of variance (ANOVA) and Fisher's protected least significant difference (PLSD) *post hoc* pairwise comparisons, with 0.05 as the significance level for all tests. The null hypothesis is that there is no difference in contact across these positions within each domain.

Consider first the /n/'s. For all three speakers, U-initial /n/'s have significantly more contact than U-medial /n/'s; IP-initial /n/'s have significantly more contact than IP-medial and IP-final-syllable /n/'s; PP-initial /n/'s have significantly more contact than PP-medial and PP-final-syllable /n/'s. More linguopalatal contact in initial position for /n/ is an initial strengthening. On the other hand, no general pattern is seen within words; only speaker 3 has more contact for W-initial /n/ than for both W-medial and W-final-syllable /n/. Speaker 1 does not show variation across word positions. For speaker 2, Word initial /n/'s have more contact than medial ones but not more than final ones.

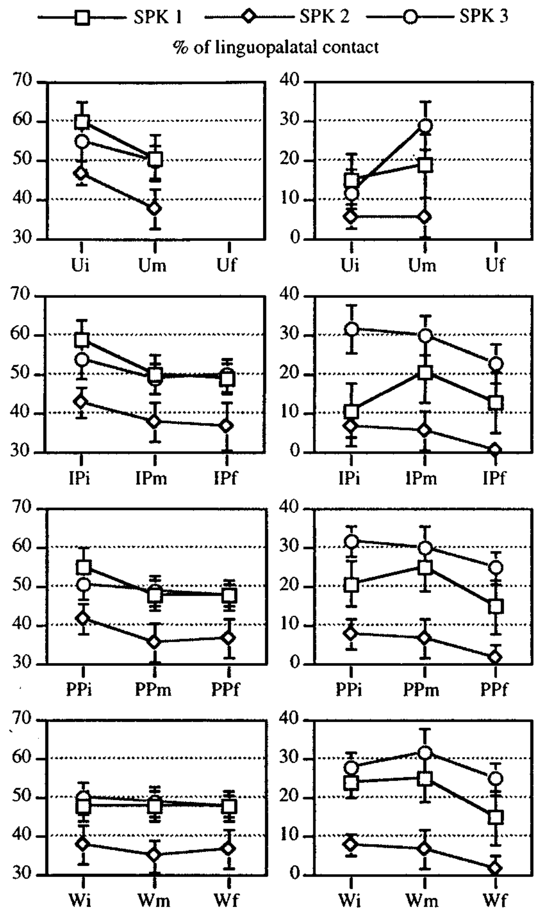

FIG. 3. Maximum linguopalatal contact for /n/'s (left) and minimum linguopalatal contact for /o/'s (right) in three positions (initial, medial, final) in each of the four prosodic domains (utterance, intonational phrase, phonological phrase, word). Speaker results are shown separately within each panel. See Table II for significance of comparisons. All data from all speakers are included here, coded exclusively. A more extreme articulation is more contact for /n/ and less contact for /o/.

Note that this initial strengthening holds although the prosodic coding is exclusive for domain initial /n/'s. However, another possible confound in this kind of analysis could be that the higher-domain-medial /n/'s would have less contact simply because they would also be in medial or final syllables in the word. Nonetheless, when we compared initials, medials, and finals within the PP and IP levels, taking only /n/'s which are W-initial or in operators, much the same result was found [(b) in Table II]. IP-initial /n/'s still had significantly more contact than medials for all three speakers. PP-initial /n/'s still had significantly more contact than medials for two of the three speakers (speakers 1 and 2); for speaker 3 (the subject who has more contact W-initially than medially and finally) the direction of difference was maintained but it was no longer significant. Thus when the word and PP levels are taken together, every speaker distinguishes initial consonants in one or the other domain.

Another confounding factor could be the position of lexical stress—this could favor one possible mechanism compared to the others, especially at the word level. For speaker 1, we recorded the reiterant version of the three numerals in all the sentence types. When the three lexical stress

TABLE II. Results of statistical comparisons for Sec. I B 1. Ficher's PLSD *post hoc* comparison of percent of linguopalatal contact between initial versus medial versus final /n/'s and /o/'s at the four prosodic domains defined for the three speakers. $* = p < 0.05$; ns$= p \geqslant 0.05$. The columns for each domain correspond to: (a) all data in Fig. 5, (b) only W-initial and operators, (c) not W-initial or PP-initial.

	/n/								/o/							
All numerals	U	IP			PP			W	U	IP			PP			W
Speaker 1	(a)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(a)	(a)	(b)	(c)	(a)	(b)	(c)	(a)
initial versus medial	>*	>*	>*		>*	>*		ns	<*	<*	<*		<*	<*		<*
initial versus final		>*			>*			ns		ns			>*			>*
medial versus final		>*		ns	ns		ns	ns		>*		>*	>*		>*	>*
Speaker 2																
initial versus medial	>*	>*	>*		>*	>*		>*	ns	ns	ns		ns	ns		>*
initial versus final		>*			>*			ns		>*			>*			>*
medial versus final		ns		ns	ns		<*	<*		>*		>*	>*		>*	>*
Speaker 3																
initial versus medial	>*	>*	>*		>*	ns		>*	<*	ns	ns		>*	>*		<*
initial versus final		>*			>*			>*		>*			>*			>*
medial versus final		ns		<*	ns		ns	ns		>*		>*	>*		>*	>*

patterns are equally represented in this way, initial strengthening of /n/ is found at every level except the word level, suggesting that lexical stress is not the cause of the overall initial strengthening pattern. However, at the word level no distinction is found between initial, medial, and final-syllable /n/'s, suggesting that there could be an effect of lexical stress.

