Interacting effects of syllable and phrase position on consonant articulation[a)]

Dani Byrd[b)]
Department of Linguistics, USC College, Los Angeles, California 90089-1693

Sungbok Lee
Department of Linguistics, USC College and Department of Electrical Engineering-Systems, USC Viterbi School of Engineering, Los Angeles, California

Daylen Riggs
Department of Linguistics, USC College, Los Angeles, California

Jason Adams
Department of Computer Science, USC Viterbi School of Engineering, Los Angeles, California

(Received 9 February 2005; revised 6 October 2005; accepted 7 October 2005)

The complexities of how prosodic structure, both at the phrasal and syllable levels, shapes speech production have begun to be illuminated through studies of articulatory behavior. The present study contributes to an understanding of prosodic signatures on articulation by examining the joint effects of phrasal and syllable position on the production of consonants. Articulatory kinematic data were collected for five subjects using electromagnetic articulography (EMA) to record target consonants (labial, labiodental, and tongue tip), located in (1) either syllable final or initial position and (2) either at a phrase edge or phrase medially. Spatial and temporal characteristics of the consonantal constriction formation and release were determined based on kinematic landmarks in the articulator velocity profiles. The results indicate that syllable and phrasal position consistently affect the movement duration; however, effects on displacement were more variable. For most subjects, the boundary-adjacent portions of the movement (constriction release for a preboundary coda and constriction formation for a postboundary onset) are not differentially affected in terms of phrasal lengthening—both lengthen comparably. *© 2005 Acoustical Society of America.* [DOI: 10.1121/1.2130950]

PACS number(s): 43.70.−h, 43.70.Bk [AL] Pages: 3860–3873

I. INTRODUCTION

Syllable and phrasal structure, as well as focal accent, have been highlighted as linguistic factors responsible for variation in the articulatory characteristics of consonants. This variation has been explored in terms of the spatial or magnitude properties of the articulatory movements and in terms of the gestures' temporal or durational properties. However, a comprehensive understanding of positionally conditioned spatiotemporal variation of articulatory gestures is still being built, particularly in terms of how the influences of different levels of linguistic structure, from syllabic to phrasal, combine in their effects on the performance of articulatory gestures.

A. Positional effects on articulation

Setting aside focal accent as a source of articulatory variation, studies of *positional* effects on articulation have largely focused on word edges and phrase edges, that is, the effect of syllable and phrasal boundaries. A diagram showing an example of the hierarchical relations among segments, syllables, and phrases is shown in Fig. 1.

A number of studies using both electropalatography (EPG) and movement tracking have reported more constricted articulatory postures for consonants in syllable onsets as compared to those in syllable codas (e.g., Browman and Goldstein, 1995; Byrd, 1996; Fougeron and Keating, 1997). For example, in EPG studies by Byrd (1996) and Keating *et al.* (1999), certain consonants were shown to have more linguapalatal contact word-(syllable-) initially than word-(syllable-) finally (/t/ and /d/ in the Keating study and /d/ and /g/ in the Byrd study). Similar patterns obtain for duration such that coda articulations are shorter than onset articulations (e.g., Byrd, 1996—an EPG study). (We note that it is not clear whether syllable and word boundaries are differentiated in English, since the relevant experiments generally use a word boundary condition to ensure a certain syllable edge.)

Other articulatory studies have examined the effects of phrase boundaries identifying longer constriction formation and release durations at phrase edges as compared to phrase medially [e.g., the articulatory point-tracking studies of Byrd *et al.* (2000), Byrd and Saltzman (1998), and Cho (in press), and the earlier seminal work on the jaw (Edwards *et al.*,

---

[a)] Portions of this work were presented in "Interacting effects of phrasal and syllable position on consonant production" Acoustical Society of America meeting, San Diego, CA, November 2004.

[b)] Electronic mail: dbyrd@usc.edu

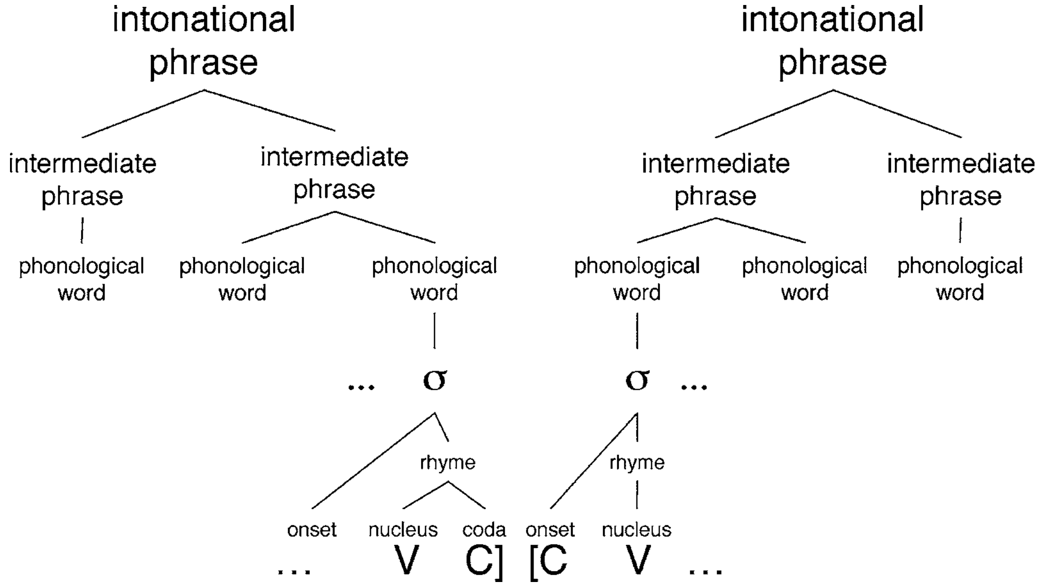

FIG. 1. A diagram showing a partial example of the hierarchical relations among segments syllables and phrases for a phrase ending in [VC] and a following phrase beginning with [CV].

1991; Beckman and Edwards, 1992)]. Additionally, larger movement displacements and greater linguapalatal contact have also been identified at the edges of strong phrasal domains [e.g., using magnetometry in Byrd and Saltzman (1998) and Tabain (2003), and EPG in Keating *et al.* (2003)]. Finally, there is some indication that phrase initial edges show more of this behavior than phrase-final edges (e.g., Byrd and Saltzman, 1998; Keating *et al.*, 1999). For example, Keating *et al.* (1999) showed that significantly more peak linguapalatal contact occurred in phrase-initial positions than in phrase-final positions. Additionally, in an EPG case study of Korean, Cho and Keating (2001) found that a range of consonants (specifically, /n/, /t/ /t^h/, and /t*/) located in domain-initial position at large boundaries had both more extreme and longer articulations than consonants located initially in lower prosodic domains and those located domain medially. However, it is not at all clear that phrase-*final* edges are not also larger/longer than their phase-medial consonant counterparts (see, e.g., Hacopian, 2003; Keating *et al.*, 1999). In Keating *et al.* (1999), the authors found that consonants located phrase finally indeed received a significant articulatory "boost" in linguopalatal contact as compared to those located phrase medially. Additionally, the magnetometer study of Cho (in press) found evidence of articulatory lengthening of labial consonants in a CV##CV sequence spanning a boundary; the articulations were longer in duration and exhibited longer time-to-peak-velocities when at a phrase boundary. Finally, Keating *et al.*'s (1999) EPG data indicate that "Averaged across consonants and speakers, the most contact is seen for consonants which are utterance-initial and word-initial; the next-most contact is seen for consonants which are word-initial but utterance-medial; the next for consonants which are utterance-final and word-final; and the least contact is seen for consonants which are word-final but utterance-medial… exactly how [utterance-medial word initial and utterance-final word-final] pattern…and which differences are statistically significant, depend on the consonant."

