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Effects of Prosody on Articulation in English

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by

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- Cho, T., Jun, S.-A., Jung, S. & Ladefoged, P. (to appear) The vowels of Cheju. *Journal of the Linguistic Society of Korea*. (An earlier version appeared in *UCLA Working Papers in Phonetics*, 98, 81-94.)
- Cho, T. (2001) Effects of morpheme boundary on gestural overlap: Evidence from Korean. *Phonetica*, 58, 129-162. (An earlier version appeared in *UCLA Working Papers in Phonetics*, 99, 71-107.)
- Cho, T. & Keating, P. (2001) Articulatory and acoustic studies of domain-initial strengthening in Korean. *Journal of Phonetics*, 29, 155-190. (An earlier version appeared in *UCLA Working Papers in Phonetics*, 97, 100-138.)

- Cho, T., Jun, S.-A. & Ladefoged, P. (2000) An acoustic and aerodynamic study of consonants in Cheju. In *Journal of the Korean Association of Speech Science*, 7, 109-141. (An earlier version appeared in *UCLA Working Papers in Phonetics*, 98, 54-80.)
- Cho, T. & Jun, S. (2000) Domain-initial strengthening as featural enhancement: Aerodynamic evidence from Korean. In *Chicago Linguistics Society*, 36(1), 31-44. (An earlier version appeared in *UCLA Working Papers in Phonetics*, 99, 57-69.)
- Cho, T. (2000) Intra-dialectal variation in Korean consonant cluster simplification: A stochastic approach. In *Chicago Linguistics Society*, 35. (Also appeared in *UCLA Working Papers in Phonology* 2.)
- Cho, T. & Ladefoged, P. (1999) Variations and universals in VOT: evidence from 18 languages. *Journal of Phonetics*, 27, 207-229.
- Cho, T. (1999) A Phonetically-driven Optimality-Theoretic analysis of opacity: with special reference to palatalization in Korean. In *Linguistics in the Morning Calm* 4, pp.181-198. (Edited by the Linguistics Society of Korea)
- Cho, T. (1999) Effect of prosody on Vowel-to-Vowel coarticulation in English. *Proceedings of International Congress of Phonetics Science (ICPhS) 99*.
- Cho, T. (1998) Intergestural timing and overlap in Korean palatalization: An Optimality-Theoretic Approach. In David Silva (eds.) *Japanese/Korean Linguistic*, vol. 8, 261-276. CSLI: Stanford University. Distributed by Cambridge University Press
- Cho, T. (1998) Domain-initial strengthening in the prosodic hierarchy: an EPG study. *Proceedings of 11th International Conference on Korean Linguistics (ICKL 11)*, July 6-9, 1998. University of Hawaii at Manoa.
- Cho, T. & Ladefoged, P. (1997) Variations and universals in VOT: evidence from 17 endangered languages. *UCLA Working Papers in Phonetics*, 95, 18-40.
- Cho, T., Taff, A., Dirks, M. & Ladefoged, P. (1997) Some phonetic structures of Aleut. *UCLA Working Papers in Phonetics*, 95, 68-90.
- Keating, P., Cho, T., Fougeron, C. & Hsu, C. (to appear) Domain-initial strengthening in four languages. In *Laboratory Phonology VI*. Cambridge University Press. (Also in *UCLA Working Papers in Phonetics* 97, 139-151.)
- Ladefoged, P. & Cho, T. (2000) Linking linguistic contrasts to reality: The case of VOT. To be published in a Festschrift for Eli Fischer-Jorgensen. (Also in *UCLA Working Papers in Phonetics* 98, 1-9.)
- Taff, A., Cho, T., Rozelle, L. & Ladefoged, P. (to appear) The phonetic structure of Aleut. *Journal of Phonetics*.

ABSTRACT OF THE DISSERTATION

Effects of Prosody on Articulation in English

This dissertation investigates how phonetic realizations are conditioned by various prosodic conditions (i.e., sentence stress, level of prosodic domains, position-in-domain), by examining articulation in three prosodically strong locations: accented syllables, domain-initial positions, and domain-final positions. In particular, this dissertation aims to understand how articulatory strengthening that may arise from these prosodically strong locations is manifested in the articulatory maximum positions, V-to-V coarticulation, movement kinematics, and mass-spring dynamical parameter settings. To accomplish this, three articulators, the tongue, the jaw, and the lips were examined concurrently, collected from six speakers of American English using an electromagnetic articulography (EMA). Results were remarkably similar across speakers.

The results regarding accent show that accented vowels are strongly articulated, having larger maximal jaw and lip openings, extreme maximal tongue positions (lower for /a/ and fronted for /i/), greater V-to-V coarticulatory resistance, and larger, longer, and faster movement. As for boundary effects, the results show that vowels at higher prosodic boundaries are strongly articulated, evident in larger maximal lip opening but not in maximal jaw opening, extreme maximal tongue position (lower for *both* /a/ and /i/), greater V-to-V coarticulatory resistance, and longer, sometimes larger, but not necessarily faster movement. Although accent and boundary both give rise to articulatory strengthening, these effects are not the same. They differ in the dimension in which the tongue is expanded, the involvement of the lips and the jaw, and the movement velocity.

The results regarding movement kinematics suggest that speech mechanisms are more complex than has generally been assumed by researchers who have adopted a mass-spring gestural model in explaining certain speech phenomena. This dissertation also provides a basis from which the window model can be further developed, accommodating prosodically-conditioned variations.

Overall, the results are interpreted in terms of the contrast maximization principle. It has been proposed that articulatory strengthening makes a sound more distinct from neighboring segments (syntagmatic enhancement) and/or makes the sound distinct from other contrastive sounds in the language (paradigmatic enhancement). Such a phonetic enhancement of linguistic contrast arising from prosodically-conditioned articulatory strengthening is interpreted as an articulatory signature for prosodic information.

Chapter I

Introduction

1.1. Background

One of the long-term goals in phonetics research has been to understand speech variation. Among various linguistic and extralinguistic factors, segmental context has been considered as one of the major sources of speech variation. That is, when sounds are produced in connected speech, their physical realizations are conditioned by neighboring sounds, a phenomenon known as coarticulation. Prosody is another major source of variation; the physical realizations of sounds are also conditioned by their prosodic positions. Thus to understand speech variation, we need to understand the segmental variation due to prosody. At the same time, it is also important to study how prosody is marked by systematic phonetic variation of segments, so as to better understand prosody itself. Finally, we want to understand the interaction of these two sources of variation – each speech sound conveys information about its segmental and prosodic contexts which could aid listeners in comprehension.

A large body of experimental literature has shown that some of the prosodically conditioned segmental variation is attributable to the location of the segments, e.g., in stressed syllables or at edges of prosodic domains. Some prosodic locations may give rise to *strengthening* of either acoustic or articulatory properties of features or gestures.

Here, the term strengthening can be defined as an increase in spatio-temporal magnitude such that, for example, consonants are articulated with extreme and longer constrictions, and vowels are articulated with their assumed targets fully realized and for a longer period of time. Stronger sounds give rise to prominence, such that, for example, larger mouth opening for a vowel can generate a louder sound, making it distinct from neighboring sounds; consonants with an extreme constriction and vowels with larger mouth opening together can lead to a salient CV contrast; and vowels with their featural targets fully realized can heighten the phonetic clarity of the vowels. In what follows, I will introduce three prosodically strong locations where segments may be strengthened.

One of the prominence-related strengthening effects comes from nuclear pitch-accent, which encodes the interplay of lexical stress and sentential stress, making certain linguistic units prominent above the rest of a phrase or a sentence. (In this dissertation, I will refer to nuclear pitch-accent simply as accent.) Accent has in general been referred to as the degree of distinctness of a given linguistic unit relative to others, and the distinctness can be achieved by means of a variety of acoustic and articulatory parameters (e.g., Jones, 1940, cited in Lehiste, 1970; Bolinger, 1958; Lehiste, 1970; Stone, 1981; Couper-Kuehlen, 1986; Beckman & Pierrehumbert, 1986; Beckman & Edward, 1994; de Jong, 1991, 1995a,

1995b). For example, in an articulatory kinematic study, de Jong (1995a, 1995b) showed that certain accented segments are produced with more extreme articulatory movements in a direction that results in an enhancement of distinctive features of the segments.

Another well-known prosodically conditioned positional effect is domain-final lengthening, which can be defined as more extreme lengthening at the end of higher prosodic domains (e.g., the intonational phrase) as compared to lower prosodic domains (e.g., the syllable) (e.g., Klatt, 1975; Cooper & Paccia-Cooper, 1980; Edwards, Beckman & Fletcher, 1991; Wightman, Shattuck-Hufnagel, Ostendorf & Price, 1992). It has also been suggested that, in addition to the lengthening effect, vowels in domain-final positions may be produced with greater articulatory magnitude, resulting in greater V-to-C displacement (Fougeron & Keating, 1997). Data reported in Edwards, et al. (1991) also suggest that domain-final vowels can be more extreme, as compared to domain-medial ones, especially when vowels are unaccented. Thus, the preboundary phonetic phenomenon can be thought of as strengthening, rather than simply as lengthening.

Finally, another strengthening effect on segments occurs domain-initially (in postboundary positions). Fujimura (1990) proposed that more forceful articulatory gestures are generally involved in syllable-initial positions, as well as word- and phrase-initial positions. Quite a few articulatory and acoustic studies have given support to domain-initial strengthening (e.g., Cooper, 1991; Pierrehumbert & Talkin, 1992; Jun, 1993; 1995; Fougeron & Keating, 1997; Keating, et al, 1999, to appear; Cho & Keating, 2001).

Cooper (1991) found that English voiceless aspirated stops in word-initial position have a larger glottal opening gesture compared to word-medial position. Pierrehumbert & Talkin (1992) reported that the /t/ in English *tomahawk* at the beginning of an Intonational phrase has a longer VOT compared to phrasal medial position. Their acoustic studies also showed, though indirectly, that English /h/ is produced with larger glottal gestures after an Intonational phrase boundary compared to phrase-medial position. Along the same lines, Jun (1993) showed that VOTs for Korean /p^h/ pattern systematically with position in Accentual Phrase and word. The differences conditioned by position were cumulative: the longest VOTs were found in Accentual Phrase-initial position (which is also word-initial), and the shortest in word-medial (which is also Accentual Phrase-medial). Relatedly, in an aerodynamic study which examined the three-way contrast stop series in Korean (lenis, fortis, and aspirated), Cho & Jun (2000) found that airflow is higher phrase-initially for the lenis and aspirated stops, suggesting larger glottal opening, while airflow for the *fortis* stop is lower phrase-initially, suggesting extreme glottal constriction. Glottalization of vowels in word-initial position as a function of prosodic structure was also found in an acoustic study by Dilley, Shattuck-Hufnagel & Ostendorf (1996).

More recently, a series of electropalatographic studies from the UCLA Phonetics Lab showed that in general consonants are produced with greater articulatory magnitude (as measured by linguopalatal contact) in domain-initial positions at each level (Word,

Intermediate (or Accentual) Phrase, Intonational Phase, Utterance) than in domain-medial positions at that level (e.g., in English, Fougeron & Keating 1997; in French, Fougeron & Keating, 1996, Fougeron, 2001; in Korean, Cho, 1998, Cho & Keating, 2001 ; in Taiwanese, Hsu & Jun, 1998; Hayashi, Hsu & Keating, 1999; see also Keating, Cho, Fougeron & Hsu, 1999, to appear for a cross-linguistic comparison). Similarly, an articulatory kinematic study (Byrd & Saltzman, 1998) showed that /m/'s in domain-initial position at higher levels tend to have greater displacement in opening-to-closing movements of the lips.

In short, previous studies point to three kinds of prosodically determined locations where segments potentially can be strongly articulated. One is in accented syllables, another is in domain-initial positions, and the third is in domain-final positions.

Such prosodically conditioned strengthening has generally been assumed to be linguistically significant, in that it may lead to an enhancement of linguistic contrasts among segments either *syntagmatically* or *paradigmatically* (see Fougeron, 1999 for a review). Syntagmatic enhancement generally refers to the heightened phonetic contrast between neighboring segments, which gives rise to enhancement of structural information, including syllable structure and prosodic structure. In contrast, paradigmatic enhancement refers to the heightened phonetic contrast between contrastive sounds or phonemes in the sound system of the language. Thus, the study of articulatory characteristics of sounds in prosodically strong locations will help us better understand effects of prosody on low level phonetic realizations and its potential linguistic significance.

The primary purpose of this dissertation is to examine potential articulatory strengthening in all of these prosodically strong locations concurrently, using a single set of speakers and experimental techniques, in order to investigate how articulatory properties of segments differ and how they are similar with respect to spatio-temporal characteristics as prosodic conditions change. Such conditions include accent, level of prosodic boundary, and position-in-domain (preboundary vs. postboundary). In particular, this dissertation aims at characterizing the nature of the potential prominence that may arise with edge-based articulatory strengthening in comparison to that arising with accent-based articulatory strengthening.

Further, given the assumption that segments may be strengthened in prosodically strong locations, this dissertation explores the possibility that strongly articulated segments also resist coarticulation with neighboring segments, preserving their canonical phonetic properties. Thus, another major focus of this dissertation will be to understand how vowel-to-vowel coarticulatory patterns vary depending on the prosodic conditions, and how the hypothesized coarticulatory variations are related to, or influenced by, the prosodically variable strengths of articulation. This will eventually lead us to better grasp the nature of segmental variations that are hypothesized to vary depending not only on the prosodic conditions imposed on the target segments themselves but also on those imposed on the neighboring segments. All in all, it is hoped that this dissertation contributes to our

knowledge of how prosody is manifested in variation in articulatory strengthening, ultimately providing us a better insight into the relationship between prosody, speech production, and linguistic prominence.

1.2. Limitations of Previous Studies

The majority of phonetic research on issues related to stress and other prosodic structures has generally been limited to one prosodic effect (either the stress effect or the edge effect). For example, de Jong (1991, 1995a) reported an extensive study of effects of stress on segmental articulation, examining both the jaw and tongue movements for vowels and consonants. But articulatory prominence that might arise at edges of prosodic boundary was not considered. On the other hand, the domain-final effect on kinematics has been investigated by various investigators (e.g., Edwards, et al., 1991 and Beckman, et al, 1992), but it has been limited to either only one articulator (usually the jaw) or one vowel (e.g., /a/), without being compared to potential domain-initial strengthening effects.

Likewise, with respect to domain-initial strengthening, there are few studies that provide possible accounts of the articulatory characteristics in domain-initial positions. Most studies, however, have focused on consonantal variations, with vowels being only opportunistically examined (except for Fougeron (2001) in which EPG data are examined for /i/). Furthermore, while the domain-final effect has been actively investigated with a focus on jaw movements for vowels, data for domain-initial vowels are generally limited either to static linguopalatal data (Farnetani & Vayra, 1996, Fougeron & Keating, 1997; Fougeron, 2001; Cho & Keating, 2000) with lack of dynamics of articulation, or to acoustic data (Pierrehumbert & Talkin, 1992; Jun, 1993, 1995; Cho & Jun, 2000), or to aerodynamic data (Fougeron, 1998; Cho & Jun, 2000). Another limitation might be that domain-initial strengthening studies did not extensively cover potential confounding effects of stress that might have allowed us to better understand the nature of different kinds of prominence. Cooper (1991) included both stress and position factors, but the domains are only word-initial vs. word medial.

More recently, Byrd & Saltzman (1998) examined kinematics of lip opening and closing movements at prosodic boundaries, but they included only /i/ as a target vowel. Similarly, Byrd (2000) limited her study of prosodic boundary effects to the tongue movement for /i/ alone. Again, these studies did not examine potential compounding effects that might come from stress.

This dissertation attempts to provide a fairly comprehensive account of articulatory properties of vowels in several aspects. First, this dissertation conducts a concurrent investigation of not only stress effects but also effects of position-in-utterance (domain-initial vs. domain-final) and boundary type (IP vs. ip vs. Wd) for two peripheral vowels, /a/ and /i/. Second, this dissertation does not limit itself to an investigation of only one

articulator, but it includes three distinct articulators, the jaw, the tongue, and the lips, recorded simultaneously, although the jaw receives the least attention here.

In what follows, I will first introduce a theory of prosodic organization that is adopted in this dissertation, and present major research questions along with relevant theoretical background.

1.3. Research Questions and Theoretical Background

1.3.1. Questions regarding articulation at domain-edges

A well-established fact about domain-edge effects is that domain-final *vocalic* articulation is mainly characterized by lengthening, and domain-initial *consonantal* articulation, by strengthening. There is only inconclusive evidence that vocalic articulation at domain-edges is also be strengthened. For example, Fougeron & Keating found strengthening of domain-final V in an English reiterant *no#no* sequence, but not cumulatively so across prosodic levels, whereas domain-initial /o/ in *no* shows no evidence of strengthening. This is perhaps because strengthening is very local to the domain edge (i.e., /o/ is #CV is not strictly domain-initial), and final lengthening extends over a much longer span than does initial lengthening. This dissertation further explores this possibility, examining various articulators' dynamic movement data. In particular, we are interested in whether domain-initial strengthening includes the vocalic articulation in CV sequences, and how the domain-initial and domain-final articulations differ in their spatio-temporal characteristics.

The next question concerns the nature of articulatory strengthening at edges of prosodic domains in comparison with articulatory strengthening in accented position. Before discussing relevant hypotheses in connection to this question, it is necessary to introduce the previously advanced hypotheses about how prominence under accent is articulated.

Edwards & Beckman (1988) and Beckman, Edward & Fletcher (1992) proposed that accent has the effect of enhancing the segments' intrinsic sonority (the Sonority Expansion Hypothesis). By sonority they mean opening and closing of the vocal tract, which is defined in terms of the amount of "impedance looking forward from the glottis" (Silverman & Pierrehumbert, 1990). So, when segments are more stressed, a vowel will be more vowel-like by opening the vocal tract more, and a consonant will be more consonant-like by closing the vocal tract more tightly.

In partial contrast to the Sonority Expansion Hypothesis, de Jong (1995a) proposed that stress hyperarticulates, or enhances distinctive features of segments in a way that maximizes lexical distinctions. That is, his local hyperarticulation hypothesis predicts that all phonemically distinctive contrasts will be directly affected by stress. (De Jong expanded Lindblom's (1990) notion of hyperarticulation, applying not only to extended

discourses, but also to individual syllables, and thus to characterize the extreme articulation localized to stressed syllables.) While the enhancement of paradigmatic contrasts (i.e., contrasts among contrastive sounds in the system) was emphasized in the model, de Jong did not reject the Sonority Expansion Hypothesis entirely, but rather integrated it into his model, positing that the sonority is one of many other distinctive features that are enhanced. In supporting this extended hyperarticulation hypothesis, de Jong (1995a) showed that the tongue position for English vowel /ʊ/ is backer, but not necessarily higher under stress, being accompanied by lower jaw position. (The extended hyperarticulation hypothesis has also been endorsed by Beckman and her colleagues (e.g., de Jong, Beckman & Edwards, 1993)). This model also appears to explain at least in part Macchi's (1985) observation that non-low vowels /u i ε/ under stress tend to have lower jaw positions but not necessarily lower tongue body position. Thus, the data in de Jong (1995a) and Macchi (1985) suggest that the jaw always lowers (leading to the sonority expansion) while the tongue does not necessarily lower with it.

However, in Harrington, et al. (2000), one of their two speakers showed that there is temporal sequencing in achieving the sonority expansion and the hyperarticulation of the vowel features: the tongue position for accented /i/ in Australian English is lower during the onglide period (consistent with the jaw lowering for sonority expansion) and higher during the offglide period (consistent the [+high] hyperarticulation).

Now, we return to the original question of the relations between boundary-induced articulatory strengthening and accent-induced strengthening. There are two competing hypotheses. First, if hyperarticulation governs both accent-based and edge-based articulatory strengthening, one might expect that both peripheral vowels /a/ and /i/ at edges of prosodic domains would be extremely articulated in a direction that results in both the sonority expansion and the featural enhancement. For example, /a/ at domain-edges may be produced with an increase in lip opening, jaw lowering, and tongue lowering and backing, which entails an enhancement of the [+back] and [+low] features as well as the sonority feature. In contrast, the high front vowel /i/ may be produced with an increase in lip opening and jaw lowering with the tongue position being fronter ([-back] enhancement) but not necessarily higher, which would otherwise be in conflict with the sonority expansion.

Alternatively, it is also possible that the prominence associated with edges of prosodic domains is different in kind from that associated with accent, such that the former is primarily driven by the sonority expansion, resulting in an enhancement of syntagmatic contrast (e.g., CV (or VC) contrast), while the latter is driven by an enhancement of both primary features and sonority. This hypothesis is consistent with the one that has already been proposed in the literature. For example, Farnetani & Vayra (1996) hypothesize that prominence under accent fits into the hyperarticulation hypothesis (i.e., an enhancement of both syntagmatic and paradigmatic contrasts) while the prominence at edges engenders sonority expansion (i.e., an enhancement of syntagmatic contrast). Similarly, Hsu & Jun (1998), based on their review of literature on prominence and their own data, hypothesized

that "since ensuring a salient C-V contrast is important in domain-edge demarcation, but not necessarily in prominence [stress] markings, we will be less likely to find examples of paradigmatic contrast enhancement in domain-edge enhancement than in prominence [stress] enhancement" (p.86). Under this hypothesis, we expect that vowels at domain-edges are extremely articulated in a direction mainly towards sonority expansion—i.e., the vowels at domain-edges are associated with an increase in lip opening, jaw lowering, and tongue lowering regardless of vowel type.

In this dissertation, we test which one of these two competing hypotheses best describes articulatory effects at the edges of prosodic domains.

1.3.2. *Questions regarding strengthening and coarticulation*

Another central issue in speech production research has been how phonetic realization of a segment varies depending on the neighboring segments. In connected speech, the articulatory movements required for one gesture are often anticipated during the production of a preceding gesture (i.e., *anticipatory coarticulation*); likewise, the articulatory requirements of one gesture are often carried over during the production of a following gesture (i.e., *carryover coarticulation*). (See Farnetani (1997) and Kühnert & Nolan (1999) for thorough reviews.) Coarticulation has generally been described in terms of how it is affected by linguistic factors (e.g., phonological contrast and intrinsic segmental properties and stress). However, no studies have systematically examined coarticulatory characteristics found at edges of prosodic domains. In particular, the question of interest in this dissertation is whether prosodically-driven strengthening is manifested in *coarticulatory resistance*.

As discussed in Farnetani & Recasens (1999), the term coarticulatory resistance, originated by Bladon & Al-Bamerni (1976), has been generally used to capture the degree to which a given segment resists potential interference of neighboring segments. Coarticulatory resistance can be found in three different instances. The first type of coarticulatory resistance can be seen when coarticulation would result in blurring or confounding of phonetic contrasts. For example, Manuel (1990) showed that vowels in languages with less crowded vowel spaces (e.g., Ndebele and Shona) have greater coarticulation with following vowels than vowels in languages (e.g., Sotho) with more crowded vowel spaces (see also Manuel (1999) for general discussion of this issue).

Secondly, greater coarticulatory resistance can be found when the target segments are inherently strong. Lindblom (1983) proposed that the degree of coarticulatory resistance is roughly inversely proportional to the degree of sonority that segments are intrinsically associated with. Similarly, Recasens (1984a, 1984b, 1985) showed that there is an inverse relationship between the degree of coarticulation and the amount of linguopalatal contact required for the articulation of target segments — that is, the more linguopalatal contact a consonant requires, the less coarticulated that consonant is with a

neighboring vowel. As another example, Farnetani (1990) showed that geminate consonants have greater coarticulatory resistance to neighboring vowels than singleton consonants.

Thirdly, some studies have alluded to the possibility that prosodically-induced, or pragmatically-induced, articulatory strengthening may also bring about coarticulatory resistance. For example, data reported in Fowler (1981) suggest that coarticulatory resistance can be found when vowels are lexically stressed. Further, de Jong, et al.(1993) and de Jong (1995a) proposed that coarticulatory resistance may come from prosodically conditioned articulatory strength, although this claim was not systematically tested. The only evidence was that coarticulation of /t/ into a following /θ/ is reduced in stressed syllables, on the basis of which it was argued that less coarticulation was due to hyperarticulation under stress, which, as a result, enhances the distinctiveness of segments. This is reminiscent of Lindblom's (1990) hypo-hyperarticulation theory, under which an increase in coarticulatory resistance between neighboring segments is construed as an articulatory consequence of hyperarticulation.

In a preliminary acoustic study (Cho, 1999), I showed that accented vowels are less coarticulated with neighboring vowels across a boundary, suggesting that putative articulatory strengthening due to accent induces greater coarticulatory resistance in vowel-to-vowel coarticulation. This dissertation further examines articulatory data regarding vowel-to-vowel coarticulation in order to address whether and how prosodically-induced articulatory strengthening is manifested in coarticulatory resistance. One prediction is that if the articulatory strengthening is driven by prominence maximization as the hyperarticulation hypothesis predicts, there will be also less contextual variation (i.e., a greater coarticulatory resistance) that may also lead to an enhancement of contrast (cf. de Jong, 1995a). (See below for a different motivation for the same prediction under the window model.)

In this connection, another question to be addressed is whether strongly articulated segments in prosodically strong locations also induce strong coarticulatory effects on neighboring segments (*coarticulatory aggression effect*). Various researchers (e.g., Bladon & Nolan, 1977; Recasens, 1987; Farnetani, 1990; Farnetani & Recasens, 1993) observed that sounds that have greater coarticulatory resistance also exert stronger influence on its neighboring vowels—"they exhibit the least contextual variation and induce the greatest" (Farnetani, 1990, p.106). Thus, if segments in prosodically strong locations show coarticulatory resistance, we can further predict that they will also trigger stronger coarticulatory influence on neighboring segments than those in prosodically weak positions do.

Finally, this dissertation will attempt to explore how prosodically conditioned coarticulatory variation can be explained under the rubric of the window model (Keating, 1990). The window model was proposed to relate contrast, coarticulatory resistance, and coarticulatory aggression by making phonetic targets vary within a specified range rather

than simply having fixed values. In the model, the featural specification of the relevant segments project articulatory and/or acoustic targets both temporally and spatially. A target window projected by a feature allows the phonetic realization to vary within a specified range. Some segments project a very narrow window, reflecting little contextual variation, while others project a very wide window, reflecting extreme contextual variation. A trajectory is constructed to pass through successive windows, with narrower windows providing stronger constraints on possible trajectories. Put differently, segments with a narrower window will have greater coarticulatory resistance as well as greater aggression, whereas segments with a wider window will be more susceptible to coarticulation. In Keating's model, however, there are some constraints:

“Windows are determined empirically on the basis of context, but once determined are not themselves contextually varied. That is, a feature value or segment class has one and only one window that characterizes all contexts taken together; it does not have different windows for different contexts. Information about the possibilities for contextual variation is already built into that one window” (p.456)

Since the model allows only one size window for a segment, further questions arise as to (a) how variation in timing between segments or gestures can be captured in the window model and (b) how spatial variation (e.g., articulatory strengthening) induced by prosodic structures can fit into this scheme.

With respect to variation in intergestural timing, Byrd (1996) proposed the Phase Window model in which timing variability that comes from a postlexical factor can be captured by weighting the phase window differently. The phase window can be weighted by a variety of linguistic and extralinguistic factors, or *influencers*, such as syllable structure, phrase boundary, stress, speaking rates, etc. This weighting determines where in the range of possible values the actual intergestural overlap will be implemented and how narrow the range will be. (See Browman & Goldstein (1998) for another way of handling variability in intergestural timing; and Cho (2001) for a discussion.) While the phase window model can capture variation in intergestural timing induced by prosodic structures, it remains still unclear how prosodically conditioned *spatial* variation can fit into this model.

As noted by Keating (1996), one possible solution to the spatial variation problem in Keating's model can be obtained along the lines of Guenther (1995)'s model, in which the target range can vary depending on extralinguistic and linguistic factors such as speaking rate, stress, and coarticulatory constraints.

Guenther's computational model on speech production (called *DIVA*, Directions (in orosensory space) Into Velocities of Articulators) specifies the vocal tract target for each speech sound in the form of *convex regions* in orosensory space defining the shape of the vocal tract. A convex region is a multidimensional region such that it can be defined in every orosensory dimension. The orosensory dimensions are quite closely related to the tract variables in the Task Dynamic model (Saltzman & Munhall, 1989), including tongue

body horizontal position, tongue body height, tongue tip horizontal position, tongue tip height, lip protrusion, lip aperture, velum height, etc. Each dimension of the orosensory target specifies a range of acceptable positions along that dimension, which allows variability that arises from constraints such as coarticulation effects in the spirit of Keating's window model. But, Guenther's model differs from Keating's in that it allows re-sizing (shrinking) of the target range while the latter does not.

In Guenther's model, crucially relevant to this dissertation is the idea that the window-like range of targets can be re-resized roughly in proportion to the scale of Linblom (1990)'s Hypo- to Hyperarticulation. The hyperarticulation can be implemented as making the windows smaller, reflecting less contextual variation, or greater coarticulatory resistance. Based on this, Guenther also suggests that local hyperarticulation due to accent (de Jong, Beckman & Edwards, 1993; de Jong, 1995a) can be accounted for by a decrease in contextual variation that is induced by a smaller range of targets (see also Keating (1996)). Under this account, we still expect greater coarticulatory resistance as the local hyperarticulation predicts, but not necessarily driven by the prominence maximization principle, but rather simply by shrinking windows. However, the model needs a mechanism to direct the shrinking of the window to the right part of the target region.

In this dissertation, based on the idea that the window-like convex region is flexible to accommodate influences of various linguistic or extralinguistic factors, I will further consider how the current window model can be modified in order to reflect prosodically-conditioned articulatory variation. An underlying assumption will be that segments in prosodically strong positions may be associated with a smaller window (reflecting coarticulatory resistance), and segments in prosodically weak positions with a larger window (reflecting coarticulatory vulnerability). Further, it will also be assumed that the window shrinks in a direction that leads to hyperarticulation of a segment's featural target.

1.3.3. Questions regarding effects of prosody on kinematic variations and dynamical accounts

Thus far, I have outlined research questions that converge on (1) how prosodically-induced articulatory variation can be accounted for in terms of articulatory strengthening and prominence enhancement, and (2) whether and how such strengthening can be manifest in coarticulatory resistance. This section introduces research questions regarding effects of prosody on kinematic variations and dynamical accounts that may illuminate how prosody is manifest in articulatory variation. Quite a few speech researchers (e.g., Edwards, et al., 1991; de Jong, 1991; Beckman, et al., 1992; Harrington, Fletcher & Roberts, 1995; Saltzman, 1995; Byrd & Saltzman, 1998; Byrd, Kaun, Narayanan & Saltzman, 2000; Byrd, 2000) have examined kinematics of articulatory movements and suggested that prosodically conditioned articulatory variation may be controlled by a particular dynamical

parameter setting in the framework of a mass-spring task dynamical model (Saltzman & Munhall, 1989; see Hawkins (1992) for an overview for non-specialists). Thus, this dissertation will examine both accent- and boundary-induced kinematic variations in order to address questions as to (1) what are kinematic characteristics of prosodically-conditioned articulatory strengthening, (2) whether and how strengthening may be accounted for by a particular dynamical parameter setting, and (3) whether different dynamical mechanisms govern articulatory characteristics that may arise from different prosodic locations. In what follows, I will first give a brief review of a mass-spring task dynamical model, and then more specific questions that are to be addressed in this dissertation.