Next consider the /o/'s, shown in the panels at the right in Fig. 3. Recall that initial strengthening, a more extreme articulation in domain initial position, would mean for /o/ less contact (greater opening), while initial weakening would mean more contact. Initial-syllable /o/'s (/o/'s in the initial CV syllable of a domain) have less contact than medial /o/'s for only half of the 12 comparisons: within all levels for speaker 1, and within utterance and word for speaker 3. In two comparisons initial-syllable /o/'s have more contact than medials, and in the other comparisons they have the same contact. So for the vowel /o/, there is some initial strengthening, but it is less prevalent than that observed for /n/, being consistent for only one speaker. These results hold whether we include only vowels in the word-initial syllable, or all vowels, at higher prosodic levels [Table III(a) and (b)].

b. Tests for domain-final effects: final versus initial and medial syllables. In this analysis we compare the final syllable with the medial and initial syllables in each prosodic domain to test for local effects in domain-final position. This test cannot be done at the utterance level, since there are no U-final test syllables. With three speakers and three levels, then, there are nine tests to be made for /n/ and for /o/. First, consider the consonants. (Recall that final-syllable /n/'s are the /n/'s in the final CV syllable of a domain.) In Fig. 3, the difference between medial and final-syllable /n/'s can be seen to vary in size and direction across levels and speakers; sometimes medials have more contact than finals (for example, speaker 1 in the IP). However, again we must be careful about confounds across levels. Medials could have more contact than finals simply because more of the medials could be initial in some lower domain(s) and get strengthened at that lower level. This is likely to be the case because domain-final syllables are almost never initial in lower domains. Therefore only domain-medial and domain-final-syllable /n/'s which are not initial in any lower domain (word

TABLE III. Hierarchical prosodic levels significantly ($p < 0.05$) distinguished by the amount of (a) linguopalatal contact for initial /n/; (b) linguopalatal contact for the final vowel V1 preceding initial /n/; (c) linguopalatal contact for the initial-syllable vowel V2 following initial /n/; (d) C-to-V contact difference (/n/ minus V2); (e) V-to-C contact difference (/n/ minus V1); (f) acoustic duration of /n/; (g) acoustic duration of final /o/ (V1). Results presented by speakers for the subset of data with the numeral "89."

	Speaker 1	Speaker 2	Speaker 3
(a)	IPi>PPi>Wi=Si (Ui=PPi and Ui=IPi)	Ui>IPi=PPi>Wi>Si	Ui=IPi>PPi=Wi>Si
(b)	IPf<PPf<Wf=Sf	IPf=PPf<Wf<Sf	IPf,PPf,Sf<Wf
(c)	IPi<Ui<PPi<Wi<Si	Ui,IPi,Si<PPi	Ui<Wi<PPi=IPi<Si
(d)	IPi>Ui>PPi>Wi>Si	Ui>IPi>PPi>Wi>Si	Ui>IPi=PPi>Si (Wi=IPi,Wi>PPi)
(e)	IPi>PPi>Wi=Si	IPi=PPi>Wi>Si	IPi=PPi=Si>Wi (IPi>Wi)
(f)	IPi>PPi>Wi>Si=Ui	IPi=PPi>Wi>Ui>Si	Ui=IPi>PPi>Wi>Si
(g)	IPf=PPf>Wf=Sf	IPf=PPf>Wf=Sf	IPf>PPf>Sf>Wf

or PP) were compared [(c) in Table II, and column (a) for the word level]. Of the nine comparisons, three give a significant difference between medial and final-syllable /n/'s: at the word and PP levels for speaker 2, and at the IP level for speaker 3, with final-syllable /n/'s having more contact than medial /n/'s, i.e., final strengthening. For the other six cases final-syllable and medial /n/'s have the same contact.

For the vowels, it can be seen in Fig. 3 that /o/'s in domain-final positions generally show the least contact. Domain-final /o/'s are more open than medial /o/'s at every level for all speakers and domain-final /o/'s are usually more open than /o/'s in domain-initial syllables, with speaker 1's IP domain the only exception. Greater opening or backing is a more extreme articulation for /o/, thus a final strengthening. This result cannot be due only to lexical stress on the final syllable of ''89,'' because in the data for speaker 1 three lexical stress patterns are included equally, and final strengthening is the same for this speaker as for the other two.

c. Tests for declination within-domain and across serial position. In the previous sections we have shown that initial /n/'s are more extreme in their constriction than medial and final-syllable ones, and final /o/'s are more extreme in their opening than initial and medial ones. There is some initial strengthening of the /o/'s in the initial CV syllable, and less consistent final strengthening of the /n/'s in the final CV syllable. In this section, we compare these results to see if they form a global trend across the three positions. In Fig. 3, a declining pattern will show a progressive decrease of contact for /n/'s (as they become less closed), and a progressive increase of contact for /o/'s (as they become more closed).

For /n/, the usual pattern is simple initial strengthening [Fig. 1(e)], but there are three comparisons showing initial strengthening combined with final strengthening [Fig. 1(g)]. There are no cases of declination. Thus the initial strengthening of /n/ is not part of a larger declining trend. For /o/, the relation across the three positions shows three different patterns. Four comparisons show a combination of initial and final strengthening [Fig. 1(g)], and three show simple final strengthening [Fig. 1(c)]. Two comparisons show a progressive opening trend [Fig. 1(a)], with final /o/'s more open than medial /o/'s and medial /o/'s more open than initial-syllable /o/'s. This progressive opening of /o/ is significant for speaker 2 at the word level, and for speaker 3 at the PP level. Thus, for these /o/'s we observed not a declination but instead a progressive strengthening. In sum, evidence for a within-domain declination has been found for none of the consonant comparisons; two vowel comparisons show a reverse declination, i.e., progressive strengthening.

We also tested for a sentence-level global trend that would depend only on serial position of a segment in the sentence. We tested whether the amount of linguopalatal contact varies linearly, either over the whole sentence or within smaller domains. This was done by testing for correlations between linguopalatal contact and linear position in the sentence, regressing serial position of the consonants (from syllable 1 to syllable 15) against their amount of contact, and using all data from all speakers. In the previous analysis we averaged all domain-medial syllables and compared them as a group to averaged domain-initial ones and domain-final ones; here we code all syllables by serial position so each could show its contribution to a potential progressive trend. We found no such trends for /n/'s or /o/'s ($r^2 \leq 0.01$) for all comparisons: over /n/'s in all syllables; stressed syllables; W-initial syllables; PP-initial syllables; IP-initial syllables; over /n/'s only in medial and final syllables, taking out the strengthened W-initial, PP-initial, IP-initial, and U-initial syllables; over all /o/'s or (following Vayra and Fowler, 1992) stressed /o/'s only). Thus we can say that in our data there is neither overall declination nor overall progressive strengthening for either consonants or vowels.

