How far, how long: On the temporal scope of prosodic boundary effects[a]

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Acoustic lengthening at prosodic boundaries is well explored, and the articulatory bases for this lengthening are becoming better understood. However, the temporal scope of prosodic boundary effects has not been examined in the articulatory domain. The few acoustic studies examining the distribution of lengthening indicate that boundary effects extend from one to three syllables before the boundary, and that effects diminish as distance from the boundary increases. This diminishment is consistent with the π-gesture model of prosodic influence [Byrd and Saltzman, J. Phonetics **31**, 149–180 (2003)]. The present experiment tests the preboundary and postboundary scope of articulatory lengthening at an intonational phrase boundary. Movement-tracking data are used to evaluate durations of consonant closing and opening movements, acceleration durations, and consonant spatial magnitude. Results indicate that prosodic boundary effects exist locally near the phrase boundary in both directions, diminishing in magnitude more remotely for those subjects who exhibit extended effects. Small postboundary effects that are compensatory in direction are also observed. © *2006 Acoustical Society of America.* [DOI: 10.1121/1.2217135]

I. INTRODUCTION

A. Articulatory studies on phrase boundary effects

Prosodic structure shapes the production of individual phonological units at phrase boundaries and under accent. In the vicinity of prosodic boundaries, segments exhibit acoustic final lengthening (e.g. Oller, 1973; Klatt, 1976; Wightman *et al.*, 1992) and initial lengthening (Oller, 1973). Articulatory studies show that at phrase edges "gestures get larger, longer, and further apart" (Byrd and Saltzman, 2003, p. 159; Byrd *et al.*, 2000). Articulations are spatially more extreme and temporally longer (Edwards *et al.*, 1991; Beckman and Edwards, 1992; Fougeron and Keating, 1997; Byrd and Salzman, 1998; Fougeron, 2001; Cho, 2006; Cho and Jun, 2000; Cho and Keating, 2001; Tabain, 2003; Keating *et al.*, 2004; Tabain and Perrier, 2005).

Phrase final and initial articulatory lengthening have been observed to increase cumulatively for larger prosodic boundaries (phrase finally: Byrd and Saltzman, 1998; Byrd, 2000; Cho, 2006; Tabain, 2003; Tabain and Perrier, 2005; and phrase initially: Byrd and Saltzman, 1998; Cho and Keating, 2001; Fougeron, 2001; Cho, 2006; Tabain, 2003; Keating *et al.*, 2004), though there is individual variation. Articulatory studies have also shown there to be less temporal overlap between articulations separated by a boundary or adjacent to a boundary (McClean, 1973; Byrd *et al.*, 2000;

Byrd and Saltzman, 1998; Byrd, 2000; see also Hacopian, 2003). This depends on boundary strength; gestures are less overlapped across stronger boundaries (Byrd, 2000; Cho, 2004).

In the spatial domain, Fougeron and Keating (1997) and others show the effects of increased linguapalatal contact to be cumulative—higher (stronger) prosodic boundaries induce greater linguapalatal contact, both phrase initially (Fougeron and Keating, 1997; Cho and Keating, 2001; Fougeron, 2001; Keating *et al.*, 1999; Tabain, 2003; Keating *et al.*, 2004) and phrase finally (Fougeron and Keating, 1997 [although their results are less consistent across speakers than their results for phrase-initial effects], Keating *et al.*, 1999; see also Hacopian, 2003; Tabain, 2003). Both phrase-final and phrase-initial magnitude results tend to vary across speakers and across segments examined (see, e.g., Byrd *et al.*, 2005), and different studies find spatial effects at different prosodic domains.

B. Acoustic and articulatory studies on the temporal scope of phrase boundary effects

While the articulatory and acoustic effects of boundaries have been examined in a number of studies, the *temporal scope* of boundary effects—i.e., the interval preceding and following a boundary over which they occur—has been far less studied. A few studies have addressed this question in the domain of acoustics. Oller (1973) examined onset and coda lengthening and found that generally both lengthen in final syllables. Berkovits (1993a, 1993b) showed that in phrase-final bisyllabic words with stress on the second (final) syllable, lengthening of segments within the final syllable is largest in the final segment and decreases in the preceding segments. Furthermore, phrase-final lengthening extends to

the initial syllable (of bisyllabic words) but is lesser in magnitude than in the final syllable. Berkovits (1994) examined lengthening of phrase-final bisyllabic words with initial and final stress and found that words with initial stress show lengthening on both the initial and the final syllable and again, that the lengthening in the segments of the final syllable increases progressively closer towards the boundary. Words with final stress in this experiment show lengthening only on the final syllable, and again, segmental lengthening increases progressively towards the boundary. Overall, the initial syllable of two-syllable words lengthens less than the final syllable, and lengthening is mainly on the final syllable (Berkovits, 1993b, 1994).

Shattuck-Hufnagel and Turk (1998) examined lengthening effects, and they showed preboundary lengthening beyond the final syllable, back to the stressed syllable of a word. Lengthening is strongest in the final syllable. The postboundary effects show more lengthening on the onset than the rime vowel, which does not appear to lengthen. Turk (1999) reported that two-syllable words show phrase final lengthening back to the rime of the stressed syllable. Significant lengthening mainly occurs on the rimes, not on the onsets. (In the case of words with stress on the second syllable, one of two subjects showed a significant *shortening* effect on the rime of the first syllable.) Lengthening in the final syllable increases from nucleus to coda.

Cambier-Langeveld (1997), in her acoustic study on Dutch, examined the preboundary extent of the effect of prosodic boundaries. She found that the lengthening is largest in the final segment, and decreases in the preceding ones. Generally, the lengthening domain is the final syllable, but significant lengthening on the nucleus of the penultimate syllable occurred in one token word (*mode*), whose last syllable consists of an onset and a *reduced* vowel. (A trend for lengthening of the penultimate nucleus also occurred in the word *tandem*, in which the vowel of the final syllable is also reduced.) As Cambier-Langeveld noted, the effect of syllable weight on the domain of final lengthening could be explained by the fact that these syllables are phonetically shorter than the syllables with an unreduced vowel. Finally, Cambier-Langeveld pointed out that even though the amount of lengthening increases with higher prosodic boundaries, the domain of lengthening does not become larger. This result is similar to Berkovits's findings, who reported that, in words with initial stress, the first syllable accounts for 25% of the lengthening, the final syllable for 75%. In words with final stress, 5% of the average lengthening was due to the initial syllable and 95% was due to the lengthening of the final syllable (Berkovits 1993a, 1994). The figures in Turk (1999) point to a similar distribution of lengthening.