1.3.3.1. Task dynamic model and dynamical parameters

As the term task dynamics implies, it describes articulatory movement in terms of the task to be executed, using dynamics that are specific not to the articulators that are executing the task, but to the task itself. The term task can be thought of as the goal of articulatory movement, such as forming an appropriate oral constriction at a location in the vocal tract in order to produce an oral fricative (e.g., /ʃ/). Such a movement pattern or an articulatory action that forms a linguistically significant constriction is called a ‘gesture.’ The dimensions along which the articulatory action or goal for constrictions is executed are called ‘tract variables.’ Some of these tract variables include lip aperture (LA), tongue-body constriction location (TBCL), and tongue-body constriction degree (TBCD). In Articulatory Phonology (Browman and Goldstein, 1989, 1990, 1992), the articulatory gesture is viewed as the phonological unit, and the information about the gestural structures (including the information about the task to be done) is fed into the task dynamic model.

In the task dynamic model, the articulatory gesture is described in terms of the behavior of the abstract ‘mass’ which is connected to a ‘spring’ and a ‘damper’ in a critically damped mass-spring system. As Hawkins (1992) describes, it is as if one end of the spring is attached to the mass, and the other end is held at the target location. Then, as the target location (the other end of the spring) changes, the spring is stretched, and the mass is pulled towards the target location. The mass-spring gestural model is critically damped, so that the mass never reaches the target location, and is not pulled back to its original location, but rather it stays in the target region, continuously and slowly reaching the equilibrium position of the spring. In short, in a critically damped mass-spring gestural model, the mass does not oscillate, but asymptotes towards the equilibrium position, such that the gesture is generally realized as a one-directional movement towards the target.

In the model, the gesture is defined as a dynamical system specified with a set of parameter values. Relevant dynamical parameters include target (underlying amplitude), stiffness (or natural frequency), damping ratio, intergestural timing, and activation time. Characteristics of the articulatory movements that result from executing gestures depend

on values of these parameters specified for a given gesture. The relationship among dynamical parameters in a critically damped mass-spring system is described in the following differential equation (Browman & Goldstein, 1990; Hawkins, 1992):

$$m\ddot{x} + b\dot{x} + k(x - x_0) = 0$$

where

- m = mass associated with the task variable
- b = damping of the system
- k = stiffness of the spring
- x_0 = equilibrium position of the spring (the target)
- x = instantaneous value of the task variable (current location of the mass)
- \dot{x} = instantaneous velocity of the task variable
- \ddot{x} = instantaneous acceleration of the task variable
- $(x - x_0)$ = instantaneous displacement of the task variable

(from Hawkins, 1992, p.17)

In this equation, the mass (m) is always set to be constant, and the damping ratio ($b/2[mk]^{1/2}$) is also usually constant. Therefore, once we know parameter values for the stiffness (k) and the target (x_0), we can solve the equation for the tract variable x (e.g., lip aperture) associated with a given gesture.

Crucially, the model assumes that any systematic articulatory or kinematic variation is interpreted as consequences of dynamical parameter settings. Thus, in theory, any systematic kinematic variations arising from prosodic conditions should be accounted for by a particular dynamical mechanism.

Some researchers (de Jong, 1991; Beckman, et al., 1992; Byrd, et al., 2000) have provided useful summaries of the kinematic consequences of various mass-spring equation parameter manipulations. The summary given in Table 1.1 follows Byrd, et al. (2000). Figure 1.1 shows schematized movement trajectories that correspond to changes in four dynamical parameters (stiffness, target, intergestural timing, and shrinking). Figure 1.2 also visualizes idealized kinematic manifestations of different dynamical specifications in four dynamical parameters by relating some kinematic measures to each other. (Figures 1.3a-f are adopted from Beckman, et al. (1992).) In what follows, I will describe each dynamical parameter, and discuss what phonetic or kinematic patterns would surface under a pure change in each parameter.

Table 1.1. Summary of kinematic consequences of various mass-spring equation parameter manipulations (based on Byrd, et al., 2000).

mass-spring parameters		measured kinematic variables				
		duration	displacement	time to peak velocity	peak velocity	avg velocity (disp/time)
stiffness	more	shorter	no change	shorter	higher	higher
	less	longer	no change	longer	lower	lower
target	bigger	no change	greater	no change	higher	higher
	smaller	no change	smaller	no change	lower	lower
truncation (intergestural timing)	more	shorter	smaller*	no change	no change	likely to decrease
	less	longer	greater*	no change	no change	likely to increase
target & stiffness ⁺ (scaled proportionally)	less shrinking	longer	greater	longer	no change	no change
	more shrinking	shorter	smaller	shorter	no change	no change

* These changes may be small if the gesture has a plateau-like shape at its peak displacement and the truncation applies primarily to the plateau-like shaped region

⁺ Where amplitude and duration are scaled proportionally (see Harrington, et al., 1995).

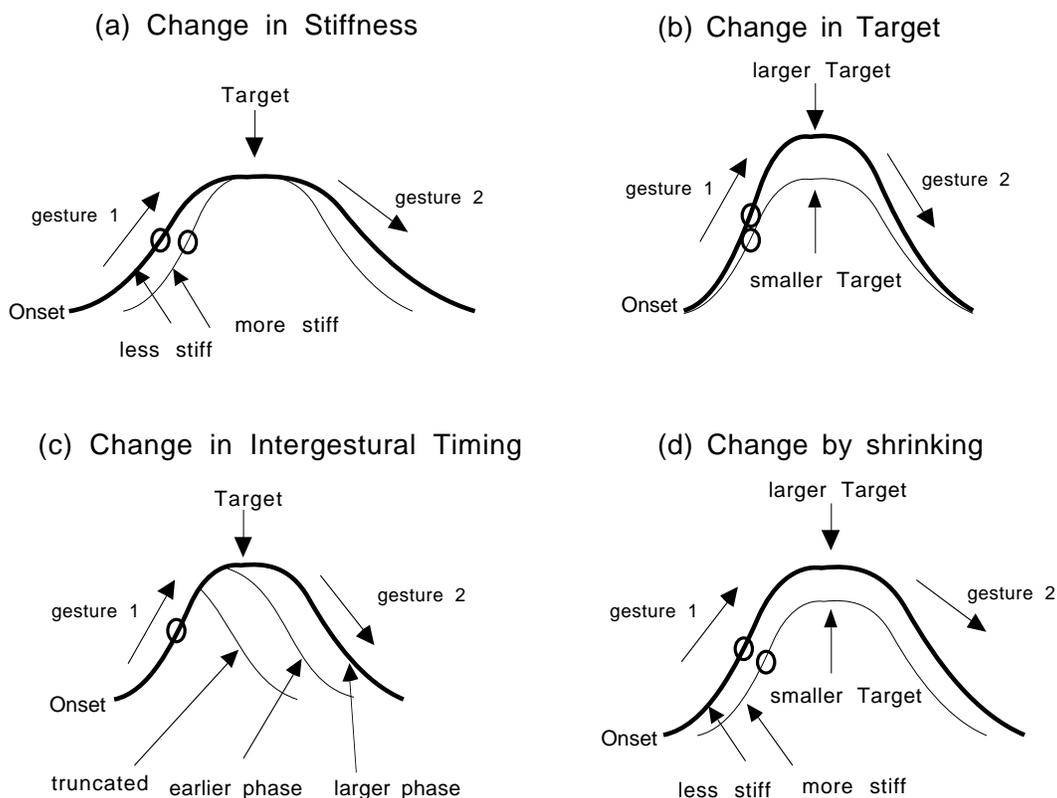


Figure 1.1. Hypothetical movement trajectories that correspond to a change in each parameter. (a) show change in stiffness; (b) change in target; (c) change in intergestural timing; and (d) change by shrinking. Empty circles indicate the timepoint of the peak velocity attainment.

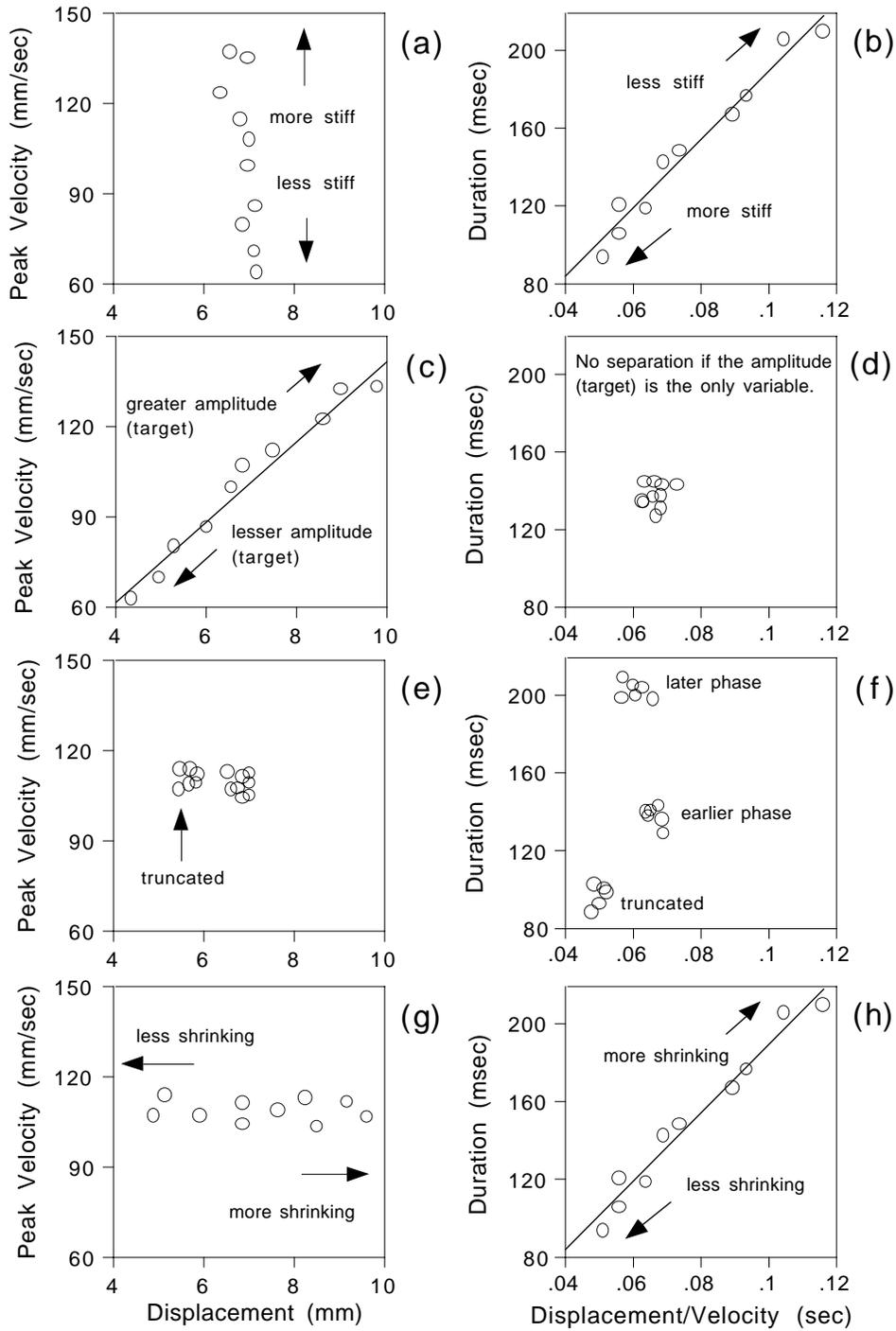


Figure 1.2. Relationships among kinematic variables that manifest dynamical parameter settings. (a) and (b) show change in stiffness; (c) and (d), change in amplitude (target); (e) and (f), change in intergestural timing or truncation; and (g) and (h), change by shrinking. Figures (a)-(f) are adopted from Beckman, et al. (1992).

Now, some notes about each parameter setting are necessary:

(1) *Stiffness*. Variation in articulatory movement duration is thought to be controlled by the stiffness parameter: the more stiff stiffer the spring (the articulator) omit, the faster the movement. An idealized pattern in a pure change in stiffness is visualized in Figure 1.1a, and its corresponding kinematic relationships in Figures 1.1a-b. If stiffness is the only parameter underlying kinematic differences, there should be a change in peak velocity, but not in displacement (i.e., the amount of the spatial distance that the articulator travels), therefore showing vertical distribution of the datapoints (Figure 1.2a). This is because in the differential equation of the mass-spring dynamical system, the slope of the line relating displacement (in the x axis) to peak velocity (in the y axis) is equivalent to $\omega=(k/m)^{1/2}$ (where k = stiffness, m = mass), and therefore, a change in stiffness (k) will change the slope value (ω) for displacement/velocity, but not the displacement value. In addition, if displacement is held constant but stiffness changes, there should be a proportional change in both duration and displacement/velocity ratio, with a diagonal distribution of the datapoints (Figure 1b)—i.e., as duration increases, peak velocity would decrease, making the displacement/velocity ratio increase (because of constant displacement). (Note also that an increase in displacement/velocity ratio means a decreased (less steep) slope, or coefficient value in the regression plot, that itself can be also used as an index of the degree of stiffness (Ostry, Keller & Parush, 1983; Kelso, Vatikiotis-Bateson, Saltzman & Kay, 1985).)

Further, the time-to-peak-velocity (the interval from the movement onset to the attainment of peak velocity) will vary as stiffness changes. Time-to-peak-velocity would be longer when the movement slows down due to decreased stiffness. (Note that some investigators (e.g., Byrd & Saltzman, 1998; Byrd, et al., 2000; and Byrd, 2000) suggested that one of the importance kinematics measures that best characterizes the dynamical stiffness parameter is absolute time-to-peak-velocity.)

(2) *Target (underlying articulatory amplitude)*. A change in target induces a change in displacement with the interval from the onset to the target being held constant. In a pure target change, peak velocity and displacement changes proportionally without a change in duration. This is because in an increase in target with stiffness being held constant, articulators have to travel farther with no extra time (as can be seen in Figure 1.1b). The only way to reach the increased target is by an increase in velocity in proportion to the change in the target value, with a diagonal distribution of the datapoints (Figure 1.2c). Further, since displacement and velocity change proportionally, there should be no change in the displacement/velocity ratios, and nor should there be a change in duration (due to no change in stiffness) (Figure 1.2d). As also can be seen in Figure 1.1b, time-to-peak-velocity remains constant.

(3) *Intergestural timing or truncation*. The truncation parameter is based on the assumption that the articulatory movement towards the target can be ‘truncated’ by an early activation of the following gesture, which keeps the articulatory movement from

reaching its assumed target, as can be seen in Figure 1.1c. Thus, under a pure change in intergestural timing, there should be no change in peak velocity because, for example, the effect of a substantially earlier following gesture is to prevent the preceding gesture from reaching its target (i.e., truncation of the preceding gesture) while stiffness and target specifications remain unchanged. However, if the gesture has a plateau-like shape at its peak displacement and the truncation applies primarily to this region, the change in displacement will be small or zero, but relatively larger if the truncation applies to the region beyond the plateau-like shape (see Figure 1.2e in comparison with Figure 1.1c). Further, there will be a substantial change in duration as the following gesture is phased earlier or later, whereas the ratio of the displacement to the peak velocity remains relatively unchanged because of no change in displacement and velocity, except the case in which enough truncation brings about a decrease in displacement (Figure 1.2f). Finally, as can be seen in Figure 1.2c, the durational change comes from a change in the interval from the timepoint of peak-velocity to the target (deceleration duration) with no change in time-to-peak-velocity.

(4) *Shrinking*. Shrinking can be defined as a change in both target and stiffness which are scaled proportionally. Shrinking can be thought of as a unique dynamical parameter that may underlie prosodically conditioned kinematic variation (see Harrington, et al. (1995), and Byrd, et al. (2000)). As can be seen in Figure 1.1d, in a pure proportional change in target and stiffness, there would be a proportional increase in both duration and displacement, which results in no change in peak velocity, giving a horizontal distribution of the datapoints (Figure 1.2g). Further, the displacement/velocity ratio will increase as duration increases, giving a diagonal distribution of the datapoints (Figure 1.2h). Note that the pattern in Figure 1.2h is similar to that in Figure 1.2b under a change in stiffness. However, in a change in stiffness, the displacement/velocity ratio increases as duration increases not because displacement increases, but because velocity decreases with displacement being held constant.

1.3.3.2. *Some previous studies*

Under the basic assumptions just described above, researchers have attempted to characterize systematic variation due to prosodic factors by pinpointing one of these dynamical parameter settings as an underlying mechanism. For example, in an effort to characterize accent-induced articulatory variation, some researchers (e.g., Edwards, et al., 1991; Beckman, et al., 1992) examined the kinematics of jaw movements, and found that under accent, the jaw opening gesture is associated with an increase in duration and displacement without a substantial increase in peak velocity. Based on this, they suggest that a change in intergestural timing is the major dynamical mechanism that governs accent-induced kinematic variations. Harrington, et al. (1995) further tested the intergestural timing hypothesis by comparing the movement trajectory of the unaccented jaw opening and closing gestures for the Australian English word 'barb' against simulated

movement trajectories representing truncated and linearly shrunk unaccented gestures. The actual movement trajectory of the unaccented gestures were found to match more closely with the trajectory simulated by truncation than to the one simulated by shrinking. This was interpreted as favoring the intergestural timing account.

However, the intergestural timing account has been controversial. For example, the actual kinematic data reported in Harrington, et al. (1995) showed that the peak velocity for the jaw opening gesture was consistently faster under accent for all three speakers, which cannot be fully accounted for by the intergestural timing account alone. (Note that under a pure change in intergestural timing, no change in peak velocity is expected.) In fact, Harrington, et al. also noted the possibility that a combination of truncation and shrinking underlies the articulation of unaccented vowels.

De Jong (1991) also examined differences in the kinematics of jaw movement for the English words 'on' and 'to' as a function of accent, and found that what is commonly observed for both 'on' and 'to' under accent is a greater displacement, suggesting that if anything, the target (or amplitude) is bigger when accented. However, de Jong himself did not entirely rule out the intergestural timing account, adding that "[i]n more extremely stressed cases this amplitude [target] change can be accompanied by a timing change—highly accented consonant gestures being initiated later than their accented counterparts" (de Jong 1991, p.125).

Furthermore, in investigating articulatory kinematics of jaw movement for accented 'Pope' and 'Pipe,' Fowler (1995) found that for 'Pope,' all three speakers exhibited larger, longer, and faster movement under accent. For 'Pipe,' one speaker showed the same pattern as for 'Pope,' while another speaker showed longer, faster, but not larger movement; the third speaker showed larger, faster, but not longer movement. It is only this last speaker's pattern, and only for 'Pipe,' that shows one clear case that can be interpretable in terms of a mass-spring gestural model: the larger, faster, but not longer movement supports the target account. In all other cases, no dynamical parameter setting could be identified as an underlying mechanism for accentuation. Based on a previous assumption that stress consists of a global increase in production effort (e.g., Öhman, 1967; Lehiste, 1970), Fowler suggested that "[p]erhaps, it is not that kinematic adjustments occur to accommodate a pitch accent, but rather that the perceptually salient pitch accent highlights *global effort* increases for the listeners" (emphasis added, p. 369). In other words, the global effort hypothesis postulates that it is not that a particular dynamical setting induces accent-induced kinematic variations but that accent-induced kinematic variations is driven by the prominence maximization principle, which is somewhat comparable to the hyperarticulation hypothesis.

The above-mentioned studies so far do not allow us to make an absolute prediction about the dynamical aspects of accent-induced articulatory variations. They present not only conflicting results but also controversial claims that cannot be taken to be conclusive. Moreover, most studies mentioned above are based only on the movement data of a single

articulator, the jaw. Thus, in this dissertation, I will re-evaluate various dynamical hypotheses by examining kinematic data from two other principal articulators, the lips and the tongue. Questions to be addressed are whether a particular dynamical parameter can be singled out as an underlying mechanism governing accent-induced variations, and if so, whether it is the intergestural timing or the target parameter. Turning to the questions regarding boundary-induced articulatory variations, we are mainly interested in whether the same dynamical account of accent-induced kinematic variations may apply to the boundary-induced kinematic variations. In fact, a few relevant studies (Edwards, et al., 1991; Byrd & Saltzman, 1998; Byrd, et al., 2000; Byrd, 2000) converge on the conclusion that the dynamical mechanism governing kinematic variations at edges of prosodic domains differs from the one that governs accent-induced variations. A change in the stiffness parameter has been taken to be a dynamical mechanism governing boundary-induced kinematic variations (as opposed to either intergestural timing or target changes). For example, Byrd & Saltzman (1998) investigated the lip opening and closing gestures for English bilabial /m/ at edges of prosodic domains, and found that movement duration and time-to-peak velocity are highly correlated. Based on this, they suggested that a local stiffness change may be the source of variation in boundary-adjacent lengthening: The higher the boundary, the less the gestural stiffness, which is consistent with the interpretation made by Edwards, et al. (1991) for the domain-final jaw closing gesture and by Byrd (2000) for the transboundary tongue movement from /ə/ to /i/.

However, there are some issues unresolved so far. First, several researchers (Edwards, et al., 1991; Fougeron & Keating, 1997; Byrd & Saltzman, 1998) have observed either directly or indirectly that articulations at domain-edges are also associated with an increase in displacement, whose dynamical mechanisms have not been fully explained. For example, Byrd & Saltzman (1998) found that the displacement of the lip closing gesture at edges of prosodic domains tends to be larger. The increased displacement, however, was interpreted as the general pattern, so-called “the-farther-the-longer” whereby the elongated duration is a necessary consequence of the expanded displacement, which is not interpreted as being due to dynamical parameter settings in either target or intergestural timing. The exact mechanism for this is not clearly discussed in their paper. Similarly, Edwards, et al. (1991) showed that the domain-final jaw opening gesture is larger before a higher than a lower prosodic boundary when the vowels being compared are unaccented, which was, again, not fully considered in terms of dynamical mechanisms. Furthermore, while domain-final articulation has received a great deal of attention, no studies have investigated how domain-initial kinematics in CV syllables varies as a function of prosodic boundary. Thus, in this dissertation, I will examine lip opening and closing data in order to further explore questions regarding (1) whether there is a systematically increased articulatory magnitude associated with domain-edges both domain-initially and domain-finally, (2) whether and how the domain-initial and domain-final CV syllables differ in terms of kinematics, and (3) whether and how any observed kinematic variations can be accounted for in the framework of a mass-spring gestural model.

1.3.3.3. *Stiffness and the π -gesture*

In an effort to characterize the prosodic edge effect, Byrd and Saltzman (Saltzman, 1995, Byrd, et al., 2000; Byrd, 2000; Byrd & Saltzman, 2000) have suggested that there might be some sort of prosodic boundary gestures that are governed by prosodic constituency in the task dynamics model. This abstract and non-tract variable ‘prosodic’ gesture is called ‘ π -gesture,’ which is hypothesized to affect degree of stiffness in non-prosodic articulatory gestures over its activation period, roughly in proportion to the strength of the boundary.

More crucially, Byrd & Saltzman (2000) suggested that a clock-slowing implementation of π -gestures may affect the activation timecourse of all the dynamical parameters. Consequently, boundary strength determines degree of clock slowing, such that the gestures adjacent to a strong prosodic boundary will get slower, and possibly spatially larger, as shown in their simulations. Relatedly, with respect to the π -gestures’ temporal domain, Byrd (2000) assumes that the π -gesture is anchored at a prosodic boundary (i.e., edges of prosodic domains), such that its clock-slowing effect is stronger near or at the domain-edges, dwindling farther from the edge. As supportive evidence, she showed that the total V_1 -to- V_2 movement duration in a $C_1V_1\#C_2V_2$ sequence is more closely related to the preboundary lengthening (attributable to V_1) than to the postboundary lengthening (attributable to V_2). This result was construed as a consequence of a stronger effect of the π -gesture on V_1 , which is immediately adjacent to the prosodic boundary, as compared to V_2 , which has C_1 intervening.

While the π -gesture model attempts to unify dynamical accounts for symbolic prosodic and segmental units by relating them to the abstract π -gesture and the tract-variable articulatory gestures, respectively, exact mechanisms of the clock-slowing implementation of π -gestures and their temporal extent are not fully documented in the literature. Thus, in this dissertation, the π -gesture hypothesis will not be directly tested, but rather it will be kept in mind, so that when necessary I will attempt to explain how the observed data fit into this scheme. The only relevant issue that this dissertation will directly address in connection to the π -gesture hypothesis, especially in terms of its temporal extent, is about the potential asymmetry between pre- and postboundary lengthening effects, for which two different vowel sequences (/a/-to-/i/ and /i/-to-/a/) will be examined.

1.3.4. *Prosodic Organization*

In order to study prosodic effects on articulation, we need a model of prosodic structure which can provide an independent scale of prosodic position and strength. One well-known scale of this kind is the *prosodic hierarchy*, which hypothesizes that speech utterances are produced in prosodic groupings of different sizes, and that they are hierarchically organized, with higher prosodic units being decomposed into lower prosodic units, or domains. These prosodic domains can be defined primarily on the basis of

syntactic structures (e.g., Selkirk, 1984, 1986; Nespor & Vogel, 1986) or on an intonational basis (e.g., Beckman & Pierrehumbert, 1986; Jun, 1993; 1998).

This dissertation adopts the model of prosodic structure in Beckman & Pierrehumbert (1986) from which the current English ToBI system has emerged. The prosodic structure is shown in Figure 1.2. This figure illustrates a prosodic hierarchy where lower domains (e.g., syllables) are grouped into immediately higher levels (e.g., words).

Another independent scale of the prosodic structure of speech is achieved by a prominence or stress hierarchy. Stress in a broad sense has been considered to be the linguistic manifestation of rhythmic structure, varying in degree of prominence across prosodic levels (e.g., Liberman & Prince, 1977; Beckman, 1986; Hayes, 1989; de Jong, Beckman & Edwards, 1993; Beckman & Edwards, 1994). In English, stress can be divided at least into four degrees: no stress or stresses below primary, primary word stress (lexical stress), phrasal stress (prenuclear pitch-accent), and sentence stress (nuclear pitch-accent) (see Shattuck-Hufnagel & Turk 1996). The degree of the stress then increases from lexical stress, to prenuclear pitch-accent, and to nuclear pitch-accent. This stress or prominence-based prosodic hierarchy is linked to some extent, though not exhaustively, to the constituent-based prosodic hierarchy, such that the lexically stressed syllable is defined as the head of the word, and the nuclear pitch-accented syllable, as the head of the Intermediate Phrase (see Beckman & Edwards, 1994).

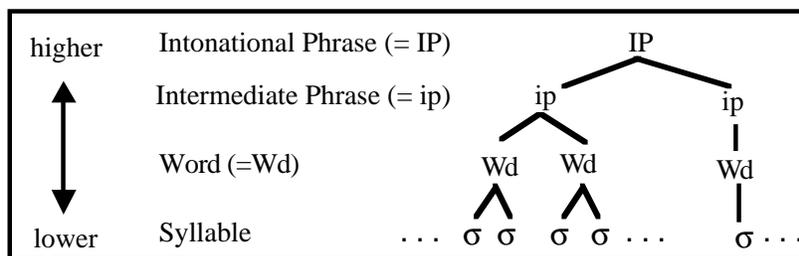


Figure 1.3. Prosodic Structure of English (from Beckman & Pierrehumbert (1996)). (Note that the foot, which is generally considered a minimal bracketing unit in assigning stress above the domain Syllable, is not shown here.)

1.5. Outline of The Dissertation

The remainder of this dissertation is organized as follows.

Chapter 2 is devoted to a description of the experimental procedures. It describes how the corpus was constructed in order to investigate concurrently effects of various prosodic conditions (accent, level of prosodic boundary, and position-in-prosodic-domain (initial vs. final)) using a single set of speakers and experimental procedures. Chapter 2 also discusses data acquisition, measurement techniques, and general statistical procedures.

Chapter 3 reports experimental results regarding effects of accent and prosodic boundary on the articulatory maxima for the tongue, the jaw, and the lips. A central question is whether articulatory characteristics found at edges of prosodic domains show an articulatory strengthening effect that might be compatible with prominence-based articulatory strengthening under accent.

Chapter 4 reports experimental results regarding how vowel-to-vowel coarticulation is influenced by accent and prosodic boundary type. The main questions to be addressed are to what extent the prosodically conditioned articulatory strengthening is manifested in coarticulatory resistance, and whether strengthening in prosodically strong locations can be equated with coarticulatory resistance.

Chapters 5 and 6 report on specific hypotheses and experimental results for the kinematics of the lip opening and closing movements and the tongue movements, respectively. Questions to be addressed are what are kinematic characteristics of prosodically conditioned strengthening, and whether and how they can be accounted for in a mass-spring gestural model.

Chapter 7 concludes with a summary and an overall discussion about prosodically-conditioned articulatory strengthening.

Chapter II

Methods

As introduced in Chapter 1, previous studies have limitations in that they generally investigated effects of prosody on articulation with a focus on either one articulator or one prosodic condition, failing to provide a comprehensive account of prosodic effects on speech production. In this dissertation, we investigate effects of various prosodic conditions (i.e., accent, level of prosodic domains, position-in-domain (initial vs. final)) on multiple articulators, by examining the movements of the tongue, the jaw, and the lips in American English, using Electromagnetic Midsagittal Articulography (Carstens Articulograph AG 100). Specific hypotheses to be tested in the experiment will be given in each chapter. This chapter gives an outline of the methodology for the experiment, including procedures of designing the speech corpus, data acquisition, measurements, prosodic transcription, and statistical methodology.

2.1. Speech Material

An important criterion for building the corpus of this study was to include both prosodic and segmental variables. In this way, various hypotheses can be evaluated using a single set of data with consistent experimental techniques.

The matrix of speech material is given in Figure 1. Each item in the corpus includes two test syllables (pre- and post-boundary), yielding a $C_1V_1\#C_2V_2$ sequence (where # = some prosodic boundary) across two real English words. First consider the criteria for the selection of test segments. The first and second consonants (C_1, C_2) are always /b/, whose articulation is known to minimally interfere with the vocalic lingual articulation. The inclusion of /b/ also allows us to examine lip opening and closing movements. The first and the second vowels (V_1, V_2) are either /i/ or /a/, resulting in four pairs: /i#bi/, /a#ba/, /i#ba/, and /a#bi/. Identical vowel sequences (/i#bi/, /a#ba/) allow us to examine effects of prosody with no contextual influence. On the other hand, the sequences with opposite vowels allow us to examine transboundary vocalic movements and coarticulatory effects.

Turning to prosodic variables, the boundary between the test syllables was varied from the Intonational Phrase boundary (IP), to the Intermediate Phrase boundary (ip), to the Word boundary (Wd). At the same time, accentuation was manipulated in preboundary and postboundary syllables, resulting in four pairs of accentual combinations: ACC#ACC, ACC#UNACC, UNACC#ACC, UNACC#UNACC. Such a manipulation of prosodic factors yields three prosodic variables: (a) prosodic boundary between test syllables; (b) accentuation of

syllables adjacent to the boundary (accented, unaccented); (c) position-in-domain of test syllables (initial, final).