As an understanding of articulatory modifications in particular prosodic positions has been acquired over past years, studies have focused primarily on *either* the syllable or the phrasal effect. (Similarly, studies on focal accent have also generally been specific only to focus, but we address the positional effects here.) Likewise, some experiments (often because of instrumentation) have attended more to spatial characteristics of consonant articulations, and others have focused more on temporal characteristics. And, finally, some studies (for example, those done with EPG) are limited to lingual consonants. The present experiment offers several contributions to the body of knowledge of positional effects on articulation. It examines both spatial and temporal variations as a function of both syllable and phrasal position for both lingual and labial consonants. Specifically, it evaluates the *interaction* of syllable and phrasal position on consonant articulation. We consider whether the effects of syllable and phrase position on the magnitude and length of consonant articulation are independent or interact to yield even greater prominence in certain circumstances. The experiment presented will allow us to address the question of the relative articulatory robustness (constriction magnitude and duration) of consonants as they occur as codas phrase medially, as codas phrase finally, as onsets phrase medially, and as onsets phrase initially.

B. The prosodic gesture model

The prosodic (π-) gesture model (Byrd and Saltzman, 2003; Byrd *et al.*, 2000) views phrase boundaries as extending over an interval at a juncture and slowing the time course of articulatory gestures that are active during that interval. Thus, the π-gesture model extends to the suprasegmental level the notion, forwarded within Articulatory Phonology (e.g., Browman and Goldstein, 1992), that phonological ges-

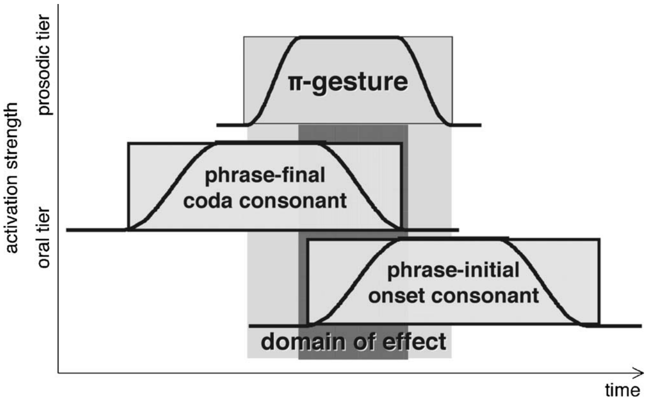

FIG. 2. A schema of the π-gesture model indicating two constriction gestures overlapping one another and a prosodic boundary (π) gesture.

tures are inherently temporal, that is, that gestures are active over a temporal interval and that the activation intervals of gestures are patterned or choreographed in an overlapping fashion. Figure 2 shows a representative partial gestural score schematizing the overlapping arrangement of a prosodic gesture, whose activation waxes and wanes, with two co-active constriction gestures.

This model of phrasal juncture predicts the same qualitative effect of a boundary on the articulatory behavior both preceding and following the boundary. For example, both phrase-final and phrase-initial constriction activation trajectories are predicted to be lengthened. This lengthening of the activation trajectories is quantitatively indexed by a longer acceleration duration (i.e., time-to-peak-velocity) in the movement trajectory. [This interval reflects the stiffness parameter of a gesture within a Task Dynamics model of speech production (Saltzman and Munhall, 1989), i.e., the parameter shaping the internal temporal properties of an articulatory gesture. A longer acceleration duration is associated with lower stiffness.] Many of the empirical findings on intra- and intergestural timing at phrase boundaries have been successfully simulated using a π gesture that slows the central clock controlling the pace at which constriction gestures unfold (see Byrd and Saltzman, 2003). The activation strength of the π gesture, and therefore the degree of local slowing, is viewed as directly corresponding to the strength of a phrasal juncture (captured in many phonological theories as depth of embedding in a prosodic hierarchy).

The π gesture model does allow for asymmetric quantitative effects around a boundary. That is, the magnitude of effect on the constriction gestures overlapping the boundary interval may differ before and after the juncture. The π gesture may be skewed rightward (yielding larger effects phrase initially) or leftward (yielding larger effects phrase finally) depending on the alignment of the π gesture with the constriction gestures or depending on the activation wave shape of the π gesture itself. [See Byrd and Saltzman (2003) for detailed modeling of these sorts of π-gesture effects on articulation.] The present experiment will evaluate the degree of symmetry in prosodic slowing at phrase boundaries by examining whether an intonational phrase boundary equivalently affects a preceding coda and a following onset consonant. In addition to the primary goal of addressing a deficit in our empirical knowledge of the interaction of phrase and syllable position on articulatory behavior, this work will help inform future prosodic modeling generally.

C. Experimental hypotheses: Temporal lengthening and spatial strengthening

Below we present an articulatory study on consonant production conducted using movement tracking (magnetometry). First, this study investigates the nature of the articulatory lengthening at phrase and syllable edges. Based on early work, longer articulations are expected at initial phrase and syllable (word) edges. Second, the present study also considers whether spatial changes in articulation pattern in the same way as temporal changes pattern. Several of the studies reviewed above have observed spatially larger articulations in phrase and syllable initial positions, but it is unclear whether spatial strengthening is limited to this position. Some previous research showing that larger displacements occur with longer durations (Kelso *et al.*, 1985; Ostry and Munhall, 1985) would suggest that spatial strengthening and lengthening should co-occur. Alternatively, the attention paid to strengthening in phrasal onset position (e.g., Keating *et al.*, 2003) might suggest that only phrase-initial onset consonants strengthen relative to phrase-medial consonants, with no comparable change found for codas at phrase edges (e.g., see Keating *et al.*, 2003). Last, and most importantly in terms of new investigation, the present study examines the *interaction* of syllable and phrase boundaries on the spatial and temporal characteristics of consonant articulation. Five subjects and both lingual and labial consonants are included.

II. METHOD

Electromagnetic articulography (the Carstens AG200 EMA system) was used to record the motion of transducers placed on the lips (at the vermillion border) and tongue tip (approximately 5 mm from the endpoint of the protruded tongue). Articulatory data were sampled at 200 Hz and simultaneous audio data at 10 kHz. Data were corrected for head movement using reference transducers adhered to the maxilla and bridge of the nose and were rotated to the sampled occlusal plane of each subject.

A. Subjects and stimuli

The consonants under examination in this study were [f], [t], and [p]. Consonants appeared in each of four positions: (1) phrase-medial coda, (2) coda at an phrase edge, (3) phrase-medial onset, and (4) onset at an phrase edge. For consonants in coda, the following phrase started with an [h] to ensure that no resyllabification occurred. The segment preceding the target consonant was controlled for not in the sense of being identical for all target consonants, but in the sense of always having a different primary articulator from each target consonant. This was done to minimize potential coarticulatory effects. The stimuli are shown in Table I.

Five subjects, denoted below as speakers A, E, M, N, and R, read the 12 sentences in eight randomized blocks. (For speaker E only two phrase boundary tokens for [t] were available for analysis due to unreliability of the tongue tip

TABLE I. Stimuli material.

	/f/
/f/: coda, phrase medial	"The doctor brought the scar**f** home for the holidays."
/f/: coda, phrase edge	"The doctor brought the scar**f**. Home weather was cold."
/f/: onset, phrase medial	"The doctor made the scar **f**oam with antiseptic."
/f/: onset, phrase edge	"The doctor made the scar. **F**oam antiseptic didn't help."
	/t/
/t/: coda, phrase medial	"The doctor had a very def**t** hand at all sorts of things."
/t/: coda, phrase edge	"The doctor was quite def**t**. Handiness was a big help."
/t/: onset, phrase medial	"That made being deaf **t**antamount to isolation."
/t/: onset, phrase edge	"It's hard being very deaf. **T**antamount to isolation."
	/p/
/p/: coda, phrase medial	"The puppy might yel**p** hideously due to its sore paw."
/p/: coda, phrase edge	"The puppy might yel**p**. Hideous illness it was not."
/p/: onset, phrase medial	"The mother might yell **p**itifully at that two-year-old."
/p/: onset, phrase edge	"The mother might yell. **P**itiful discipline had failed."

receiver at this point in the experiment; for this reason, only [f] and [p] tokens are included in the analysis for speaker E, so that the full-interaction model could still be run.) Total tokens for each subject and consonant are shown in Table II.

B. Data analysis

1. Kinematic landmarks

Movement trajectories and accompanying first-order derivatives (velocity trajectories) were smoothed with a 15-Hz low-pass filter (ninth-order Butterworth). Different signals were used for measurement of each consonant. For consonant [t], the *y* position and velocity of the transducer on the tongue tip (TT*y*) were used. For the two other consonants, a derived signal was created. For [p], the Euclidean distance between the lower and upper lip (lip aperture, LA) and its accompanying velocity trajectory were used. For [f], the Euclidean distance between the transducer on the lower lip and the stationary transducer on the maxilla (lower lip aperture, LLA) and its accompanying velocity trajectory were used.