2. Hierarchical level of the domain boundary (across-domain comparisons)

a. Effects on linguopalatal contact. The next analysis focuses on the hierarchical nature of the strengthenings found above. For example, we ask whether the initial strengthening found for /n/ in different prosodic domains is cumulative, whether contact for initial consonants is greater when they are initial in higher prosodic domains than when they are initial only in lower prosodic domains. The comparisons were made by ANOVA followed by Fischer LPSD *post hoc* comparisons, with 0.05 as the significance level, for all pairings of domain initial /n/'s: W-initial /n/'s which are not also initial in PP, IP, or U; PP-initial /n/'s which are not also initial in IP or U; IP-initial /n/'s which are not also initial in U; and U-initial /n/'s. In order to compare W-initial consonants with ones initial in a lower domain, we included in the comparison syll-initial consonants that are not also W-initial or W-final (i.e., W-medial consonants). Similar comparisons are made with domain-final vowels and vowels in domain-initial syllables.

Figure 4(a) shows the average maximum contact for initial /n/'s according to the consonants' highest domain, for just the sentences with ''89'' (the numeral for which all the speakers produced all the sentence types) for the individual speakers. The general tendency is that the contact is related to the hierarchical level of the domain boundary: Higher levels show more contact. However, as can be seen in the figure, speakers vary. Not all levels are reliably distinguished, and although three or four levels are distinguished, the speakers differ in which levels those are. Table III(a) summarizes the significant differences for each speaker. In speaker 1's data, IP-initial, PP-initial, and W-initial/syll-initial /n/'s are distinct, but U-initial is not different from either IP-initial or PP-initial, and W-initial is not different from syll-initial (W-medial) (as already seen in the previous section). Speaker 2 distinguishes U-initial, IP-initial/PP-initial, W-initial, and syll-initial, but IP-initial is not different from PP-initial. Speaker 3 distinguishes IP-initial/U-initial, W-initial/PP-initial, and syll-initial, but U-initial and IP-initial are not different from each other, nor are PP-initial and W-initial (as already seen in the previous section). In sum, syllable is distinguished from word (2 speakers), word is distinguished from PP (2 speakers), and PP is distinguished from a higher domain (3 speakers), but whether that higher domain is the IP or the utterance is variable.

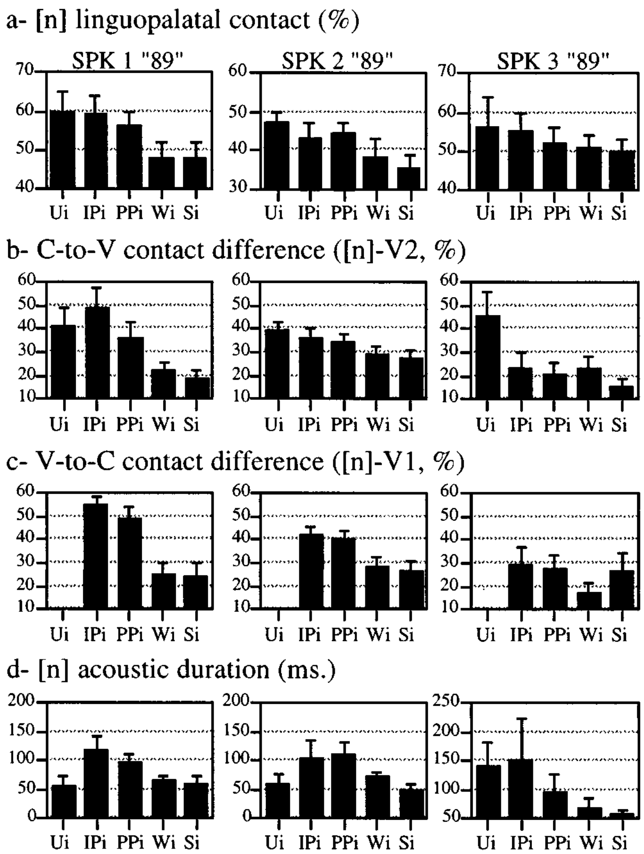

FIG. 4. Data on initial position at five hierarchical levels (utterance, intonational phrase, phonological phrase, word, syllable) for (a) maximum linguopalatal contact for /n/; (b) difference in contact between initial /n/ and following vowel (C-to-V); (c) difference in contact between initial /n/ and preceding (final) vowel (V-to-C); (d) acoustic duration for /n/. Data for three speakers, subset of the corpus with ''89'' in four sentence types.

We can also ask whether the strengthening found for domain-final /o/'s is cumulative in the same way. As there are no U-final /o/'s, there are four levels that could be distinguished. Some tokens had to be excluded from this analysis because an /o/ showed no contact at all: Its opening is greater than that of /o/'s showing contact on the pseudopalate, but we have no way to infer its real degree of opening. There were 47 such /o/'s excluded, generally IP-final, sometimes PP-final, mostly for speaker 2. Table III(b) presents the comparison for the domain-final vowels (V1) preceding the strengthened initial /n/. No speaker distinguishes all four levels. The only common result is that W-final /o/'s are consistently less open than PP- and IP-final /o/'s. It seems that above the word, final /o/'s are simply always quite open, their degree of openness depending very little on their hierarchical prosodic position.