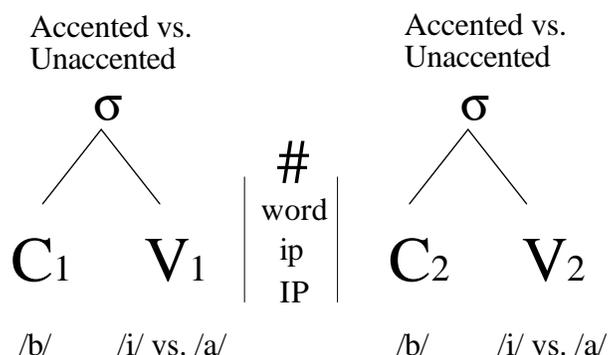


Figure 2.1. Speech material of $C_1V_1\#C_2V_2$ sequence. The corpus contains all logical combinations of the variables.

Thus, the corpus contains every combination of the prosodic and segmental factors, which yields a total of 48 different sequences (3 prosodic boundaries \times 2 accentual patterns in the preboundary syllable \times 2 accentual patterns in the postboundary syllable \times 2 preboundary vowel types \times 2 postboundary vowel types). Note that in this corpus we can always single out a set of sentences which differ from each other only in one prosodic condition, with other conditions being controlled for. (Some sample sentences are given below in Table 1.2. in section 2.3, and the whole corpus in Appendix I.)

2.2. Speakers

Six native speakers of American English participated in the experiment. Four speakers were linguistics PhD students at UCLA; one speaker was a postdoctoral researcher; and one was an undergraduate linguistics student at UCLA. In order to control for the variation in rounding in the low vowel, speakers whose dialect lacked the phoneme /ɔ/ were chosen. Two of the speakers had participated in an acoustic pilot study (Cho, 1999), and one of the two in an EMA pilot study.

Speakers were all trained in the production of English sentences in the ToBI framework prior to the experiment. Before the actual recording date, each speaker participated in an approximately two-hour long practice session during which he or she practiced the sentences in a mini discourse situation in order to be able to produce the intended renditions as naturally as possible.

2.3. Procedures

The target sequences were obtained from real sentences in a mini discourse situation intended to induce the desired variety of accent-placement patterns and prosodic groupings. A sample sentence set is given in Table 2.1. In each target sentence, the words highlighted in bold receives pitch accent. The prompt was read silently by the speaker to cue the intended accent patterns, which were provided using partial ToBI (Tone and Break Index) transcriptions in the script (see section 2.5 below for more information about ToBI transcriptions). Six American English speakers were recorded reading the target sentences. Each sentence was read twice in succession, and the entire list was read twice, for a total of four repetitions per sentence. This yielded a total of 1152 sentence tokens for analysis (48 sentence types x 6 speakers x 4 repetitions).

An EMA system (Carstens Articulograph AG 100) was used to track articulatory movements of the articulators. In the EMA system, three transmitter coils set up an electromagnetic field around the head of a speaker, as shown in Figure 2.2. Each transmitter generates an alternating electromagnetic field. The magnetic field strength can be determined from the voltage in a sensor coil (transducer) attached to an articulator (e.g., the tongue), which is inversely proportional to the cube of its distance from a transmitter. Using this fact, the EMA system calculates positional values of sensor coils attached midsagittally to articulators in an X-Y coordinate system, which allows for tracking the horizontal (x) and vertical (y) movements of articulators such as the tongue, the jaw, and the lips. Another fact to be noted about the EMA system is that because recordings are relative to the helmet, they are in head-space rather than room-space, unlike microbeam recordings (e.g., if a speaker moves the whole head without talking, no articulatory movement is registered) (See Schoenle (1988); Schoenle, Mueller & Wenig (1989); Tuller, Shao & Kelso (1990); Hoole (1996) for more technical information on the Carstens system; Perkell, Cohen, Svirsky, Matthies, Garabieta & Jackson (1992) for another articulograph system (EMMA)).

In this experiment, eight transducer coils were used as illustrated in Figure 2.3. Two reference transducers were placed on the nose (R1) and upper gumline, or maxilla, (R2) in order to correct for head movement inside the helmet. The correction procedure for head movement modifies the co-ordinate system individually until both reference transducers stay still, eliminating any errors caused by helmet movement during the recording session.

Six transducers were located on articulators. Two were mounted on the upper and lower lips at the vermilion borders (L1,L2) to monitor lip closing and opening movements. In order to register tongue movement, three transducers were placed on the tongue: one 1 cm from the tongue tip (T1), one at the tongue mid section, about 2 cm from T1 (T2), and one at the tongue dorsum, about 2 cm from T2 (T3). To track jaw movement, a transducer was placed on the lower gumline, directly beneath the lower front teeth (J).

Table 2.1. A subset of the corpus containing /ba#ba/ sequence with different prosodic boundaries (IP, ip, Wd) and accentual patterns.

= Word boundary:

(a) ACC.-UNACC.

Prompt: Did you just say "Little **Boo** bopped the girl last night"?

Target: No, "Little **Bah # bopped** the girl"

rendition : H* L- L%

(b) UNACC.-ACC.

Prompt: Did you just say "Little Bah **popped** the girl last night"?

Target: No, "Little Bah # **bopped** the girl"

rendition : H* L- L%

(c) ACC.-ACC.

Target: You know what? Little **Bah # bopped** the girl.

rendition : H* H* L- L%

(d) UNACC.-UNACC.

Prompt: Did you just say "**Big** Bah bopped the girl last night"?

Target: No, "**Little** Bah # bopped the girl"

rendition : H* L- L%

= Intermediate or Intonational Phrase boundaries (ip or IP):

(e) ACC.-UNACC.

Prompt: Did you say "Little **Boo** bopped the **boy** last night"?

Target: No, " Little **Bah # bopped** the **girl**."

rendition 1: H*L- H* L- L%

rendition 2: H*L-L% H* L- L%

(f) UNACC.-ACC.

Prompt: Did you say "**Big** Bah **popped** the girl last night"?

Target: No, " **Little** Bah # **bopped** the girl.

rendition 1: H* L- H* L- L%

rendition 2: H* L-L% H* L- L%

(g) ACC.- ACC.

Prompt: Did you say "Little **Boo** **popped** the girl"?

Target: No, " Little **Bah # bopped** the girl.

rendition 1: H*L- H* L- L%

rendition 2: H*L-L% H* L- L%

(h) UNACC.-UNACC.

Prompt: Did you say "**Big** Bah bopped the **boy** last night"?

Target: No, " **Little** Bah # bopped the **girl**"

rendition 1: H* L- H* L- L%

rendition 2: H* L-L% H* L- L%

Finally, in order to align the articulatory space to the occlusal plane (based on a line from the lower edge of the upper central incisors to the lower edge of the upper molars), a bite-plate with two additional transducers was used as illustrated in Figure 2.4. (The bite-plate was made for each speaker by laminating a piece of thick paper, roughly the size of a credit card.) The articulatory space was rotated so that the x -axis was the occlusal plane. The amount of the rotation was determined by using x' (distance between two x points) and y' (distance between two y points) values of the two reference transducer coils on the bite plate. The rotation angle is the arctangent of y'/x' ($\theta = \tan^{-1} y'/x'$). This rotation provided the corrected horizontal (x) axis in the coordinate system, so that the x axis is parallel to the bite (i.e., occlusal) plane with the y axis being perpendicular to that, and this is consistent across speakers.

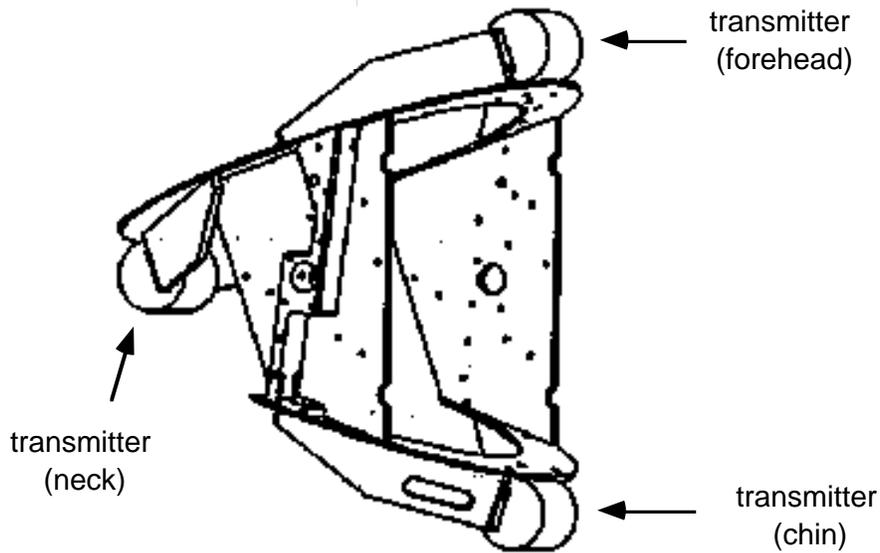


Figure 2.2. The EMA helmet with three transmitters.

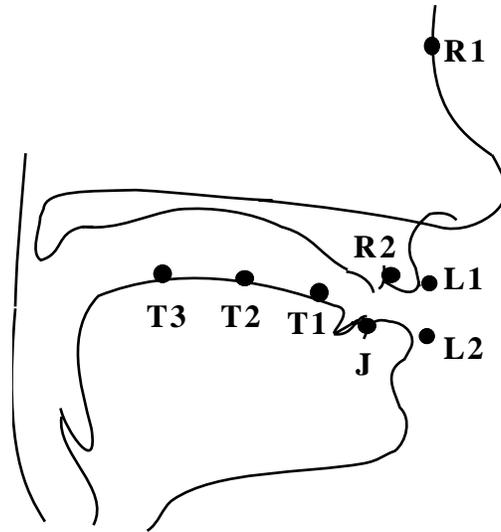


Figure 2.3. Locations of transducer coils. Two are placed at two reference points (R1, R2); two at the upper and lower lips at the vermillion borders (L1,L2); one at the lower front teeth (J); and three at the tongue blade (T1), tongue mid section (T2), and tongue dorsum (T3).

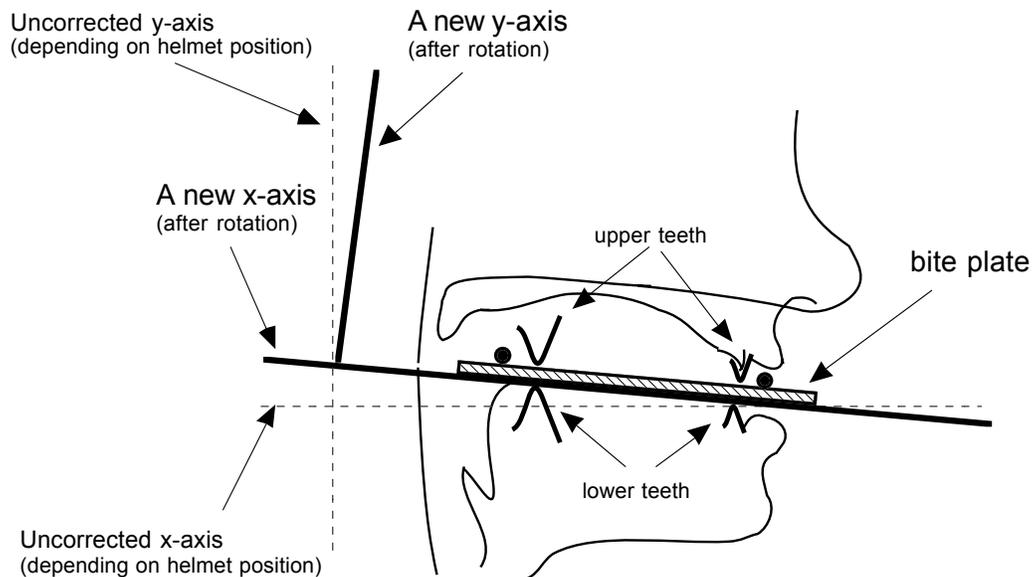


Figure 2.4. A schematic of the rotation to the occlusal plane using a bite plate with two reference transducers. This rotation provides the corrected horizontal (x) axis in the coordinate system, so that the x axis is parallel to the bite (i.e., occlusal) plane with the y axis being perpendicular to that.

Note that while this rotation technique has generally been used in articulatory studies using a magnetometer (e.g., Byrd, et al., 2000, Byrd, 2000), a slightly different but compatible technique has been used in some other studies using X-ray microbeam (e.g., de Jong, 1991, 1995a). For example, the X-ray microbeam system uses the x-dimension paralleled to the occlusal plane which is usually defined based on two reference points—one at the lower gumline at the mandible incisor and one on a mandible molar. (Since the EMA system registers movements only midsagittally, a point on a mandible molar cannot be used as a reference point in an EMA study.)

The EMA data were sampled at 500 Hz. A separate acoustic recording was made for alignment purposes. The obtained kinematic signals were then submitted to low-pass filtering with a filter cutoff of 50 Hz. During the experiment for one speaker, signals for the transducer coil attached at the jaw (lower gumline) were lost. Thus, in order to make results consistent across articulators, the data for the maximum positions of articulators were extracted from five speakers excluding this speaker.

The data processing procedures were done using Carstens' Tailor software, which was further customized to conduct this experiment. This program allows for head movement correction and data rotation as described above, filtering kinematic signals, and conversion of signals into new signals (e.g., Euclidean distance between two transducers). Based on processed data, measurements were made using Eanalyse 3.0, which displays movement trajectories in x and y dimensions, two-dimensional movement traces, and derivatives (e.g., velocity signals).

For detailed procedures, see the UCLA Phonetic Laboratory EMA website (<http://www.humnet.ucla.edu/humnet/linguistics/faciliti/facilities/physiology/ema.html>).

2.4. Measurements

2.4.1. Measurements in Chapter 3: *Maximum positions of the tongue, jaw, and lips.*

The positions of the tongue, jaw, and lip transducers at the most extreme points in vowels were extracted from the EMA data. These articulatory maxima were extracted at separate times and with different methods for each articulator.

Tongue measurements. The extreme points of the tongue mid and tongue dorsum transducers were extracted with two methods. The extreme points were primarily identified from the tangential velocity signal as minima (at which the tongue movement is supposed to come to a standstill momentarily (see Löfqvist, Gracco & Nye, 1993; Löfqvist, 1999)), as shown in Figure 2.5. These points were cross-checked by inspecting a sagittal display of the tongue movement trajectories, in which “turn-around” points could be found. These usually correspond to the tangential velocity minima. Cross-checking

was especially useful when there were more than a single tangential velocity minimum point locally. In such a case, a careful inspection of the sagittal display was performed frame by frame. Based on this, the point that best matched the extreme points in the tongue height and the tongue backness for a vowel was taken. For example, for /i/, a point that revealed the highest and the most anterior tongue position was taken; for /a/, a point that revealed the lowest and the most posterior tongue position was taken.

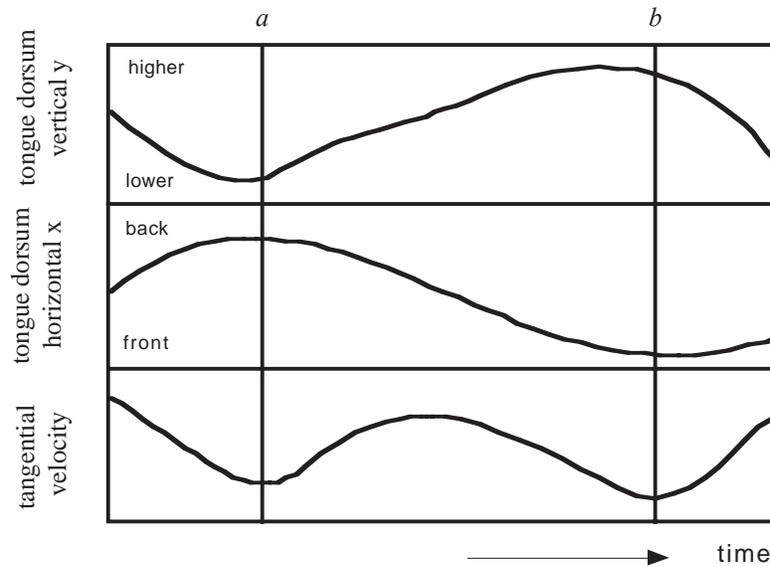


Figure 2.5. Schema for an /a#bi/ sequence indicating the extreme points of the tongue dorsum for (a) /a/ and (b) /i/, which were identified from the tangential velocity signal as minima.

The measurements for the tongue mid-section and tongue dorsum transducers were always taken at the same timepoint. In most cases, the tangential velocity minima for the two transducers were synchronized. But, in some cases when they did not occur at the same time, a compromise timepoint was found by inspecting a sagittal display.

Finally, in order to factor out the jaw contribution to the tongue position, especially in the x axis, the tongue position values in the x axis are recalculated relative to the lower jaw position (i.e., the values for the lower gumline transducer), and the tongue position values in the y axis, relative to the upper maxilla (i.e., the values for the upper gumline transducer). Taking the jaw contribution into account is important especially when examining the tongue maximum position in the horizontal (x) axis because the jaw lowering is likely to entail tongue backing without actual tongue movement in a posterior direction.

Jaw measurements. The extraction of the extreme points for the jaw during vowels was performed by taking the maximum Euclidean distance between the transducer at the lower gumline and the transducer at the upper gumline (reference point) from the

movement profile of the jaw opening (see section 2.4.3 below for detailed procedure for obtaining Euclidean distance). Since the upper gumline remains still, a greater value in the jaw Euclidean distance means not only a larger jaw opening but also a lower and possibly backer jaw position since the jaw rotates backwards as it lowers.

Lip measurements. As in the jaw measurements, the extreme points for the lips during vowels were taken from the lip aperture profile as the maximum Euclidean distance between the upper and lower lip transducers.

2.4.2. Measurements in Chapter 4: Tongue position differences

For the purpose of the coarticulatory study, only the tongue dorsum (TD) and tongue mid (TM) transducer coils were considered for analysis. Positional values for x and y for the tongue (TM and TD) were measured at a variety of acoustic time points: the onset, first quarter ($\frac{1}{4}V$), middle ($\frac{1}{2}V$), third quarter ($\frac{3}{4}V$) and end of each vowel; and first quarter ($\frac{1}{4}B$), middle ($\frac{1}{2}B$), and third quarter ($\frac{3}{4}B$) of the intervening /b/. Figure 2.6 shows these measured time points and a corresponding schematic articulatory trajectory from which positional values were extracted.

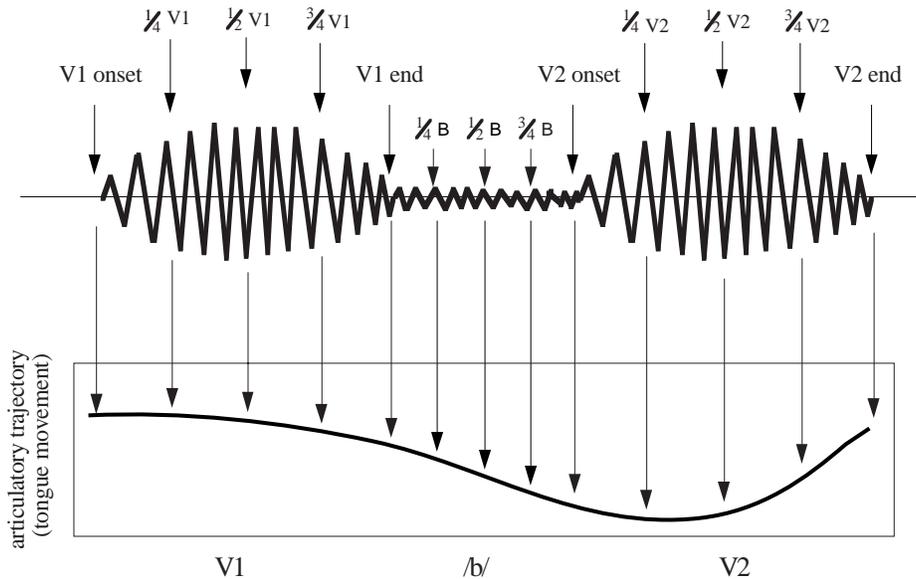


Figure 2.6. Schema of an acoustic waveform and a corresponding articulatory trajectory of a vertical tongue movement for /i#ba/.

It was necessary to normalize speaker differences, specifically for the sizes of their vocal tracts and tongues, and the position of the EMA helmet. To accomplish this, peak x

and y values were obtained for each vowel. Absolute x and y values were then converted to percentage-point values relative to the peak x and y values. For example, if a speaker had a minimum x value of 100 mm and a maximum x value of 300 mm, then an x value of 200 mm was normalized as 50%.

In this experiment, we are interested in vowel-to-vowel coarticulatory patterns observed in the overall tongue body configuration, rather than a single point on the tongue. Thus, normalized values were averaged over the tongue mid (TM) and the tongue dorsum (TD), and the analysis and discussion will be based on such averaged data. Two kinds of comparisons are made in assessing the degree of coarticulation. First, x and y values for the test vowels ($V1 \neq V2$) were compared with x and y values for the control vowels ($V1 = V2$), as prosodic boundary and accentuation varied. Note that in Chapter 4, accentuation in the target vowel will be referred to simply as Accent and the accentuation in the (encroaching) vowel across a boundary, as Neighboring Accent.

The terms *X-distance* and *Y-distance* are used to indicate the distance between the test and control vowels in x and y dimensions, as illustrated in Figure 2.7. In addition, the *Euclidean distance* (U-distance) between the test and control vowels is used as the index of how much the vowel in the test condition is coarticulated with the neighboring vowel, combining X- and Y-distances. In general, the greater the distance, the greater the coarticulatory effect, because the test vowel has been pulled away more from the control vowel and pushed towards the encroaching vowel. Figure 2.7 illustrates such a comparison at the onset of V2, but any point in Figure 2.6 could be compared in the same way.

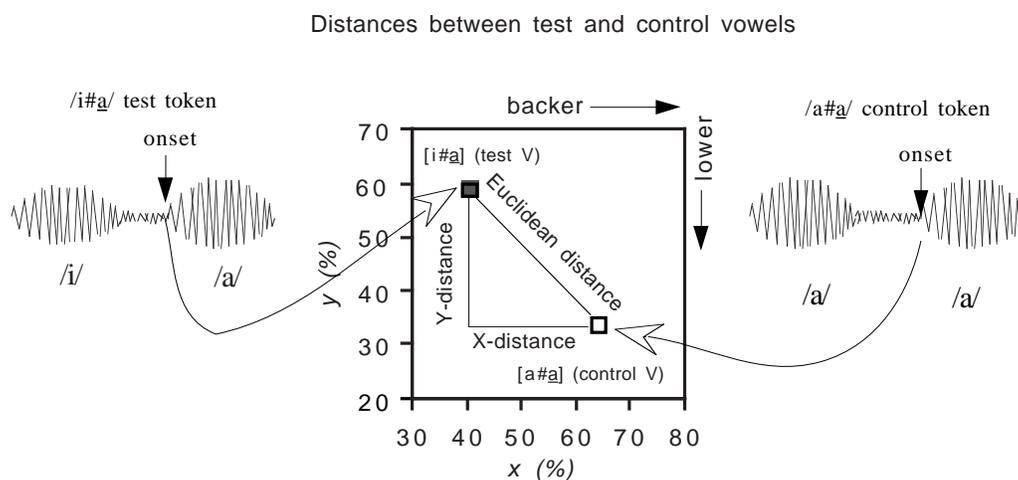


Figure 2.7. U-, X-, and Y-distances between test and control vowels.

Cross-boundary distance between opposite vowels

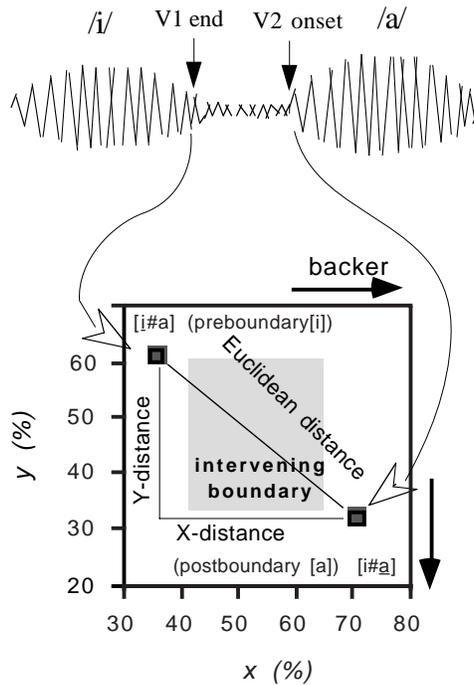


Figure 2.8. Cross-boundary distances between consecutive vowels spanning a prosodic boundary.

Second, the spatial difference between two consecutive opposite vowels (e.g., /a#i/) was considered in order to assess the overall degree of coarticulation regardless of its directionality (*the reciprocal coarticulatory effect*). (Note that in this case there is no comparison between control and test vowels.) As shown in Figure 2.8, the two data points (the two gray squares) were extracted from two different time points of a single sentence token: one is a preboundary point (e.g., V₁ end), and the other is a postboundary point (e.g., V₂ onset). U-, X- and Y-distances between these two data points were calculated for three time frames: (1) $\frac{3}{4}V_1 - \frac{1}{4}V_2$, (2) V₁ end-V₂ onset, and (3) $\frac{1}{4}B - \frac{3}{4}B$. (See Figure 2.6 for the location of these time points.) These measurements do not tell how much the observed degree of coarticulation is due to a carryover effect vs. an anticipatory effect, but rather they indicate the overall degree of coarticulation, combining the two directional effects. These measures will be referred to as *cross-boundary* distances. In this case, a larger cross-boundary distance indicates a lesser degree of coarticulation, in that the consecutive vowels are more differentiated.

In addition, the duration of the vowel-to-vowel interval was measured for the same three intervals as for cross-boundary distances in order to examine the relationship between the degree of reciprocal coarticulation and timing. Note that the interval between V₁ end and V₂ onset is measured as the acoustic duration of the intervening consonant /b/. This

will also allow us to observe variation in duration of the intervening /b/ as a function of prosodic position and accentuation.

In reporting results, target (encroached) vowels will be underlined as in /i#a/ or /a#i/. For example, /i#a/ means that the target vowel is /i/ and coarticulation is examined in the anticipatory direction; similarly, /i#a/ means that the target vowel is /a/ in the carryover direction.

2.4.3. Measurements in Chapter 5: Lip kinematics

For examining kinematics of the lip opening and closing movements, only /ba#ba/ and /bi#bi/ are included in order to control for the vowel type. To obtain lip opening and closing movement data, horizontal (x) and vertical (y) position signals for two sensor coils (one from the upper lip and the other from the lower lip) are combined into one dimension, Lip Aperture. The Euclidean distance between these two sensor coils is used as an index of Lip Aperture, which is calculated, following Byrd & Saltzman (1998), according to the following formula:

$$\text{Lip Aperture} = \sqrt{(\text{lip aperture } x)^2 + (\text{lip aperture } y)^2}$$

where lip aperture x = upper lip x – lower lip x

lip aperture y = upper lip y – lower lip y

The Lip Aperture signal derived by this formula is displayed and serves as the basis for all the lip measurements.

The onset and target timepoints of the lip closing and opening movements are ideally determined from the zero-crossings in the velocity signal. However, zero-crossings are often not well-defined, even though the signal has been low-pass filtered. Although the Lip Aperture signals generally do not show as much of the hovering of the velocity signals around zero as the tongue movement signals do, there were still many cases in which the velocity hovered quite a bit around zero, especially for tokens at edges of higher prosodic boundary.

The usually way of dealing with multiple zero-crossings is to define values above and below zero which are counted as the movement onset and target, respectively. Thus, to be consistent throughout the dataset, a velocity noise window was defined as 5% of the highest peak velocities of each lip opening and closing movements across the entire dataset. In other words, the onset was defined at the moment at which the velocity passed zero and reached 5% of the highest peak velocity obtained from the entire dataset; likewise, the target (or the offset) was defined at the moment at which the velocity reached

5% of the highest peak velocity *before* zero. This procedure was done separately for each of the six speakers who participated in the experiment.

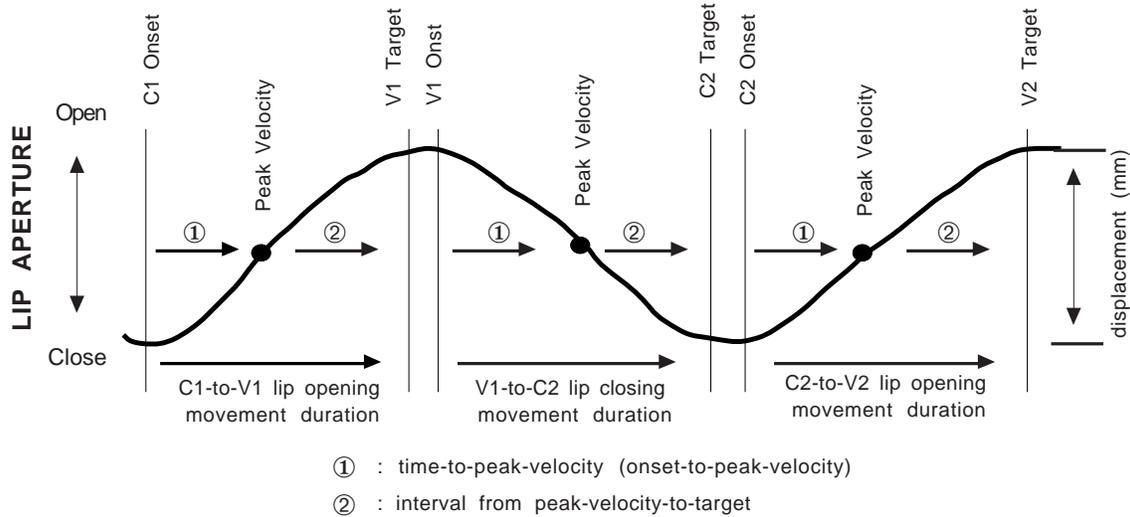


Figure 2.9. Schema of the lip opening and closing movement trajectory with an indication of the measured kinematic variables.

Various dependent variables are calculated at/between the moments of movement onset, target, and peak velocity. The measured variables that are examined in this chapter are schematized in Figure 2.9. As can be seen in the figure, five different measures are made for each lip opening and closing movement:

- (a) *displacement (mm)*: the spatial difference between the onset and the target of the lip opening or closing movements (C_1 -to- V_1 lip opening displacement; V_1 -to- C_2 lip closing displacement; and C_2 -to- V_2 lip opening displacement). Note that this measure differs from the measure taken at the maximum position in Chapter 3, in that displacement is a kinematic, not a static positional measure.
- (b) *total movement duration*: the temporal interval from the onset to the target of the lip opening or closing movements (C_1 ONS-TO- V_1 TARG; V_1 ONS-TO- C_2 TARG; and C_2 ONS-TO- V_2 TARG);
- (c) *time-to-peak-velocity*: the temporal interval from the movement onset to the timepoint of peak velocity, which is sometime referred to as acceleration duration (C_1 ONS-TO- V_2 PKVEL; V_1 ONS-TO- C_2 PKVEL; and C_2 ONS-TO- V_2 PKVEL);
- (d) *deceleration duration*: the interval from the timepoint of peak velocity to the movement target (C_1 PKVEL-TO- V_2 TARG; V_2 PKVEL-TO- C_2 TARG; and C_2 PKVEL-TO- V_2 TARG);
- (e) *peak velocity*: the actual peak velocity value taken from the velocity signal for each opening and closing lip movement.