TABLE II. Total tokens analyzed for each subject and for each consonant.

Speaker	/f/	/t/	/p/	Total
A	32	32	30	94
E	32	0	32	64
M	32	32	32	96
N	29	32	31	92
R	32	31	32	95
Total	157	127	157	441

In order to identify the articulatory magnitude and duration of the consonant articulations, kinematic landmarks were algorithmically identified in *y*-velocity trajectory and recorded automatically. Time and position for consonant onset, target, and end were defined by zero-crossings of the velocity trajectory. Additionally, the time of peak velocity for

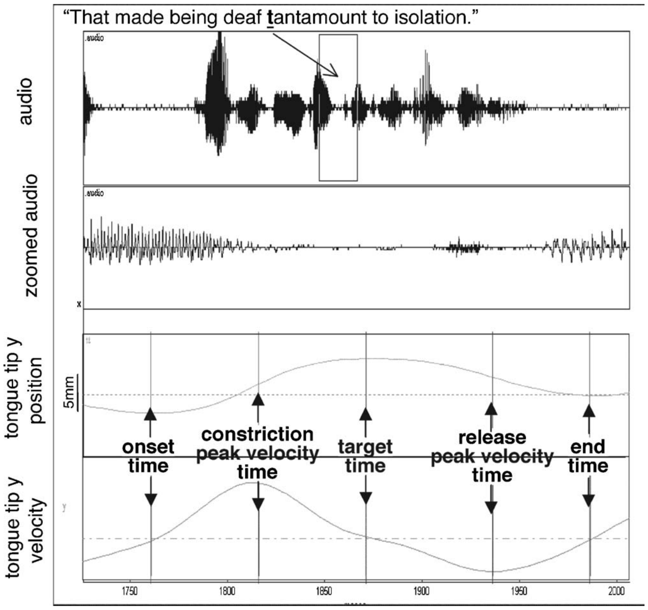

FIG. 3. An example token (speaker A) showing the audio signal (top panel), the zoomed audio signal (second panel), the smoothed tongue tip *y* position trajectory (third panel), and tongue tip *y* velocity trajectory (bottom panel). In the trajectories, the algorithmically defined timepoints of onset, target, and end (determined by velocity zero crossings) and of constriction and release peak velocities (determined by velocity extrema) are shown.

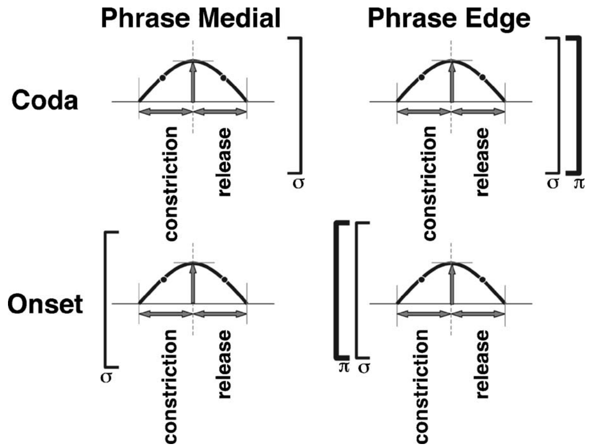

FIG. 4. A schema showing the measurements and conditions for the experiment. $]_\sigma$ and $_\sigma[$ refer to final and initial syllable edges, respectively, and $]_\pi$ and $_\pi[$ to final and initial phrase edges, respectively.

both the constriction and release of the consonant were recorded. (In the occasional case of multiple peak velocities, the highest peak velocity point was the landmark selected.)[1] Figure 3 shows an example data token with the kinematic landmarks marked.

The kinematically defined timepoints and positions of movement onset, target, and end and constriction and release time-peak-velocity (acceleration duration) were used to calculate several dependent measures of gestural magnitude and duration:

Temporal variables

(i) Total duration (end timepoint − onset timepoint)
(ii) Constriction duration (target timepoint − onset timepoint)
(iii) Release duration (end timepoint − target timepoint)
(iv) Constriction time-to-peak-velocity (constriction peak velocity timepoint − onset timepoint)
(v) Release time-to-peak-velocity (release peak velocity timepoint − target timepoint)

Spatial variables

(i) Extremum position (position at target timepoint)
(ii) Constriction displacement [|position at target timepoint − position at onset timepoint|]
(iii) Release displacement [|position at target timepoint − position at end timepoint|]

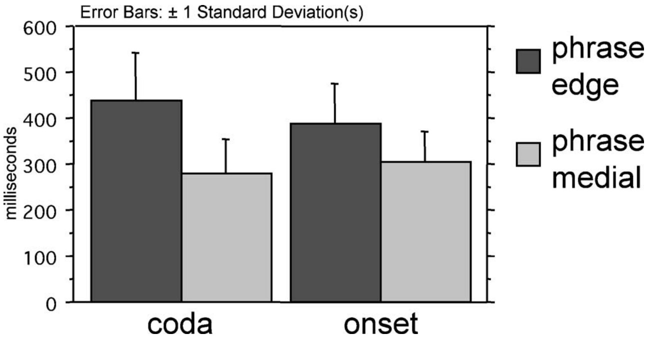

FIG. 5. Total duration (constriction duration plus release duration) (all subjects pooled).

The schema shown in Fig. 4 serves to orient the reader to the measurements and conditions in the experiment.

2. Statistical testing

A three-factor full interaction ANOVA (Statview by SAS) was used to test, separately for each subject, the effects of consonant ([f], [t], [p]), syllable position (onset/coda), phrase position (edge/final), and their interactions on the temporal and spatial dependent variables listed above. A criterial p value was set at $p < 0.05$. For all speakers and dependent variables, main effects of the consonant factor were predicted and observed. This main effect will not be reported below, as it is not relevant to addressing the hypotheses concerning syllable and phrasal position effects. Interesting significant crossover interactions of the consonant factor with the syllable or phrase factors will, however, be identified.

III. RESULTS

A. Duration

1. Total duration

As predicted, all subjects shared a main effect of phrasal position on total duration; consonants were longer at phrase edges than phrase medially. The result, pooled across subjects and consonants, is shown in Fig. 5.

The main effect of syllable position on the total duration variable was significant for two out of the five subjects (speakers E and R), and three subjects (A, E, and R) also had a significant interaction between syllable and phrase position such that phrasal lengthening was greater for codas than it was for onsets. Statistical results are shown in Table III.

TABLE III. Total duration effects statistical results (consonants pooled).

Total duration	Syllable main effect	Phrase main effect	Two-way interaction effect
Speaker A	n.s. coda 372 ms; onset 356 ms	$F(1,83)=94.05$, $p<0.0001$ edge 428 ms; medial 298 ms	$F(1,83)=22.920$, $p<0.0001$
Speaker E	$F(1,56)=13.697$, $p=0.0005$ coda 381 ms; onset 331 ms	$F(1,56)=54.223$, $p<0.0001$ edge 436 ms; medial 299 ms	$F(1,56)=28.335$, $p<0.0001$
Speaker M	n.s. coda 329 ms; onset 348 ms	$F(1,84)=29.170$, $p<0.0001$ edge 374 ms; medial 302 ms	n.s.
Speaker N	n.s. coda 334 ms; onset 343 ms	$F(1,80)=77.236$, $p<0.0001$ edge 403 ms; medial 279 ms	n.s.
Speaker R	$F(1,83)=11.1$, $p=0.0013$ coda 366 ms; onset 333 ms	$F(1,83)=231.731$, $p<0.0001$ edge 424 ms; medial 276 ms	$F(1,83)=23.902$, $p<0.0001$

TABLE IV. Constriction duration effects statistical results (consonants pooled).