Recall that speaker 1 and to some extent speaker 3 showed strengthening of /o/'s in domain-initial syllables (V2). We can ask whether this strengthening is cumulative too. Results are presented in Table III(c). More levels are distinguished by /o/'s in initial syllables than by final /o/'s, but the number and order are different for the speakers. The only common result, which in fact holds for all three speakers, is that U-initial-syllable /o/ has less contact (more strengthening) than PP-initial-syllable /o/.

b. Effects on V-to-C and C-to-V linguopalatal contact difference. Above we have seen the effects of prosodic position on the extreme contact for /n/ and for /o/, considered separately. In this section we consider the entire sequence V_1CV_2, to see whether the articulatory contrast between successive segments is also affected by their prosodic position. One measure of this is the contact difference between the preceding /o/ (V1) and /n/, the V-to-C contact difference. These segments are heterosyllabic and span a prosodic boundary. The other measure is between the /n/ and the following /o/ (V2), the C-to-V contact difference. These segments are tautosyllabic and the syllable follows a prosodic boundary.

Figure 4(b) shows the C-to-V contact difference for the subset of the corpus with ''89'' for the three speakers. Significance of the comparisons is presented in Table III(d). The C-to-V contact difference generally shows more distinctions than either /n/ or /o/ alone—five levels for two speakers, three for the third—and in general these distinctions follow the same hierarchical order as do those made by /n/ contact. Figure 4(c) and Table III(e) show the V-to-C contact difference and the significance of the comparisons. This difference is large, but not strongly cumulative.

Another way to see if an increase in contact for /n/ is accompanied by a change in contact for /o/ is to look for a correlation. For speaker 1, a strengthened /n/ is also surrounded by strengthened (i.e., more open) vowels, as shown by a negative correlation between the amount of contact for /n/ and the amount of contact for V1 ($r^2=0.5$) and for V2 ($r^2=0.2$). For speaker 2, a strengthened initial /n/ is accompanied by an increase of contact of the following vowel (V2 less open, positive correlation, $r^2=0.2$), while the amount of contact of the preceding vowel is not correlated with the contact of /n/. For speaker 3, the contact of vowels and /n/'s is independent ($r^2=0.01$).

3. Results for acoustic duration

Figure 4(d) presents the average acoustic duration of initial /n/'s according to the consonant's highest domain, for the subset of the corpus with ''89'' for the three speakers. Significant comparisons are given in Table III(f). Comparison with Fig. 4(a) shows that the durations of /n/ follow the same patterns as for linguopalatal contact, and except for U-initial /n/, they follow the prosodic hierarchy, with greater initial lengthening in higher domains. Speakers 1 and 3 distinguish four prosodic levels by /n/ duration (IP-initial greater than PP-initial, greater than W-initial, greater than syll-initial). The acoustic duration of U-initial /n/ is like syll-initial /n/ (speaker 1), or IP-initial /n/ (speaker 3). Speaker 2 does not distinguish between IP-initial and PP-initial /n/'s, and U-initial /n/'s are shorter than W-initial. Thus speakers 1 and 3 each make one more prosodic-domain distinction by /n/ duration than by /n/ linguopalatal contact, and speaker 2 the same number.

In contrast to the results for initial /n/, domain-final vowel lengthening [Table III(g)] is only weakly cumulative. For two speakers (1 and 2) only two levels are distinguished by duration, IP-final and PP-final being longer than W-final and syll-final /o/'s. For speaker 3, four levels are distinguished, but not in the expected order: IP-final is longer than PP-final, which is longer than syll-final, which is longer than W-final. Thus, in our corpus, final vowels are generally poor indices of the hierarchical level of prosodic domains both in their spatial (linguopalatal contact) and temporal characteristics, though all three speakers have longer vowels phrase-finally than W-finally.

Since duration and linguopalatal contact pattern similarly, linear regressions of acoustic duration of /n/ against maximum linguopalatal contact were carried out. For all speakers, all segments in the four sentence types with ''89,'' and in the flat sentence type with ''70'' and ''100,'' were used (this is more of the data than used in the factorial analyses reported above). Despite the similarity of patterning for the two variables, the correlation between them was minimal, whether we consider all /n/'s ($r^2=0.06$), domain-initial ($r^2=0.04$) or final-syllable /n/'s ($r^2=0.006$), or all the /n/'s except initial ones ($r^2=0.05$) or except final-syllable ones ($r^2=0.09$) or except the U-initial ones ($r^2=0.07$) (which show the greatest variation between speakers). The vowels, on the other hand, show a somewhat stronger correlation—the longer the vowel is, the less contact it has (the more open it is) ($r^2=0.3$). So for vowels, duration may be a contributing factor to the degree of opening (or the reverse). This correlation would likely be greater if the most open vowel positions were more reliably tracked by EPG.

II. GENERAL DISCUSSION AND CONCLUSION

We found that the articulation of consonants and vowels varies as a function of their position in long sentences. This variation appears to be a localized effect at prosodic domain edges, i.e., a strengthening of initial consonants and final vowels, and not a global declining trend. Initial strengthening of consonants is found at different prosodic levels and tends to be cumulative. Finally, this cumulative initial strengthening of consonants is accompanied by a cumulative lengthening, though the correlation between strengthening and lengthening is weak.

A. Initial strengthening

1. Within domains

Within each prosodic domain, /n/'s in initial CV syllables were found to have greater contact than /n/'s in medial and final CV syllables, while /n/'s in medial and final CV syllables had comparable contact, at the utterance, IP, and PP or word levels. That is, we found initial strengthening for /n/ in that the articulation of /n/ was more extreme in domain-initial positions. There were three cases combining initial and final strengthening of /n/. There was no declination in the articulation of /n/ at any level for any speaker. Neither was there final weakening; however, it must be borne in mind that the possibility of a weakening of final (coda) consonants at any or all prosodic levels cannot be rejected, since we looked only at CV syllables.

When the same comparisons were made for /o/'s, the only consistent result was that /o/'s in final syllables were found to have less contact than /o/'s in initial and medial syllables in almost every case. Since less contact means greater opening/backing for /o/, this is a more extreme articulation and therefore a final strengthening. We also observed some combinations of final and initial strengthening, and some progressive strengthening, but because these were not consistent, no reliable overall pattern across the three positions emerges for /o/ in the way that one does for /n/.