Based on these measured variables, the relationships between some of these variables are further examined, in order to investigate detailed dynamical aspect of prosodic effects. Kinematic relationships that are examined include:

- (f) *relationship between total movement duration and time-to-peak-velocity*
- (g) *relationship between total movement duration and deceleration duration*
- (h) *relationship between total movement duration and displacement/velocity ratio*
- (i) *relationship between peak velocity and displacement*

These kinematic relationship variables will also help check the possibility that different settings of more than one dynamical parameter may underlie prosodically conditioned kinematic differences. Detailed discussion of each relationship is given in section 1.3.3.1 in Chapter 1.

2.4.4. Measurements in Chapter 6: Tongue kinematics

Tongue movements are from /i/-to-/a/ and vice versa. As in the procedures for obtaining lip movement signals, the onset and target timepoints of V_1 -to- V_2 vocalic movements are determined by a velocity noise window around the zero crossings in the velocity signal. This time, a larger velocity noise window (10%) was used since the tongue movement data are noisier than the lip aperture data. (Byrd (2000) also noted noisier tongue movement data as compared to the lip aperture data.)

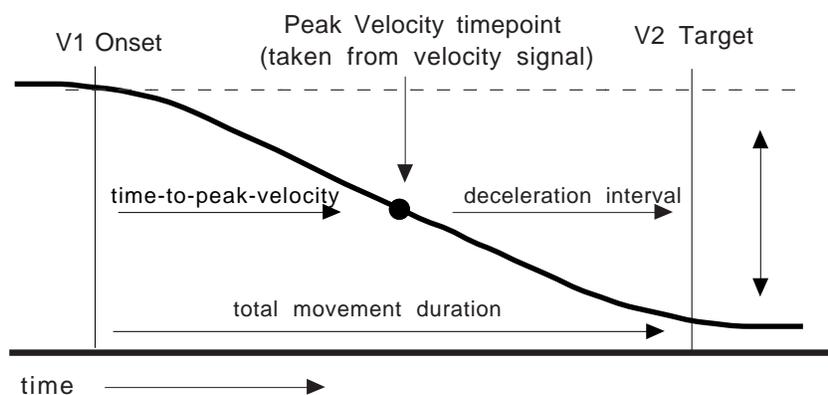


Figure 2.10. Schema of the /i/-to-/a/ tongue lowering movement in the y dimension with an indication of the measured kinematic variables.

Various dependent variables, equivalent to the Lip Aperture variables, are calculated based on timepoints of movement onset, target, and peak velocity. The

measured variables that are examined in this chapter are schematized in Figure 2.10. (Note that following Byrd (2000), the variable name $V_{1\text{ONS}}$ refers to the onset of V_1 -to- V_2 movement away from V_1 .) As can be seen in the figure, five different measures are made; these are made separately for each tongue movement dimension (x and y), giving ten measures per token. Note also that for the sake of clarity, ‘X’ and ‘Y’ are attached to each variable to show whether the measurement is made in the x or y dimension (e.g., X-displacement, Y-peak velocity). Basic measured variables include:

- (a) *displacement (mm)*: the amount of spatial difference between V_1 onset and V_2 target;
- (b) *total movement duration* ($V_{1\text{ONS-T0-V2TARG}}$): the interval from V_1 onset to V_2 target;
- (c) *time-to-peak-velocity* ($V_{1\text{ONS-T0-V2PKVEL}}$): the interval from V_1 onset to the timepoint of peak velocity, which is sometime referred to as acceleration duration;
- (d) *deceleration duration* ($V_{2\text{PKVEL-T0-V2TARG}}$): the interval from the timepoint of peak velocity to V_2 target;
- (e) *peak velocity*: the actual peak velocity value

Among these measured variables are two durational components (measures **c** and **d**) of the total movement duration that may require further explanation. As noted by Byrd (2000), in examining boundary-induced durational variation, the *cross-boundary tongue* movement data do not tell us whether the variation in the total movement duration is caused by preboundary lengthening (associated with the phrase-final vowel (V_1)) or by postboundary lengthening (associated with the phrase-initial vowel (V_2)). This is because the gestures associated with the phrase-final vowel (V_1) and the phrase-initial vowel (V_2) are not distinguishable in the movement data. This confounding can be dissolved by breaking down the total movement duration into two durational components: the interval $V_{1\text{ONS-T0-V2PKVEL}}$ (time-to-peak-velocity) and the interval $V_{2\text{PKVEL-T0-V2TARG}}$ (deceleration duration). The second component (deceleration duration) specifically indicates lengthening for the postboundary V_2 whereas the lengthened time-to-peak-velocity (the first component) may be interpreted as preboundary lengthening attributable to the movement for V_1 , especially when there is no boundary effect on the deceleration duration. Thus, in the absence of boundary effects on the interval $V_{2\text{PKVEL-T0-V2TARG}}$, any observed lengthening in the total movement duration must be specific to the preboundary lengthening.

Based on these measured variables, as was the case for lip movements, relationships between some of these variables are further examined, in order to investigate detailed dynamical aspects of prosodic effects. Kinematic relationships that are to be examined include:

- (f) *the relationship between total movement duration and time-to-peak-velocity*
- (g) *the relationship between total movement duration and deceleration duration*

- (h) *the relationship between total movement duration and displacement/velocity ratio;*
- (i) the relationship between peak velocity and displacement

It should be noted here that variable (f) will be compared to (g) in order to see whether both durational components contribute to the total movement duration. In particular, in examining boundary-induced durational variation, if there is no close relationship between the total movement duration and the deceleration duration, an elongated total movement duration can be interpreted as being due to preboundary lengthening; on the other hand, a close relationship between the total movement duration and the deceleration duration would reflect that postboundary lengthening contributes to the lengthening in total movement duration.

2.5. Prosodic Transcription

The relevant $C_1V_1\#C_2V_2$ portion of the audio recording was transcribed, with the aid of an acoustic display, by two trained ToBI transcribers (one the author) following the criteria set forth in the ToBI transcription system (Silverman, et al. 1992, Beckman & Elam, 1997). In general, pitch accents receive either H^* or $L+H^*$, and three prosodic boundaries were identified: the Intonational Phrase boundary (marked by a boundary tone and a break index 4); the Intermediate Phrase boundary (marked by a break index 3, a phrasal tone and no boundary tone); the Word boundary (marked by a break index 1, in the middle of an Intermediate Phrase). The phrase tone was always L^- , and the boundary tone was either $L\%$ or $H\%$. Figure 2.11 shows sample tokens of /ba#ba/ with ACC-UNACC sequences for three different prosodic boundaries.

The two transcribers identified locations of pitch accent the same in every token of the entire dataset. The only difference between the two transcribers came from a choice between the Intonational Phrase boundary and the Intermediate Phrase boundary. Because the difference between IP and ip boundaries is an important experimental variable in this study, only tokens whose renditions were agreed on by the two transcribers were used for analysis. Out of 1152 sentence tokens, transcriptions of 1109 tokens (96.3%) reached agreement between transcribers.

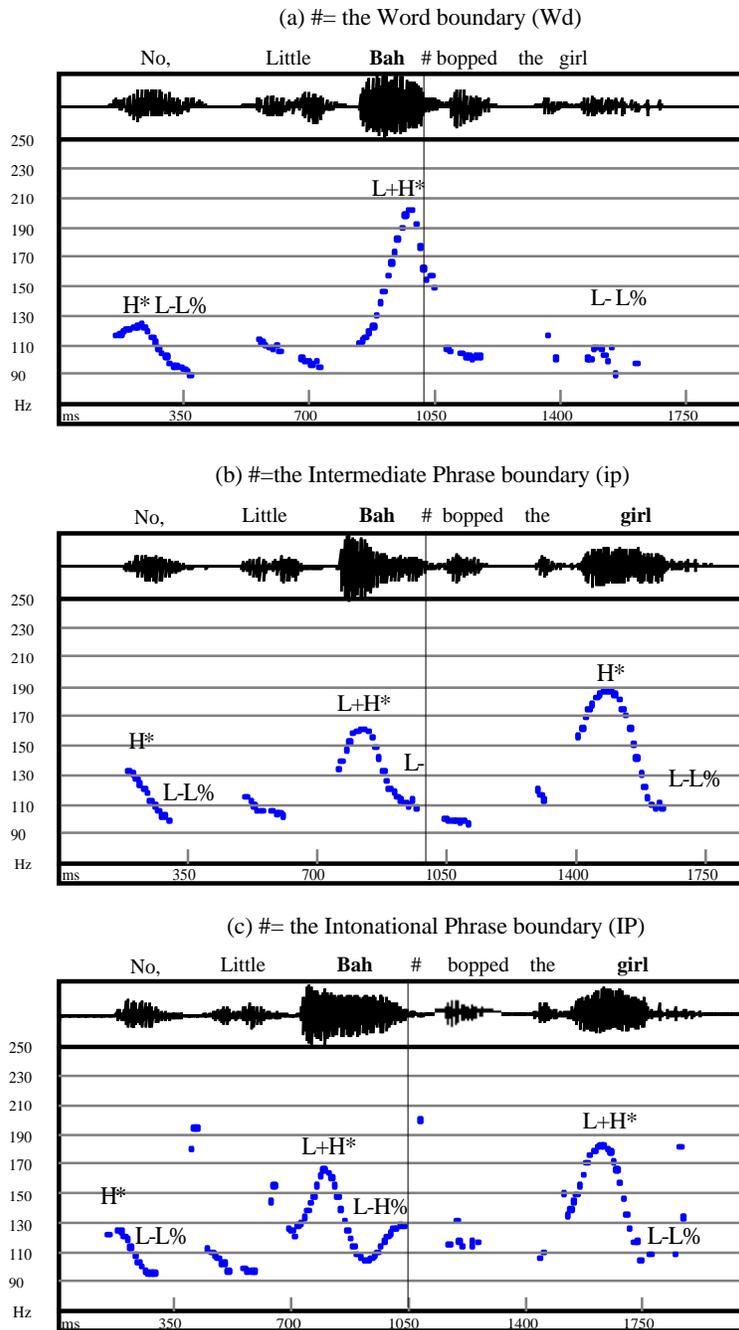


Figure. 2.11. Samples of ToBI transcriptions for /ba#ba/, ACC-UNACC with varying prosodic boundaries: (a) the Word boundary (marked by neither a phrasal tone nor a boundary tone and the break index of 1), (b) the Intermediate Phrase boundary (marked by a phrasal tone (L-) and the break index of 3), and (c) the Intonational Phrase boundary (marked by a boundary tone (H%) and the break index of 4). The vertical line indicates the acoustic endpoint of the preboundary vowel.

2.6. Statistics

In this section, I will outline the overall statistical methodology employed in this dissertation. Statistical procedures that are specific to individual chapters will be reported in these chapters.

Evaluation of the systematic influence of prosodic factors was primarily based on repeated measures General Linear Model Analyses of Variance (ANOVAs). The individual subjects were the experimental units. In other words, each data point is an averaged value over four repetitions of each prosodic and vowel context. (Note also that even though there are some missing data due to disagreement between transcribers, the statistical analyses are not influenced by that, because averaged values over repetitions are entered for a statistical analysis.) There were no between-subjects experimental factors. The within-subject factors considered were Prosodic Boundary (IP, ip, Wd), Accent (ACC, UNACC), Accent of Neighboring Vowel (ACC, UNACC), and Vowel Type (/a/ vs. /i/, or /a/-/i/ vs. /i/-/a/). In conducting repeated measures ANOVAs, analyses were adjusted to meet another statistical assumption, namely, the sphericity assumption; that is, that the variance of the difference scores for all pairs of treatment levels are homogeneous (Huynh & Feldt, 1970). In order to avoid violating the sphericity assumption, Huynh-Feldt corrected degrees of freedom were used in generating F ratio and p values. (See Max & Onghena, 1999 for a tutorial on statistical issues of reduction to experimental units and the sphericity assumption.) In reporting the results of repeated measures ANOVAs, p -values less than 0.05 are considered significant.

In order to observe patterns within a factor, *posthoc* tests were performed, when there is a significant effect, which requires using a factorial design. However, the basic assumptions of the ANOVA are violated when there are heterogeneous variances, and the observations on a given subject are correlated especially in cases of repeated observations and of multiple pairwise comparisons. In order to avoid this, a Bonferroni correction was employed using the Bonferroni/Dunn model. Further, as a safeguard, a conservative criterion for confidence level was used with the lowered alpha level of 3% (equivalent to $p < 0.01$ when there are three levels to compare within a factor.) The SPSS statistical package (version 10, SPSS Inc., 1999) and StatView (version 5.0.1, SAS Inc., 1999) were used to perform repeated measures ANOVAs and *posthoc* comparisons, respectively.

Finally, it should be noted that the main purpose of this dissertation is to investigate overall effects of prosody across speakers. Repeated measures ANOVAs with data pooled across speakers will show significance effects only if most speakers contribute to any observed variations. In fact, qualitative observations of individual speakers' behavior with respect to significant main effects revealed that consistent patterns were found across all speakers in most cases, with an occasional exception that one speaker showed a somewhat different pattern, but not different enough to cause overall non-significance. In addition, in some cases, one or two speakers out of five or six speakers showed quite a noticeable

different pattern from the rest of the speakers. In such a case, p -values were generally slightly higher than 0.05, i.e., non-significant. I will report cases when p -values are less than or equal to 0.075 as non-significant trends, in order to make note of tendencies for a majority of the subjects. However, reporting a trend is neither to support nor to reject a certain hypothesis, but rather it is done to point out that some speakers behave differently from others.

It goes without saying that any non-significant effects of prosodic factors examined in this dissertation in principle could be due to either speaker variation, in which some speakers show one direction and some others, the opposite direction, or to no distinct patterns at all. Although investigating individual speakers is necessary in order to obtain better insight into prosodically conditioned articulatory variation, their systematic analysis is beyond the scope of this dissertation. Instead, I will occasionally make some note of individual speakers' behavior based on qualitative observations when it is needed, especially when p -values are less than or equal to 0.075. It is hoped that follow-up studies of this dissertation will include a systematic investigation of inter-speaker variation.

Chapter III

Effects of Accent and Prosodic Boundary on Articulatory Maxima: Tongue, Jaw, and Lip

The present chapter discusses the effects of accent and prosodic boundary on the maximum positions of the tongue, jaw, and lips. Ultimately, this chapter attempts to understand how prosodically-conditioned patterns in articulatory maxima are linguistically significant, evaluating current phonetic theories of prominence (the sonority expansion model vs. the hyperarticulation model). What is at issue in this chapter is whether the hypothesized boundary-induced articulatory strengthening is driven by the same principle that may underlie the accent-induced articulatory prominence. With these goals in mind, hypotheses to be evaluated are laid out in the following section.

3.1. Hypotheses

The local hyperarticulation hypothesis (de Jong, 1995a) predicts a hyperarticulation of the tongue in a direction that enhances features with respect to place of articulation. In contrast, the jaw expansion model (Macchi, 1985) predicts that the jaw for accented vowels will be invariantly lowered regardless of the specification of vowel height. These hypotheses are compatible: the jaw can lower while the tongue can raise under accent (e.g., Harrington, et al, 2000). This chapter examines three articulators (not only the tongue and the jaw, but also the lips) concurrently to test a hypothesis:

HYPOTHESIS 3.1: There is an effect of accent on the tongue, the jaw lowering, and the lip opening.

H3.1a: the jaw is lowered when accented

H3.1b: the lip opening is larger when accented

H3.1c: the tongue is hyperarticulated towards the vowel's targets

HYPOTHESIS 2.1 predicts that when vowels are accented, the tongue will be advanced and raised for the high front vowel /i/, but more retracted and lowered for the back low vowel /a/ (featural enhancement), whereas the jaw and lip openings will be larger for both types of vowels (sonority expansion).

Turning to articulation at domain edges, hypotheses regarding domain-edge effects may make predictions different from HYPOTHESIS 2.1. As mentioned in Chapter 1, various studies have indicated that boundary-induced articulatory strengthening is driven by enhancing a structural (or syntagmatic) contrast among neighboring segments around a

prosodic boundary (e.g., Fougeron & Keating, 1997; Hsu & Jun, 1996; Fougeron, 2001). If this is true, then one might expect all three articulators to converge on sonority expansion to heighten #CV or V#C contrasts—i.e., the position of all three articulators will be lower at their peak. This leads to an hypothesis:

HYPOTHESIS 3.2: There is an effect of boundary on the tongue, the jaw lowering, and the lip opening.

H3.2a: the jaw is lowered at higher prosodic boundaries

H3.2b: the lip opening is larger at higher prosodic boundaries

H3.2c: the tongue is lower at higher prosodic boundaries

HYPOTHESES 3.2 will be tested separately for domain-initial (postboundary) and domain-final (preboundary) vowels since there have been different predictions made in the literature. For example, Beckman, et al. (1992) suggested that domain-final vowels tend to lengthen only, without greater displacement, whereas one can expect vowels at domain-edges to be both spatially and temporally magnified in a direction that results in a greater #CV or V#C displacement .

Relatedly, a detailed report on domain-final jaw movements (Edwards, et al., 1991) suggests that spatial strengthening in domain-final positions may vary depending on accentuation, such that some evidence of jaw expansion in domain-final positions, as opposed to domain-medial positions, can be found when the vowels being compared are unaccented. This leads to the formulation of another hypothesis:

HYPOTHESIS 3.3. HYPOTHESIS 3.2 holds only for unaccented vowels.

Finally, as mentioned in Chapter 1, researchers have suggested that strongly articulated segments may not only resist coarticulation but also encroach on neighboring vowels more (Bladon & Nolan, 1977; Recasens, 1987; Farnetani, 1990; Keating, 1990; Farnetani & Recasens, 1993). Thus, this chapter further examines whether the tongue position even at its peak is influenced by the accentuation of the neighboring vowel. The results regarding this research question will be also relevant to the coarticulatory study reported in the next chapter. The hypothesis to be tested is:

HYPOTHESIS 3.4. There is an effect of the accent of neighboring vowels on the maximum tongue position of the target vowel.

3.2. Measurements and Statistics

As described in section 2.4.1 in Chapter 2, the tongue maximum positions were extracted from signals in x and y dimensions separately, while the maximum jaw and lip opening values were extracted from Euclidean distance profiles which were derived from the upper and lower jaw transducers and the upper and lower lip transducers, respectively.

Evaluation of the systematic influence of prosodic factors on articulatory maxima was based on repeated measures Analyses of Variance (ANOVAs). The within-subject factors considered were Prosodic Boundary (IP, ip, Wd), Accent (ACC, UNACC), Type of Neighboring Vowel (/i, a/), and Accent of Neighboring Vowel (ACC, UNACC). Note that the factor Type of Neighboring Vowel is included in order to see whether the tongue position shows a coarticulatory effect even at its peak. The results are reported based on repeated measures four-way ANOVAs with five speakers, separately for /a/ and /i/. As discussed in section 2.6 in Chapter 2, each data point is an averaged value over four repetitions of each prosodic and vowel context, and a Huynh-Feldt corrected degree of freedom was used in generating F ratio and p values for Prosodic Boundary (3-level factor), with $p < 0.05$ as a significance level. Further, *posthoc* tests were performed with the Bonferroni/Dunn model at the lowered alpha level of 3% (equivalent to $p < 0.01$ when there are three levels to compare within a factor—i.e., Boundary Type). See section 2.6 in Chapter 2 for an outline of statistical procedures.

In what follows, I will report results separately for the four within-subject prosodic factors with domain-final (preboundary) and domain-initial (postboundary) positions examined separately (sections 3.3 and 3.4). Then in section 3.5, I will discuss results in connection to the hypotheses.

3.3. Result 1: Articulatory Maxima in Preboundary (Domain-final) Vowels ($V_1\#$)

3.3.1 Effect of Accent on V_1

3.3.1.1. Accent effect on V_1 maximum tongue position

First, consider the tongue position in the x dimension (i.e., the tongue backness). Results of repeated measures ANOVAs show that there is no main effect of Accent on /a#/ in the x dimension, either for the tongue dorsum (TD) or for the tongue mid (TM), whereas /i#/ shows a significant main effect of Accent on the tongue mid ($F[1,4]=11.071$, $p < 0.05$), but not significantly on the tongue dorsum, ($F[1,4]= 6.867$, $p < 0.075$, *trend*). (The non-significant trend was because one speaker (S2) showed a deviant pattern.) These results show different patterns for different vowels /a#/ and /i#/ , in that the maximum tongue

backness in /a#/ is not influenced by Accent, whereas /i#/ is associated with a more advanced tongue position when accented than when unaccented, as shown in Figure 3.1.

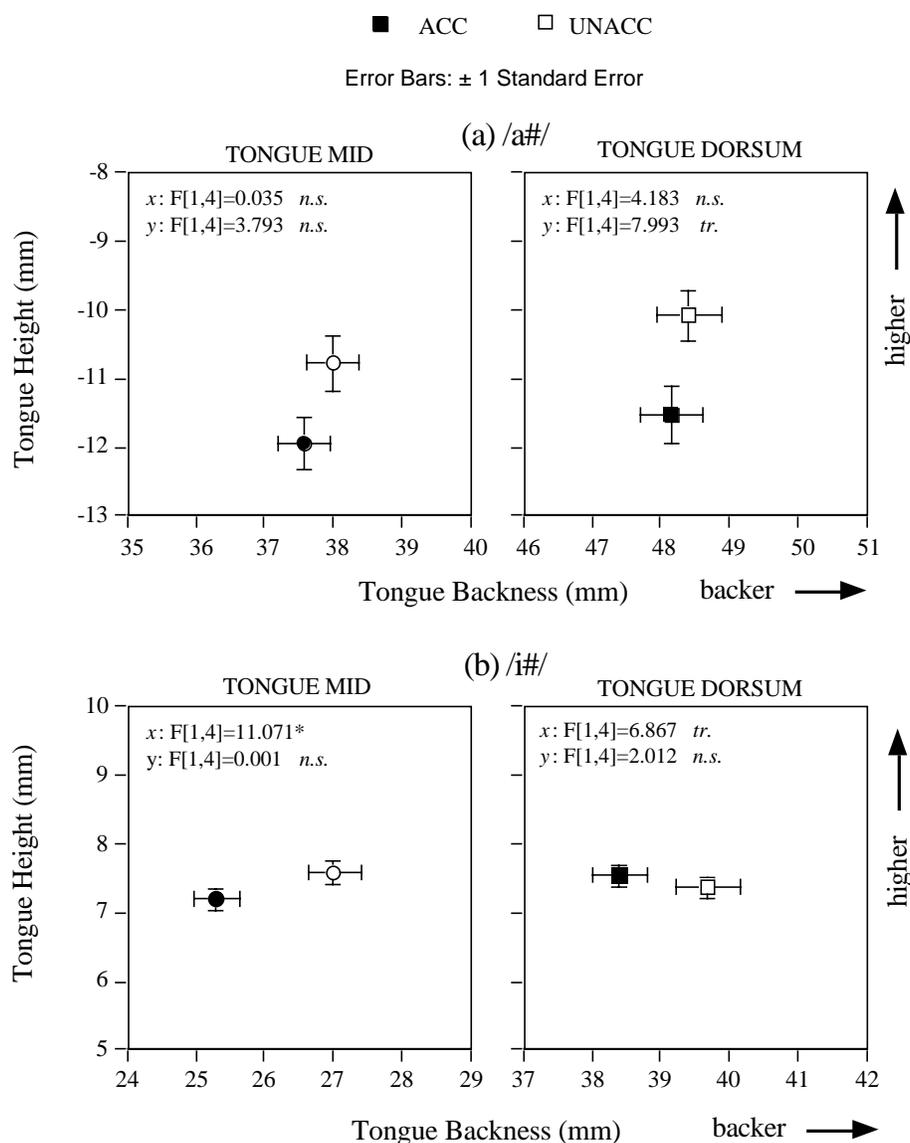


Figure 3.1. Effect of Accent on the maximum position of the tongue in preboundary vowels /a#/ and /i#/. F-ratios from repeated measures ANOVAs are provided for the x and y dimensions separately. * refers to $p < 0.05$; $tr.$, $p \leq 0.075$.

Now consider the tongue position in the y (height) dimension. The maximum tongue position in the y dimension also shows vowel differences, but in a direction somewhat opposite of the case in the x dimension. This time, there is no main effect of Accent on /i#/, whereas /a#/ shows a tendency towards a lower tongue dorsum for /a#/ when accented than unaccented ($F[1,4]=7.993$, $p < 0.075$, ns trend for TD). (The non-

significant trend was because one speaker (S2) showed a deviant pattern.) However, no effect is obtained for TM.

To sum up, for accented /a#/ , the tongue tends to be lower but not necessarily backer, whereas for accented /i#/ , the tongue is fronter but not necessarily higher.

3.3.1.2. Accent effect on V_1 lip and jaw opening maxima

First consider the lip opening maxima. There is a main effect of Accent on the lip opening maxima for both /a#/ and /i#/ ($F[1,4]=16.637$, $p<0.025$ for /a#/; $F[1,4]=42.253$, $p<0.005$ for /i#/). As shown in Figure 3.2a, the lip opening is greater when accented than when unaccented for both /a#/ and /i#/ . (Note that Figure 3.2 shows lip opening and jaw opening in only one dimension, based on the Euclidean distance between the two articulators, which is different from the figure plotting the tongue position in the x and y dimensions.)

Jaw opening maxima show a similar pattern, in that the amount of jaw opening is significantly greater when accented than when unaccented for /a#/ ($F[1,4]=9.812$, $p<0.05$ for /a#/), while /i#/ shows a trend ($F[1,4]=6.189$, $p<0.075$ for /i#/), as shown in Figure 3.2b. (For this trend, one speaker (S3) showed a pattern different from others.)

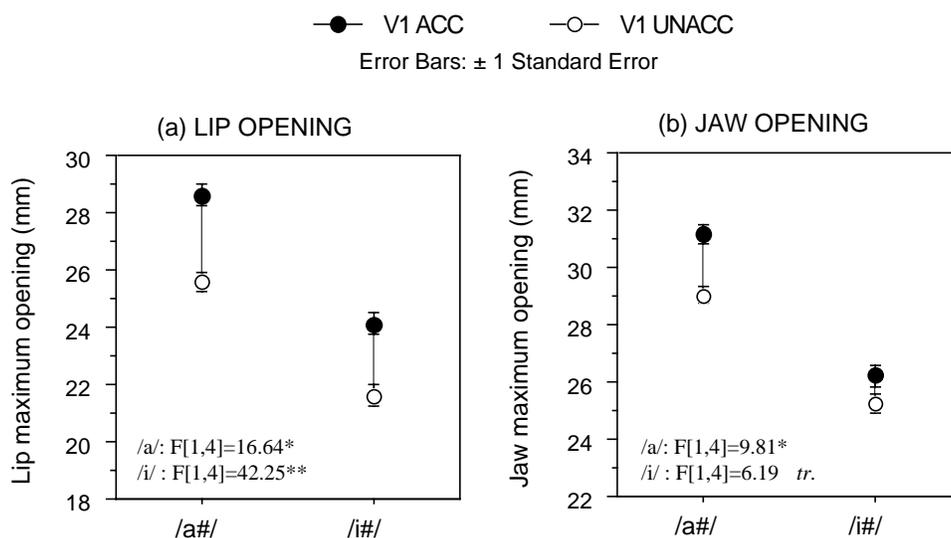


Figure 3.2. Effect of Accent on the lip and jaw opening maxima in preboundary vowels /a#/ and /i#/ . F-ratios from repeated measures ANOVAs are provided for the x and y dimensions separately. (** refers to $p<0.01$; *, $p<0.05$; tr., $p\leq 0.075$.)

3.3.2. Effect of Boundary Type on V_1

3.3.2.1. Boundary effect on V_1 maximum tongue position

With respect to the x dimension, /a#/ shows a main effect of Boundary Type on both the tongue dorsum (TD) and the tongue mid (TM) ($F[1.3,5.2]=13.051$, $p<0.05$ for TD; $F[1.3,5.0]=10.555$, $p<0.05$ for TM), such that the tongue position is more retracted before a higher boundary, as shown in Figure 3.3. In pairwise *posthoc* comparisons, /a#/ shows a pattern of $IP>Wd$ for both TD and TM ($p<0.01$, Bonferroni/Dunn). On the other hand, /i#/ shows no main effect on either TD or TM.

Consideration of the tongue position in the y dimension is next. Unlike the results for the x dimension, both /a#/ and /i#/ show main effects of Boundary Type in the y dimension (for /a#, $F[2,8]=13.640$ for TD, $F[2,8]=9.219$ for TM, both $p<0.05$; for /i#, $F[1.8,7.4]=6.701$ for TD, $F[1.4,5.8]=6.714$, both $p<0.05$). This effect is shown in Figure 3.3, in which the tongue position is on average progressively lower before a higher boundary for both /a#/ and /i#. In other words, not only the low vowel /a#/ but also the high vowel /i#/ is associated with a lowered tongue position before a higher prosodic boundary. Pairwise *posthoc* comparisons show that there is a pattern of $IP\geq ip>Wd$ in the y dimension for all cases ($p<0.01$, Bonferroni/Dunn), except for the tongue dorsum in /i#/ which shows a pattern of $IP>Wd$.

3.3.2.2. Boundary effect on V_1 lip and jaw opening maxima

There is a main effect of Boundary Type on the lip opening maxima for both /a#/ and /i#/ ($F[1.2,4.7]=7.202$, $p<0.05$, for /a#/; $F[1.4,5.6]=9.553$, $p<0.05$ for /i#/), such that the lip opening is larger at a higher prosodic boundary. This effect is shown in Figure 3.4a, in which the lip opening is greater for IP than ip or Wd at $p<0.01$ (Bonferroni/Dunn).

Turning to the boundary effect on the jaw opening maximum, in contrast to the case for the lip opening, there is no main effect of Boundary Type on the jaw opening maxima for /a#. Further, /i#/ shows a main effect ($F[2,8]=7.313$, $p<0.05$), but in a direction that is opposite to the case for the lip opening. That is, as can be seen in Figure 3.4b, there is a small but significant increase in the jaw opening for Word, as compared to IP or ip ($p<0.01$, Bonferroni/Dunn), meaning that the jaw is higher for the IP-final /bi#/ than for the word-final /bi#.