Constriction duration	Syllable main effect	Phrase main effect	Two-way interaction effect
Speaker A	$F(1,83)=24.443$, $p<0.0001$ coda 169 ms; onset 226 ms	$F(1,83)=24.833$, $p<0.0001$ edge 226 ms; medial 168 ms	n.s.
Speaker E	$F(1,56)=6.673$, $p=0.0124$ coda 181 ms; onset 208 ms	n.s. ($p=0.0515$) edge 205 ms; medial 184 ms	n.s.
Speaker M	$F(1,84)=11.515$, $p=0.0011$ coda 163 ms; onset 200 ms	$F(1,84)=16.301$, $p=0.0001$ edge 204 ms; medial 159 ms	$F(1,84)=6.494$, $p=0.0126$
Speaker N	$F(1,80)=39.173$, $p<0.0001$ coda 172 ms; onset 231 ms	$F(1,80)=91.294$, $p<0.0001$ edge 251 ms; medial 159 ms	$F(1,80)=4.193$, $p=0.0439$
Speaker R	$F(1,83)=135.494$, $p<0.0001$ coda 118 ms; onset 197 ms	$F(1,83)=142.475$, $p<0.0001$ edge 198 ms; medial 117 ms	$F(1,83)=54.223$, $p<0.0001$

2. Constriction formation

It is important to note that the total duration measure does not consider the intervals of constriction formation and release separately. When constriction duration in particular is examined (see Table IV), four of the subjects had a main effect of phrase position on constriction duration. The fifth (E) had a near significant effect ($p=0.0515$) (recall that only [f] and [p] tokens could be included for E), and an interaction with consonant indicates that her [p]'s did not lengthen. The constriction durations for consonants at phrase edges were longer than for those located phrase medially. Additionally, syllable onset constrictions were longer than those for syllable codas, as indicated by a significant main effect of syllable position for all subjects. The mean constriction durations are shown in Fig. 6 for consonants separately (speakers A, M, N, and R pooled, i.e., the speakers with a significant phrasal effect). Three subjects (M, N, and R) had an interaction between syllable and phrase position such that longer constriction durations occurred for onsets located phrase initially than for codas located phrase finally.

The temporal properties of consonant release immediately preceding a boundary (i.e., the coda release) will be analyzed in the next section, but, for the sake of completeness, the release durations for the onset consonants show no effect of a preceding phrase boundary for speakers A, N, and M; for speaker E the releases lengthen slightly in the phrase boundary condition [$F(1,30)=4.498$, $p=0.0423$] and for speaker R the reverse obtains [$F(1,45)=12.301$, $p=0.001$].

In order to further investigate the mechanism of the positional lengthening, time-to-peak-velocity (i.e., the acceleration interval) for the constriction formation was examined (see Table V). Four of the five subjects showed main effects of both syllable and phrase position on constriction time-to-peak-velocity. For all speakers, onset time-to-peak-velocities were longer than in codas. For the four speakers with a significant main effect of phrase position, consonants located at phrase edges had longer time-to-peak-velocities than their counterparts located phrase medially. The fifth subject, who did not have a main effect for phrase boundary (again E), had an interaction with consonant as above, namely the majority pattern is reversed for her [p]. The majority pattern did not show any interaction of syllable and phrase position. Only two of the subjects (M and R) had such an interaction, and it was not consistent across consonants. For subject M, coda [p]s (only) did not lengthen at phrase edges, thereby contributing to the shorter means for codas at phrase edges. For subject R, onsets lengthened much more than codas. The constriction duration and time-to-peak-velocity patterns are shown in Fig. 7 with the speakers pooled.

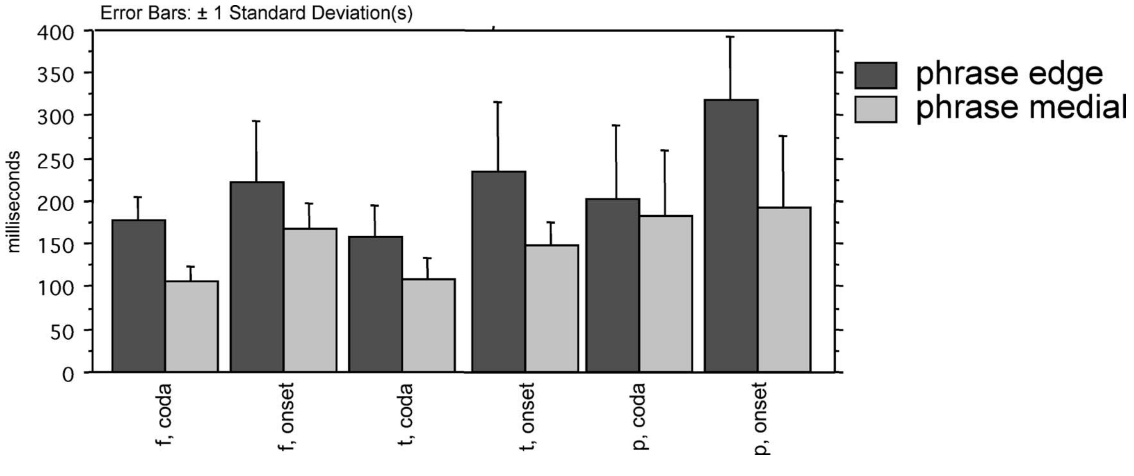

FIG. 6. Constriction duration (subject E excluded).

TABLE V. Constriction time-to-peak-velocity effects statistical results (consonants pooled).

Constriction time-to-peak-velocity	Syllable main effect	Phrase main effect	Two-way interaction effect
Speaker A	$F(1,83)=27.104$, $p<0.0001$ coda 104 ms; onset 163 ms	$F(1,83)=20.968$, $p<0.0001$ edge 160 ms; medial 108 ms	n.s.
Speaker E	$F(1,56)=6.552$, $p=0.0132$ coda 106 ms; onset 134 ms	n.s. edge 118 ms; medial 122 ms	n.s.
Speaker M	$F(1,84)=7.847$, $p=0.0063$ coda 108 ms; onset 137 ms	$F(1,84)=8.387$, $p=0.0048$ edge 137 ms; medial 108 ms	$F(1,84)=7.191$, $p=0.0088$
Speaker N	$F(1,80)=5.238$, $p=0.0247$ coda 103 ms; onset 131 ms	$F(1,80)=18.472$, $p<0.0001$ edge 143 ms; medial 95 ms	n.s.
Speaker R	$F(1,83)=73.480$, $p<0.0001$ coda 59 ms; onset 110 ms	$F(1,83)=90.001$, $p<0.0001$ edge 113 ms; medial 56 ms	$F(1,56)=38.309$, $p<0.0001$

3. Local duration

The final and initial consonants' constrictions intervals are not, however, equivalently "close" to the boundary. The onset consonant's constriction immediately follows the boundary, but, for the coda consonant, it is the release interval, rather than the constriction interval, that is immediately adjacent to the boundary. For this reason, an additional temporal analysis was conducted on what we term local duration—this is the duration of the consonant articulation interval (either constriction formation or release) located immediately adjacent to the phrase boundary. For codas, this is the constriction release phase (the time that elapses during the motion of the articulator from its target to the end of the articulation) and, for onsets, this is the constriction formation phase (the time that elapses from when the constriction starts until the time that the target is reached). The local duration measurement is shown schematically in Fig. 8. This analysis is particularly useful in examining a phrase boundary by syllable position interaction to determine the degree of symmetry in phrasal lengthening to the left and right of the boundary. (Syllable position main effects are expected in this case since release durations are being compared to constriction durations.) Results are given in Table VI.

For all subjects local durations for consonants located at phrase boundaries were significantly and robustly longer than local durations for consonants located phrase medially. The pooled average local duration for consonants phrase medially was approximately 160 ms, and the average local duration for consonants located at phrase boundary was approximately 256 ms. Most (3/5) subjects had no interaction effect—local durations at phrase edges were affected similarly for codas and onsets. The two subjects with an interaction effect (A and E) displayed greater lengthening for codas than for onsets.