In the articulatory domain, there are only a few studies that tangentially examine the temporal extent or scope of phrasal lengthening. Byrd and Saltzman (1998) compared opening movements for C_1 and closing movements for C_2 in $[C_1V_1\#C_2V_2]$ sequences and show that the postboundary temporal effect is stronger. Byrd (2000) reported that, in $[C_1V_1\#C_2V_2]$ sequences, V_1 exhibits longer articulatory duration than V_2. A further indication of progressive final lengthening is evident in the results of Edwards *et al.* (1991)

and Beckman and Edwards (1992). They examined jaw movement in a VC sequence phrase finally and found that there is an increase in duration of the jaw opening and jaw closing movements, and that the effects are more prominent in the final jaw closing. Fougeron and Keating (1997) examined palatal contact in $[n_1o_1\#n_2o_2]$ sequences. They found for the consonants that there is a boundary effect not just domain initially (n_2), but also in some cases domain finally (n_1); however, the effect is much stronger closer to the boundary (that is, for n_2). Similarly for the vowel, the boundary effect was much stronger for the vowel closer to the boundary (o_1) than for the vowel farther away from the boundary (o_2). Their results can be taken to indicate a progressively decreasing effect of the phrase boundary (see also, Gendrot, 2005).

Together, the acoustic and articulatory studies point to decreased lengthening with distance from a phrasal boundary. Absolute phase final segments lengthen more than preceding ones. Furthermore, even though the degree of lengthening is a function of boundary type, the temporal locale of lengthening seems often to be largely, though not entirely, limited to the boundary-adjacent segments. Articulatory studies addressing the temporal scope of the boundary effects are sparse.

C. The π-gesture framework

Findings as to the temporal scope of phrasal effects on articulations have theoretical implications for the prosodic gesture (π-gesture) framework of Byrd and Saltzman (Byrd and Saltzman, 2003; Byrd *et al.*, 2000; Byrd, 2000). The π-gesture model extends the notion of phonological units being defined as intrinsically temporal (e.g., Browman and Goldstein, 1992), by viewing prosodic events such as phrase boundaries as having a temporal interval of activation, similar to constriction gestures. Many of the phrasal effects of longer duration, greater magnitudes, and decreased intergestural overlap have been successfully captured by simulations of boundaries, implemented as π-gestures, interacting with articulatory gestures within this model (Byrd and Saltzman, 2003). In this simulation work, a π-gesture on the prosodic tier influences all constriction gestures that are concurrently active with it. This overlap among suprasegmental and constriction gestures is shown in Fig. 1.

During the activation of a phrasal π-gesture, the central clock controlling the rate of activation-unfolding for active gestures is slowed (Byrd and Saltzman, 2003). The amount of slowing down depends on the strength of activation of the π-gesture, which is a reflection of the strength of the prosodic boundary. Because the π-gesture has a temporally discrete and smoothly varying interval of activation, the π-gesture model predicts that boundary effects should be local, that is, not discontinuous (Byrd and Saltzman, 2003). Further, because the π-gesture waxes and wanes in activation, the lengthening associated with a π-gesture is predicted to likewise increase in degree as the π-gesture's peak activation is reached and then decrease (Byrd and Saltzman, 2003).[1]
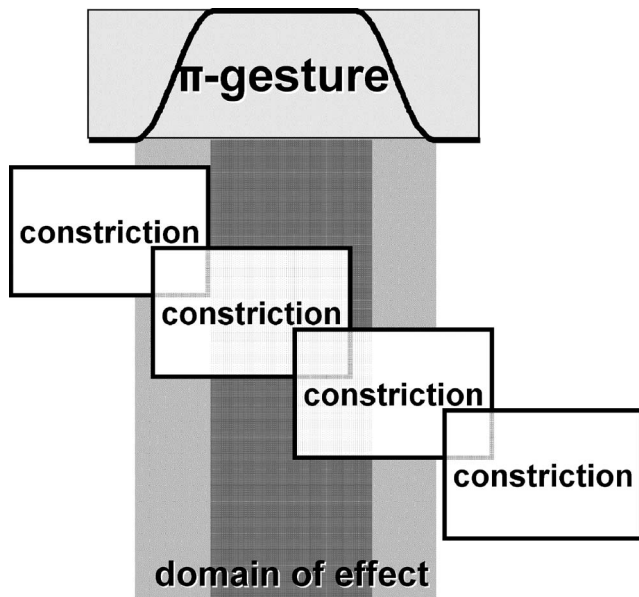
FIG. 1. A schema of the π-gesture model representing the overlap of a π-gesture at a phrasal juncture with several closing movement gestures. Shading darkness represents strength of the π-gesture effect as the π-gesture's activation increases to maximum (darkest shading). The constriction gestures are representative of *any* consonant or vowel. In our experiment, the constrictions potentially represent the consonants N D D N.

D. Goals of the present study

The primary goal of this study is an empirical one—that is, to investigate the temporal scope of prosodic lengthening in the articulatory domain, since such articulatory data are not currently available in the literature. This articulatory kinematic experiment explicitly investigates the preboundary and postboundary extent of phrasal effects in the articulatory domain. Based on the results from the acoustic studies, we expect that the strongest articulatory lengthening will appear near the phrase edge but that lengthening could also be possible more remotely. We also seek to add to the description of the general nature of prosodically-driven temporal perturbation to articulation. We report spatial magnitude effects as well, primarily for the purpose of determining if they mirror the temporal effects observed for the vertical tongue tip movement, i.e., the tongue tip *y* trajectories (and, of course, for the purpose of adding to the limited data in the kinematic literature on phrasal spatial effects). We do not evaluate these spatial results in a theoretical context here.