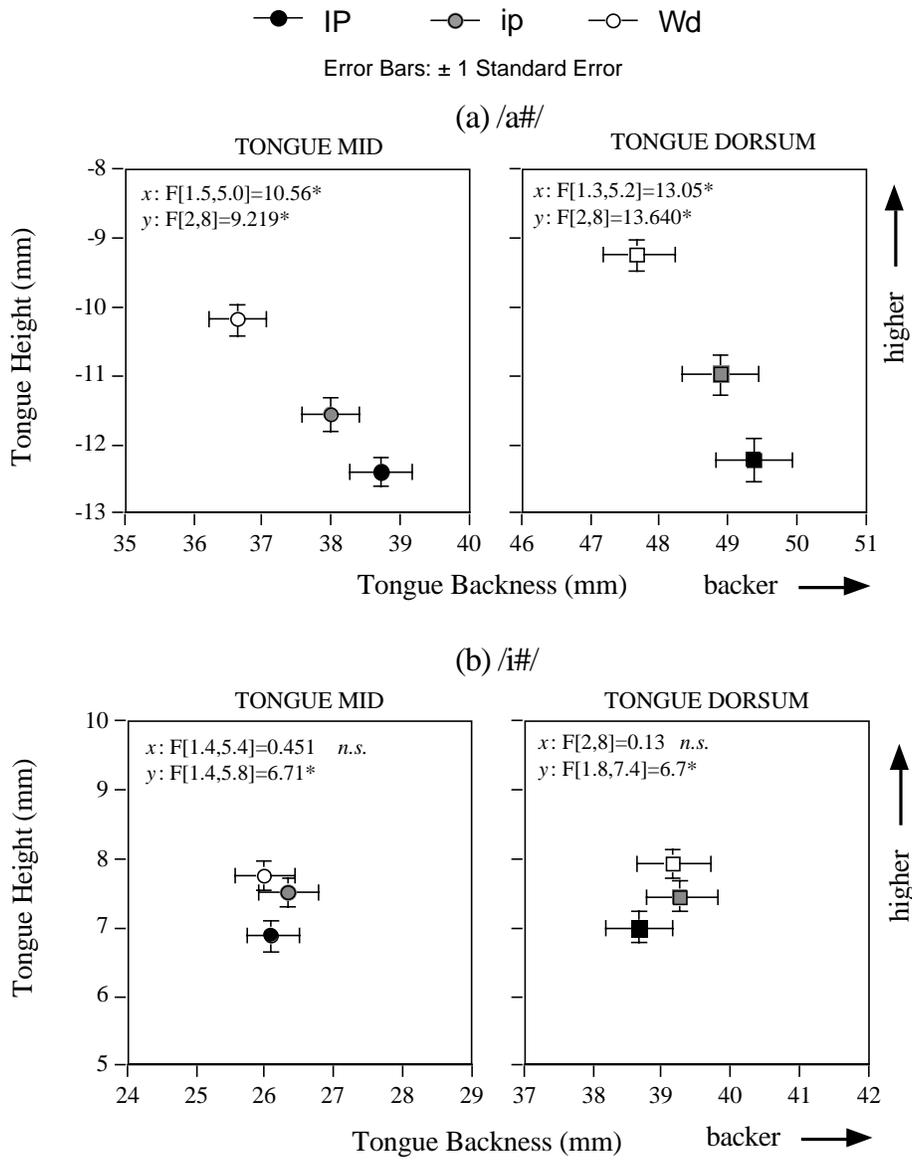


Figure 3.3. Effect of Boundary Type on the maximum position of the tongue in preboundary vowels /a#/ and /i#/. F-ratios from repeated measures ANOVAs are provided for the x and y dimensions separately. * refers to $p < 0.05$; tr., $p \leq 0.075$.

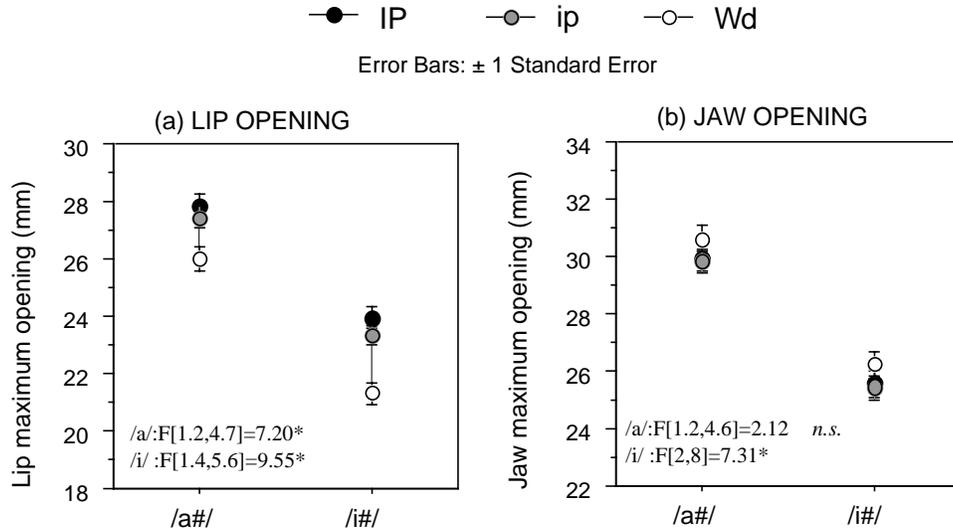


Figure 3.4. Effect of Boundary Type on the lip and jaw opening maxima in preboundary (domain-final) vowels /a#/ and /i#/. F-ratios from repeated measures ANOVAs are provided for the x and y dimensions separately. (** refers to $p < 0.01$; *, $p < 0.05$.)

3.3.3. Effects of the neighboring vowel (V_2) on V_1

This section examines the effect of the neighboring vowel V_2 on V_1 , in order to see whether V_2 Type (/a/ vs. /i/) influences the tongue position maximum during the preboundary vowel V_1 .

There is no main effect of V_2 Type on the tongue position in either the x or the y dimensions, either for /a#/ or for /i#/. This means that the V_2 Type (/a/ vs. /i/) does not consistently influence the maximum tongue position for the preboundary vowel (V_1). In most cases, there is no significant interaction between V_2 Type and other factors for either /a#/ or /i#/. The only significant interaction that involves V_2 Type is a V_2 Type by Boundary Type interaction for TD for /i#/ in the y dimension ($F[2,8]=4.499$, $p < 0.05$). This effect is due to the fact that there is a tendency towards a lower tongue position for /i#/ before /#ba/ than before /#bi/ for IP and ip, but the opposite is true for Word.

Next, consider the effect of V_2 Accent on V_1 . Neither a main effect nor a non-significant trend of V_2 Accent on the tongue position of V_1 is obtained for either /a#/ or /i#, indicating that there is no consistent influence of V_2 Accent on the maximum tongue position of V_1 . Further, there is no V_2 Accent by V_2 Type interaction for either /a#/ or /i#. This suggests that, even when $V_1\#V_2$ forms a sequence of opposite vowels (/a#i/ or /i#a/), V_2 Accent does not influence the maximum tongue position of V_1 , showing no coarticulatory effect. No other interactions among factors that include V_2 Type were found.

3.4. Result 2: Articulatory Maxima in Postboundary (domain-initial) Vowels (#CV₂)

3.4.1. Effect of Accent on C₂V₂

3.4.1.1. Accent effect on CV₂ maximum tongue position

Postboundary (domain-initial) vowels /#ba/ and /#bi/ show different Accent effects, depending on the dimension of the tongue (x vs. y). For /#ba/, there is a significant Accent effect on the tongue position only in the y dimension ($F(1,4)=10.06$ for TD; $F[1,4]=11.106$ for TM, both, $p<0.05$), such that the tongue position is lower when /#ba/ is accented than when it is unaccented, as shown in Figure 3.5a. However, there is no main effect on /#ba/ in the x dimension. (Note that the ACC/UNACC mean difference shows an unexpected direction, indicating that, if any, the tongue for the back vowel /#ba/ tends not to be more retracted, but rather, more advanced when accented than when unaccented.)

Unlike /#ba/, /#bi/ shows a robust effect of Accent in the x dimension ($F[1,4]=23.145$, $p<0.01$ for TD; $F[1,4]=44.297$, $p<0.01$ for TM), such that the tongue for the front vowel /#bi/ is more advanced when accented than when unaccented, as shown in Figure 3.5b. On the other hand, in the y dimension, the tongue position for the high vowel /#bi/ is not higher but lower when accented than when unaccented, as evident in the difference found for TM ($F[1,4]=9.416$, $p<0.05$), but not for TD.

3.4.1.2. Accent effect on V₂ lip and jaw opening maxima

Both lip and jaw opening maxima show main effects of Accent for both /#ba/ and /#bi/ ($F[1,4]=17.597$, $p<0.025$ for the lip, /#ba/; $F[1,4]=32.954$, $p<0.005$ for the lip, /#bi/; $F[1,4]=18.941$, $p<0.025$ for the jaw, /#ba/; $F[1,3]=53.931$, $p<0.001$ for the jaw, /#bi/). As shown in Figure 3.6, accented V₂ is associated with greater jaw and lip openings than unaccented V₂ regardless of V₂ Type.

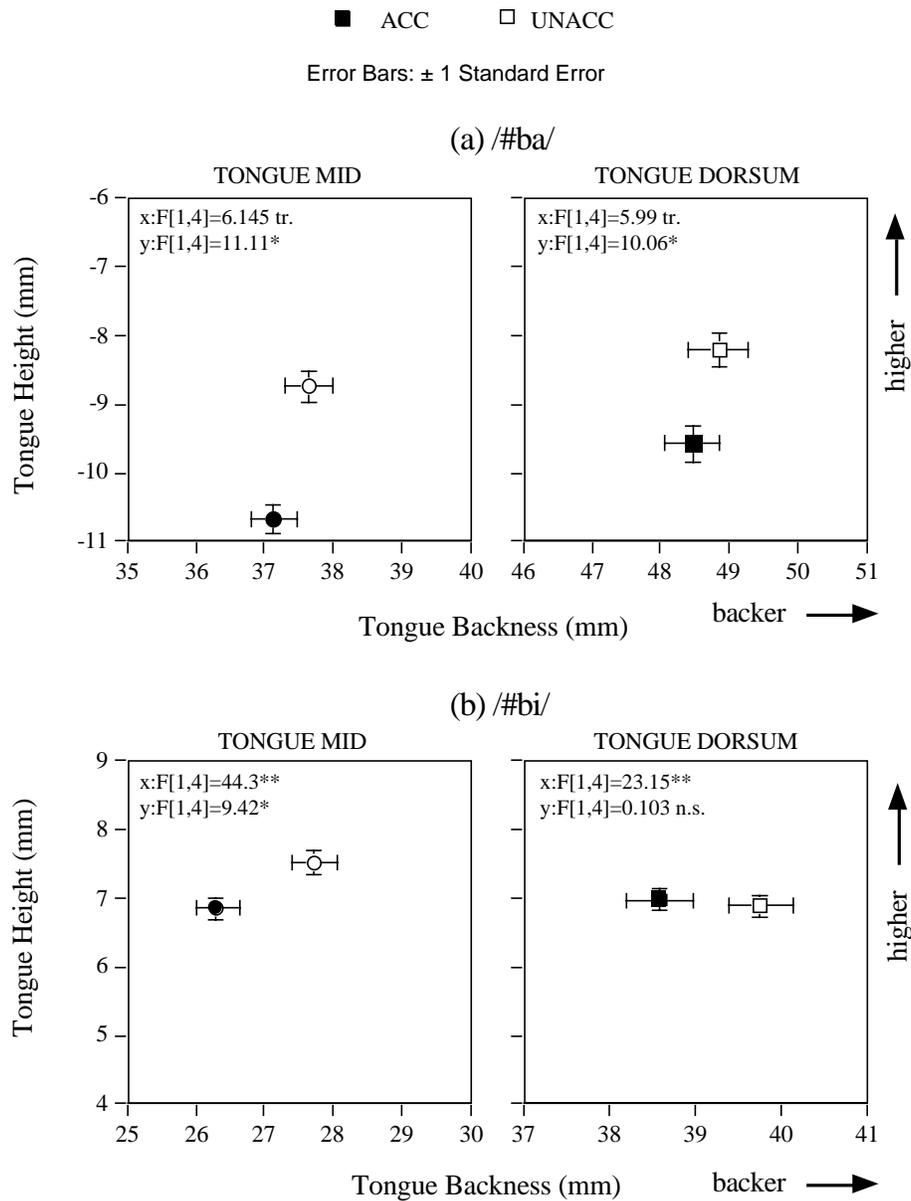


Figure 3.5. Effect of Accent on the maximum position of the tongue in postboundary vowels /#ba/ and /#bi/. F-ratios from repeated measures ANOVAs are provided for the x and y dimensions separately. (** refers to $p < 0.01$; *, $p < 0.05$; *tr.*, $p \leq 0.075$.)

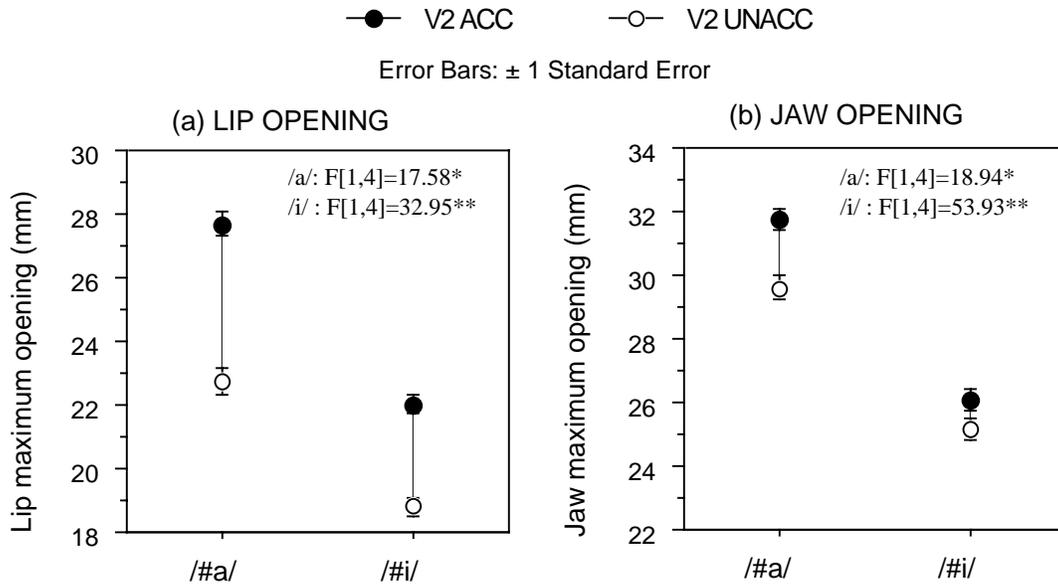


Figure 3.6. Effect of Accent on the lip and jaw opening maxima in postboundary vowels /#ba/ and /#bi/. F-ratios from repeated measures ANOVAs are provided for the x and y dimensions separately. (** refers to $p < 0.01$; *, $p < 0.05$.)

3.4.2. Effect of Boundary Type on C_2V_2

3.4.2.1. Boundary effect on C_2V_2 maximum tongue position

There is no main effect of Boundary Type on the maximum tongue position of the postboundary V_2 for either /#ba/ or /#bi/ in either the x or the y dimensions. As shown in Figure 3.7, the tongue position is not different at a higher prosodic boundary in either the x or the y dimensions, which is opposed to the boundary effect on preboundary V_1 .

3.4.2.2. Boundary effect on V_2 lip and jaw maxima

There is no main effect of Boundary Type on the maximum lip opening, either for /#ba/ or for /#bi/, as can be inferred from Figure 3.8a.

As for the boundary effect on the jaw opening, there is no main effect on the maximum jaw opening in /#ba/, but a main effect is obtained for /#bi/ ($F[1.3,5.9]=6.859$, $p < 0.05$), such that the amount of jaw opening for /#bi/ is significantly smaller for IP and ip than for Word ($p < 0.01$, Bonferroni/Dunn), as shown in Figure 3.9b. Recall that a greater jaw opening (or lowering) at a word boundary was also found for the preboundary /i#. There is no Boundary Type by Accent interaction for either the lip or the jaw opening maxima.

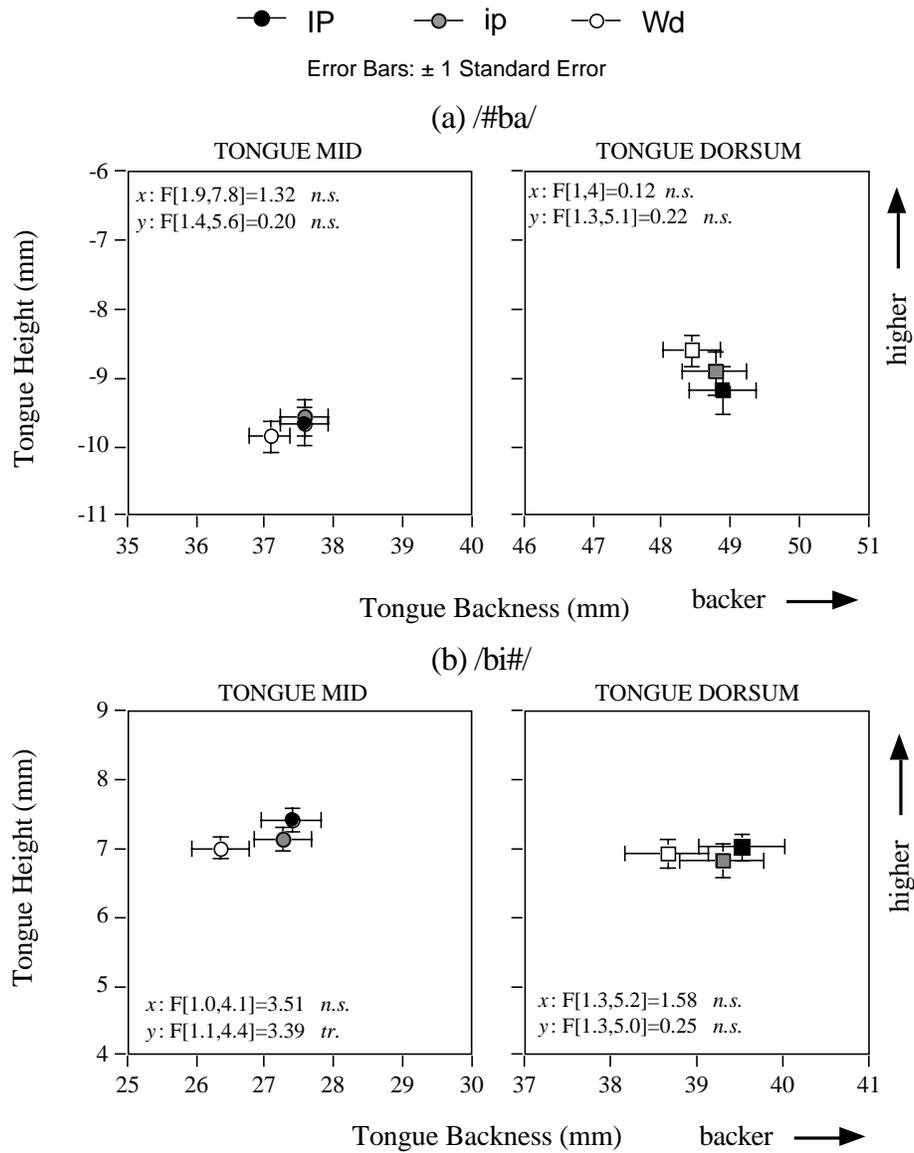


Figure 3.7. Effect of Boundary Type on the maximum position of the tongue in postboundary vowels /#ba/ and /#bi/. F-ratios from repeated measures ANOVAs are provided for the x and y dimensions separately. (* refers to $p < 0.05$; *tr.*, $p \leq 0.075$.)

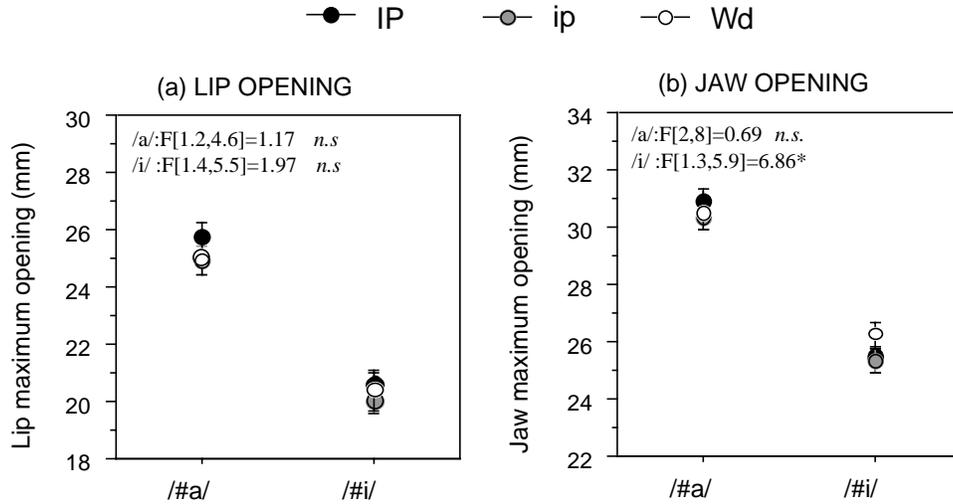


Figure 3.8. Effect of Boundary Type on the lip and jaw opening maxima in postboundary vowels /#ba/ and /#bi/. F-ratios from repeated measures ANOVAs are provided for the x and y dimensions separately. (** refers to $p < 0.01$; *, $p < 0.05$.)

3.4.3. Effects of the neighboring vowel (V_1) on V_2

Regarding the effect of V_1 Type on the maximum tongue position of V_2 , no main effect on /#bi/ is obtained, whereas /#ba/ shows a main effect of V_1 Type on both TD and TM ($F[1,4]=318.150$, $p < 0.001$; $F[1,4]=33.770$, $p < 0.005$, respectively), as opposed to the effect V_2 Type on preboundary vowel V_1 , which showed no main effect on either /a#/ or /i#/. In other words, the maximum tongue position of /#ba/ coarticulates with the V_1 Type (/a/ vs. /i/) in the y dimension, such that it is higher after /i#/ than after /a#/, showing coarticulation of /#ba/ with the preceding vowel /i#/. However, there is neither a V_1 Type by Boundary Type interaction nor a V_1 Type by V_1 Accent interaction, which means that the effect of V_1 Type does not vary with Boundary Type or V_1 Accent.

Next, consider the effect of V_1 Accent on V_2 . No main effect is obtained for either /#ba/ or /#bi/. More importantly, there is neither a V_1 Accent by V_1 Type interaction for any measured variables, indicating that the coarticulatory effect (V_1 Type effect) is not influenced by V_1 's accent.

3.5. Summary & Discussion

This chapter has examined prosodically-conditioned variation in the maximum position of the tongue and in the jaw and lip opening maxima, focusing on effects of accent, boundary type, and identity of two vowels. A summary of the results appears in Table 3.1, and is recapitulated below:

Accent effect:

- (a) Both the lip and the jaw openings are larger when accented than when unaccented regardless of vowel type (/a/ vs. /i/) and position-in-domain (preboundary vs. postboundary).
- (b) A low back vowel /a/ is lower when accented, but not necessarily backer in both the domain-initial and the domain-final positions.
- (c) The high front vowel /i/ is fronter when accented than when unaccented in both the domain-initial (postboundary) and domain-final (preboundary) positions, but it is not necessarily higher when accented.

Boundary effect:

- (d) There is no boundary effect on domain-initial vowels (#CV₂) for any measured variables except that jaw opening is smaller (i.e., jaw raising) after a phrase boundary (i.e., IP) than after a word boundary.
- (e) For the domain-final (preboundary) vowel (V₁#), lip opening is larger before a higher boundary (IP) than before a lower boundary (Wd) for both /a/ and /i/. But no effect of Boundary Type on jaw opening for /a#/ is found, whereas for /i#, jaw opening is smaller (i.e., jaw raising) before an IP boundary than before a Wd boundary.
- (f) For the domain-final (preboundary) vowel (V₁#), the tongue for the low back vowel /a#/ is lower and backer before a higher boundary than before a lower prosodic boundary; the tongue for the high front vowel /i/ is not fronter and higher, but rather lower before a higher prosodic boundary than before a lower prosodic boundary.

Effect of neighboring vowel:

- (g) The only main effect found with respect to the neighboring vowel is the effect of V₁ Type on domain-initial vowel /#ba/, such that the maximum position of the tongue for /#ba/ is higher after /i#/ than after /a#/. No other effects were found.
- (h) There is no main effect of Accent of Neighboring Vowel on the realization of the target vowel.

Table 3.1. Summary of main effects of Accent and Boundary Type on preboundary (_#) and postboundary (#_) vowels. Cells with descriptions indicate that effects are significant. When the described effect is applicable only to either TD or TM, it is parenthetically specified. *tr* refers to a non-significant trend ($p \leq 0.075$).

V-Type	Gestures	Accent Effect		Boundary Effect	
		# (V ₁)	# (V ₂)	_# (V ₁)	#_ (V ₂)
/a/	<i>tongue</i> <i>x</i>	<i>n.s.</i>	<i>n.s.</i>	Backer	<i>n.s.</i>
	<i>tongue</i> <i>y</i>	Lower ^{<i>tr</i>} (TD)	Lower	Lower	<i>n.s.</i>
	Lip	More open	More open	More open	<i>n.s.</i>
	Jaw	More open	More open	<i>n.s.</i>	<i>n.s.</i>
/i/	<i>tongue</i> <i>x</i>	Fronter	Fronter	<i>n.s.</i>	<i>n.s.</i>
	<i>tongue</i> <i>y</i>	<i>n.s.</i>	Lower (TM)	Lower	<i>n.s.</i>
	Lip	More open	More open	More open	<i>n.s.</i>
	Jaw	More open ^{<i>tr</i>}	More open	Less open	Less open

3.5.1. Characteristics of Accent and Featural Enhancement

Regarding the effect of accent on articulatory maxima, we hypothesized based on earlier work (Macchi, 1985; Edwards & Beckman, 1988; Beckman, et al., 1992; de Jong, 1991, 1995a; Harrington, et al., 2000) that in the presence of accent, the maximum position of the tongue is expanded in ways that enhance place features for different vowels /a,i/, whereas the jaw and lip openings are independently expanded in order to increase sonority (HYPOTHESIS 3.1). As far as the opening of the vocal tract is concerned, our results show that accented vowels are associated with an increase in jaw and lip openings for low and high vowels /a,i/, indicating sonority expansion.

However, results about the tongue position showed that the high front vowel /i/ is more fronted when accented, but not necessarily higher. In fact, there was a significant lowering of the tongue body for accented /i/ in domain-initial positions which works against the featural enhancement with respect to the feature [+high]. Likewise, the low back vowel /a/ was lower but not necessarily backer. These results do not lend full support to the featural enhancement account as predicted by the hyperarticulation hypothesis.

Now the question arises as to the extent to which the results in this chapter can be accounted for by the hyperarticulation hypothesis. The main idea of the hyperarticulation hypothesis is that accented syllables are more extremely articulated in the direction of their assumed articulatory targets, enhancing distinctive features of segments (i.e., enhancement of phonemic distinctions), which also will maximize lexical distinctions. However, as introduced in Chapter 1, this account subsumes sonority expansion as far as features like [sonorant] are concerned. Thus, under this account, the sonority expansion hypothesis is no longer a separate hypothesis. As far as the sonority feature is concerned, the hyperarticulation is supported, as evident in the fact that the jaw and lip openings are larger when accented and that the tongue is positioned in a way that does not conflict with the sonority expansion.

However, as for primary place features, there seems to be some interaction between place and sonority features. The vowel /a/ is associated with two place features [+low] and [+back], and the feature that is enhanced is the one that also involves sonority expansion, i.e., [+low]. In contrast, for the vowel /i/ which is associated with two place features [-back] and [+high], neither of the features involves sonority expansion. In this case, the feature [-back] but not [+high] is enhanced, presumably because an enhancement of the latter would work against sonority expansion. In short, what emerges from this observation is that when a vowel has a place feature whose enhancement also results in sonority expansion, that feature is enhanced (in the case of /a/), whereas when a vowel has a place feature whose enhancement is in direct conflict with sonority expansion, the enhancement of that feature is suppressed (in the case of /i/)¹. This observation is also supported by a finding reported in de Jong (1995a) who showed that the tongue position for English vowel /u/ (with two place features [+high] and [-back]) is backer but not necessarily higher under accent.

These results require a more refined definition of featural enhancement under the hyperarticulation hypothesis. If the enhancement of every primary feature for a vowel is expected under hyperarticulation, our results do not lend support to this account. The only way of interpreting our data in the framework of the hyperarticulation hypothesis is to assume sonority expansion as the most important mechanism characterizing accent. If the ultimate goal of accent is to maximize lexical distinctions as originally proposed under the rubric of the hyperarticulation hypothesis, such lexical distinction is not necessarily maximized by enhancement of all the distinctive features, but rather primarily by making

¹ However, results reported in Harrington, et al. (2000) showed that only one of the two speakers had a fronter but not higher tongue position for Australian English /i/ whereas the other speaker showed the opposite direction (i.e., a higher but not fronter tongue position). While such inconsistency between two speakers may weaken the generalization that our data are getting at, there is also a possibility that the dialectal difference between American English and Australian English gives rise to such a difference. Note also that the significant patterns reported in this chapter are obtained when all five speakers behave similarly; thus our result here is a robust one.

segments louder (by making the mouth more open), and other featural enhancement may add to lexical distinctions in ways that does not conflict sonority expansion.

This account can be further considered in terms of articulatory economy in the phonetic implementation. From the results we can infer that the phonetic enhancement due to accent makes no direct reference to all phonological distinctive features, but rather the phonetic component chooses the most efficient ways of maximizing phonetic clarity, which may be also constrained in part by extralinguistic factors such as vocal tract physiology. This also goes in line with a view that the phonetic behavior is not directly dictated by phonological information (cf. de Jong, 1995b). Phonological featural representations may simply be useful for the informational structure in which the lexicon and the morphological systems are organized. If this is so, it is conceivable that once the information about phonological features together with the postlexical prosodic information (i.e., accent in this case) is fed into the phonetic component, the phonetic component may utilize phonological featural information insofar as phonetic clarity is achieved in a physically economical way. This idea is also compatible with the global effect hypothesis (Fowler, 1995) which states that the phonetic goal of accent is to simply maximize prominence in order for listeners to understand better. Under this account, not all features need to be enhanced. Speakers may choose to heighten the phonetic clarity for /i/ via spatial expansion in the *x* dimension (enhancing [-back]), avoiding an extra effort for narrowing an already narrowed vocal tract constriction for /i/. Likewise, for accented /a/, it may also be the case that speakers choose to expand the articulation only in the *y* dimension, enhancing both sonority and [+low] features, which may be enough to heighten the phonetic prominence, avoiding an extra effort to move the tongue further back.

3.5.2. Asymmetry between domain-initial and domain-final articulations

One of the interesting results presented in this chapter is that there is almost no effect of Boundary Type on vowel articulation in domain-initial syllables. Recall that the only significant result with respect to boundary effect is on #V₂ articulation (for both /#ba/ and /#bi/) with the jaw being raised (i.e., less jaw opening) after a higher prosodic boundary than after a lower prosodic boundary. This indicates no expansion of the jaw for a higher prosodic boundary. Thus, we can conclude from the data for domain-initial vowel articulation in #C₂V₂ that articulatory maxima for the tongue and lip aperture are not influenced by the level of prosodic boundary, whereas the jaw maximum shows a somewhat unexpected pattern with the higher prosodic boundary showing an decrease in the jaw opening. These results are consistent with the EPG data in Fougeron & Keating (1997) which showed that the vocal tract opening for /no/ (in reiterant speech) as measured by linguopalatal contact was larger for phrase-initial positions (IP or ip) than for phrase-medial positions only for one speaker out of three, showing no consistent increase in the

vocal tract opening at a higher domain-initial position. This is presumably because the effect of domain-initial strengthening is robust primarily on the domain-initial consonant in #CV, but the degree of strengthening may wane when it comes to the vowel articulation. However, the results reported in this chapter are not compatible with the French data reported in Fougeron (2001), in that French /i/ in #CV syllables tends to have a lesser degree of constriction phrase-initially than phrase-medially, showing a strengthening effect even on the vowel.