For local time-to-peak-velocity, all subjects showed patterns similar to that for local duration (see Table VII). The portion of the consonant immediately local to the phrase boundary had a longer time-to-peak-velocity than the like portion phrase medially. Pooled across subjects and consonants there was a difference between the two phrasal conditions of 59 ms for onsets and 37 ms for codas. An asymmetry between codas and onsets exists for three subjects (M, N, and R) as indicated by a significant interaction effect of phrase and syllable position. For these subjects, the lengthening effect on time-to-peak-velocity was greater for onsets than it was for codas. A fourth subject with an interaction effect (E) had the asymmetry in the other direction. However, this only occurred due to a lack of effect in her onset

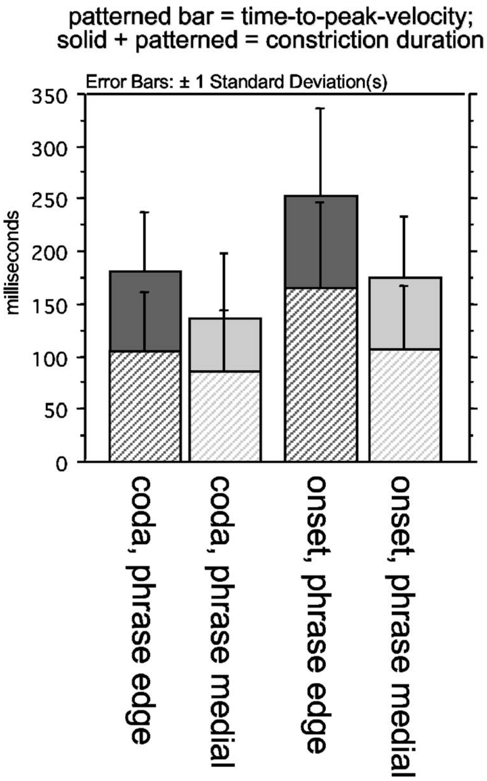

FIG. 7. Constriction duration (solid+patterned) and time-to-peak-velocity (patterned) (all subjects pooled).

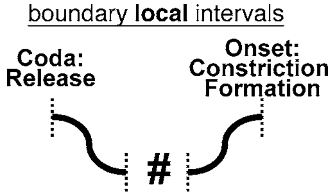

FIG. 8. A schema showing the local duration measure (i.e., release duration for codas and constriction duration for onsets).

TABLE VI. Local duration effects statistical results (consonants pooled).

Local duration	Syllable main effect	Phrase main effect	Two-way interaction effect
Speaker A	$F(1,83)=4.789$, $p=0.0315$ coda 203 ms; onset 226 ms	$F(1,83)=71.670$, $p<0.0001$ edge 261 ms; medial 167 ms	$F(1,83)=12.025$, $p=0.0008$
Speaker E	n.s. coda 228 ms; onset 208 ms	$F(1,56)=51.755$, $p<0.0001$ edge 266 ms; medial 170 ms	$F(1,56)=36.749$, $p<0.0001$
Speaker M	$F(1,84)=8.597$, $p=0.0043$ coda 166 ms; onset 200 ms	$F(1,84)=30.803$, $p<0.0001$ edge 215 ms; medial 151 ms	n.s
Speaker N	$F(1,80)=27.094$, $p<0.0001$ coda 162 ms; onset 231 ms	$F(1,80)=44.604$, $p<0.0001$ edge 244 ms; medial 155 ms	n.s
Speaker R	$F(1,83)=28.268$, $p<0.0001$ coda 248 ms; onset 197 ms	$F(1,83)=209.982$, $p<0.0001$ edge 291 ms; medial 156 ms	n.s

[p]s (recall from above that speaker E's [p]s behaved aberrantly); her onset and coda [f]s lengthen comparably, not showing any asymmetry. The overall means for local duration and local time-to-peak-velocity are shown in Fig. 9.

4. Summary for temporal patterning results

Generally, constriction formation was longer for consonants located in syllable onsets than for codas, and constriction formation was longer in duration for both onsets and codas at phrase boundaries. This effect of lengthening was most robust for consonant intervals most local to the boundary; that is, the constriction release for codas and the constriction formation for onsets. As expected based on previous work (e.g., Byrd *et al.*, 2000; Cho, in press), these portions exhibited a longer total duration and a longer time-to-peak-velocity when they occurred at phrasal boundaries.

The overall pattern of lengthening is shown in Fig. 10. Generally, the interval of boundary effect, i.e., the span over which temporal lengthening is exhibited, includes the constriction formation of phrase-final codas, their release, and the constriction formation (but not release) of onsets. Specifically, the most lengthening occurs for the releases of the preboundary codas and the constrictions of the postboundary onsets. These lengthen comparably as indicated by the lack of interaction effect in Table VI for the majority of subjects (3/5)—the mean amount of lengthening for these three subjects was 101 ms for onset constrictions and 90 ms for coda releases. (The other two subjects had more lengthening for coda releases.) In turn, the postboundary onset constriction lengthens more than the preboundary coda constriction for the majority of subjects, as indicated by the significant interaction effect for three of five subjects in Table IV. The amount of lengthening for onset constrictions at a phrase boundary was 73 ms (sp. M), 106 ms (sp. N), and 120 ms (sp. R), as compared to 17 ms (sp. M), 71 ms (sp. N), and 46 ms (sp. R) for coda constrictions preceding the boundary. Finally, recall from Sec. III A 2 that there was no lengthening of the onset consonant release after a phrase boundary for three of five speakers. (The other two show opposite directions of effect, such that one lengthens and one shortens the release following the phrase boundary.) Thus we conclude that the general pattern for consonant articulation adjacent to a phrase boundary is a great deal of lengthening in the immediate neighborhood of the boundary, lesser lengthening more remotely preceding the boundary, and no lengthening more remotely after a boundary.

B. Spatial results

The results concerning spatial characteristics of consonants at different syllable and phrase positions are not as consistent or conclusive as the results concerning temporal lengthening. Unlike the temporal domain, spatial strengthening is not exhibited consistently across subjects, consonants, or syllable position.

This may indeed reflect speaker variability, however, it is also possible that the EMA technique introduces limitations. Whereas EPG, for example, can evaluate changes in extrema positions due to tissue compression after the active and passive articulator have come into contact, EMA is not suited to such evaluation. In the case of the consonants /f/,

TABLE VII. Local interval (release for codas and constriction formation for onsets) time-to-peak-velocity effects statistical results (consonants pooled).

Local TPV	Syllable main effect	Phrase main effect	Two-way interaction effect
Speaker A	$F(1,83)=21.942$, $p<0.0001$ coda 110 ms; onset 163 ms	$F(1,83)=36.988$, $p<0.0001$ edge 171 ms; medial 102 ms	n.s.
Speaker E	$F(1,56)=20.676$, $p<0.0001$ coda 90 ms; onset 134 ms	$F(1,56)=9.931$, $p=0.0026$ edge 127 ms; medial 96 ms	$F(1,56)=6.567$, $p=0.0131$
Speaker M	$F(1,84)=57.859$, $p<0.0001$ coda 68 ms; onset 137 ms	$F(1,84)=13.825$ $p=0.0004$ edge 119 ms; medial 86 ms	$F(1,84)=6.980$, $p=0.0098$
Speaker N	$F(1,80)=53.848$, $p<0.0001$ coda 58 ms; onset 131 ms	$F(1,80)=7.976$, $p=0.0060$ edge 112 ms; medial 81 ms	$F(1,80)=10.448$, $p=0.0018$
Speaker R	n.s. coda 95 ms; onset 110 ms	$F(1,83)=54.018$, $p<0.0001$ edge 137 ms; medial 69 ms	$F(1,83)=8.498$, $p=0.0046$

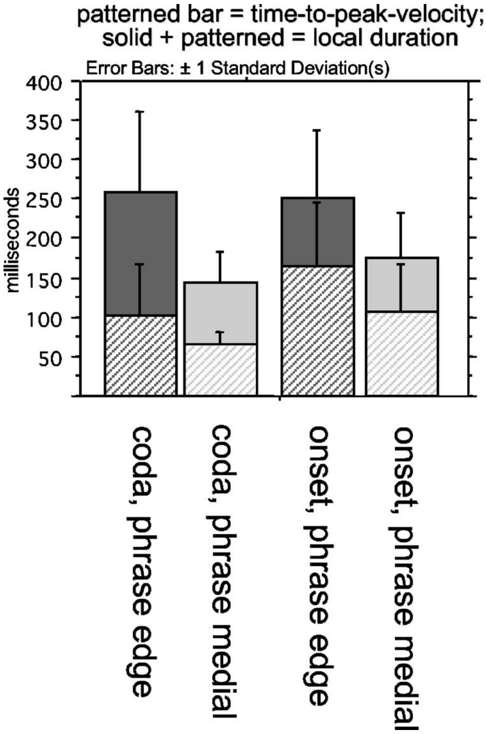

FIG. 9. Local duration (solid) and local time-to-peak-velocity (patterned) (all subjects pooled).