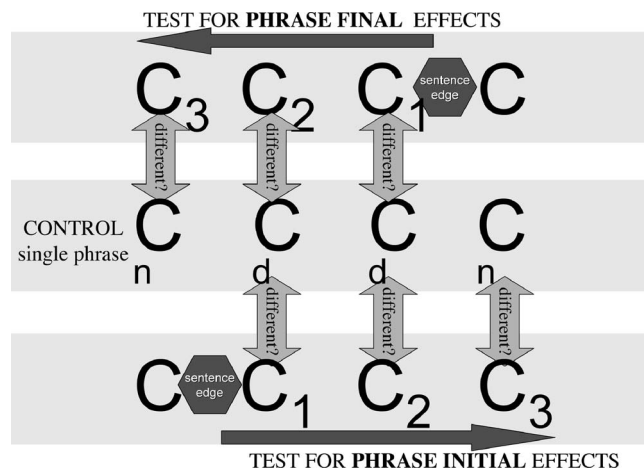We also pursue the additional secondary goal of evalu-

FIG. 2. Schematized experimental design.

ating whether the pattern of results is consistent with the π-gesture model of Byrd and Saltzman (2003). Because a π-gesture has a temporally discrete interval of activation with a smoothly waxing and waning function, it would be expected that boundary effects should be local to the boundary and not discontinuous (Byrd and Saltzman, 2003). Further, because the π-gesture waxes and wanes in activation, the degree of lengthening associated with a π-gesture is likewise expected to increase (as the π-gesture's peak activation is reached) and then decrease (Byrd and Saltzman, 2003). Lastly, prosodically driven lengthening is expected to be generally symmetrical [this is not a requirement of the model, merely the null hypothesis adopted in Byrd and Saltzman (2003)].

II. METHOD

A. Stimuli and subjects

Three stimuli, given in Table I, were used to test phrase boundary effects on preboundary and postboundary sequences of consonants, with the same phonological string appearing in each. The target sequence in each utterance was [...nVdVdVnV...]. The articulation of the tongue tip consonants will be investigated using articulatory movement tracking of a transducer placed on the tongue tip. For ease of presentation, we will denote the target sequence as [N D D N].

In order to avoid any confounding effect of accent at the phrase boundary, subjects were asked to emphasize (place in

TABLE I. Stimulus 1 is testing for preboundary effects; the consonants to be measured are N D D. Stimulus 2 is testing for postboundary effects; the consonants to be measured are D D N. Stimulus 3 is the control utterance and contains a phrase-medial sequence of consonants. (Subjects were instructed to emphasize the underlined word to control somewhat for focal accent placement.)

Effect	Consonants	Sentence
Preboundary effects	N D D	Birdhunting, we were shocked to see a **n**ew **d**o**d**o. Knock on wood that there are more.
Postboundary effects	D D N	At the zoo, we were shocked to see a Gnu. **D**o**d**o **kn**ocking about, however, would have been more surprising.
Control	N D D N	Birdhunting, we were shocked to see a **n**ew **d**o**d**o **kn**ocking on wooden posts.

focus) the underlined words ("shocked" and "more"), thus ensuring that the words containing the experimental target consonants did not receive a tonic accent. Sentence 1 probes for preboundary effects using the consonants (N D D). These consonants are compared to the parallel consonants in the control sentence (Sentence 3) in which the sequence is entirely phrase medial. Sentence 2 probes for postboundary effects using the consonants (D D N). They are likewise compared to the parallel phrase-medial consonants in the control utterance. The experimental design is schematized in Fig. 2. It should be noted that the preboundary consonant is not immediately before the boundary but is rather the onset consonant of the preboundary syllable; unlike the postboundary onset consonant, which is absolutely phrase-initial.

Four subjects, all native speakers of American English with no known speech or hearing disorders, participated. Subjects will be referred to as Subject A, Subject D (the first author), Subject E, and Subject J. The stimuli were pseudo-randomized in blocks of three stimuli with no adjacent identical tokens. Subjects read each utterance 12 times and were instructed to read in a casual conversational style. (For Speaker D, 3 of the 36 tokens [1 control and 2 postboundary] were lost due to data collection error.)

The audio recordings were evaluated using ToBI guidelines (Beckman and Elam, 1997). They were realized with the expected intonation: The utterance testing the postboundary effect was realized with an intonation phrase boundary (marked by a boundary tone and a break index 4) after the word "Gnu." The utterance testing the preboundary effect was realized with an intonation phrase boundary (marked by a boundary tone and a break index 4) after the word "dodo." The control utterance was realized as one or as two intonation phrases ("birdhunting" was sometimes realized as a separate intonation phrase)—but, crucially, the relevant consonants under examination were all within one intonation phrase. Thus, we confirm that the experiment will be able to test the effects of the presence of an intonational phrase boundary on the consonant sequence using the no-boundary sentence as a control.

B. Data collection

The Carstens Articulograph (AG200) was used to track a sensor adhered to the tongue tip. (For a subset of the subjects, a tongue dorsum sensor was adhered as well, though it was irrelevant for the analysis design of this study.) Reference sensors were tracked on the maxilla and bridge of the nose and a sample of the occlusal plane of each subject was acquired. Articulatory data were sampled at 200 Hz, and acoustic data at 16 kHz. After data collection, data were corrected for head movement and rotated to the occlusal plane. The tongue tip y (vertical) signal was differentiated, and signals were smoothed before and after differentiation with a ninth-order Butterworth filter of cutoff frequency 15 Hz. [For all speakers' tongue tip constrictions, the x (horizontal) component of the movement was negligible; the consonants were dominantly formed in the vertical direction.]

C. Data analysis

For each of the consonants to be analyzed (N D D for the preboundary effects, D D N for the postboundary effects, and N D D N for the control condition), three timepoints were defined: The onset of the closing movement, the closing movement extremum (also initiation of consonant opening movement), and the end of the opening movement. These timepoints were defined by zero-crossings in the tongue tip velocity trajectory (For the last consonant ([n]) in all conditions, the endpoint of opening movement could not be reliably identified and is not analyzed.) By definition, the end of opening movement for consonant one is also the onset of closing movement for consonant two, etc.; that is, a total of eight timepoints were identified. There were cases where there were two zero-crossings for the tongue tip extremum for a consonant—the first consonant ([n]) across all sentences and the second consonant [d] in the [N # D D N] sentence—in these cases, the spatially highest peak was selected to designate the extremum point. Further, at the boundary, there were cases for subjects A, J, and E in which there were multiple zero-crossings at the end of the preboundary consonant opening, defining both the end of the opening movement and simultaneously the beginning of the closing movement. The zero-crossing selected for this point was that which was temporally closest to the highest peak velocity of the upcoming postboundary consonant.

Additionally, the spatial position of the tongue tip y trajectory was measured at each of these timepoints. Finally, for each closing and opening movement, the time of peak velocity was also measured, yielding an additional eight timepoints. In the case of preboundary [d] opening and postboundary [n] closing, multiple velocity peaks sometimes occurred, and in such cases, the fastest peak was chosen. Thirteen atypical tokens were excluded from the analysis.