Turning to the domain-final articulation, unlike the domain-initial vowels, the domain-final vowels (V₁#), which occur immediately before the boundary, do show effects of Boundary Type on articulatory maxima for the tongue and the lip opening. For both /a#/ and /i#, the tongue is lower and the lip opening is larger domain-finally before a higher prosodic boundary, apparently leading to an increase in sonority.

Considering both the domain-initial and domain-final articulations, the data only for the domain-final articulation lend support to HYPOTHESIS 3.2, which predicts a larger vocal tract opening at higher prosodic boundaries. However, jaw lowering (HYPOTHESIS 3.2a) is not evident in our data.

The results can now be considered in terms of a structural (syntagmatic) enhancement of contrast across the boundary. The lowered tongue positions before a higher prosodic boundary can be taken to give rise to a greater V#C displacement. The enhancement of V₁#C₂ contrast is consistent with Fougeron & Keating's (1997) finding that English reiterant speech /no#no/ (where # is some prosodic boundary) is associated with a more expanded V#C (i.e., /o#n/) displacement (as measured by linguopalatal contact) at a higher prosodic boundary. (In fact, this observation is further supported by the kinematic data of lip opening and closing movements, as will be reported in Chapter 5, which show that V#C lip closing displacement is generally larger across a higher prosodic boundary.) The data presented in this study reinforce the idea that the expanded V#C displacement may play an important role in demarcating a higher prosodic boundary.

The next question is whether the increased articulatory magnitude for domain-final vowels varies with accent. Based on previous studies (e.g., Edwards, et al., 1991), it was hypothesized that the articulation of domain-final vowels would be more extreme than that of domain-medial vowels, only when the vowels being compared are unaccented (HYPOTHESIS 3.3). However, we found a lowered tongue position and an expanded lip opening for both /i#/ and /a#/ without any significant Accent by Boundary Type interaction, suggesting that the effect of boundary type on the articulatory maxima is consistent regardless of Accent.

These results are not fully compatible with Beckman, et al.'s (1992:77) generalized remark regarding domain-final articulation that “[u]nlike the greater length of a nuclear-accented syllable [with a greater articulatory displacement], intonation-phrase-final lengthening is *not* accompanied by any significant difference in articulator displacement.” The basis for this remark is that the jaw closing gesture for ‘pop’ is temporally longer, but

not spatially larger domain-finally. However, this generalized remark does not seem to apply to our tongue and lip opening data. As already mentioned above, the data presented in this chapter show that among the three articulators that were examined, it is only the jaw maxima that do not show expanded articulation for domain-final vowels. Thus, one possible conjecture is that the jaw is less sensitive to a change in the level of prosodic boundary than other articulators. And Beckman, et al.'s conclusion was based on jaw kinematics. So, they were premature to conclude that there is no articulatory displacement associated with intonational-phrase final lengthening.

Another potential asymmetry between domain-initial and domain-final vocalic articulations is that domain-final vowels do not show any effect of the type of the neighboring vowel (i.e., coarticulatory effect from V_2), whereas the maximum tongue position of domain-initial /#ba/ (but not /#bi/) is influenced by the type of the neighboring vowel (i.e., V_1 Type), showing a coarticulatory effect even in the maximum position of vowels. This coarticulatory sensitivity of domain-initial vowels appears to be related to their lack of articulatory strengthening. Other articulators showed no coarticulatory effects.

Finally, regarding coarticulatory effect, we also hypothesized that the vocalic articulation at its peak may be influenced by accentuation of the neighboring vowel (HYPOTHESIS 3.4). However, the results in this chapter showed no such effect, rejecting this hypothesis. Note, however, that in this chapter, we simply tested whether the tongue maximum positions are influenced by the neighboring vowel type and accent. More complete coarticulatory effects are reported in the next chapter (Chapter 4) as results of examining various temporal points during vowels.

3.5.3. Boundary-induced vs. Accent-induced Articulatory strengthening

Results presented in this chapter show that vowels are more extremely articulated when they are either accented or located domain-finally, suggesting that there is some sort of articulatory strengthening. However, no evidence for articulatory strengthening is observed with respect to domain-initial vowels in #CV syllables. One of the major goals of this dissertation is to examine whether the articulatory strengthening that may occur at edges of prosodic domains can be accounted for by the same principle governing the articulatory strengthening that may arise with accent.

Our data suggest that there is one common property that can characterize both accent and domain-final boundary effects: vowels are articulated with an increase in sonority, as evident in an increase in the lip opening and the tongue lowering. However, it is not entirely clear whether the featural enhancement as predicted by the hyperarticulation hypothesis account can also apply to boundary-induced strengthening. Considering the articulation of /i/, there seems to be no evidence for featural enhancement: The domain-

final vowel /i/ is associated with neither a fronter nor a higher tongue position before a higher prosodic boundary. On the other hand, domain-final /a/ is associated with a lower and backer tongue position before a higher prosodic boundary, suggesting an enhancement of the features [+back], which does not involve sonority expansion. This opens up the possibility that the articulatory strengthening at domain-final positions may also be driven by a featural enhancement. However, an enhancement of [+back] was not found for accented /a/, showing the boundary-induced featural enhancement for /a#/ is not the same as the accented-induced one for /a/.

At the moment, given these results, we can conclude that both boundary- and accent-induced articulatory strengthening appears to be governed by sonority expansion, showing a commonality, whereas there is only weak evidence for boundary-induced featural enhancement, which, if any, is not compatible with accent-induced featural enhancement.

Chapter IV

Prosodically Conditioned V-to-V Coarticulatory Resistance

The present chapter investigates the effect of prosodic factors on variability of vowel-to-vowel coarticulation. As introduced in Chapter 1, it has been suggested in the literature that strongly articulated segments may give rise to coarticulatory resistance and possibly coarticulatory aggression as well. Previous studies generally point to three kinds of prosodically strong locations where segments may be strongly articulated: accented or stressed syllables, domain-final positions, and domain-initial positions. It is in these three prosodically strong positions that vowel-to-vowel coarticulatory resistance is examined in this chapter. However, results reported in Chapter 3 indicate that not all three of these positions show strengthening: only accented syllables and domain-final positions, but not domain-initial positions, showed more extreme articulation. Moreover, even in accented and domain-final syllables, the direction of strengthening varied with vowel types (/i/ vs. /a/) and the tongue dimension (height vs. backness). Although these results are based on the maximum tongue positions, we may expect that vowels that show strengthening effects on the maximum tongue positions will also show coarticulatory resistance with neighboring vowels. With this in mind, in what follows, I will formulate hypotheses that are to be tested in this chapter.

4.1. Hypotheses

Previous studies have suggested that vowels in lexically stressed syllables may resist coarticulation with neighboring vowels (e.g., Fowler, 1981). Extending this to sentential level stress, or accent (cf. de Jong, 1995a), we test a hypothesis:

HYPOTHESIS 4.1: Accented vowels are more resistant to coarticulation with neighboring vowels than unaccented vowels are.

However, as mentioned above, results regarding the maximum tongue positions reported in Chapter 3 showed that accented vowels are more extremely articulated than unaccented vowels, only in the tongue height dimension for /a/, and only in the tongue backness dimension for /i/. Thus, we might expect that accent-induced coarticulatory resistance may be greater in the tongue dimension in which strengthening is associated with—i.e., /a/ would show coarticulatory resistance primarily in the tongue height dimension, and /i/, primarily in the tongue backness dimension. This possibility will be explored in connection to HYPOTHESIS 4.1.

Turning to domain-edge effects, we examine whether the vowels at edges of prosodic domains in general also resist coarticulation by testing a hypothesis:

HYPOTHESES 4.2: Vowels are more resistant to coarticulation at domain-edges than domain-medially, such that the degree in vowel-to-vowel coarticulation is less across a higher prosodic boundary than across a lower prosodic boundary.

Related to this hypothesis, results in Chapter 3 showed no strengthening in domain-initial vowels in #CV, whereas domain-final vowels, especially /a#, showed strengthening in both the tongue height and backness dimension. In fact, results in Chapter 3 showed that it was only the domain-initial vowel /a/ in #CV that showed variation due to neighboring vowel types even at its peak tongue position (i.e., coarticulation of /#a/ with /i/). Based on this, we can further predict that vowels in domain-initial positions will show more coarticulation (i.e., lesser degree of coarticulatory resistance) than domain-final vowels in vowel-to-vowel coarticulation patterns that are to be examined at time points near edges of target vowels. Thus, we test a hypothesis:

HYPOTHESIS 4.3: Domain-initial vowels in #CV are more susceptible to coarticulation than domain-final vowels are.

With respect to coarticulatory aggression, researchers (Bladon & Nolan, 1977; Fowler, 1981; Recasens, 1987; Farnetani, 1990; Farnetani & Recasens, 1993) observed that sounds that have greater coarticulatory resistance also exert stronger influence on their neighbors. In particular, Fowler (1981) showed that a lexically stressed syllable exerts a more powerful influence on a nearby unstressed syllable within a word. This leads to an additional hypothesis regarding sentence level stress across prosodic boundaries:

HYPOTHESIS 4.4: Vowels are more susceptible to coarticulation with neighboring accented vowels than with neighboring unaccented vowels.

Again, when testing this hypothesis, I will also examine whether greater coarticulatory aggression is associated with the articulatory strengthening found in Chapter 3.

This chapter also tests whether any observed coarticulatory resistance can be accounted for by vowel-to-vowel temporal distance. In his classic study of vowel reduction, Lindblom (1963) suggested that vowel reduction is a coarticulatory process that largely depends on duration—shorter durations would result in target undershoot, shifting the vowel articulation towards the articulation of the neighboring segments. Relatedly, Shin (1997) showed that vowel-to-vowel coarticulation in VCV sequences in Korean may vary as a function of the intervening consonant duration: the longer the consonant duration, the less the vowel-to-vowel coarticulation. Since our coarticulatory data are also based on VCV sequences, it may be reasonable to expect that shorter intervals between transconsonantal target vowels would also induce a greater degree of coarticulation. Put

differently, if two vowels are farther apart from each other, we may also expect smaller degree of coarticulation between the two vowels. Thus, we test a hypothesis:

HYPOTHESIS 4.5: Degree of vowel-to-vowel coarticulation is correlated with temporal vowel-to-vowel distance, such that the shorter the temporal distance, the greater the degree of coarticulation.

Finally, the data presented in this chapter also provide some basis for an examination of vowel-to-vowel coarticulatory variation as a function of inherent segmental properties. As mentioned in Chapter 1, Lindblom (1983) suggested that the degree of CV coarticulation is correlated with a sonority hierarchy. Keating, Lindblom, Lubker & Kreiman (1994) showed that alveolar consonants (less sonorous) show less degree of coarticulation with vowels, and /h/ (more sonorous) the most (Keating, et al., 1994). Further, they showed that vowels affect consonants more than the reverse, suggesting that articulatory variation in vowels is not attributable to the consonantal influence. However, there has been little work testing this hypothesis with respect to sonority differences in vowels. In this chapter, examining two opposite (low back vs. high front) vowels (/a,i/) will also allow us to make note of this hypothesis, given that the open vowel /a/ is more sonorous than the closed vowel /i/.

4.2. Measurements and Statistics

Articulatory data obtained with the magnetometer allows us to observe coarticulatory patterns not only for the acoustically defined vowel periods in VCV, but also for the consonantal periods during which vocalic movements cannot otherwise be observed. The measurement procedure is given in detail in section 2.4.2 in Chapter 2. To review briefly: there are two types of measurements that test for coarticulation. The first examines paradigmatic coarticulatory effects, by comparing spatial values (in the x and y dimensions) for the test vowels ($V_1 \neq V_2$) with those for the control vowels ($V_1 = V_2$). The second type of measurements is for the spatial difference between positional values of the two consecutive opposite vowels (e.g., /a#i/) in order to assess the overall degree of syntagmatic coarticulation regardless of its directionality (*the reciprocal coarticulatory effect*). Further, vowel-to-vowel temporal distance was measured for the same three intervals that were used in examining the reciprocal coarticulatory effect, in order to explore the relationship between the degree of reciprocal coarticulation and duration.

Evaluation of the systematic influence of prosodic factors on coarticulatory patterns was made based on repeated measures Analyses of Variance (ANOVAs). (See section 2.6 in Chapter 2 for an outline of statistical methodology.) The within-subject factors considered for the analysis of carryover and anticipatory effects were Boundary Type (IP, ip, Wd), Accent (ACC, UNACC), and Neighboring Accent (ACC, UNACC). The results

for the analysis of the carryover and anticipatory effects are based on repeated measures three-way ANOVAs performed separately for /a/ and /i/. For the analysis of reciprocal coarticulatory effects on the cross-boundary distances, data were submitted to repeated measures four-way ANOVAs with Vowel Sequence (/a#i/ vs. /i#a/) as an additional within-subject factor. This procedure was done separately for each timepoint tested (see Figure 2.6 in Chapter 2 for various timepoints). See section 2.6 in Chapter 2 for general statistical methodology. Finally, in order to examine whether the variation in duration affects the degree of coarticulation, the analysis of covariance (ANCOVA) was employed with the Duration factor as a covariate (regressor). (See section 4.3.4 for a detailed procedure for ANCOVA.)

4.3. Results

4.3.1. Carryover effect

In this section, we will examine carryover coarticulatory effects—how much the articulation of a postboundary (domain-initial) vowel is influenced by a differing preboundary vowel, which is hypothesized to vary with prosodic factors (Accent, Neighboring Accent, Prosodic Boundary). In what follows, for the sake of simplicity, the effect of each factor will be reported first with all timepoints tested separately, followed by the interactions between factors. Recall that x and y values for the test vowels ($V_1 \neq V_2$) were compared with x and y values for the control vowels ($V_1 = V_2$). The terms *U-distance* (Euclidean distance), *X-distance* and *Y-distance* are used to indicate the articulatory distance between the test ($V_1 \neq V_2$) and control ($V_1 = V_2$) vowels: the longer these distances are, the more coarticulation (see Figure 2.7 in Chapter 2). The time points that are examined in domain-initial vowels include two points during the intervening /b/ (the middle ($\frac{1}{2}B$) and third quarter ($\frac{3}{4}B$)) and two points during the vowel in #CV (V_2 onset and first quarter ($\frac{1}{4}V_2$)) (see Figure 2.6 in Chapter 2).

4.3.1.1. Postboundary (domain-initial) /a/ in /i#a/

Effect of Accent in /i#a/. Repeated measures three-way ANOVAs show that there is a robust effect of Accent on carryover coarticulation. First, consider the effect on U-distance. There is a significant main effect of Accent on U-distance at the third quarter point of the intervening /b/ ($\frac{3}{4}B$) ($F[1,5] = 10.059, p < 0.025$) and at the V_2 onset ($F[1,5] = 7.194, p < 0.05$). No other effects are found for U-distance, although there is a non-significant trend found at the midpoint of the intervening /b/ ($\frac{1}{2}B$) ($F[1,5] = 4.821, p < 0.075$). (The mean ACC/UNACC differences for individual speakers suggests that this non-significant effect is due to the fact that five speakers show one direction while one speaker

(S1) shows the opposite.) Table 4.1 shows a summary of main effects at various time points for U-, X-, and Y-distances.

Table 4.1. Summary of main effects in repeated measures ANOVAs for carryover coarticulatory effects in /i#a/. (** refers to $p < 0.01$; *, $p < 0.05$; ^{tr}, $p \leq 0.075$.)

(a) Accent, $F(1,5)$:

	$\frac{1}{2}$ B	$\frac{3}{4}$ B	V ₂ onset	$\frac{1}{4}$ V ₂
U-distance	4.820 ^{tr}	10.055*	7.195*	0.389
X-distance	4.074	4.849 ^{tr}	4.583	1.328
Y-distance	2.326	7.650*	10.439*	5.849 ^{tr}

(b) Boundary Type, F -values with Huynh-Feldt corrected df :

	$\frac{1}{2}$ B	$\frac{3}{4}$ B	V ₂ onset	$\frac{1}{4}$ V ₂
U-distance	F(2,10) 13.267**	F(2,10) 20.127**	F(2,6.65) 12.098**	F(2,10) 0.535
X-distance	F(1.49,7.46) 18.041**	F(1.29,6.43) 61.723**	F(1.50,7.52) 46.329**	F(1.10,5.55) 2.008
Y-distance	F(2,10) 7.742**	F(2,10) 12.150**	F(2,10) 10.210**	F(2,10) 1.431

(c) Accent of the Neighboring Vowel, $F(1,5)$:

	$\frac{1}{2}$ B	$\frac{3}{4}$ B	V ₂ onset	$\frac{1}{4}$ V ₂
U-distance	0.655	0.115	0.844	1.928
X-distance	4.074	6.069 ^{tr}	4.419	0.694
Y-distance	0.120	0.218	0.679	0.224

^{tr} $p \leq 0.075$ * $p < 0.05$ ** $p < 0.01$

The effect of Accent is further illustrated in Figure 4.1, which shows mean differences in U-distance (and X- and Y-distances) between the test (/i#a/) and control (/a#a/) conditions. One expected pattern over the timecourse is that the distance between the test and the control conditions is relatively large at the midpoint of the intervening /b/ ($\frac{1}{2}$ B) (showing robust coarticulation with a preceding vowel /i#/) and becomes smaller

over the timecourse. Note also that vowels in both control and test conditions in Figure 4.1 show, on the average, a lowered tongue position when accented than unaccented, indicating accent-induced strengthening even before the midpoint of the vowel. In particular, at V_2 onset and $\frac{1}{4}V_2$ the ACC/UNACC differences are found primarily in Y-distance, showing that accent-induced coarticulatory resistance lies primarily in the tongue height dimension. This is consistent with the prediction made at the outset of this chapter that the tongue dimension which shows robust strengthening also reveals robust coarticulatory resistance in that dimension.

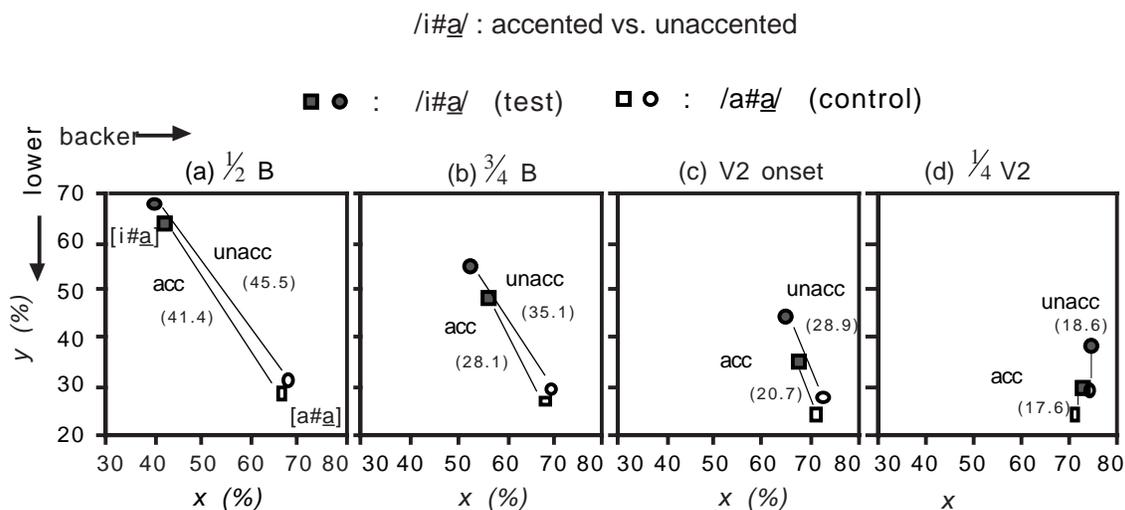


Figure 4.1. The effect of accent on /a/ on carryover coarticulation in /i#a/. Mean U-distances are provided in parentheses.

Turning to the effect of Accent on coarticulation with respect to the difference between the test and the control conditions, as shown in the figure, the mean U-distance is always smaller when the target vowel /a/ is accented than when it is unaccented, significantly so at points $\frac{1}{2}B$, $\frac{3}{4}B$, and V_2 onset. That is, the accentuation of postboundary (domain-initial) /#a/ induces coarticulatory resistance to the preboundary (domain-final) vowel /i#/.

Repeated measures ANOVAs performed separately for X- and Y-distances show that the accent effect of the postboundary /#a/ rests more on the y dimension of the tongue movement than on the x dimension. As given in Table 4.1, only a non-significant trend is found for X-distance at $\frac{3}{4}B$ ($F[1,5]=4.849$, $p<0.075$), whereas there is a significant main effect for Y-distance at $\frac{3}{4}B$ ($F[1,5]=7.650$, $p<0.05$) and at the V_2 onset ($F[1, 5]=10.349$, $p<0.025$). (Note that even at the first quarter of the vowel ($\frac{1}{4}V_2$), there is a trend for Y-distance ($F[1,5]=5.849$, $p<0.075$.) The overall larger F-ratio for Y-distance than for X-distance also indicates that the size of effect is greater for Y-distances. This shows that the

coarticulatory effect on /#a/ is greater in the tongue height dimension than in the tongue backness dimension. This is consistent with the results in Chapter 3 which showed a more robust ACC/UNACC difference in the maximum tongue position in the tongue height (y) dimension than in the tongue backness (x) dimension. In other words, the accent-induced coarticulatory difference is robust in the same tongue dimension in which a robust accent-induced difference was found in the maximum tongue position.

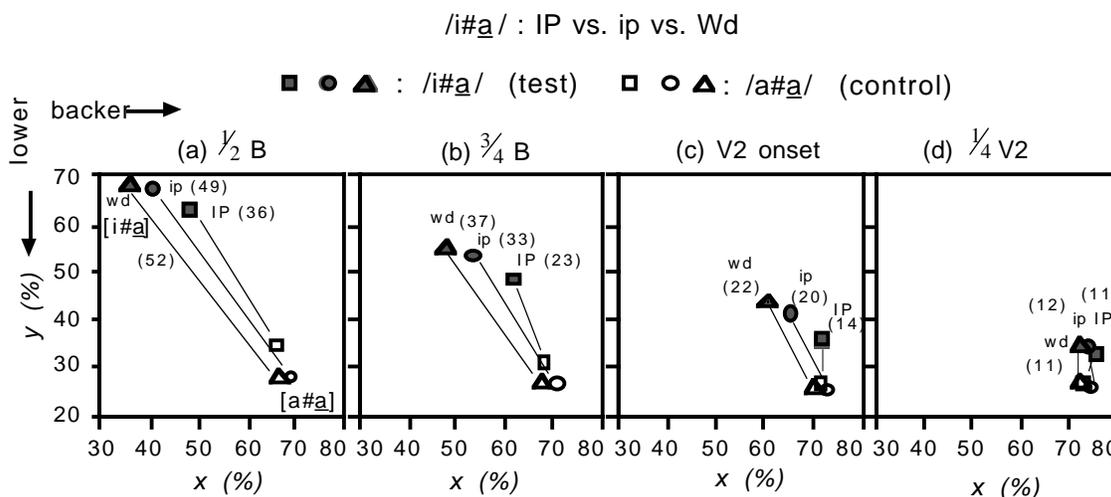


Figure 4.2. The prosodic boundary effect on carryover coarticulation in /i#a/. Mean U-distances are provided in parentheses.

Effect of Boundary Type in /i#a/. There is a robust effect of Prosodic Boundary on U-distance. A significant main effect is found at various time points during the consonant (at $\frac{1}{2}B$ ($F[2,10]=13.267, p<0.005$), $\frac{3}{4}B$ ($F[2,10]=20.127, p<0.001$), and at the V_2 onset ($F[2,10]=12.098, p<0.01$)). The mean U-distance is smallest for IP, intermediate for ip, and greatest for Wd at these time points, as shown in Figure 4.2. Bonferroni/Dunn pairwise *posthoc* comparisons show a two-way distinction ($IP < (ip = Wd)$) at $\frac{1}{2}B$ and V_2 onset, and a three-way distinction ($IP < ip < Wd$) at $\frac{3}{4}B$ ($p < 0.01$). This indicates that the domain-initial /#a/ shows greater coarticulatory resistance to a preceding /i#/ across higher prosodic boundaries than across lower ones.

When the data are considered separately for X- and Y-distances, as shown in Table 4.1b, there is a significant main effect of Prosodic Boundary for both distances at three time points ($\frac{1}{2}B$, $\frac{3}{4}B$, and V_2 onset). There is a two-way distinction ($IP < (ip = Wd)$) in both X- and Y-distances for all three time frames, except for X-distance at $\frac{3}{4}B$, which has a three-way distinction ($IP < ip < Wd$). Overall, this result shows that the Prosodic Boundary influences both X- and Y-distances, in contrast to the Accent effect, which shows coarticulatory resistance primarily in Y-distance.

Accent effect of the neighboring (preboundary) vowel in /i#a/. There is no significant main effect of Neighboring Accent on any of the dependent variables. Only one case of a non-significant trend is found for X-distance at the third quarter point of the intervening /b/ ($\frac{3}{4}B$) ($F[1,5]=6.069, p<0.75$). (Note that five speakers showed the same pattern in one direction while one speaker (S1) showed the opposite, which may give rise to non-significance.) Overall, the results do not support the coarticulatory aggression hypothesis that an accented neighboring vowel encroaches on a target vowel more than an unaccented neighboring vowel does.

Interactions in /i#a/. There are no robust interactions between prosodic factors in the carryover effect on /i#a/. No significant interactions are found either during the target vowel ($\frac{1}{4}V_2$ or V_2 onset) or at the third quarter point of the intervening /b/ ($\frac{3}{4}B$). This confirms that all the patterns observed for main effects are in fact consistent across conditions.

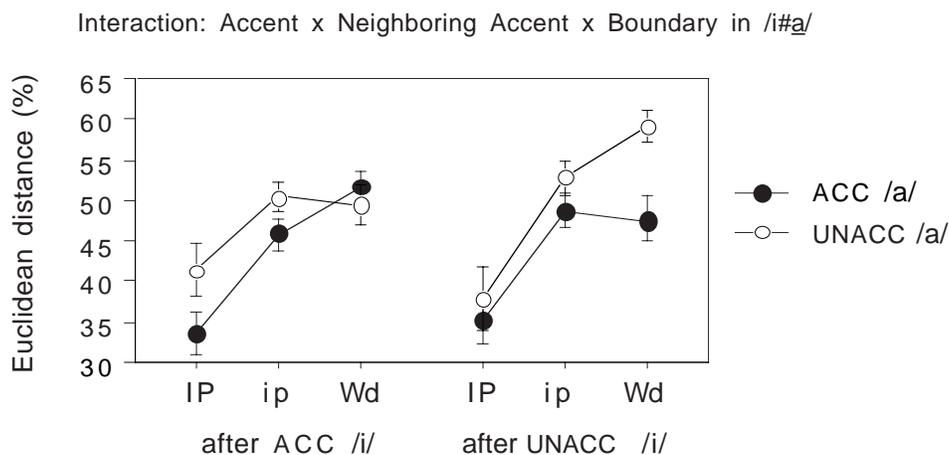


Figure 4.3. Mean U-distance by Accent (on V_2), Neighboring Accent (on V_1), and Boundary Type. Error bars = ± 1 standard errors.

There is a significant three-way Accent x Boundary x Neighboring Accent interaction at the midpoint of the intervening /b/ ($\frac{1}{2}B$) (for U-distance, $F[2,10]=5.113, p<0.05$; for X-distance, $F[1.7,8.4]=5.582, p<0.05$; and for Y-distance, $F[2,10]=3.928, p<0.075$ (*ns trend*)). This interaction is shown in Figure 4.3. *Posthoc* comparisons indicate that the interaction for U-distance at $\frac{1}{2}B$ is in part due to the fact that three-way distinctions (IP<ip<Wd) by Boundary Type are made only when the target and neighboring vowels are either both accented or both unaccented. In addition, it is also in part due to the fact that U-distance is significantly shorter when a neighboring vowel is accented ($p<0.01$)—i.e., a postboundary /#a/ is less coarticulated with an accented neighboring vowel (V_1) when vowels are across a Word boundary. This does not support the coarticulatory aggression hypothesis. (A similar interaction is observed at $\frac{1}{4}V_2$, but as

a non-significant trend for X-distance ($F[1.8,8.8]=3.591$, $p<0.075$.) This observation should not be generalized across time points, however, as the significant pattern is found only at the midpoint of the intervening /b/.

4.3.1.2. Postboundary (domain-initial) /#i/ in /a#i/

Effect of Accent in /a#i/. The results regarding the effect of Accent in /a#i/ is shown in Figure 4.4. A first thing to be noted in the figure is that overall coarticulatory effect is large (irrespective of Accent) during the consonant /b/ ($\frac{1}{2}B$, $\frac{3}{4}B$), relatively smaller at V_2 onset, and apparently null when it comes to the first quarter of V_2 ($\frac{1}{4}V_2$). Note also that /#i/ is generally fronter when accented than unaccented, consistent with the strengthening found in the maximum tongue position. Furthermore, the overall ACC/UNACC differences in the test condition comes from the tongue backness dimension as well, which shows greater coarticulatory resistance as compared to the tongue height dimension. This is also consistent with the prediction that the robust strengthening effect as found in the tongue maximum position also leads to robust coarticulatory resistance.

Turning to the effect of Accent on target /#i/ in comparison to the control condition, carryover coarticulation is not as robust as that of /#a/ in /i#a/. There is no main effect of Accent on U-distance at any of the time points being examined, as summarized in Table 4.2a, although the mean U-distance is shorter for accented /#i/ than for unaccented /#i/, as seen in Figure 4.4.

Examining X- and Y-distances, a significant effect is found only for Y-distance at the first quarter point of the vowel ($\frac{1}{4}V_2$) ($F[1,5]=10.884$, $p<0.025$). As shown in Figure 4.4, accented /#i/ has a slightly, but significantly, smaller Y-distance than unaccented /#i/. There is a non-significant trend found at the V_2 onset for both X- and Y-distances ($F[1,5]=5.505$, $p<0.075$; $F[1,5]=6.103$, $p<0.075$, respectively), which shows a tendency towards less X- and Y-distances when /#i/ is accented than when it is unaccented. (The failure of reaching non-significance appears to be due to one speaker showing the opposite direction: speaker S3 for X-distance, and speaker S2 for Y-distance.) Overall, results indicate that accented /#i/ in a postboundary position is more resistant to coarticulation with a neighboring vowel (V_1) than unaccented /#i/ is, at least reliably so for height. The overall effect, however, does not appear to be robust since no significant effects are found at $\frac{1}{2}B$, $\frac{3}{4}B$, or V_2 onset.