/p/, and /t/ here, lip aperture for /p/ and, possibly, lower lip aperture for /f/ might continue to show small effects of tissue compression as the lip receivers are on soft tissue at the vermillion border. For /t/, such effects would not be observed as the tongue tip receiver contacts the hard palate. Also, as for any point-tracking technology, the point (i.e., receiver) under examination might not be optimally located to reflect the maximal constriction location. However, because point tracking is a widespread technology often used in prosody investigations, we will, with these limitations in mind, examine constriction displacement and extremum position to determine, at least for magnetometry studies, whether the spatial variables pattern in the same way as the temporal variables. One might want to be conservative about the degree to which these spatial results are directly comparable to results using other methodology.

Because of the different nature of the consonant measures, each consonant's spatial behavior will be analyzed in separate two-factor ANOVAS, with syllable position and phrase boundary being the independent variables. The means for displacement and extremum position are given in Table VIII, though of course not every cell for each subject represents significant differences. (When a subject had no significant effects for a consonant, those means are omitted for brevity.) The significant ANOVA results are shown in Table IX.

1. /p/ spatial results

For the consonant /p/, four of the five subjects (excepting M) showed an effect of syllable position on displace-

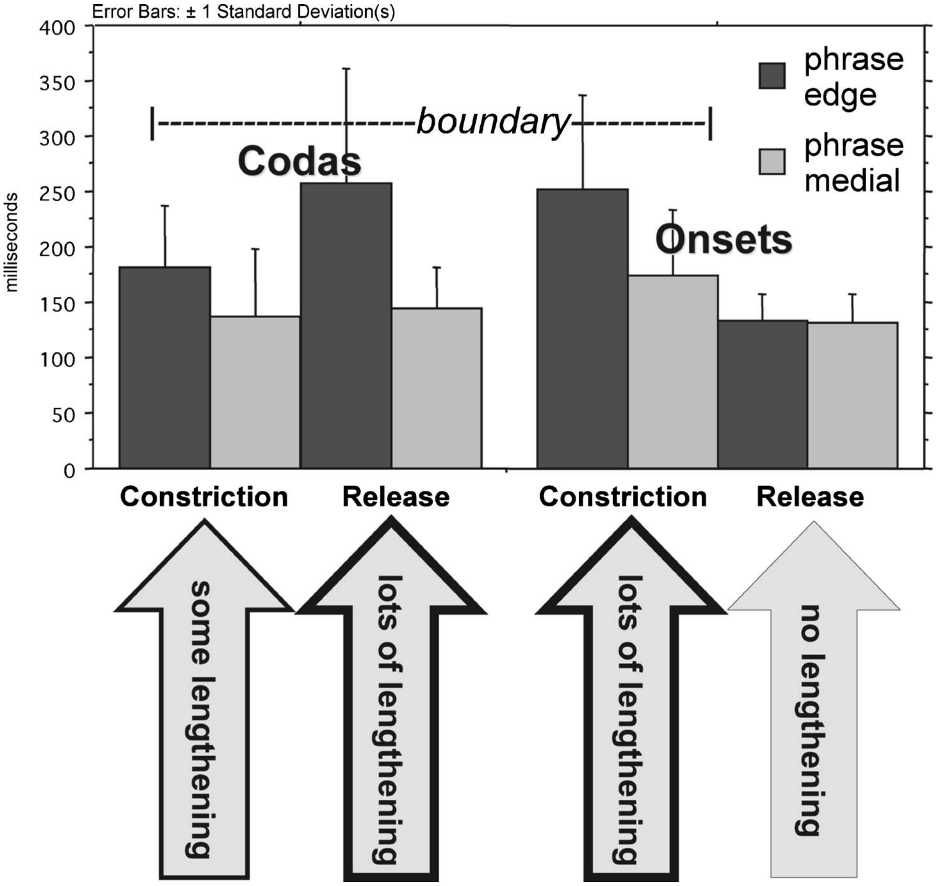

FIG. 10. Overview of temporal lengthening effects at phrase edge for codas and onsets (all subjects pooled).

TABLE VIII. Constriction displacement and extremum means. (Speaker A's /f/s do not appear because there were no significant effects; likewise Speaker M's displacement means for /p/ and /t/ and N's for /f/ were not significantly different.)

Consonant	Speaker	Syllable position	Phrasal position	Displacement value (mm)	Extremum value[a]
f	E	coda	phrase edge	3.2	22.6
f	E	coda	phrase medial	4.0	21.2
f	E	onset	phrase edge	6.5	20.2
f	E	onset	phrase medial	4.6	20.5
f	M	coda	phrase edge	4.4	24.2
f	M	coda	phrase medial	3.2	24.0
f	M	onset	phrase edge	5.2	24.5
f	M	onset	phrase medial	4.9	22.6
f	N	coda	phrase edge	n.s.	18.1
f	N	coda	phrase medial	n.s	19.5
f	N	onset	phrase edge	n.s.	17.5
f	N	onset	phrase medial	n.s.	18.3
f	R	coda	phrase edge	11.1	21.7
f	R	coda	phrase medial	9.6	23.2
f	R	onset	phrase edge	12.4	20.2
f	R	onset	phrase medial	12.3	20.7
t	A	coda	phrase edge	8.2	2.0
t	A	coda	phrase medial	4.0	0.5
t	A	onset	phrase edge	10.0	3.2
t	A	onset	phrase medial	8.5	2.3
t	M	coda	phrase edge	n.s.	2.0
t	M	coda	phrase medial	n.s.	−0.8
t	M	onset	phrase edge	n.s.	3.9
t	M	onset	phrase medial	n.s.	−1.7
t	N	coda	phrase edge	5.6	−0.8
t	N	coda	phrase medial	3.8	−0.8
t	N	onset	phrase edge	5.9	−0.3
t	N	onset	phrase medial	5.7	−0.3
t	R	coda	phrase edge	15.1	−7.5
t	R	coda	phrase medial	13.9	−7.1
t	R	onset	phrase edge	15.0	−6.0
t	R	onset	phrase medial	16.2	−6.6
p	A	coda	phrase edge	9.6	17.0
p	A	coda	phrase medial	9.7	17.8
p	A	onset	phrase edge	10.7	16.5
p	A	onset	phrase medial	11.2	17.8
p	E	coda	phrase edge	11.0	16.3
p	E	coda	phrase medial	11.7	15.3
p	E	onset	phrase edge	8.1	16.1
p	E	onset	phrase medial	12.1	15.2
p	M	coda	phrase edge	n.s.	17.4
p	M	coda	phrase medial	n.s.	16.4
p	M	onset	phrase edge	n.s.	17.4
p	M	onset	phrase medial	n.s.	17.5
p	N	coda	phrase edge	10.5	14.9
p	N	coda	phrase medial	9.8	14.6
p	N	onset	phrase edge	12.4	13.9
p	N	onset	phrase medial	10.2	13.9
p	R	coda	phrase edge	15.1	18.9
p	R	coda	phrase medial	14.6	18.7
p	R	onset	phrase edge	16.3	16.7
p	R	onset	phrase medial	16.4	18.0

[a] For extremum position /f/ and /p/ aperture in mm; /t/ position in mm in head-based coordinates where increasingly positive numbers indicate increasingly high vertical positions in the mouth.

TABLE IX. Spatial effects statistical results.