For each consonant's closing movement and opening movement, the following dependent variables were derived from the measured timepoints of the tongue tip vertical (y) transducer:

1 Duration:
 • For closing movement: Time from onset of closing movement to extremum.
 • For opening movement: Time from extremum to end of opening movement.

2 Time-to-peak-velocity:
 • For closing movement: Time from onset of closing movement to peak closing velocity.
 • For opening movement: Time from onset of opening movement to peak opening velocity.

3 Extremum position (one tongue tip y extremum for each [n], [d], [d], and [n]).

4 Displacement:
 • For closing movement: Euclidean distance between position at closing movement onset and at extremum.
 • For opening movement: Euclidean distance between position at extremum and at end of opening movement.

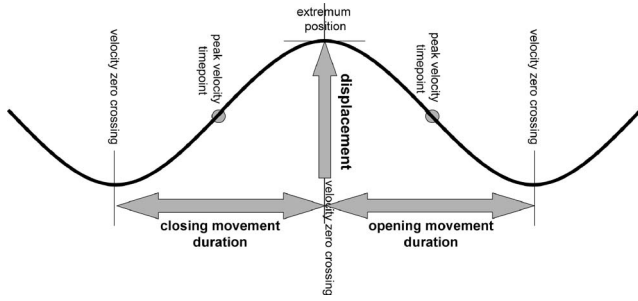These kinematic landmarks and derived variables are

FIG. 3. Schema of the measured points in the tongue tip vertical (y) trajectory.

schematized in Figure 3 for a single consonant (note that displacement can potentially be affected by either or both onset and offset position). Time-to-peak-velocity has proven to be a good indicator of gestural stiffness within a mass-spring gestural model as modeled within Task Dynamics (Saltzman and Munhall, 1989) and similar models of movement control, i.e., the parameter shaping the internal temporal properties of an articulatory gesture. Stiffness is the primary control parameter that has been implicated in phrasal lengthening (e.g., Edwards *et al.*, 1991; Beckman and Edwards, 1992; Byrd *et al.*, 2000) and a slowed gating-in of target stiffness is one of the consequences of clock slowing within the π-gesture model (Byrd and Saltzman, 2003).

Two-tailed *t*-tests were conducted testing the preboundary and postboundary effect on duration, time-to-peak-velocity, extremum position, and displacement. Criterial significance was set at $p < 0.05$. All and only statistically significant results are reported.

III. RESULTS

In presenting the details of temporal scope of effect, it will be convenient to numerically designate the consonant position relative to the utterance edge. To do this, we will use the designation C1 to refer to the consonant that is either the final (for the preboundary condition) or initial (for the post-

boundary condition) consonant in the test utterance, C2 to refer to the next-most preceding/following consonant, etc. Recall, however, that the while the postboundary C1 is immediately following the boundary, the preboundary C1 is the onset consonant of the preboundary syllable and thus not immediately at the final phrase edge.

Regarding acoustic pauses at the boundary, Speakers A, E, and J's pauses (i.e., silences) in the preboundary test utterance range from 350 to 650 ms; while for Speaker D's, only three were longer than 200 ms (the longest at 350 ms). Speakers A, E, and J's pauses (i.e., silences) in the postboundary test utterance range from 200 to 970 ms; while for Speaker D's, only four were longer than 200 ms (the longest at 350 ms), as with her preboundary condition sentence. In the preboundary condition, Speakers A, E, and J place the end of the opening movement for preboundary C1 in the second half of the acoustic pause; whereas for speaker D, this movement ends in all but one case during the vowel. Likewise, in the postboundary condition, Speakers A, E, and J place the beginning of the closing movement for postboundary C1 in the second half of the acoustic pause; whereas for speaker D, this movement starts during the preboundary vowel).

Another point to consider is that while this study explicitly controls for tonic accent, the possibility of variation in

TABLE II. Preboundary temporal scope of effect on C1: *t*-test results and means (SD) (ms). The reported n is the total number of tokens in the test plus the control conditions.

	Preboundary temporal scope of effect on C1: C3 C2 C1]			
	C1 closing movement duration	C1 closing movement time-to-peak-velocity	C1 opening movement duration	C1 opening movement time-to-peak-velocity
Subject A $n=24$	n.s. Control: 76 (5) Test: 79 (5)	n.s. Control: 45 (4) Test: 48 (4)	$t=15.351$, $p<0.0001$ Control: 86 (13) Test: 564 (107)	$t=3.959$, $p=0.0007$ Control: 31 (3) Test: 36 (3)
Subject D $n=21$	$t=4.120$, $p=0.0006$ Control: 98 (7) Test: 113 (9)	$t=2.462$, $p=0.0235$ Control: 56 (7) Test: 65 (8)	$t=2.445$, $p=0.0244$; n=20 Control: 82 (6) Test: 143 (83)	n.s. Control: 45 (8) Test: 49 (6)
Subject E $n=23$	n.s. Control: 88 (7) Test: 86 (2)	n.s. Control: 55 (9) Test: 52 (3)	$t=19.268$, $p<0.0001$ Control: 96 (10) Test: 560 (79)	n.s. Control: 40 (5) Test: 41 (8)
Subject J $n=18$	n.s. Control: 69 (2) Test: 69 (3)	n.s. Control: 36 (2) Test: 37 (3)	$t=8.634$, $p<0.0001$ Control: 62 (8) Test: 396 (116)	$t=6.288$, $p<0.0001$ Control: 32 (3) Test: 41 (3)

TABLE III. Postboundary temporal scope of effects on C1 *t*-test results and means (SD) (ms). The reported *n* is the total number of tokens in the test plus the control conditions.

	Post-boundary temporal scope of effect on C1: [C1 C2 C3			
	C1 closing movement duration	C1 closing movement time-to-peak-velocity	C1 opening movement duration	C1 opening movement time-to-peak-velocity
Subject A *n*=24	*t*=3.584, *p*=0.0017 Control: 70 (7) Test: 151 (78)	*t*=3.071, *p*=0.0056 Control: 37 (5) Test: 92 (61)	n.s. Control: 149 (21) Test: 131 (35)	n.s. Control: 97 (19) Test: 96 (31)
Subject D *n*=18	*t*=5.857, *p*<0.0001 Control: 92 (7) Test: 225 (76)	*t*=4.940, *p*=0.0001 Control: 49 (6) Test: 125 (51)	*t*=3.720, *p*=0.0019 Control: 107 (5) Test: 137 (26)	*t*=3.927 *p*=0.0012 Control: 63 (6) Test: 94 (25)
Subject E *n*=22	*t*=5.067, *p*<0.0001 Control: 65 (11) Test: 98 (18)	*t*=5.369, *p*<0.0001 Control: 29 (4) Test: 51 (13)	n.s. Control: 122 (6) Test: 118 (5)	n.s. Control: 73 (7) Test: 75 (3)
Subject J *n*=20	*t*=2.448, *p*=0.0248 Control: 91 (18) Test: 174 (100)	*t*=2.964, *p*=0.0083 Control: 31 (8) Test: 104 (73)	*t*=4.063, *p*=0.0007 Control: 120 (10) Test: 167 (34)	*t*=4.194, *p*=0.0005 Control: 85 (8) Test: 135 (35)