Finally, we showed that most of the prosodic domains considered are delimited by strengthened articulations. The beginning edge of prosodic domains is marked by lengthening and increasing contact for the consonant. The final edge of prosodic domains is marked by lengthening and decreasing contact for the vowel. As a result of these initial and final edge effects, a prosodic domain is set off at both its edges. This finding can be related to Dilley *et al.* (1996), who showed that glottalization of word-initial vowels occurs more frequently at onsets of higher prosodic constituents, therefore marking off these constituents.

2. Across domains

When /n/'s that are initial in different prosodic domains are compared, initial strengthening is found to be somewhat cumulative. /n/'s that are initial in some higher prosodic domains have more linguopalatal contact than /n/'s initial in some lower prosodic domains. The experiment allowed comparisons of five levels of prosodic structure: syllable, word, phonological (or intermediate) phrase, intonational phrase, and utterance. Overall, three or four levels were distinguished by significant differences in linguopalatal contact of the initial consonant. IP-initial /n/'s were always distinct from word- and syllable-initial /n/'s. But differences between speakers are noteworthy, in both how many, and which, levels were distinguished. Thus while there is clearly some cumulative initial strengthening across domains, it does not seem to be tied to distinguishing specific prosodic levels; we can say only that speakers distinguished three or four levels this way.

There is no reason to expect any one articulatory or acoustic correlate to distinguish all prosodic domains. Wightman *et al.* (1992) found that preboundary vowel duration distinguished only four of the seven perceptually distinct levels they tested. If we compare the distinctions made by acoustic duration and by different linguopalatal contact measures, it seems that C-to-V difference and initial lengthening are, for two of the three speakers, better correlates of the prosodic hierarchy. In contrast, it is surprising that final vowel lengthening marked only two distinctions in our corpus, between word and higher levels, but not between the two phrasal levels as was shown in Wightman *et al.* (1992). We have no explanation for this.

3. What about declination?

In the Introduction we sketched an alternative account of supralaryngeal declination of initial consonants as described by Krakow *et al.* (1994), based on nested initial strengthening or final weakening. Our experiment shows initial strengthening for consonants; can we then account for declination by this strengthening? The plausibility of an initial strengthening account of declination over three datapoints depends on whether initial strengthening can distinguish three prosodic levels. Initial strengthening would give a pattern looking like declination if the consonants compared are initial in these three prosodic domains and if the hierarchical levels of these domains decreases along with their serial position in the sentence. To see this, consider again Fig. 2, our sample data, for example the top utterance. It is possible to pick three datapoints for /n/ which show declination: for example, the first /no/ (which is U-initial and IP-initial), the eighth /no/, corresponding to the second ''plus'' (which is PP-initial), and the 13th /no/, corresponding to the beginning of the last numeral (which is W-initial). This apparent declination is only the consequence of three different degrees of strengthening at the word, PP, and IP levels. If only these points had been considered, we would have concluded that there is declination. Yet all of our systematic comparisons testing for declination yielded none.

B. What is the nature of this strengthening?

The terms ''strengthening'' and ''weakening,'' as well as the variants ''fortition'' and ''lenition,'' are often used to characterize segment variation or historical changes (Hock, 1992), but it is seldom that those terms are phonetically or articulatorily defined, or that the mechanism leading to the variation is explained. Our results lead us to think that the variation we observe is the result of a general phenomenon in speech, which we call *articulatory strengthening at prosodic-domain edges*. We have considered this strengthening to mean more extreme articulation, that is, spatial variation. Strengthening may also involve greater lengthening, that is, temporal variation. Our observations of linguopalatal contact variation are only the result of this strengthening and are not sufficient to establish its nature. Here we will propose and discuss some possible mechanisms that may induce the more extreme articulations of strengthened segments.

(1) *Increased duration*. In general, shorter durations often (though not necessarily) lead to articulatory undershoot (Lindblom, 1963; Moon and Lindblom, 1994). Conversely, stronger segments could have more extreme articulations because they are longer, and thus have time to reach their targets. However, in our data the spatial variation observed is not strongly correlated with the temporal variation.

(2) *Increased distance between segments*. Recall that there is greater difference in linguopalatal contact between /n/ and /o/ at higher prosodic boundaries, for V-to-C and especially for C-to-V. Possibly, after an open final vowel there could be overshoot of the following lingual target. This was suggested for the jaw in /ata/, /asa/, and /ada/ (though not /ana/) sequences by Keating *et al.* (1994), or, since movement velocity is usually proportional to displacement, the larger displacements from an open final vowel to the following initial consonant would involve higher velocities. Higher velocity would result in a greater impact of the tongue against the palate at closure (A. Löfqvist, personal communication). In both cases (overshoot or higher velocity) more compression of the tongue tissue, and therefore greater contact, would result. But in both cases if it is /n/'s distance from the preceding vowel that leads to /n/'s greater contact, then we should see a negative correlation between the contact for V1 and C. This is so for speaker 1, C has the most contact just when V1 has the least. And speaker 1 is the one subject who has consistent initial strengthening of /o/, V2 has the least contact just when C has the most. So for this subject, the spatial distance between successive oral targets could be an important factor in initial strengthenings. Whether the relevant distances, movements, and velocities are those of the tongue, the jaw, or both, cannot be addressed with EPG.

(3) *Increased coarticulation*. Strengthening could increase the overlap of /n/ with surrounding vowels, in which case contact at the back of the palate for /o/ could occur during /n/, increasing the total contact measured for /n/. In this case there should be some correlation between the contacts for adjacent /n/'s and /o/'s, such that when one has more contact the other also has more contact. For one speaker (speaker 2) there is a weak correlation of this kind ($r^2 = 0.2$); for the other speakers the correlations were either near zero, or showed less coarticulation. In general these correlations and the increased displacement between C and V's at higher prosodic boundaries do not support this hypothesis. Furthermore, this hypothesis would have nothing to say about the decreased contact for strengthened /o/.