Subject	Consonant	Syllable effect	Phrase effect	Interaction
Displacement				
A	p	$F(1,27)=7.938$, $p=0.0089$		
	t	$F(1,28)=137.6$, $p<0.0001$	$F(1,28)=111.7$, $p<0.0001$	$F(1,28)=25.346$, $p<0.0001$
	f			
E	p	$F(1,28)=7.953$, $p=0.0087$	$F(1,28)=30.139$, $p<0.0001$	$F(1,28)=15.396$, $p=0.0005$
	f	*		*
M	p			
	t			
	f	$F(1,28)=20.177$, $p<0.0001$	$F(1,28)=7.341$, $p=0.0114$	
N	p	$F(1,27)=5.633$, $p=0.025$	$F(1,27)=8.817$, $p=0.0062$	
	t	$F(1,28)=11.073$, $p=0.0025$	$F(1,28)=9.944$, $p=0.0038$	$F(1,28)=5.773$, $p=0.0231$
	f			
R	p	$F(1,28)=6.84$, $p=0.0142$		
	t	$F(1,27)=8.182$, $p=0.0081$		$F(1,27)=9.391$, $p=0.0049$
	f	$F(1,28)=47.192$, $p<0.0001$	$F(1,28)=8.02$, $p=0.0085$	$F(1,28)=5.960$, $p=0.0212$
Extremum Position				
A	p		$F(1,27)=30.645$, $p<0.0001$	
	t	$F(1,28)=83.103$, $p<0.0001$	$F(1,28)=54.499$, $p<0.0001$	
	f			
E	p		$F(1,28)=16.108$, $p=0.0004$	
	f	$F(1,28)=20.809$, $p<0.0001$		$F(1,28)=6.902$, $p=0.0138$
M	p	$F(1,28)=5.028$, $p=0.033$		$F(1,28)=5.19$, $p=0.0306$
	t		$F(1,28)=12.743$, $p=0.0013$	
	f		$F(1,28)=8.156$, $p=0.008$	$F(1,28)=4.873$, $p=0.0356$
N	p	$F(1,27)=10.064$, $p=0.0037$		
	t	$F(1,28)=4.7$, $p=0.0388$		
	f	$F(1,25)=13.291$, $p=0.0012$	$F(1,25)=19.951$, $p=0.0001$	
R	p	$F(1,28)=18.794$, $p=0.0002$		$F(1,28)=4.932$, $p=0.0346$
	t	$F(1,27)=21.771$, $p<0.0001$		$F(1,27)=4.663$, $p<0.0399$
	f	$F(1,28)=176.5$, $p<0.0001$	$F(1,28)=45.12$, $p<0.0001$	$F(1,28)=12.095$, $p=0.0017$

ment; three of these had larger displacements in onset position. Only two subjects (E, N) showed an effect of phrase position on /p/ displacement, and they differed in direction of effect. An interaction for speaker E indicated that the displacement difference for phrase position is mostly limited to her onsets, with onset /p/ having a large phrase medial and small phrase edge displacement.

Results for lip aperture extremum values for /p/ indicate that three subjects (M, N, R) had a syllable effect such that onsets were more constricted than codas; however, two of these (M, R) had an interaction with phrase position. Speaker M exhibited a phrasal aperture difference for coda /p/s (smaller aperture phrase medially than at edges) but not for onset /p/. Speaker R's phrasal difference were only seen for onsets, where phrase edge coda /p/s had smaller apertures (i.e., were more constricted) than phrase medial coda /p/s. Two other subjects had a phrasal effect (A, E), in opposite directions of one another.

2. /f/ spatial results

For the consonant /f/, three of the five subjects (E, M, R) had a significant effect of syllable position on displacement, and two (M, R) had a phrasal effect on /f/ displacement. Speakers E and R, however, had an interaction effect. For speaker M (who lacked an interaction), phrase edge /f/ had larger displacements than phrase medial ones, and onsets had larger displacements than codas. Both speakers R and E, like speaker M, exhibited larger onset than coda displacements for /f/. For speaker R, only coda /f/ exhibited a phrasal difference such that phrase edge codas had larger displacements. For speaker E, the larger displacement at phrase edges as compared to phrase medial position was found for onsets, but codas were little different in the two phrasal contexts.

For /f/ extremum position, three of five subjects (E, N, R) had a syllable effect with onset /f/s having smaller apertures (more constricted) than coda /f/s, but speaker E and R also had a significant interaction with phrase position, as did speaker M. Speakers M, N, and R had a significant main effect of phrase position. Speaker N, who lacked an interaction effect, had smaller /f/ extremum aperture (i.e., were more constricted) for onsets than codas and for phrase edges than for phrase medially. The other speakers with interactions patterned as follows. For speaker M, only onsets showed an extremum aperture difference as a function of phrasal position with edges being less constricted than medial position. For speaker E, only codas showed an extremum aperture difference as a function of phrasal position with edges being less constricted than medial position. For speaker R, the phrasal effect was found for coda /f/s such that phrase edges are more constricted than phrase-medial codas.

3. /t/ spatial results

For the consonant /t/, displacement was significantly affected by syllable position for three of four subjects (A, N, R) and was significantly affected by phrase position for two subjects (N, R). (Recall that for the consonant /t/, speaker E was not represented.) However, all of these three speakers had a significant interaction effect as well. All three exhibited greater displacements for onsets than codas, though for speaker R this was limited to phrase medial position. Speaker A exhibited a large displacement for phrase edge codas, as compared to medial codas. The same direction of effect existed for onsets but was smaller in magnitude. Speaker N exhibited larger phrase edge as compared to medial displacements for coda /t/s but only a negligible effect, albeit in the same direction, for onset /t/s. Speaker R similarly exhibited large displacements for coda /t/s at phrase edges but no phrasal effect on onset /t/s.

Vertical extremum tongue tip position for /t/ was significantly affected by syllable position for three speakers (A, N, and R), just as with displacement, such that /t/ was more constricted in onset than in codas. Speakers A and M also had a phrasal main effect such that phrase edges had a higher (more constricted) extremum position. Speaker R exhibited an interaction effect such that phrase-edge onsets have a higher (more constricted) extremum position than phrase-medial onsets, thereby accentuating the coda versus onset distinction at phrase edges. Speakers A and N showed higher (more constricted) extremum positions for onsets than codas in both phrasal positions.

4. Summary of spatial patterning results

The spatial data were highly inconsistent both within and across subjects and within and across consonants. At best, the following generalizations can be distilled for the majority of subjects. With regard to syllable position effects, most speakers (three subjects) exhibited larger displacements in onset than in coda position for all three consonants. For most speakers for /f/ and /t/ and for two speakers for /p/, consonants also showed more constricted extrema in onsets than in codas, in line with previous studies. With regard to phrase position effects, for /f/ and /t/, most speakers exhibited larger displacements at phrase edges than phrase medially, though this pattern is not limited to only coda or onset consonants. Similarly for /f/ and /t/, consonants at a phrase edge generally showed more constricted extrema positions than when they occurred medially.

In sum, the above results on spatial strengthening lacked consistency across subjects, consonant locations, and consonants, though there were tendencies to strengthen at onsets and phrase edges. When phrasal strengthening did occur, it was *not* limited to onsets; phrase-final codas likewise could exhibit spatial strengthening patterns.

IV. DISCUSSION

The above results on spatiotemporal syllable position effects are consistent with those of previous articulatory studies (e.g., Browman and Goldstein, 1995; Keating *et al.*, 1999). Generally, consonants occurring syllable initially had longer total durations, constriction durations, and time-to-peak-velocities than those that occurred syllable finally. The notion that consonants are more prominent in word- or syllable-initial positions holds on a temporal level, as they exhibit significant amounts of lengthening when located in this position. With regard to the effect of syllable position on the spatial characteristics of consonant articulation, most subjects showed increased ranges of movement for the constriction formation portion of consonants located syllable initially than for those located syllable finally. Additionally, most showed this same spatial difference in terms of articulator extremum position—onsets had more extreme positions of articulator target achievements than codas. These results support previous studies, such as Byrd (1996) and Keating *et al.* (1999), that found similar strengthened articulation of onsets as compared to codas using electropalatography.

As for the phrasal influences on consonant articulation, the present results are likewise generally consistent with previous experiments when the temporal domain is considered (e.g., Byrd *et al.*, 2000; Cho and Keating, 2001). For all subjects, consonants that occurred at phrase-initial or phrase-final boundaries were longer in duration than those located phrase medially. They were longer in total duration, constriction duration, and time-to-peak-velocity. However, spatial strengthening of articulation of consonants occurring at phrase boundaries did not always occur, nor was it consistent across subjects or consonants. For constriction displacement, strengthening did not occur for the majority of subjects. However, when it did occur, consonants located at phrase edges had larger ranges of displacement than their phrase-medial counterparts. The majority of the speakers also showed greater articulator extrema positions for consonants located at phrase boundaries. This pattern of strengthening (when it did occur) is similar to that found in EPG (and other) studies reporting increased strengthening of consonants occurring at domain-initial boundaries, such as Keating *et al.* (2003). However, the strengthening that the subjects exhibited in the current study differs from what previous research has suggested in that strengthening was not limited to domain-initial positions. Consonants in phrase-final coda positions also showed the strengthening pattern, as suggested by an examination of strengthening of the consonantal portions adjacent to the phrasal boundary. Such behavior is preliminarily reported in Keating *et al.* (1999), and similar effects have been observed for vowels (e.g., Byrd *et al.*, 2000; Cho, 2005; Tabain, 2003).