pre- and post-tonic accent exists. In the postboundary condition, all subjects place a very small accent on "dodo knocking" in *both* the control and the postboundary test sentences. Regarding the postboundary test sentence, for two speakers (A and J), there were differences in the accent size of F0 perturbation in the postboundary and control conditions, although, as noted above, the control condition also had a posttonic accent. For the other two speakers, these differences do not occur. Therefore, it is reasonable to conclude that the consistency, observed below across subject results, reflects the prosodic boundary effects, not any accentual differences.

We will start with a discussion of the preboundary effects, and follow that with a discussion of the postboundary effects, with temporal effects considered first and spatial effects following.

A. Preboundary temporal scope of effect: C3 C2 C1] (N D D])

T-test results for the preboundary scope of temporal effects on C1 are shown in Table II; there were no significant results for preboundary C2 and C3 (these means are included in the Appendix). All subjects show a significant and large effect of a phrase boundary on the duration of opening movement of the preboundary C1 consonant, which was longer in the test than control utterance. Two subjects (A and J) show a significant effect in their time-to-peak-velocity for C1 opening movement in that reaching peak velocity takes longer in the test than in the control condition. One subject (D) shows a significant effect on early movement intervals, in that C1 closing movement and C1 closing movement time-to-peak-velocity are longer in the test than in the control condition.

B. Postboundary temporal scope of effect: [C1 C2 C3 ([D D N)

In the postboundary direction, all subjects have longer closing durations and time-to-peak-velocities for C1 in the test condition as compared to the control condition. *T*-test results are given in Table III. For two subjects (D and J), C1 opening movement also shows longer durations and time-to-peak-velocity.

However, an interesting and unexpected result was observed for C2 and C3, and this result was obtained across subjects for both the closing and opening movements of the postboundary C2 and C3. (Recall that while C3 opening movement time-to-peak-velocity was measured, C3 opening movement duration was not). Subjects show *shorter* durations for these consonants in the test condition compared to the control no-boundary condition. These effects were quite uniformly significant (see Table IV).

In sum, there is a significant lengthening effect on C1 closing and (for some subjects) opening movement, and a significant shortening effect for C2 and C3. It is important to note that while this shortening is compensatory in direction (relative to the preceding lengthening), the shortening was not nearly as large in magnitude as the phrase-initial lengthening.

C. Scope of spatial effects

The preboundary spatial effects are inconsistent across subjects and across consonants. Means are given in Table V and the Appendix and significant results detailed below. While all speakers have temporally longer C1 opening movement and two had longer time-to-peak-velocities, there are no consistent preboundary effects in the spatial domain. While three subjects have a significant effect on preboundary C1 opening displacement, some have larger movements

TABLE IV. Postboundary temporal effects on C2 and C3 *t*-test results and means (SD) (ms). NB: These are all shortening effects in direction for the test condition. The reported *n* is the total number of tokens in the test plus the control conditions.

	Postboundary temporal scope of effect on C2: [C1 C2 C3			
	C2 closing movement duration	C2 closing movement time-to-peak-velocity	C2 opening movement duration	C2 opening movement time-to-peak-velocity
Subject A n=24	t=4.229, p=0.0003 Control: 76 (5) Test: 68 (4)	t=7.317, p<0.0001 Control: 45 (4) Test: 35 (2)	t=4.095, p=0.0005 Control: 86 (13) Test: 64 (13)	n.s. Control: 31 (3) Test: 31 (6)
Subject D n=18	t=4.283, p=0.0006 Control: 98 (7) Test: 84 (8)	t=3.908, p=0.0013 Control: 56 (7) Test: 44 (6)	t=6.494, p<0.0001 Control: 82 (6) Test: 67 (3)	t=3.599, p=0.0024 Control: 45 (8) Test: 34 (5)
Subject E n=22	t=3.551, p=0.002 Control: 88 (7) Test: 80 (4)	t=3.691, p=0.0014 Control: 55 (9) Test: 45 (5)	t=8.011, p<0.0001 Control: 96 (10) Test: 65 (9)	t=4.58, p=0.0002 Control: 40 (5) Test: 32 (3)
Subject J n=20	t=2.240, p=0.0379 Control: 69 (2) Test: 65 (5)	t=3.176, p=0.0052 Control: 36 (2) Test: 33 (3)	t=6.484, p<0.0001 Control: 62 (8) Test: 40 (6)	t=7.131, p<0.0001 Control: 32 (3) Test: 21 (4)
	Postboundary temporal scope of effect on C3: [C1 C2 C3			
	C3 closing movement duration	C3 closing movement time-to-peak-velocity		C3 opening movement time-to-peak-velocity
Subject A n=24	t=3.501, p=0.002 Control: 84 (7) Test: 74 (7)	t=4.357, p=0.0003 Control: 47 (6) Test: 37 (4)		n.s. Control: 80 (7) Test: 76 (14)
Subject D n=18	t=4.233, p=0.0006 Control: 90 (7) Test: 70 (13)	n.s. Control: 40 (6) Test: 39 (2)		t=2.473, p=0.025 Control: 54 (5) Test: 49 (4)
Subject E n=22	t=6.279, p<0.0001 Control: 91 (6) Test: 77 (4)	t=4.220, p=0.0004 Control: 50 (9) Test: 37 (3)		t=3.606, p=0.0018 Control: 73 (5) Test: 65 (6)
Subject J n=20	t=5.348, p<0.0001 Control: 115 (18) Test: 81 (9)	t=2.107, p=0.0494 Control: 38 (7) Test: 33 (3)		n.s. Control: 62 (16) Test: 54 (3)

(Subject D, t=4.8, p=0.0001, n=21) and some smaller (Subject A t=5.154, p<0.0001, n=24; Subject E, t=5.035, p<0.0001, n=23). With regard to C1 closing, though one subject (D) has a longer preboundary C1 closing duration, no spatial effect is observed for her; only one subject (J) has an effect on C1 closing movement displacement (t=2.992, p=0.0086, n=18), such that the boundary condition is smaller than control. Subject J also shows smaller displacements in the boundary condition for C2 opening (t=3.432, p=0.0034, n=18) and closing movements (t=2.896, p=0.0105, n=18). Two subjects (A and J) have an effect on C3 opening (A: t=2.137, p=0.044, n=24; J: t=2.403, p=0.0287, n=18) in opposite directions, J again with smaller displacements in the boundary condition. Finally, Subject E shows a significant effect on C3 closing movement displacement (t=2.120, p=0.0461, n=23).