(4) *Greater coarticulatory resistance*. Conversely, stronger segments could resist coarticulatory undershoot because they resist blending with overlapping gestures (Fowler and Saltzman 1993, p. 182). Strengthening of /n/ would involve more contact because the tongue blade is not pulled away from its constriction target by /o/'s tongue body articulation, and vice versa for /o/. This hypothesis is supported by the increased V-to-C and (especially) C-to-V displacements at higher prosodic levels.

(5) *Increased effort or energy*. Articulatory strengthening could also result from a greater overall effort in speech that would also affect the pulmonary and laryngeal systems, as has been proposed for stress (Ladefoged, 1967; Sluijter *et al.*, 1997). Variations observed in supralaryngeal articulations would only be an indirect effect of this overall energy increase (Öhman, 1967; Vayra and Fowler, 1992). Another possibility could be that initial strengthening is the result of a localized increase in supralaryngeal articulatory effort. Fujimura (1990a) suggested that prosodic-domain initial consonants are characterized by more ''forceful'' articulatory gestures. Variation of articulatory effort was also suggested by Straka (1963 p. 91), who defined articulatory energy in terms of the force of contraction of the muscles primarily involved in the articulation of the segment, specifically excluding respiratory and laryngeal systems. Straka found that in more ''forceful'' (''renforcée'') pronunciation there was greater linguopalatal contact for consonants and less contact for all vowels, and as a consequence an increased difference in openness between successive segments. This is what we found at prosodic domain edges.

In conclusion, there are a number of possible mechanisms that might result in the strengthening we have observed, but resolving this question would require much further work.

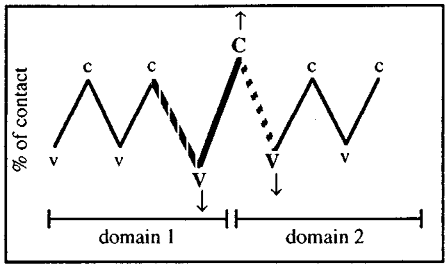

FIG. 5. Schematic summarizing linguopalatal contact for segments spanning a boundary. Dashed line shows difference between final-syllable /n/ and final /o/ in a domain; bold line shows difference between final /o/ and initial /n/; dotted line shows difference between initial /n/ and initial-syllable /o/.

C. Enhancement and the listener

The mechanisms discussed above present strengthening as either the automatic, unplanned consequence of some other aspect of speech production, or something learned as part of the language. In either case it might be useful linguistically. We can think of three ways in which initial strengthening could benefit a listener. Two of these have to do with prosodic parsing. First, strengthening could help with segmentation of the signal into words and higher domains. Recall that in Sec. I B 2 *b* it was shown that there is some enhancement of V-to-C and C-to-V linguopalatal contact differences at prosodic boundaries. Figure 5 combines these two aspects into a single scheme for a CV♯CV sequence, where ♯ is some prosodic boundary. This schematic shows that the articulatory contrast between the consonant after the boundary and its surrounding vowels is enhanced because they are more extreme in opposite directions. This articulatory enhancement of the contrasts within the sequence may contribute to marking the prosodic boundary even more clearly than do the vowel or consonant alone. A similar enhancement of CV contrasts at domain-initial boundaries in Italian has been discussed by Farnetani and Vayra (1996, p. 12): ''Also boundaries are signalled by an increase in CV contrast: initial boundaries are marked by a strengthening of consonant closure and by an increase in vowel posteriority (...).''

Second, the degree of strengthening could possibly tell the listener about the strength of the prosodic boundary, similar to the way that Wightman *et al.* (1992) suggest that listeners could use degree of final lengthening. A listener would know that when an initial consonant is more than minimally strengthened, the boundary (or break) must be stronger. In particular, IP boundaries could be distinguished from word boundaries in this way. Our results would not support a stronger claim, that listeners might judge the absolute level of any new domain from the degree of strengthening. There is simply too much interspeaker variation.

The third way in which initial strengthening could benefit a listener concerns lexical access. If initial strengthening enhances the segment-specific articulations of consonants and vowels, then it could enhance cues that aid in identifying each segment. de Jong (1995) proposes that stress involves a local hyperarticulation that makes each segment more different from all other segments of the language, so that lexical contrasts are more distinctive. Along the same lines, enhanced accessibility of segmental information in domain-initial positions would be particularly helpful, particularly for word-initial segments which are important in word recognition (Cole *et al.*, 1978; Hawkins and Cutler, 1988) and at domain beginnings where there is less top-down (e.g., syntactic and semantic) information available.

Of course the linguistic function of initial strengthening presupposes that strengthening has one or more acoustic/auditory correlates. We found that the variation in linguopalatal contact for /n/ and /o/ is accompanied by variation in acoustic duration, though the two measures are not strongly correlated. The acoustic duration differences would be potentially available to listeners. It remains to be seen whether the linguopalatal contact differences have any other associated acoustic properties, and whether these can be heard by listeners.

D. Prosody and articulation

Our results underline a point made by a few other researchers: the importance of understanding, controlling, and reporting the prosody of speech materials in articulation experiments. For the individual experimenter, unsought variation in prosody is a potential confound both within and across speakers, as our own experiment shows. It can also make comparisons across studies difficult or impossible, as researchers have always known. Yet, at the same time, awareness of prosodic differences between sentences can turn apparent random variation into predictable, lawful regularities of speech production, as we hope to have shown here.

This is not to say that prosody is easy to control, or that experiments on prosodic effects are easy to design. It can be especially difficult to find sequences of real words that can occur across a variety of prosodic boundaries and that contain segments appropriate to a given method of articulatory data collection (in our case, lingual consonants). Reiterant speech finesses this difficulty, but some subjects may not be able to produce it fluently (Larkey, 1983) (thought this was not a problem in the present study). It may also be the case that reiterant speech induces somewhat exaggerated rhythmic alternations. These in turn may enhance the prosodic phrasing, and thereby its manifestation in articulation. The present experiment does not address this point, and our results need to be confirmed with experiments using real words (see Fougeron and Keating, 1996 for French).