Crucially, the present study sought to examine the *interaction* of syllable and phrasal position on the articulation of consonants, a phenomenon that has not been much explored. The results indicate that generally spatiotemporal phrasal effects exist comparably preceding and following a boundary. When constriction formation is examined, three of five subjects showed a larger phrasal lengthening effect on onsets, but this is not surprising when one considers that the constriction formation of the onset is immediately adjacent to the phrase edge whereas that interval for the coda is slightly farther removed (it is the constriction release that is the interval immediately preceding the phrase edge). When the intervals immediately local to the phrase edge are compared, most subjects (3/5) did not show an interaction of syllable position with phrasal position; that is, leftward and rightward phrasal lengthening were comparable. For those speakers that do show an asymmetry in the temporal effect, coda releases lengthened more but onset constrictions' time-to-peak-velocity lengthened more. Finally, with regard to syllable and phrase position interactions in the spatial domain, strengthening does not exactly pattern similarly to lengthening, nor is it limited to onsets, as previous research has suggested. Consonant codas at phrase boundaries may strengthen equally to onsets. Overall, temporal lengthening is consistent and its presence for a consonant can be predicted depending on the consonant's location within the syllable and within the phrase. However, spatial strengthening in terms of articulator displacement is not as consistent, nor is its presence as predictable as lengthening. In sum, strengthening does not necessarily pattern like lengthening.

Recall that that our research agenda included an examination of the relative spatiotemporal strength of codas phrase medially, codas phrase finally, onsets phrase medially, and onsets phrase initially. This ranking was examined with consonants for four speakers for constriction duration and local duration (with speaker E excluded since her data did not include [t], and her [p]s were seen to be aberrant from the general pattern). Speakers do not always agree in the positional rankings, but some generalizations do emerge. For constriction duration, onsets at phrase edges are consistently the longest and phrase medial codas consistently the shortest, but speakers varied in whether they differentiated the medial onsets from the medial or phrase edge codas. For local duration, subjects consistently had longer durations at phrase edges than medially but were not in agreement on if or how initial (i.e., onset) constriction duration and final (i.e., coda) release duration patterned. Most subjects (3/4) also had longer medial onset constriction durations than medial coda release durations. With regard to spatial prominence, the great variability between subjects and consonants and the small size of many effects makes it impossible to rank these positions in the spatial domain.

The results concerning temporal lengthening of consonants give support for the π gesture model (Byrd and Saltzman, 2003). Qualitatively, the local edges of both codas and onsets are lengthened similarly for most subjects at a phrase boundary. This supports the conception of the π gesture spanning the boundary interval, overlapping the portion of the consonant most local to the boundary, and the prediction of like leftward and rightward qualitative effects. Quantitatively, the effect on gestural stiffness is seen on both left and right sides of the π gesture. However, for three subjects there is some evidence to suggest that the quantitative effect of the π gesture is more robust rightward. That is, the effect on gestural stiffness is more readily seen and more robust for phrase-initial edges than for phrase-final edges. This suggests that in further modeling work of prosodic boundary effects within this framework the activation trajectory or the phasing of the π gesture might have a rightward skew for some speakers (see Byrd and Saltzman, 2003). In general, across prosodic modeling frameworks the possibility of subtle speaker-specific differences in a common mechanism of boundary-adjacent lengthening will need to be accommodated.

V. CONCLUSION

The present study contributes to an understanding of prosodic signatures on articulation by examining the effects of phrasal and syllable position on the constriction formation and release of consonants. Spatial effects on the consonant articulations were quite variable, differing among speakers and consonants. Phrasal strengthening was possible for both coda and onset consonants at phrase edges. Onsets were generally spatially strengthened in comparison to codas in equivalent phrasal position. The temporal results were quite consistent and indicate that syllable and phrasal position both affect the movement duration. Syllable-initial consonants had longer articulatory durations as compared to like consonants syllable-finally. Articulations at phrase edges were also consistently longer than those phrase medially. For most subjects, the boundary-adjacent portion of the movement (constriction release for a preboundary coda and constriction formation for a postboundary onset) are not differentially affected in terms of phrasal lengthening—both lengthen comparably. This indicates that the boundary-adjacent articulatory lengthening is roughly symmetrical in the immediate vicinity of the boundary.

ACKNOWLEDGMENTS

The authors are grateful for the support of NIH's NIDCD and of the USC Undergraduate Research Program and for the assistance and advice of Professors James Mah and Shri Narayanan. The authors also thank Marija Tabain and an anonymous reviewer for their helpful comments.

---

[1] A couple of tokens for each subject showed multiple velocity zero-crossings at target attainment, due to a plateaued shape for the position trajectory. In these cases, the middle crossing was generally selected.

Beckman, M. E., and Edwards, J. (**1992**). "Intonational categories and the articulatory control of duration," in *Speech Perception, Production, and Linguistic Structure*, edited by Y. Tohkura, E. Vatikiotis-Bateson, and Y. Sagisaka (Ohmasha, Tokyo), pp. 359–375.

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

Browman, C., and Goldstein, L. (**1995**). "Gestural syllable position effects in American English," in *Producing Speech: Contemporary Issues. For Katherine Safford Harris*, edited by F. Bell-Berti and L. Raphael (AIP, Woodbury, NY), pp. 19–34.

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

Byrd, D., and Saltzman, E. (**1998**). "Intragestural dynamics of multiple prosodic boundaries," J. Phonetics **26**, 173–199.

Byrd, D., and Saltzman, E. (**2003**). "The elastic phrase: Modeling the dynamics of boundary-adjacent lengthening," J. Phonetics **31**, 149–180.

Byrd, D., Kaun, A., Narayanan, S., and Saltzman, E. (**2000**). "Phrasal signatures in articulation," in *Papers in Laboratory Phonology V*, edited by M. B. Broe and J. B. Pierrehumbert (Cambridge U.P., London), pp. 70–87.

Cho, T. (in press). "Manifestation of prosodic structure in articulatory variation: Evidence from lip kinematics in English," in *Laboratory Phonology 8: Varieties of Phonological Competence*, edited by L. M. Goldstein, D. H. Whalen, and C. T. Best (Mouton de Gruyter, Berlin).

Cho, T. (**2005**). "Prosodic strengthening and featural enhancement: Evidence from acoustic and articulatory realizations of /a, i/ in English," J.

Acoust. Soc. Am. **117**, 3867–3878.

Cho, T., and Keating, P. (**2001**). "Articulatory and acoustic studies on domain-initial strengthening in Korean," J. Phonetics **29**, 155–190.

Edwards, J., Beckman, M. E., and Fletcher, J. (**1991**). "The articulatory kinematics of final lengthening," J. Acoust. Soc. Am. **89**, 369–382.

Fougeron, C., and Keating, P. (**1997**). "Articulatory strengthening at edges of prosodic domains," J. Acoust. Soc. Am. **101**, 3728–3740.

Hacopian, N. (**2003**). "A three-way VOT contrast in final position: Data from Armenian," J. Int. Phonetic Assoc. **33**, 51–80.

Keating, P., Wright, R., and Zhang, J. (1999). "Word-level asymmetries in consonant articulation" UCLA Working Papers in Phonetics 97.

Keating, P., Cho, T., Fougeron, C., and Hsu, C. (**2003**). "Domain-initial strengthening in four languages,"in *Papers in Laboratory Phonology 6*, edited by J. Local, R. Ogden, and R. Temple (Cambridge U.P., London), pp. 143–161.

Kelso, J. A. S., Vatikiotis-Bateson, E., Saltzman, E., and Kay, B. (**1985**). "A qualitative dynamic analysis of speech production: phase portraits, kinematics, and dynamic modeling," J. Acoust. Soc. Am. **77**, 226–280.

Ostry, D. J., and Munhall, K. (**1985**). "Control of rate and duration of speech movements," J. Acoust. Soc. Am. **77**, 640–648.

Saltzman, E. L., and Munhall, K. G. (**1989**). "A dynamical approach to gestural patterning in speech production," Ecological Psychol. 1, 333–382.

Tabain, M. (**2003**). "Effects of prosodic boundary on /aC/ sequences: articulatory results," J. Acoust. Soc. Am. **113**, 2834–2849.