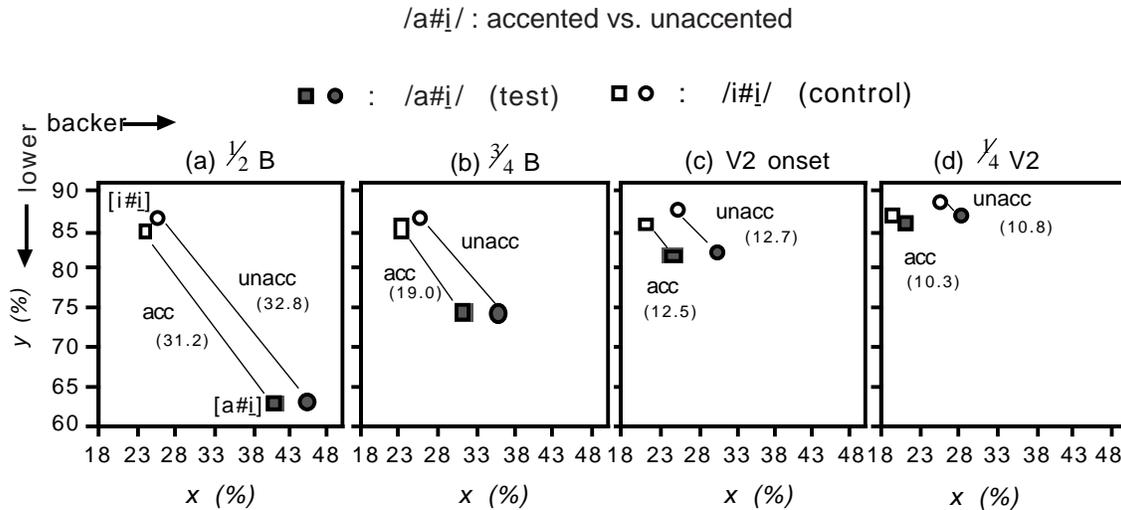


Figure 4.4. The effect accent on /#i/ on carryover coarticulation in /a#i/. Mean U-distances are provided in parentheses.

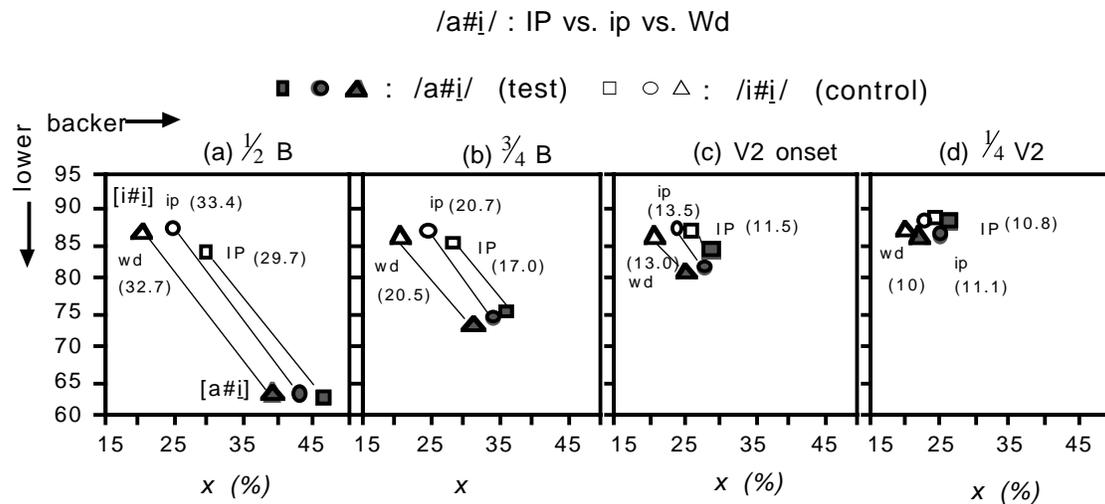


Figure 4.5. The effect of Boundary Type on carryover coarticulation in /a#i/. Mean U-distances are provided in parentheses.

Effect of Boundary Type in /a#i/. There is a significant effect of Boundary Type, but only for Y-distance, as was the case with the accent effect. As summarized in Table 4.2b, a significant effect on Y-distance is found at three time points: at $\frac{1}{2}B$ ($F[2,10]=4.109$, $p<0.05$), $\frac{3}{4}B$ ($F[2,10]=9.182$, $p<0.005$) and V_2 onset ($F[2,10]=7.542$, $p<0.01$). This prosodic boundary effect is illustrated in Figure 4.5. (Note that the domain-initial /#i/ is generally backer after a higher prosodic boundary at $\frac{1}{2}B$, $\frac{3}{4}B$ and the V_2 onset, and the difference becomes indiscernible at $\frac{1}{4}V_2$.) In the figure, the mean Euclidean distance is smaller for the IP boundary than for other boundaries, but the difference is significant only

for Y-distance. For Y-distance, there is a two-way distinction (IP<(ip=Wd)) at three time points (at $\frac{1}{2}$ B, $\frac{3}{4}$ B and the V₂ onset) ($p<0.01$, Bonferroni/Dunn *posthoc* tests). This reveals that a postboundary (domain-initial) vowel /#i/ is more resistant to coarticulation with a neighboring vowel /a#/ (V₁) across a higher prosodic boundary (IP) than across a lower prosodic boundary (ip, wd), at least with respect to the tongue height.

Table 4.2. Summary of main effects in repeated measures ANOVAs for carryover coarticulatory effect in /a#i/. (** refers to $p<0.01$; *, $p<0.05$; tr, $p\leq 0.075$)

(a) Accent, $F(1,5)$:

	$\frac{1}{2}$ B	$\frac{3}{4}$ B	V ₂ onset	$\frac{1}{4}$ V ₂
U-distance	1.179	0.765	0.017	0.064
X-distance	3.280	4.546	5.505 ^{tr}	3.755
Y-distance	0.739	2.631	6.103 ^{tr}	10.884*

(b) Prosodic Boundary, F -values with Huynh-Feldt corrected df .

	$\frac{1}{2}$ B	$\frac{3}{4}$ B	V ₂ onset	$\frac{1}{4}$ V ₂
U-distance	F(2,10) 1.238	F(2,10) 2.271	F(1.47,7.35) 0.998	F(1.61,8.07) 0.930
X-distance	F(1.48,7.42) 0.837	F(2,10) 2.361	F(2,10) 0.963	F(2,10) 0.002
Y-distance	F(2,10) 4.109*	F(2,10) 9.182**	F(2,10) 7.542**	F(1.80,9.01) 1.729

(c) Accent of the Neighboring Vowel, $F(1,5)$:

	$\frac{1}{2}$ B	$\frac{3}{4}$ B	V ₂ onset	$\frac{1}{4}$ V ₂
U-distance	0.051	0.075	0.004	0.107
X-distance	0.446	0.210	0.195	0.213
Y-distance	2.891	4.93 ^{tr}	3.469	0.260

^{tr} $p\leq 0.075$ * $p<0.05$ ** $p<0.01$

Accent effect of the neighboring (preboundary) vowel in /a#i/. There is no significant main effect of Neighboring Accent on any of the dependent variables at any point in time (see Table 4.2c). As in /i#a/, this result contradicts the aggression hypothesis. Note that there is only a non-significant trend for Y-distance at $\frac{3}{4}$ B ($F[1,5]=4.93$, $p=0.079$), showing that Y-distance tends to be shorter when a preceding vowel is accented than when it is unaccented. (Mean differences for individual speakers show that four out of six speakers show this pattern.) This confirms that there is no coarticulatory aggression effect.

Interactions. No significant interaction is found at either time point during the target vowel (V_2 onset or $\frac{1}{4}V_2$) or $\frac{3}{4}$ B for any of the dependent variables. Thus, the observations reported for main effects can be viewed as consistent across all conditions.

4.3.1.3. Summary of carryover coarticulatory effect

In this section, we have examined how the postboundary (domain-initial) vowels /a/ and /i/ are coarticulated with preboundary (domain-final) vowels under various prosodic conditions. Several points are recapitulated:

- a. The accent of the postboundary target vowel has a significant influence on the carryover coarticulation for both /a/ and /i/—accented vowels are less coarticulated with preceding vowels than unaccented vowels. The main effect is primarily due to a difference in Y-distance, especially for /a/.
- b. No main effect of the accent of the neighboring (preboundary) vowel is found in either /a#i/ or /i#a/ . Only a trend is found (due to one or two speakers' deviant patterns), but in a direction that renders the coarticulatory aggression hypothesis weaker—target vowels tend to be less coarticulated to accented neighboring vowels.
- c. There is a main effect of the Boundary Type factor for both /i#a/ and /a#i/, showing that postboundary vowels are less coarticulated with (or more resistant to) neighboring vowels across higher prosodic boundaries than across lower prosodic ones. This supports the coarticulatory resistance hypothesis. The main effect results from differences in both X- and Y-distances for /i#a/, but only from Y-distance differences for /a#i/.
- d. Carryover effects under various prosodic conditions are more robust when the target vowel is /a/ in /i#a/ than when it is /i/ in /a#i/ . The overall effect size is always far greater for /i#a/ than for /a#i/ . In addition, that U-, X-, and Y-distances are significantly greater for /a/ than for /i/.

e. Robust accent-induced coarticulatory resistance is generally found in the tongue dimension in which the tongue maximum position showed a robust strengthening effect, reported in Chapter 3.

4.3.2. Anticipatory Effect

In this section, we will examine anticipatory coarticulatory effects—how much the articulation of a preboundary (domain-final) vowel is influenced by a differing postboundary vowel. The time points that are examined in domain-final vowels include two points during V# ($\frac{3}{4}V_1$, V_1 end) and two points during the intervening /b/ (the first quarter ($\frac{1}{4}B$) and the middle ($\frac{1}{2}B$)) (see Figure 2.6 in Chapter 2).

4.3.2.1. Preboundary (domain-initial) /a/ in /a#i/

Effect of accent in /a#i/. Figure 4.6 shows the effect of Accent on coarticulation of /a#/. The first thing to be noted in the figure is that the degree of coarticulation is generally progressively increasing during the timecourse as the timepoint gets closer to the following vowel. When we just compare accented /a#/ and unaccented /a#/ irrespective of the test/control conditions, we can observe that accented /a#/ is generally fronter than unaccented /a#/. It is also noticeable that accented /a#/ is lower than unaccented /a#/ in the vowel at $\frac{3}{4}V_1$, which is consistent with the strengthening results found in the maximum tongue position reported in Chapter 3 (the maximum tongue position for accented /a/ is lower but not necessarily backer).

Let's now consider the effect of Accent on the coarticulation of the target /a#/ relative to the control condition. There is a significant main effect of Accent on U-distance at the third quarter point of V_1 ($\frac{3}{4}V_1$) ($F[1,5]=6.781$, $p<0.05$). Although the mean U-distance is shorter (the vowel is more resistant) when preboundary /a#/ is accented than when it is unaccented at three time points (V_1 end, $\frac{1}{4}B$, and $\frac{1}{2}B$) as can be seen in Figure 4.6, the difference in U-distance is significant at at $\frac{3}{4}V_1$.

Repeated measures ANOVAs performed separately for X- and Y-distances, show that there is a significant main effect of Accent on X-distance at all time points, while there is none on Y-distance, as summarized in Table 4.3. This shows that the accent effect for the target vowel /a#/ on anticipatory coarticulation comes primarily from the x dimension of tongue movement.

Table 4.3. Summary of main effects in repeated measures ANOVAs for anticipatory coarticulatory effect in /a#i/. (** refers to $p < 0.01$; *, $p < 0.05$; ^{tr}, $p \leq 0.075$)

(a) Accent, $F(1,5)$:

	$\frac{3}{4}V_1$	V_1 end	$\frac{1}{4}B$	$\frac{1}{2}B$
U-distance	6.781*	1.095	2.405	4.224
X-distance	8.399*	9.064*	8.332*	6.757*
Y-distance	0.411	0.072	0.543	1.912

(b) Prosodic Boundary, F -values with Huynh-Feldt corrected df .

	$\frac{3}{4}V_1$	V_1 end	$\frac{1}{4}B$	$\frac{1}{2}B$
U-distance	F(1.42,7.09) 0.812	F(1.44,7.23) 6.522*	F(1.17,5.87) 10.239*	F(1.31,6.59) 8.688*
X-distance	F(2,10) 4.959*	F(1.55,7.77) 4.324 ^{tr}	F(1.12,5.55) 5.252 ^{tr}	F(1.22,6.09) 4.682 ^{tr}
Y-distance	F(2,10) 0.566	F(1.26,6.30) 7.971*	F(1.08,5.41) 2.190	F(1.07,5.36) 2.030

(c) Accent of the Neighboring Vowel, $F(1,5)$:

	$\frac{3}{4}V_1$	V_1 end	$\frac{1}{4}B$	$\frac{1}{2}B$
U-distance	0.766	1.432	0.006	1.924
X-distance	0.861	0.762	0.473	3.061
Y-distance	0.090	3.212	0.202	0.874

^{tr} $p \leq 0.075$ * $p < 0.05$ ** $p < 0.01$

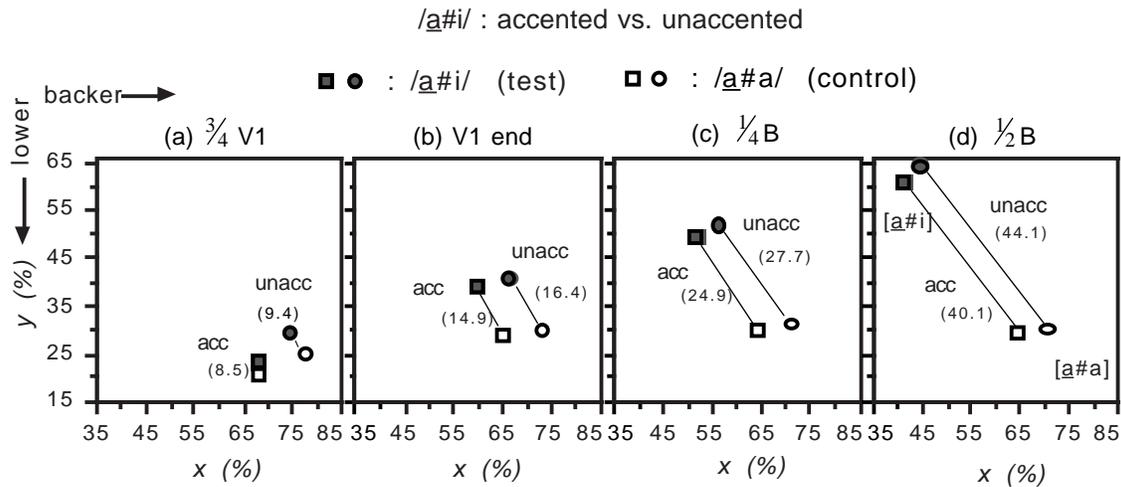


Figure 4.6. The effect of accent on /a#i/ on anticipatory coarticulation in /a#i/. Mean U-distances are provided in parentheses.

Effect of Boundary Type in /a#i/. The prosodic boundary effect on U-distance is found to be significant at the end of V₁, the first quarter of /b/ (1/4B), and the midpoint of the intervening /b/ (1/2B) (F[1.5,7.2]=6.522, $p < 0.05$ at the V₁ end; F[1.2,5.9]=10.239, $p < 0.025$ at 1/4B; F[1.3,5.6]=8.688, $p < 0.025$ at 1/2B). These effects are shown in Figure 4.7, in which the mean U-distance is always shorter when the intervening boundary is IP, than when it is ip or Wd. *Posthoc* comparisons show the pattern IP < ip = Wd at the level of $p < 0.01$ at three time points (V₁ end, 1/4B, and 1/2B).

Considering X- and Y-distances, X-distance shows a significant main effect at 3/4V₁ (F[2,10]=4.592, $p < 0.05$), and Y-distance, at the end of V₁ (F[1.3,6.3]=7.971, $p < 0.025$). In *posthoc* comparisons, at least a two-way distinction (IP < (ip=Wd)) is made at three time points (V₁ end, 1/4B, and 1/2B) for both X- and Y-distances. A three-way distinction (IP < ip < Wd) is found for X-distance at the end of V₁. Overall, the coarticulatory resistance of /a#i/ to a following /#i/ is greater across higher prosodic boundaries than across lower ones, and the effect is found for both X- and Y-distances.

Finally, it should be noted from Figure 4.7 that the tongue is generally backer before a higher prosodic boundary. The backer tongue position at a higher prosodic boundary is consistent with the strengthening effect (i.e., backer before a higher prosodic boundary) found in the tongue maximum position reported in Chapter 3. However, a lowered tongue position before a higher prosodic boundary (which was found in the tongue maximum position) is not evident at the timepoints shown in the figure.

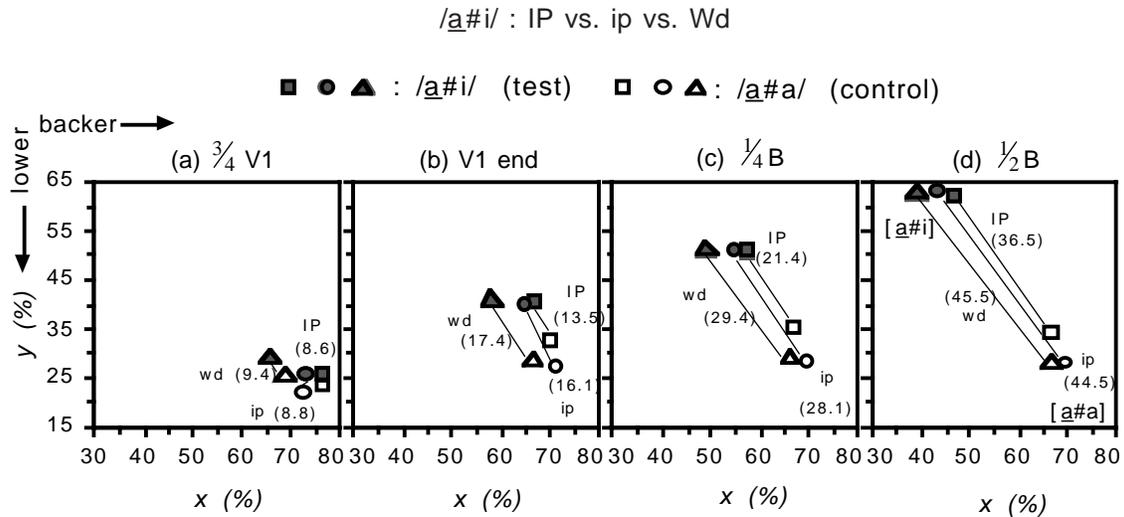


Figure 4.7. The prosodic boundary effect on anticipatory coarticulation in /a#i/. Mean U-distances are provided in parentheses.

Accent effect of the neighboring vowel. There is no main effect of Neighboring Accent on any of the dependent variables at any point in time. (But see interactions below.)

Interactions in /a#i/. Two significant interactions between prosodic factors are found for /a#i/. First, there is a significant Accent x Neighboring Accent interaction at the end of V₁ for U-distance (F[1,5]=5.523, p<0.05). Recall that there was no main effect at this time point for either Accent or Neighboring Accent. *Posthoc* comparisons show that this interaction comes from the fact that U-distance is shorter (showing greater coarticulatory resistance) for an accented target vowel /a#i/ than for an unaccented target vowel /a#a/, but only when neighboring /#i/ (V₂) is unaccented (p<0.01), as can be seen in Figure 4.8. In addition, the difference due to the accent of the neighboring vowel (V₂) reaches significance only when the target vowel is unaccented, indicating that unaccented /a#a/ resists coarticulation to a following accented vowel more than to a following unaccented vowel. (This is compatible with the findings for carryover effect in contradicting the aggression hypothesis.)

There is no other significant effect at any time point during the vowel. The only other significant interaction is a two-way Boundary Type x Neighboring Accent interaction at the midpoint of the intervening /b/ (1/2 B) for U-distance (F[2,10]=5.411, p<0.05) and for X-distance (F[2,10]=5.992, p<0.025). (Y-distance shows a non-significant trend (F[2,10]=3.337, p<0.075) at 1/2 B.) The interaction for U-distance is shown in Figure 4.9. This two-way interaction can be explained in part by the fact that there is a clear distinction between IP and ip/Wd, with a larger mean difference between them when the neighboring vowel is unaccented than when it is accented.

Another factor contributing to the U-distance interaction is that the difference due to the accent of the neighboring vowel (V_2) reaches significance only for IP ($p < 0.01$, Bonferroni/Dunn *posthoc* test), but not for ip and Wd at $\frac{1}{2}B$. This indicates that across IP boundaries only, preboundary /a#/ is coarticulated more with an accented neighboring vowel than with an unaccented neighboring vowel. It should be noted here that the greater degree of coarticulation with the accented neighboring vowel in fact lends support to the aggression hypothesis. However, this effect should not be viewed as a general anticipatory pattern since it is observed only at the midpoint of the intervening /b/ and only across IP boundaries. Across Word boundaries, for example, the opposite direction is found, as seen in Figure 4.9, taking support away from the aggression hypothesis.

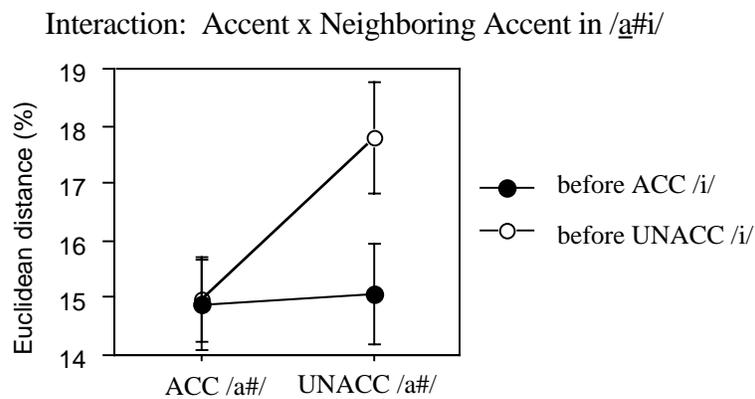


Figure 4.8. Mean U-distance by Accent and Neighboring Accent at the end of V_1 in /a#/. Error bars = \pm standard errors.

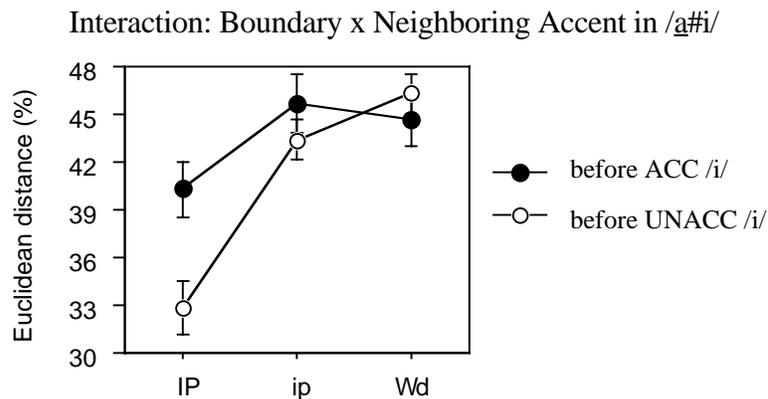


Figure 4.9. Mean U-distance by Boundary Type and Neighboring Accent at the midpoint of the intervening /b/ ($\frac{1}{2}B$) in /a#/. Error bars = \pm standard errors.

4.3.2.2. Preboundary (domain-final) /i/ in /i#a/

Effect of accent in /i#a/. There is no effect of Accent on U-distance at any of the time points being examined. The mean U-distance is shorter for accented /i#/ than for unaccented /i#/ , as shown in Figure 4.10, but the difference does not reach a significant level. However, significant effects are found for X-distance at all time points, as summarized in Table 4.4a. The X-distance is significantly shorter for accented /i#/ than for unaccented /i#/ . In other words, preboundary /i#/ is coarticulated less with (is more resistant to) a following vowel /#a/ when it is accented, and this effect is primarily due to the difference in X-distance.

It should also be noted here with respect to ACC/UNACC differences shown in Figure 4.10 that /i#/ is generally fronter when accented than unaccented, being consistent with the strengthening effect found in the maximum tongue position reported in Chapter 3. We can also see in the figure that coarticulatory resistance comes from the difference in the tongue backness dimension, consistent with the prediction that where there is strengthening (in tongue backness), there is coarticulatory resistance.

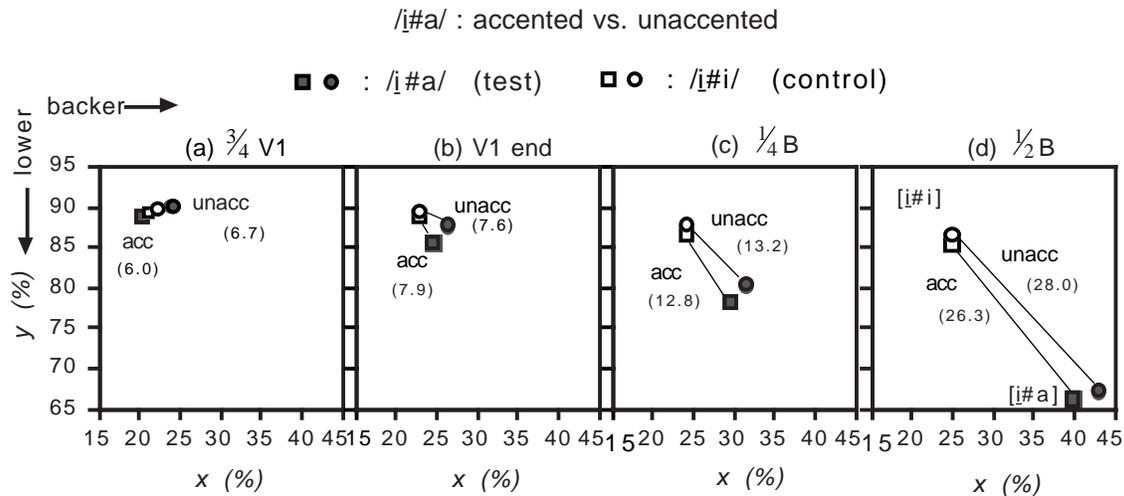


Figure 4.10. The accent effect for /i/ on anticipatory coarticulation in /i#a/. Mean U-distances are provided in parentheses.

Effect of Boundary Type in /i#a/. The effect of Boundary Type is not robust for preboundary (domain-final) /i#/ . There is no main effect on U-distance at any of the time points being examined, although the mean U-distance is smaller for IP than for ip, or Wd at 3/4 V₁, V₁ end, and 1/4 B, as shown in Figure 4.12.

For X-distance, there is only a trend at the end of V₁ [F(2,10) = 3.328, p < 0.075]. This failure to reach a significant effect appears to be due to two speakers (S2, S5) who

showed a pattern opposite the expected direction that four other speakers showed. This indicates that Boundary Type has an influence on the degree of coarticulation at least to some degree for X-distance —there is greater coarticulatory resistance across the higher prosodic boundary for some speakers, but not all.

When considering the data in Figure 4.11 without making a test/control distinction, we see observe that /i#/ is generally backer (deviating from its assumed feature target [-back]) before a higher prosodic boundary, while this pattern is no longer observable at $\frac{3}{4}V_1$, which is consistent with lack of the boundary effect on the maximum tongue position for /i#/, reported in Chapter 3.

Table 4.4. Summary of main effects in repeated measures ANOVAs for anticipatory coarticulatory effect in /i#a/. (** refers to $p < 0.01$; *, $p < 0.05$; ^{tr}, $p \leq 0.075$)

(a) Accent, $F(1,5)$:

	$\frac{3}{4}V_1$	V_1 end	$\frac{1}{4}B$	$\frac{1}{2}B$
U-distance	1.201	0.197	0.048	2.804
X-distance	33.222**	15.270*	7.790*	8.625*
Y-distance	0.837	2.399	0.665	0.100

(b) Prosodic Position, F -values with Huynh-Feldt corrected df .

	$\frac{3}{4}V_1$	V_1 end	$\frac{1}{4}B$	$\frac{1}{2}B$
U-distance	F(2,10) 0.214	F(1.91,9.54) 0.667	F(2,10) 0.549	F(1.74,8.73) 0.483
X-distance	F(2,10) 2.469	F(2,10) 3.428 tr	F(1.33,6.69) 0.946	F(1.25,6.12) 0.574
Y-distance	F(2,10) 0.125	F(2,10) 0.819	F(2,10) 0.754	F(2,10) 0.323

(c) Accent of the Neighboring Vowel, $F(1,5)$:

	$\frac{3}{4}V_1$	V_1 end	$\frac{1}{4}B$	$\frac{1}{2}B$
U-distance	0.606	2.848	0.019	4.372
X-distance	0.041	0.075	0.037	3.608
Y-distance	0.286	1.690	0.042	5.119 ^{tr}

^{tr} $p \leq 0.075$

* $p < 0.05$

** $p < 0.01$

Accent effect of the neighboring vowel in /i#a/. There is no significant effect of Neighboring Accent on any of the dependent variables at any time points, not supporting the coarticulatory aggression hypothesis. (There was a non-significant trend for Y-distance at the midpoint of the intervening /b/ ($\frac{1}{2}B$), showing that, if anything, preboundary (domain-final) vowel /i/ is *more* coarticulated to a following *unaccented* vowel, contradicting the coarticulatory aggression hypothesis.)

Interactions in /i#a/. There is a three-way Accent x Boundary Type x Neighboring Accent interaction at three time points ($\frac{3}{4}V_1$, V_1 onset, and $\frac{1}{4}B$) in the anticipatory effect for /i#a/. Both U- and X-distances show a significant interaction at the first quarter of /b/ ($\frac{1}{4}B$) ($F[2,10]=4.662$, $p<0.05$ and $F[1.9,9.5]=7.272$, $p<0.025$, respectively), while only X-distance shows significant effects at $\frac{3}{4}V_1$ and V_1 onset as well ($F[1.8,8.9]=8.640$, $p<0.005$ and $F[2,10]=23.418$, $p<0.001$, respectively). Figure 4.12 shows this interaction effect at the end of V_1 for X-distance. One important point to be drawn from this interaction is that there is a clear three-way distinction ($IP<ip<Wd$) with large mean differences between prosodic levels when the target vowel /i#/ is accented *and* followed by an unaccented vowel /#a/ (as shown in the filled circles in the right panel of Figure 4.12).

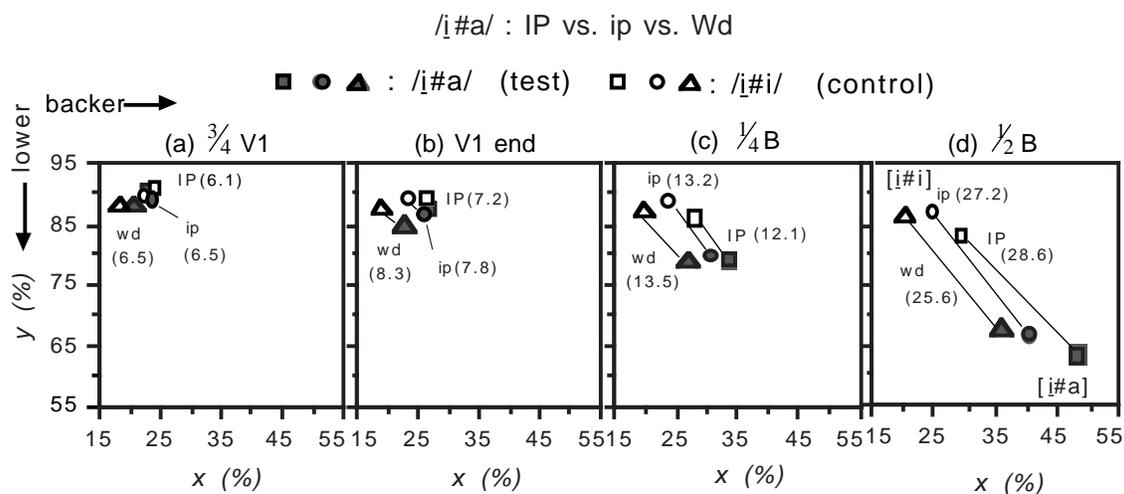


Figure 4.11. The prosodic boundary effect on anticipatory coarticulation in /i#a/. Mean U-distances are provided in parentheses.