Another difficulty in such experiments is that the phrasings of the test sentences are unclear unless the utterances are prosodically analyzed. The use of orthographic devices such as punctuation (e.g., commas) or parentheses in the test materials does not guarantee that subjects will produce any particular phrasing. In our study there was variation both within and across speakers, requiring *post hoc* prosodic transcription to determine the actual phrasing of each token.

E. Conclusion

Most previous research on prosodic demarcation has focused on the ends of prosodic domains. Our results add to the much smaller literature on beginnings of domains. At least some tongue blade and body articulations are more extreme in domain-initial positions. We have shown that position with respect to prosodic boundaries affects articulatory constriction, something that would seem to be an inherent property of a sound.

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[1]The term ''declination'' originally comes from the study of intonation, where it refers to a downtrend in fundamental frequency ($f0$) [see Ladd (1984) or 't Hart *et al.* (1990) for reviews]. Subglottal pressure also declines over an utterance, and some of the downtrend in $f0$ has been attributed to the downtrend in subglottal pressure (Gelfer *et al.*, 1987).

[2]The first syllable of ''70'' and the second syllable of ''100'' were stressed for all three speakers, and other syllables in those numerals were unstressed. For two speakers, the last syllable of ''89'' was stressed and the other syllables unstressed, but for one speaker (speaker 3) both the first and last syllables of ''89'' were stressed and only the middle syllable was unstressed.

Abacus Concepts (**1992**). *StatView* (Abacus Concepts, Inc., Berkeley, CA).

Beckman, M., and Edwards, J. (**1994**). ''Articulatory evidence for differentiating stress categories,'' in *Phonological Structure and Phonetic Form: Papers in Laboratory Phonology III*, edited by P. A. Keating (Cambridge U.P., Cambridge, England), Chap. 2, pp. 7–33.

Beckman, M., Edwards, J., and Fletcher, J. (**1992**). ''Prosodic structure and tempo in a sonority model of articulatory dynamics,'' in *Papers in Laboratory Phonology II: Gesture, Segment, Prosody*, edited by G. Docherty and D. R. Ladd (Cambridge U.P., Cambridge, England), pp. 68–86.

Beckman, M., and Pierrehumbert, J. (**1986**). ''Intonational structure in English and Japanese,'' Phonology (Yearbook) **3**, 255–310.

Browman, C., and Goldstein, L. (**1992**). ''Articulatory phonology: an overview,'' Phonetica 49, 155–180.

Byrd, D. (**1996**). ''Influences on articulatory timing in consonant sequences,'' J. Phon. **24**, 209–244.

Byrd, D. M. (**1994**). ''Articulatory timing in English consonant sequences,'' Ph.D. dissertation, UCLA, distributed as UCLA Working Papers in Phonetics **86**, 1–196.

Byrd, D., Flemming, E., Mueller, C. A., and Tan, C. C. (**1995**). ''Using regions and indices in EPG data reduction,''J. Speech Hear. Res. **38,** 821–827.

Byrd, D., Narayanan, S., Kaun, A., and Saltzman, E. (**1997**). ''Phrasal signatures in articulation,'' to appear in *Proceedings of Laboratory Phonology V* (Cambridge U.P., Cambridge, England).

Cole, R., Jakimik, J., and Cooper, W. (**1978**). ''Perceptibility of phonetic features in fluent speech,'' J. Acoust. Soc. Am. **64,** 44–56.

Cooper, A. (**1991**). ''Laryngeal and oral gestures in English /p,t,k/,'' *Proceedings of the XIIth International Congress of Phonetic Sciences 2, University of Provence* (Aix-en-Provence, France), pp. 50–53.

de Jong, K. (**1995**). ''The supraglottal articulation of prominence in English: Linguistic stress as localized hyperarticulation,'' J. Acoust. Soc. Am. **97,** 491–504.

Dilley, L., Shattuck-Hufnagel, S., and Ostendorf, M. (**1996**). ''Glottalization of word-initial vowels as a function of prosodic structure,'' J. Phonetics **24**, 423–444.

Farnetani, E., and Vayra, M. (**1996**). ''The role of prosody in the shaping of articulation in Italian CV syllables,'' in *Proceedings of the 1st ESCA Tutorial and Research Workshop on Speech Production Modeling and 4th Speech Production Seminar*, Autrans, France, edited by P. Perrier, F. Bustarret, and R. Laboissière (Institut National Polytechnique de Grenoble, France).

Fougeron, C., and Keating, P. (**1996**). ''Variations in velic and lingual articulation depending on prosodic position: Results for two French speakers,'' UCLA Working Papers in Phonetics **92**, 88–96 (Also available electronically in the European Student Journal of Language and Speech at http://web-sls.essex.ac.uk/web-sls/).

Fowler, C. A., and Saltzman, E. (**1993**). ''Coordination and coarticulation in speech production,'' Lang. Speech **36**, 171–195.

Fromkin, V. (**1965**). ''Some phonetic specifications of linguistic units: an electromyographic investigation,'' UCLA Working Papers in Phonetics **3**, 1–184.

Fujimura, O. (**1990a**). ''Methods and goals of speech production research,'' Lang. Speech **33**, 195–258.

Fujimura, O. (**1990b**). ''Articulatory perspectives of speech organization,'' in *Speech Production and Speech Modelling*, edited by W. J. Hardcastle and A. Marchal (Kluwer, Dordrecht), pp. 323–342.

Gelfer, C. E., Harris, K. S., and Baer, T. (**1987**). ''Controlled variables in sentence intonation,'' in *Laryngeal Function in Phonation and Respiration*, edited by T. Baer, C. Sasaki, and K. S. Harris (Little, Brown, Boston, MA), pp. 422–435.

Hawkins, J., and Cutler, A. (**1988**). ''Psycholinguistic factors in morphological asymmetry,'' in *Explaining Language Universals*, edited by J. Hawkins (Blackwells, Oxford), pp. 281–317.