For extremum position, two subjects (E and J) show a significant effect for C2 (E t=3.965, p=0.0007, n=23; J t=2.367, p=0.0309, n=18) and one subject (E) for C3 (t =3.556, p=0.0019, n=23). In all instances, the test condition showed less extreme positions than the control condition.

In contrast, postboundary spatial effects are more consistent and pattern consistently with the observed temporal effects. Results are shown in Table V. All subjects show larger displacements for C1 closing movement in the boundary condition. Note that this was the position for which all subjects show postboundary lengthening. For C1 opening movement, one subject has a slightly larger displacement in the test condition; and for C2 displacement, Subject E shows more displacement and Subject J shows less displacement in the test condition. A consistent pattern of smaller displacements was obtained for C2 opening movement and C3 closing movement for all subjects' boundary condition. Note that these were the two positions that also show consistent compensatory temporal shortening.

We note that postboundary C1 displacement differences are driven almost entirely by differences in onset position of the movement; namely for C1, the tongue tip started at a

TABLE V. Postboundary spatial effects *t*-test results and means (SD) (mm). The reported *n* is the total number of tokens in the test plus the control conditions.

| | Postboundary spatial scope of effect: [C1 C2 C3 | | | | |
	C1 closing movement displacement	C1 opening movement displacement	C2 closing movement displacement	C2 opening movement displacement	C3 closing movement displacement
Subject A $n=24$	$t=5.503$, $p<0.0001$ Control: 4.0 (1) Test: 6.5 (1)	n.s. Control: 12.8 (1.1) Test: 11.5 (2)	n.s. Control: 10.4 (1.1) Test: 9.1 (2)	$t=5.662$, $p<0.0001$ Control: 7.7 (1.4) Test: 4.3 (1.6)	$t=5.491$, $p<0.0001$ Control: 9.8 (1.5) Test: 6.3 (1.6)
Subject D $n=18$	$t=9.38$, $p<0.0001$ Control: 3.1 (0.5) Test: 6.9 (1.2)	n.s. Control: 9.5 (1.2) Test: 10.3 (1.1)	n.s. Control: 8.6 (1) Test: 7.9 (1)	$t=3.455$, $p=0.0033$ Control: 5.5 (1.5) Test: 3.3 (0.7)	$t=2.973$, $p=0.009$ Control: 5.5 (1.4) Test: 3.7 (0.8)
Subject E $n=22$	$t=10.593$, $p<0.0001$ Control: 3.9 (2.1) Test: 11.3 (0.9)	$t=2.433$, $p=0.0245$ Control: 12.6 (1.3) Test: 13.6 (0.6)	$t=3.568$, $p=0.0019$ Control: 10.6 (1.2) Test: 12.1 (0.7)	$t=7.951$, $p<0.0001$ Control: 9.5 (0.7) Test: 5.9 (1.3)	$t=9.943$, $p<0.0001$ Control: 12.1 (0.5) Test: 7.3 (1.5)
Subject J $n=20$	$t=6.972$, $p<0.0001$ Control: 1.6 (0.8) Test: 7.2 (2.3)	n.s. Control: 13.2 (1) Test: 13.1 (1.6)	$t=2.154$, $p=0.045$ Control: 9.5 (0.6) Test: 8.7 (0.8)	$t=6.707$, $p<0.0001$ Control: 6.3 (1.7) Test: 2.1 (1.1)	$t=5.732$, $p<0.0001$ Control: 9.7 (1.9) Test: 5.6 (1.3)

lower position. (That is, for all subjects, there is a significant effect for C1 closing movement in that the test condition had lower onset positions.) For C2 and C3 displacement changes, however, both onset and extremum positions change differentially—contributing to individuals' displacement effects. Subject D had a postboundary effect on C2 extremum position ($t=2.918$, $p=0.0101$, $n=18$) and Subject E had an effect on C3 extremum position ($t=3.387$, $p=0.0029$, $n=22$), with the direction of the effect opposite for each subject. As for onset position, Subject E had an effect on C2 onset position, and for C3 all subjects except D showed such an effect—but the direction of the effect varied.

D. Summary of results

1. Summary of preboundary effect

The most salient preboundary results are the temporal effects. All subjects have longer C1 opening movement durations, and two subjects have a longer time-to-peak-velocity as well in this position. One subject also has longer duration and time-to-peak-velocity for the C1 closing movement. Recall that this closing movement was for the consonantal onset of the preboundary syllable, i.e., that a vowel removes this consonant from immediate adjacency to the phrase edge.
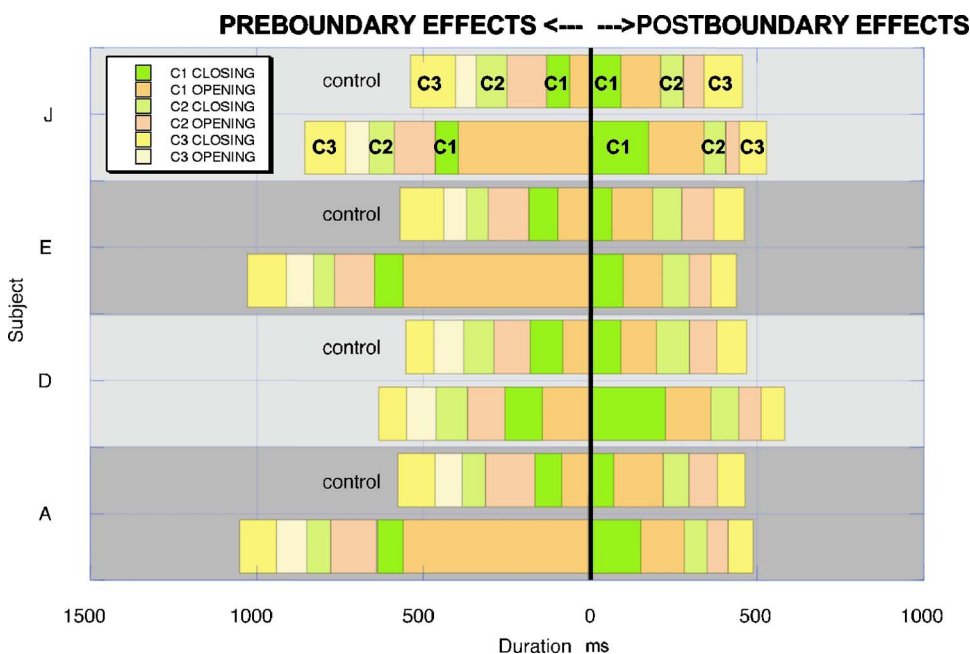

FIG. 4. (Color online) Consonant closing movement and opening movement duration results. The top bar for each speaker's pair is control and the bottom bar is test. (The bold line at center is merely a graphical convenience to separate results in the two conditions.)

Byrd *et al.*: Temporal scope of boundary effects

The spatial effects are inconsistent across subjects and conditions. For the C1 opening movement, there are no consistent spatial effects to accompany the temporal effects—some subjects have larger C1 opening movements and some smaller. For the speaker who had a longer C1 closing movement duration, no spatial effect was observed.

2. Summary of postboundary effect

The temporal effects show a clear postboundary pattern. For C1, there was a lengthening effect. The C1 closing movement has a longer duration and longer time-to-peak-velocity for all subjects. The C1 opening movement shows longer opening movement duration and longer time-to-peak-velocity for two subjects.

However, the closing movements and the opening movement examined for C2 and C3 show a *shortening* after C1 lengthening. All subjects show a shortening in duration and time-to-peak-velocity for the C2 closing movement. For the C2 opening movement, all subjects show shortening in duration, and three subjects show shortening of time-to-peak-velocity. For the C3 closing movement, all subjects show shorter duration, and three subjects show shorter time-to-peak-velocity. For the C3 opening movement, time-to-peak-velocity is shorter for two subjects. Despite its compensatory direction, the degree of shortening is quite small; much smaller than previous lengthening.

Overall, the postboundary spatial effects consistently correspond to the temporal effects. That is, for C1 closing movement, all subjects show a larger displacement in the boundary condition. For C2 opening movement and for C3 closing movement, all subjects show smaller displacement in the boundary condition.

A summary of the temporal results that indicates the scope of boundary related temporal lengthening is shown in Fig. 4. (The bold line down the center of Fig. 4 is presented solely for the graphical ease of placing the preboundary and postboundary results on a single graph, i.e., it has no theoretical or methodological significance.)

IV. DISCUSSION

The main findings of the experiment are: (a) Preboundary temporal effects, (b) postboundary temporal and spatial effects, (c) followed further into the phrase by postboundary compensatory shortening effects (accompanied by smaller displacements).

The prosodic π-gesture model (Byrd and Saltzman, 2003) predicts that activation slowing of articulatory gestures will increase as the π-gesture's activation increases and wane as the π-gesture's activation decreases. Our results show a strong local lengthening of the opening movement of the C1 preboundary consonant (in the CV syllable preceding the boundary) and of the closing movement of the C1 postboundary consonant. One subject (D) also shows lengthening of the closing movement of the preboundary C1 consonant, and, importantly, this effect is smaller in magnitude than the

effect on the phrase-final C1 opening (a change of 15 ms for closing movement versus 61 ms for opening movement). Postboundary, two subjects also have effects on the opening movement of C1—again, the effect is smaller than that shown for the immediately phrase-initial C1 closing (Subject D: Closing movement, the mean difference is 133 ms versus opening movement, 30 ms; Subject J closing movement, the mean difference is 91 ms versus opening movement, 48 ms). Thus, for the subjects for whom the boundary effect extends further than the boundary-adjacent movement—further leftward than C1 release preboundary, and further rightward than C1 closing postboundary—the effect of the boundary decreases with distance from the phrase edge (i.e., for Subject D, preboundary, and for Subjects D and J, postboundary). These decreasing effects are compatible with the π-gesture model in which the activation of the prosodic gesture extends over an interval, waxing and waning in strength.

The phrase-final and initial lengthening effects are roughly symmetrical, though the time-to-peak-velocity is affected only for two subjects preboundary; but for all four subjects, postboundary—presumably because the postboundary consonant is immediately at the phrase edge, unlike the preboundary syllable-onset consonant. Spatial effects are consistent for the postboundary articulations and pattern with the temporal effects, but this is not the case in the preboundary direction.

Particularly interesting results are the compensatory effects shown postboundary for C2 and C3, which to our knowledge have not been reported previously. It should be noted that they are much smaller than the lengthening effects, so are not "literally" compensatory. It is our view that the compensatory shortening is not a direct effect of the π-gesture; in other words, it is not a planned prosodic shortening that is occurring. Rather, it appears that, following the prosodic lengthening, there is an attraction of the constriction gestures back in the direction of the prosodically unmodified or unperturbed timing. If the prosodic lengthening were not compensated for at all, the effect of a phrase boundary would be to prolong the time of the utterance for precisely the duration of the local phrasal lengthening; this is unlikely to be the case. Studies on focal accent have suggested that while local gesture duration does affect global utterance duration, it does not prolong the utterance duration for the whole amount of the prosodic lengthening (Weismer and Ingrisano, 1979; consider also Lindblom and Rapp, 1973; Saltzman *et al.*, 2000). The compensatory shortening shown after a phrasal lengthening in our results indicates that the timing that would have been expected without prosodic warping is partially restored.

We conclude from the results of this articulatory kinematic experiment that the temporal prosodic effects on articulation are near the juncture, though not confined to the articulations immediately preceding or following the juncture; and they wax and wane in magnitude, both phrase finally and phrase initially. We further suggest that local gesture-to-gesture speech timing is sensitive to prosodic events, even downstream of those prosodic modifications.