Hinton, V. A. (**1996**). ''Interlabial pressure during production of bilabial phones,'' J. Phonetics **24**, 337–349.

Hock, H. H. (**1992**). ''Initial strengthening,'' in *Phonologica 1988*, edited by W. U. Dressler *et al.* (Cambridge U.P., Cambridge, England), pp. 101–110.

Jun, S. (**1993**). ''The phonetics and phonology of Korean prosody,'' Ph.D. dissertation, Ohio State University.

Keating, P. A. (**1995**). ''Effect of prosodic position on /t,d/ tongue/palate contact,'' poster presented at the XIIIth International Congress of Phonetic Sciences, Stockholm, 1995 (unpublished).

Keating, P. A., Lindblom, B., Lubker, J., and Kreiman, J. (**1994**). ''Variability in jaw height for segments in English and Swedish VCVs,'' J. Phonetics **22**, 407–422.

Klatt, D. H. (**1975**). Vowel lengthening is syntactically determined in a connected discourse,'' J. Phonetics **3**, 129–140.

Krakow, R. A. (**1989**). ''The Articulatory Organization of Syllables: A kinematic analysis of labial and velic gestures,'' Ph.D. dissertation, Yale University.

Krakow, R. A., Bell-Berti, F., and Wang, Q. E. (**1994**). ''Supralaryngeal declination: evidence from the velum,'' in *Producing Speech: A Festschrift for Katherine Safford Harris*, edited by F. Bell-Berti and L. Raphael (AIP, Woodbury, NY), Chap. 23, pp. 333–353.

Ladd, D. R. (**1984**). ''Declination: A review and some hypotheses,'' Phonology (Yearbook) **1**, 53–74.

Ladefoged, P. (**1967**). *Three Areas of Experimental Phonetics* (Oxford U.P., London).

Larkey, L. (**1983**). ''Reiterant speech: An acoustic and perceptual validation,'' J. Acoust. Soc. Am. **73,** 1337–1345.

Lindblom, B. (**1963**). ''Spectrographic study of vowel reduction,'' J. Acoust. Soc. Am. **35,** 1773–1781.

Löfqvist, A. (**1996**). Personal communication.

Maeda, S. (**1976**). ''A characterization of American English Intonation,'' Ph.D. dissertation, MIT.

Moon, S. J., and Lindblom, B. (**1994**). ''Interaction between duration, context, and speaking style in English stressed vowels,'' J. Acoust. Soc. Am. **96,** 40–55.

Öhman, S. (**1967**). ''Word and sentence intonation: a quantitative model,'' STLQ Progr. Status Rep. Stockholm **2/3**, 20–54.

Oller, D. K. (**1973**). ''The effect of position in utterance on speech segment duration in English,'' J. Acoust. Soc. Am. **54,** 1235–1247.

Pierrehumbert, J., and Beckman, M. (**1988**). *Japanese Tone Structure* (MIT, Cambridge, MA).

Pierrehumbert, J., and Talkin, D. (**1992**). ''Lenition of /h/ and glottal stop,'' in *Papers in Laboratory Phonology II: Gesture, Segment, Prosody*, edited by G. Docherty and D. R. Ladd (Cambridge U.P., Cambridge, England), Chap. 4, pp. 90–117.

Shattuck-Hufnagel, S., and Turk, A. (**1996**). ''A prosody tutorial for investigators of auditory sentence processing,'' J. Psycholinguistic Res. **25**(2), 193–247.

Silverman, K., Beckman, M., Pitrelli, J., Ostendorf, M., Wightman, C., Price, P., Pierrehumbert, J., and Hirschberg, J. (**1992**). ''TOBI: A Standard for Labeling English Prosody,'' *1992 International Conference on Spoken Language Processing*, edited by J. J. Ohala, T. M. Nearey, B. L. Derwing, M. M. Hodge, and G. E. Wiebe (University of Alberta, Edmonton, Canada), Vol. 2, pp. 867–870.

Sluijter, A. M. C., van Heuven, V. J., and Pacilly, J. J. A. (**1997**). ''Spectral balance as a cue in the perception of linguistic stress,'' J. Acoust. Soc. Am. **101,** 503–513.

Straka, G. (**1963**). ''La division des sons du langage en voyelles et consonnes: peut-elle être justifiée?'' Travaux de Linguistique et de Littérature, Centre de Philologie et de Littératures Romanes de l'Université de Strasbourg, Vol. I, pp. 17–99.

't Hart, J., Collier, R., and Cohen, A. (**1990**). *A Perceptual Study of Intonation: An Experimental-Phonetic Approach to Speech Melody*, Cambridge Studies in Speech Science and Communication (Cambridge U.P., Cambridge, England), Chap. 5, pp. 121–150.

Thorsen, N. (**1985**). ''Intonation and text in Standard Danish,'' J. Acoust. Soc. Am. **77,** 1205–1216.

Vaissière, J. (**1986**). ''Comment on Abbs's Paper,'' in *Invariance and Variability in Speech Processes*, edited by J. S. Perkell and D. H. Klatt (Erlbaum, Hillsdale, NJ), pp. 220–222.

Vaissière, J. (**1988**). ''Prediction of velum movement from phonological specifications,'' Phonetica **45**, 122–139.

van Lieshout, P. H., Starkweather, C. W., Hulstijn, W., and Peters, H. F. M. (**1995**). ''Effects of linguistic correlates of stuttering on emg activity in nonstuttering speakers,'' J. Speech Hear. Res. **38,** 360–372.

Vayra, M., and Fowler, C. (**1992**). ''Declination of supralaryngeal gestures in spoken Italian,'' Phonetica **49**, 48–60.

Wightman, C. W., Shattuck-Hufnagel, S., Ostendorf, M., and Price, P. J. (**1992**). ''Segmental durations in the vicinity of prosodic phrase boundaries,'' J. Acoust. Soc. Am. **92,** 1707–17.