APPENDIX

TABLE A1. Means (SD) (ms) for preboundary C2 and C3 durations (no significant differences exist).

n includes test+control	C2 closing movement duration	C2 closing movement time-to-peak-velocity	C2 opening movement duration	C2 opening movement time-to-peak-velocity	C3 closing movement duration	C3 closing movement time-to-peak-velocity	C3 opening movement duration	C3 opening movement time-to-peak-velocity
Subject A $n=24$	Control: 70 (7) Test: 72 (8)	Control: 37 (5) Test: 38 (5)	Control: 149 (21) Test: 136 (18)	Control: 97 (19) Test: 90 (15)	Control: 111 (30) Test: 110 (34)	Control: 40 (5) Test: 41 (5)	Control: 82 (25) Test: 92 (24)	Control: 80 (23) Test: 88 (19)
Subject D $n=21$	Control: 92 (8) Test: 95 (9)	Control: 49 (6) Test: 45 (7)	Control: 107 (5) Test:112 (10)	Control: 63 (6) Test: 63 (6)	Control: 82 (6) Test: 83 (7)	Control: 41 (4) Test: 43 (6)	Control: 90 (9) Test: 87 (8)	Control: 90 (9) Test: 87 (8)
Subject E $n=23$	Control: 65 (11) Test: 62 (3)	Control: 29 (4) Test: 30 (3)	Control: 122 (6) Test: 120 (4)	Control: 73 (7) Test: 69 (5)	Control: 129 (19) Test: 117 (32)	Control: 47 (3) Test: 50 (13)	Control: 69 (14) Test: 81 (24)	Control: 66 (12) Test: 73 (14)
Subject J $n=18$	Control: 91 (18) Test: 76 (18)	Control: 31 (9) Test: 47 (24)	Control: 120 (10) Test: 120 (6)	Control: 85 (8) Test: 84 (5)	Control: 133 (33) Test: 122 (34)	Control: 37 (8) Test: 38 (4)	Control: 64 (26) Test: 71 (28)	Control: 62 (21) Test: 67 (22)

TABLE A2. Means (SD) for preboundary displacement (mm) (* indicates a significant difference as detailed in text).

n includes test+control	C3 closing movement displacement	C3 opening movement displacement	C2 closing movement displacement	C2 opening movement displacement	C1 closing movement displacement	C1 opening movement displacement
Subject A $n=24$	Control: 3.8 (0.7) Test: 4.1 (0.8)	*Control: 2 (0.8) Test: 2.8 (1.0)	Control: 4 (1.0) Test: 4.4 (0.9)	Control: 12.8 (1.1) Test: 12.8 (0.9)	Control: 10.4 (1.1) Test: 10.5 (1.3)	*Control: 7.7 (1.4) Test: 4.4 (1.7)
Subject D $n=21$	Control: 4.9 (0.7) Test: 4.9 (0.8)	Control: 3 (0.5) Test: 3 (0.8)	Control: 3.1 (0.5) Test: 3.3 (0.5)	Control: 9.5 (1.2) Test: 9.9 (0.8)	Control: 8.6 (1.0) Test: 9.4 (1.4)	*Control: 5.5 (1.5) Test: 9.0 (1.8)
Subject E $n=23$	Control: 9.7 (0.7) Test: 8.4 (2.0)	Control: 4.3 (1.7) Test: 3.9 (1.3)	Control: 3.9 (2.1) Test: 3.6 (1.1)	Control: 12.6 (1.3) Test: 12 (1.1)	Control: 10.6 (1.2) Test: 10.7 (0.7)	*Control: 9.5 (0.7) Test: 8.0 (0.7)
Subject J $n=18$	Control: 3.2 (0.9) Test: 3.2 (0.6)	*Control: 1.2 (0.5) Test: 0.7 (0.4)	*Control: 1.6 (0.8) Test: 8 (0.3)	*Control: 13.2 (1.0) Test: 11.7 (0.8)	*Control: 9.4 (0.6) Test: 8.1 (1.2)	Control: 6.3 (1.7) Test: 4.6 (2.7)

TABLE A3. Means (SD) for extremum position (mm) (* indicates a significant difference). Negative numbers refer to positions below the occlusal plane.

n includes test+control	Preboundary			Postboundary		
	C3 extremum	C2 extremum	C1 extremum	C1 extremum	C2 extremum	C3 extremum
Subject A $n=24$	Control: −2.3 (0.4) Test: −2.1 (0.8)	Control: −4.0 (5.0) Test: −0.5 (0.5)	Control: −2.7 (0.4) Test: −2.8 (0.9)	Control: −0.4 (0.5) Test: −0.6 (0.7)	Control: −2.7 (0.4) Test: −3.0 (0.7)	Control: −0.6 (0.7) Test: −1.0 (0.5)
Subject D $n=21$ (prebound); $n=18$ (postbound)	Control: 5.5 (0.8) Test: 5.3 (1.0)	Control: 5.6 (0.7) Test: 5.6 (0.9)	Control: 4.7 (0.4) Test: 5.1 (1.0)	Control: 5.6 (0.7) Test: 6.3 (0.9)	*Control: 4.7 (0.1) Test: 3.9 (0.3)	Control: 4.7 (0.6) Test: 4.3 (0.6)
Subject E $n=23$ (prebound); $n=22$ (postbound)	*Control: −5.089 (0.7) Test: −6.414 (1.0)	*Control: −5.5 (0.7) Test: −6.8 (0.8)	Control: −7.6 (0.6) Test: −8.0 (0.6)	Control: −5.5 (0.7) Test: −5.6 (0.5)	Control: −7.6 (0.6) Test: −7.1 (0.4)	*Control: −4.9 (0.6) Test: −5.8 (0.5)
Subject J $n=18$ (prebound); $n=20$ (postbound)	Control: −4.2 (0.7) Test: −4.4 (0.3)	*Control: −3.8 (0.5) Test: −4.3 (0.2)	Control: −7.6 (0.3) Test: −7.9 (1.0)	Control: −3.8 (0.5) Test: −3.7 (1.1)	Control: −7.6 (0.3) Test: −8.1 (1.1)	Control: −4.2 (0.7) Test: −4.6 (0.5)

[1]It is interesting to speculate as to the accommodation of extremely long pauses, where in some sense the speech stream stops and restarts again, within the π-gesture framework. There are two (simultaneously viable) ways to view pauses within the π-gesture framework. First, one might view a pause as resulting from an extremely strong π-gesture, such that there is no qualitative difference between strong boundaries with and without a pause; a strong enough π-gesture simply slows articulation to an "effective" stop. It may be sensible in this regard to think about boundaries with pauses as having a flattened or plateaued π-gesture activation trajectory shape (Byrd and Saltzman 2003). A second possibility is to have overlapping phrase-final and phrase-initial π-gestures, *but* the model critically assumes these to have the same quality and nature of effect (Byrd and Saltzman 2003). In either case, a pause could be understood as a period during which planning of a gestural score for the upcoming utterance is occurring (see, Goldstein *et al.* 2006). (We thank Elliot Saltzman for helpful input on this matter.)

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