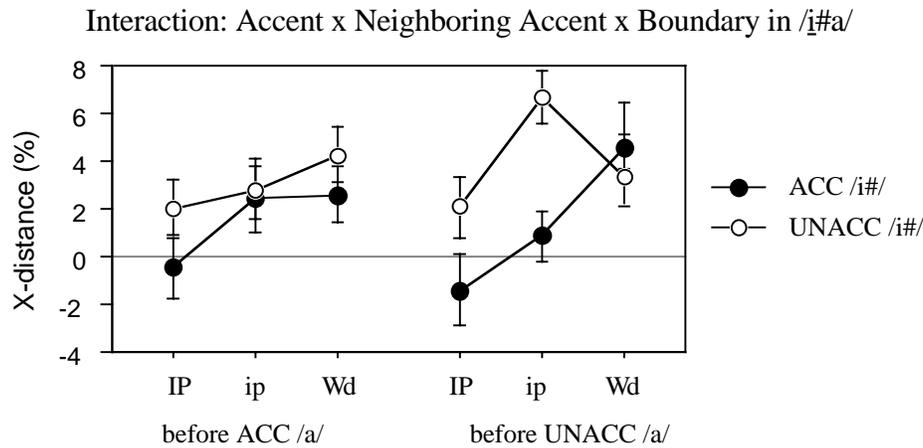


Figure 4.12. Mean X-distance by accent, neighboring accent, and Boundary Type at the end of V_1 in /i#a/. Error bars = \pm standard errors.

4.3.2.3. Summary of anticipatory coarticulatory effect.

In this section, we have examined how preboundary (domain-final) vowels /a#/ and /i#/ are coarticulated with postboundary (domain-initial) vowels under various conditions. Several points are recapitulated:

- a. The accent of a target (preboundary) vowel has a significant influence on the anticipatory coarticulation of both /a#/ and /i#/#—vowels under accent are less coarticulated with following vowels than are vowels under no accent, supporting the coarticulatory resistance hypothesis.
- b. No main effect of the accent of a neighboring (postboundary) vowel is found for either /a#i/ or /i#a/. Thus, there is no support for the coarticulatory aggression hypothesis.
- c. There is a main effect of Boundary Type on /a#i/, but not on /i#a/, for which only a trend is found at V_1 end. (For this trend, two speakers contribute to non-significance.) Overall, results, especially for /a#/, show that, in accord with the coarticulatory resistance hypothesis, preboundary vowels tend to be less coarticulated with (or more resistant to) neighboring vowels across higher prosodic boundaries than across lower ones.
- d. Some significant interactions are found between factors, indicating that effects of accent (either on the target vowel or on the neighboring vowel) tend to be stronger when the neighboring vowel is unaccented. This interaction is more robust for /a#i/ than for /i#a/.
- e. An anticipatory effect is found for both /a#i/ and /i#a/, although the size of the effect, as inferred from the F -ratio, is slightly larger for /i#a/. The main effect of Boundary Type, however, is found only for /a#i/, indicating that /a#/ undergoes

more robust coarticulatory variations due to Boundary Type factors than /i#/ does. Furthermore, U-, X- and Y-distances are significantly greater for /a#/ than for /i#, indicating an overall greater degree of coarticulation for /a#/ than for /i#.

f. The data also suggest that strengthening effects found at the maximum position in Chapter 3 are further observable even at timepoints near the domain edges. Moreover, /i#/ shows accent-induced coarticulatory resistance primarily in the x dimension, consistent with the prediction that where there is strengthening, there is coarticulatory resistance.

4.3.3. *The Reciprocal coarticulatory effect*

In this section, we examine reciprocal effects in order to assess the overall degree of coarticulation, regardless of its directionality. Results of repeated measures four-way ANOVAs are reported with the within-subject factors Vowel Sequence (/a#i/ vs. /i#a/), Boundary Type, Preboundary Accent, Postboundary Accent. The dependent variables are cross-boundary U-, X- and Y-distances between opposite vowels for three time intervals: (1) $\frac{3}{4}V_1 - \frac{1}{4}V_2$, (2) V_1 end- V_2 onset, and (3) $\frac{1}{4}B - \frac{3}{4}B$. These distances will show how close the articulations of two consecutive but different vowels are (see Figure 2.8 in Chapter 2). A shorter cross-boundary distance, as reported in this section, means a greater degree of *syntagmatic* coarticulation, as opposed to the cases of carryover and anticipatory coarticulatory effects, reported above, where a shorter distance between the test and control conditions indicates a lesser degree of *paradigmatic* coarticulation.

4.3.3.1. *Effect of accent*

First consider the effect of preboundary (V_1) accent. There is no robust effect of Preboundary Accent on cross-boundary distances, as summarized in Table 4.5a. The only significant effect is for the time interval $\frac{1}{4}B - \frac{3}{4}B$ ($F[1,5]=7.349$, $p<0.5$ for U-distance; $F[1,5]=6.249$, $p<0.075$ (*ns trend*) for X-distance; $F[1,5]=7.742$, $p<0.05$ for Y-distance). At this time interval ($\frac{1}{4}B - \frac{3}{4}B$), as shown in the upper panel of Figure 4.13, mean cross-boundary distances are significantly shorter (indicating a greater degree of coarticulation) when preboundary vowels (V_1) are *accented* than when they are unaccented. However, this pattern, which contradicts the coarticulatory resistance hypothesis, should not be generalized, to be an overall effect of Preboundary Accent, since it occurs only for the interval during the consonant ($\frac{1}{4}B - \frac{3}{4}B$). With this in mind, the overall result, then, indicates that the accent of the preboundary vowel (V_1) does not affect reciprocal coarticulation, at least not in such a way that the accentuation of the preboundary vowel induces coarticulatory resistance, as we saw in the previous section. (There is no significant interaction between Preboundary Accent and other factors.)

Table 4.5. Summary of main effects in repeated measures ANOVAs for reciprocal coarticulatory effect. (** refers to $p < 0.01$; *, $p < 0.05$; ^{tr}, $p \leq 0.075$)

(a) V₁ accent, $F(1,5)$:

	$\frac{3}{4}V_1 - \frac{1}{4}V_2$	V ₁ end-V ₂ onset	$\frac{1}{4}B - \frac{3}{4}B$
U-distance	0.028	3.924	7.349*
X-distance	1.502	4.099	6.249 ^{tr}
Y-distance	5.134	2.034	7.742*

(b) V₂ accent, $F(1,5)$:

	$\frac{3}{4}V_1 - \frac{1}{4}V_2$	V ₁ end-V ₂ onset	$\frac{1}{4}B - \frac{3}{4}B$
U-distance	48.813**	89.951**	41.463**
X-distance	47.194**	88.119**	17.647**
Y-distance	20.407**	48.877**	37.852**

(c) Prosodic Boundary, F -values with Huynh-Feldt corrected df .

	$\frac{3}{4}V_1 - \frac{1}{4}V_2$	V ₁ end-V ₂ onset	$\frac{1}{4}B - \frac{3}{4}B$
U-distance	F(1.23, 6.17)	F(2,10)	F(1.80,9.01)
	2.741	4.612*	5.193*
X-distance	F(2,10)	F(2,10)	F(2,10)
	1.575	3.412 ^{tr}	3.270 ^{tr}
Y-distance	F(1.45,7.24)	F(2,10)	F(2,10)
	2.892	4.882*	3.798 ^{tr}

(d) Vowel Sequence (/a#i/ vs. /i#a/), $F(1,5)$:

	$\frac{3}{4}V_1 - \frac{1}{4}V_2$	V ₁ end-V ₂ onset	$\frac{1}{4}B - \frac{3}{4}B$
U-distance	1.006	15.195*	7.001*
X-distance	2.834	9.209*	9.119*
Y-distance	28.855**	6.145 ^{tr}	4.251

^{tr} $p \leq 0.075$ * $p < 0.05$ ** $p < 0.01$

In contrast to the case of the Preboundary Accent effect, Postboundary Accent *does* influence coarticulatory patterns. For cross-boundary U-distance, there is a significant main effect of Postboundary Accent for all three intervals being examined ($F[1,5]=48.813$,

$p < 0.001$ for $\frac{3}{4}V_1 - \frac{1}{4}V_2$; $F[1,5]=89.951$, $p < 0.001$ for $V_1\text{end} - V_2\text{onset}$; $F[1,5]=41.463$, $p < 0.001$ for $\frac{1}{4}B - \frac{3}{4}B$). X- and Y-distances also show significant main effects for these intervals, as summarized in Table 4.5b. The cross-boundary distance is significantly longer (indicating a lesser degree of coarticulation) when postboundary vowels (V_2) are accented than when they are unaccented, as can be seen in the lower panels of Figure 4.13 to be true for all cases. This indicates that accentuation of postboundary vowels triggers coarticulatory resistance, supporting the coarticulatory resistance hypothesis. (Note, however, there is a significant Vowel Sequence x Postboundary Accent interaction, as reported below.)

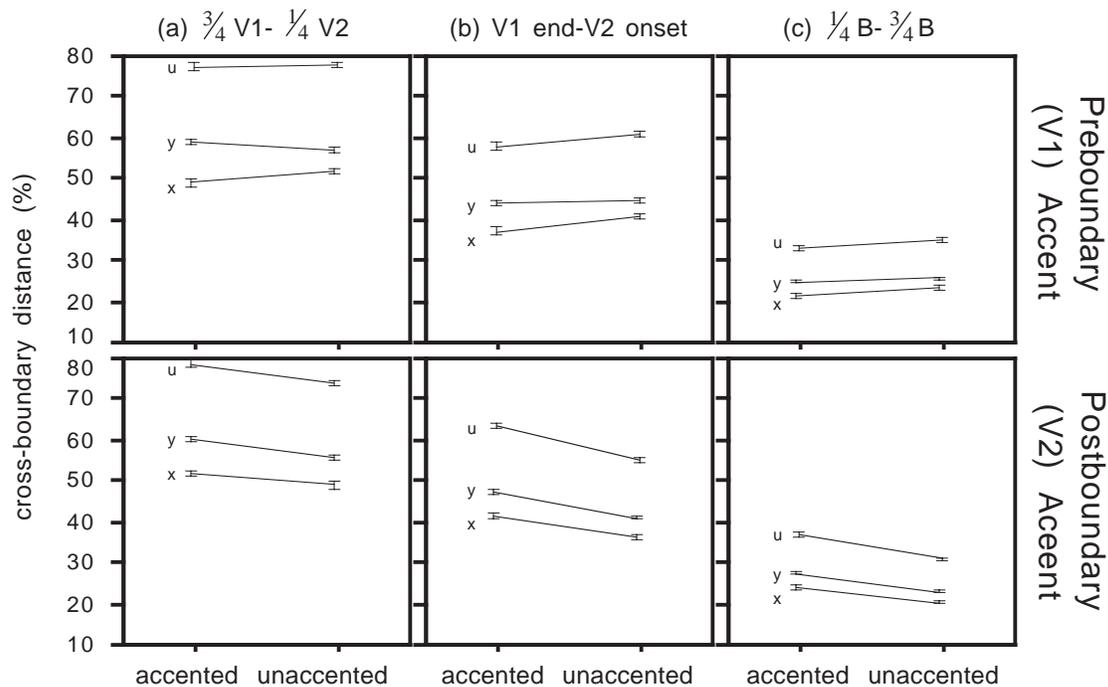


Figure 4.13. Mean cross-boundary U-, X- and Y-distances by preboundary (V_1) accent (the upper panel) and postboundary (V_2) accent (the lower panel) at three time intervals. Error bars = \pm standard errors.

4.3.3.2. Effect of Boundary Type

Overall, there is a significant effect of Boundary Type. For cross-boundary U-distance, the effect of Boundary Type is significant for the time intervals $V_1\text{end} - V_2\text{onset}$ ($F[2,10]=4.612$, $p < 0.05$) and $\frac{1}{4}B - \frac{3}{4}B$ ($F[1.8,9.0]=5.193$, $p < 0.05$). Considering the cross-boundary X- and Y-distances for these two intervals, all cases show a non-significant trend, as shown in Table 4.5c, except for Y-distance in the $V_1\text{end} - V_2\text{onset}$ interval, for which a significant Y-main effect is found ($F[2,10]=4.883$, $p < 0.05$). No other effects are found for the $\frac{3}{4}V_1 - \frac{1}{4}V_2$ interval.

As shown in Figure 4.14, there is a three-way distinction (IP>ip>Wd) for the intervals $V_1\text{end}-V_2\text{onset}$ and $\frac{1}{4}B-\frac{3}{4}B$ ($p<0.01$) for U-distance as well as for X- and Y-distances (Bonferroni/Dunn *posthoc* tests). The only exception to this pattern is the cross-boundary X-distance in the $V_1\text{end}-V_2\text{onset}$ interval, for which there is just a two-way distinction (IP>(ip=Wd)). (Note also that although there is no main effect of Boundary Type for the interval $\frac{3}{4}V_1-\frac{1}{4}V_2$, the mean cross-boundary distances are always longer for IP than for Wd.) Overall, the longer cross-boundary distance across higher prosodic boundaries indicates that vowels are more resistant to coarticulation with each other across higher prosodic boundaries than across lower ones.

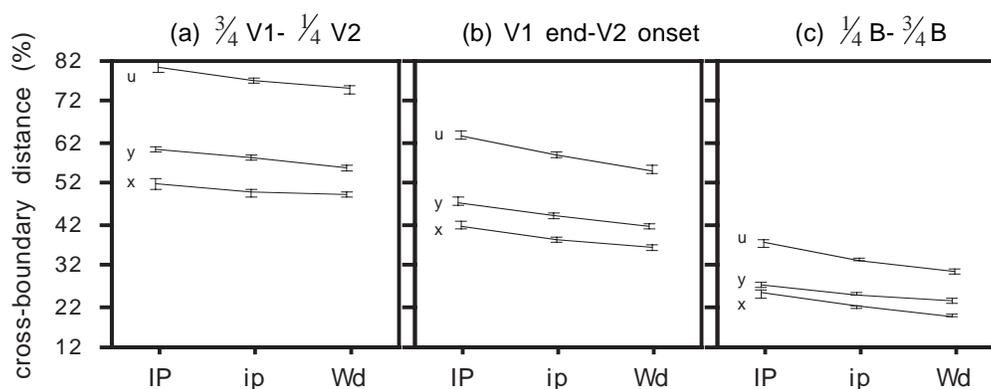


Figure 4.14. Mean cross-boundary U-, X-, and Y-distances by prosodic position at three time intervals. Error bars = \pm standard errors.

4.3.3.3. Effect of Vowel Sequence (/a#i/ vs. /i#a/)

The Vowel Sequence factor has a significant influence on cross-boundary distances at various intervals. There is a significant main effect of Vowel Sequence on cross-boundary U-distance for the $V_1\text{end}-V_2\text{onset}$ interval ($F[1,5]=15.195$, $p<0.025$) and for the $\frac{1}{4}B-\frac{3}{4}B$ interval ($F[1,5]=7.001$, $p<0.05$). There is also a significant effect on X- and Y-distances at these time intervals, as summarized in Table 4.5d. Figure 4.15 shows these effects. Note that all the cross-boundary distances are significantly shorter (less coarticulated) in /a#i/ than in /i#a/ for the intervals $V_1\text{end}-V_2\text{onset}$ and $\frac{1}{4}B-\frac{3}{4}B$. However, there is no consistent effect for the $\frac{3}{4}V_1-\frac{1}{4}V_2$ interval, as /a#i/ has a shorter cross-boundary distance than /i#a/ for X-distance but the reverse is true for Y-distance. Despite this inconsistency, what emerges is that cross-boundary distances are shorter (and therefore, show a greater degree of coarticulation) for /a#i/ than for /i#a/ at least for the intervals $V_1\text{end}-V_2\text{onset}$ and $\frac{1}{4}B-\frac{3}{4}B$. (However, that there are interactions between Vowel Sequence and other factors. See below.)

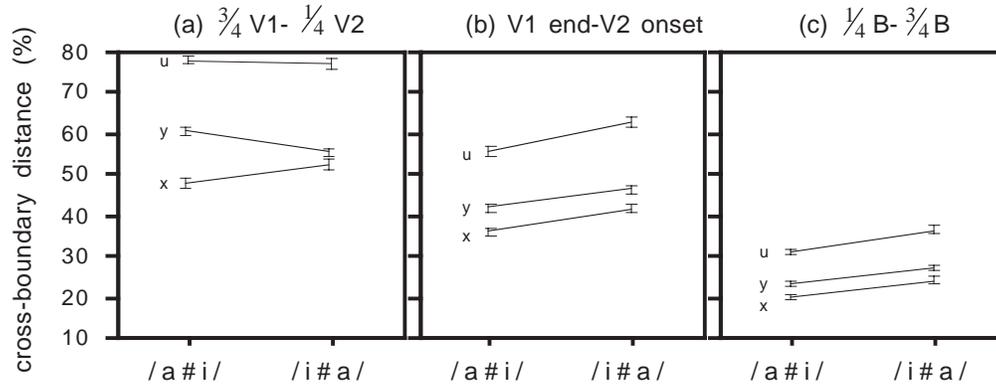


Figure 4.15. Mean U-, X- and Y-distances by vowel sequence in three time intervals. Error bars = \pm standard errors.

4.3.3.4. Interactions

One of the most robust interactions between factors is a two-way Vowel Sequence \times Postboundary Accent interaction for cross-boundary X- and Y-distances, as shown in Figure 4.16. *Posthoc* tests show that the interaction for cross-boundary X-distance results primarily from the fact that the difference due to Postboundary Accent is significant for /a#i/ at the level of $p < 0.01$, but not for /i#a/, as can be seen in Figure 4.16a. On the other hand, for cross-boundary Y-distance, the difference due to Postboundary Accent is significant not for /a#i/, but for /i#a/, as shown in lower panels in Figure 4.16. In short, for X-distance, coarticulatory resistance due to Postboundary Accent holds only for /a#i/; but for Y-distance, it holds only for the opposite vowel sequence, /i#a/. This means that the accent of postboundary /i/ mainly influences the x dimension of tongue movement, whereas the accent of postboundary /a/ influences the y dimension of tongue movement. This is consistent with results about the accent-induced differences in the tongue maxima in Chapter 3, which showed that the postboundary /#a/ under accent was produced with a lowered tongue body (i.e., more extreme articulation in the y dimension), whereas the postboundary /#i/ under accent was produced with a fronted tongue body (i.e., more extreme articulation in the x dimension). In other words, the accent-induced coarticulatory difference is robust in the same tongue dimension that also shows a robust accent-induced difference in maximum tongue position.

There is no other significant interaction found for the time intervals $V_{1\text{end}}-V_{2\text{onset}}$ and $\frac{1}{4}B-\frac{3}{4}B$ for any of the dependent variables. For the interval $\frac{3}{4}V_1-\frac{1}{4}V_2$, however, there is a three-way Vowel Sequence \times Preboundary Accent \times Postboundary Accent interaction for cross-boundary U-distance ($F[1,5]=8.228$, $p < 0.05$). (No significant interaction is found for X- and Y-distances.) This interaction is quite complex, but one point is especially worth addressing. The difference due to Postboundary Accent is greatest when the preboundary vowel is unaccented in the vowel sequence /i#a/.

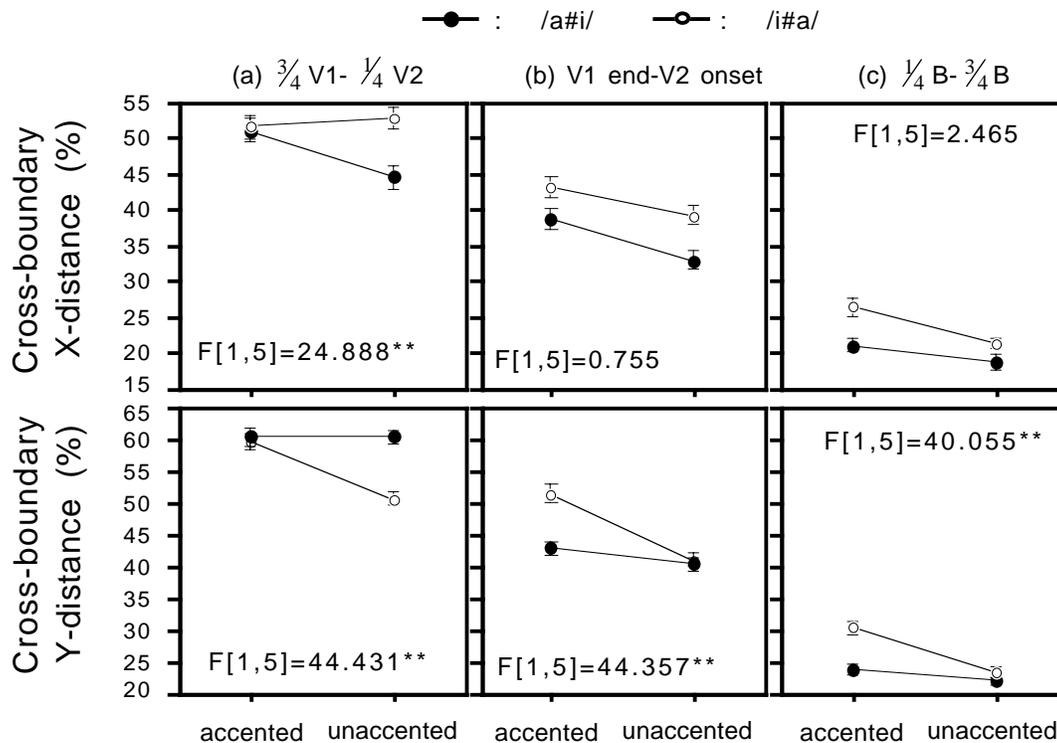


Figure 4.16. Mean cross-boundary X- and Y-distances by Postboundary Accent and Vowel Sequence for three time intervals. F-values are provided in each panel with ** referring to $p < 0.01$; *, $p < 0.05$; ^{tr}, $p < 0.08$. Error bars = \pm standard errors.

4.3.3.5. Summary of reciprocal coarticulatory effect

Thus far, we have examined reciprocal coarticulatory effects, regardless of their directionality under various conditions. There are several points worth recapitulating:

- a. The accentuation of a preboundary (domain-final) vowel (V_1) does not necessarily trigger coarticulatory resistance, as cross-boundary distances are not significantly longer for accented V_1 than for unaccented V_1 . However, accentuation of V_1 triggers coarticulatory resistance when the following vowel (V_2) is *unaccented*.
- b. In contrast to the Preboundary Accent effect, the accentuation of a postboundary (domain-initial) vowel (V_2) does have a significant influence on the reciprocal coarticulatory effect, in that the accentuation of V_2 in general brings about coarticulatory resistance.

- c. The reciprocal coarticulatory pattern is significantly influenced by Boundary Type—i.e., a greater coarticulatory resistance (less degree of coarticulation) is found across higher prosodic boundaries than across lower ones.
- d. The pattern of coarticulation varies with Vowel Sequence: cross-boundary distances are in general shorter for /a#i/ than for /i#a/.
- e. Postboundary Accent interacts with Vowel Sequence (/a#i/ vs. /i#a/), such that differences due to V₂ Accent hold only in /a#i/ for X-distance (only for $\frac{3}{4}V_1 - \frac{1}{4}V_2$), but only in /i#a/ for Y-distance (for all three time points). This is in accordance with findings about accented-induced difference in the maximum positions of the tongue as reported in Chapter 3—i.e., postboundary /#i/ shows a more robust effect of Accent on the *x* dimension, but postboundary /#a/, on the *y* dimension.

4.3.4. *Temporal distance and coarticulatory resistance*

In the previous section, we found that the degree of the reciprocal (syntagmatic) coarticulation (as measured by cross-boundary U-, X-, and Y-distances) is significantly affected by Boundary Type and Accent, without considering durational differences. However, coarticulatory resistance might be due to lengthening arising from Boundary Type and/or Accent. In this section, we first examine variation in vowel-to-vowel temporal interval between V₁ end and V₂ onset as a function of Boundary Type and Accent. Then, we examine whether and how much of the observed coarticulatory effects can be accounted for by the vowel-to-vowel temporal distance.

Overall, the results of repeated measures four-way ANOVAs show that the vowel-to-vowel temporal interval (roughly equivalent to the duration of the intervening /b/) is significantly affected by Postboundary Accent (V₂ Accent) ($F[1,5]=112.543$, $p<0.001$) and Boundary Type ($F[2,10]=4.882$, $p<0.05$), but not by Preboundary Accent (V₁ Accent). (Note that in the previous section we also found no effect of Preboundary Accent on cross-boundary articulatory measures.) As can be seen in Figure 4.17, the mean vowel-to-vowel interval is longer when the postboundary vowel is accented; it is also longest for IP, intermediate for ip, and shortest for Wd. There is no interaction between these two factors. Thus, we observe that the difference due to Postboundary Accent is maintained across prosodic boundaries. *Posthoc* comparisons show that the observed difference is significant for each level of Boundary at $p<0.01$.

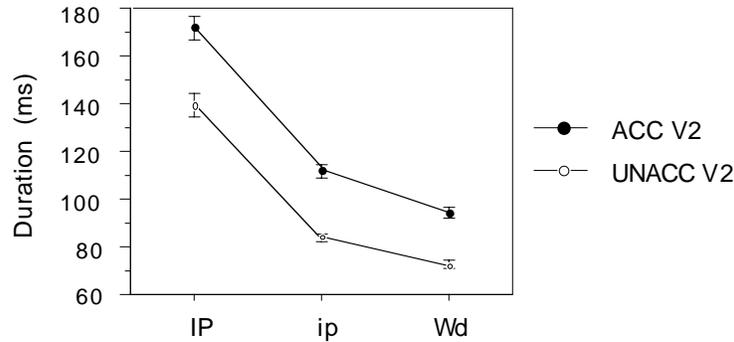


Figure 4.17. Mean cross-boundary interval between V_1 end and V_2 onset by Postboundary (V_2) Accent and Boundary Type. Error bars = \pm standard errors.

In order to examine whether the variation in duration affects the degree of coarticulation, the factorial model of the Analysis of Covariance (ANCOVA) was employed with each cross-boundary distance (U-, X-, and Y-distances) for the time interval V_1 end- V_2 onset as a dependent variable, and Duration as a covariate (regressor) at that time interval. (As Kirk (1995) noted, however, assumptions for the factorial model are less restrictive than repeated measures model, so in conducting the factorial analysis, the level of significance was set to $p < 0.005$ in order to counteract the relatively large degree of freedom which may inflate the size of the effect, possibly causing Type I or *alpha* error.)

As a first step, in order to see whether the regressor, Duration, has a different effect on the degree of coarticulation for different levels of prosodic factors (i.e., Postboundary (V_2) Accent and Boundary Type), a test for *homogeneity of slopes* among regression lines for each level of the factor was conducted. (StatView performs a separate regression for each level when the interaction between a covariate and a factor is included in ANCOVA.) The results show that there is no significant interaction between Duration and either prosodic factor for any dependent variable, suggesting that the slope of the regressor does not differ depending on the level of the factor. In other words, the hypothesis of homogeneity of slopes is supported, justifying an elimination of the interaction involving the covariate from the ANCOVA model (see pp. 80-81 in StatView Reference (1998)). Thus, ANCOVAs with no inclusion of covariate-factor interactions were performed for covariance of each dependent variable (cross-boundary U-, X-, and Y-distances) and Duration, with two factors Postboundary (V_2) Accent and Boundary Type, separately for each vowel sequence (/a#i/ and /i#a/).

Results of ANCOVAs show that for the /i#a/ sequence, duration for the time interval V_1 end- V_2 onset significantly affects all dependent variables (U-, X-, and Y-distances) (for /i#a/, $F[1,67]=30.567$, $p < 0.0001$, $F[1,67]=15.605$, $p < 0.0005$, $F[1,67]=29.697$, $p < 0.0001$ for U-, X-, and Y-distances, respectively). This means that the degree of coarticulation co-varies significantly with the temporal duration for the /i#a/

sequence. However, for the /a#i/ sequence, only U-distance is influenced by Duration, but with a weaker evidence of significance ($F[1,67]=7.888$, $p<0.01$), not reaching the significance level ($p<0.005$) set forth for ANCOVAs conducted in this study. There is no effect of Duration on either X- or Y-distances. These results show that overall, the temporal duration affects the degree of coarticulation, especially in the /i#a/ sequence.

The duration-coarticulation covariance is further evident in a simple regression analysis. Converted percentage data were submitted to simple regression analyses in which dependent variables of cross-boundary U-, X-, and Y-distances are regressed against the temporal distance between V_1 end and V_2 onset. (In order to perform regression analysis with datapoints across speakers, normalized variables were employed in this study, since speakers show different magnitudes of variables, especially in duration. For this, cross-boundary U-, X-, and Y-distances and duration for the time interval V_1 end- V_2 onset were normalized by transforming values into percentages for each speaker. Each converted percentage value is the percentage contribution of each raw datapoint to the sum of the whole datapoints.) Figure 4.18 shows these results for each vowel sequence. On the one hand, as seen in the left column of the figure, the /a#i/ sequence shows no robust linear relationship between cross-boundary positional distances and temporal distances, as inferred from regression values ranging from $R^2=0.053$ to $R^2=0.144$. On the other hand, as shown in the right panels of Figure 4.18, the /i#a/ vowel sequence shows a more robust linear relationship between cross-boundary distances and temporal distances, especially for the Y-distance-duration relationship ($R^2=0.5$) and the U-distance-duration relationship ($R^2=0.454$). For X-distance, there is a weaker X-distance-duration relationship ($R^2=0.243$).

The asymmetry between /a#i/ and /i#a/ is further evident in Table 4.6 which shows that /i#a/ is generally associated with higher R^2 values than /a#i/, especially in regression analyses for Vowel Sequence x V_2 Accent (Table 4.6b). This asymmetry is consistent with results about the reciprocal coarticulatory effect, reported in the previous section, which showed a more robust coarticulatory effect on /i#a/ than on /a#i/. Further, we found that Y-distance for /i#a/ is more sensitive to prosodic conditions than X-distance. This is also consistent with a more robust spatial-temporal relationship for Y-distance than for X-distance, as seen in the right panel of Figure 4.18.

Given that there is a significant covariance between duration and cross-boundary coarticulatory distances, more reliably in the /i#a/ sequence, the next task is to determine whether there is still a significant effect of prosodic factors on coarticulation when such durational influence is factored out. With regards to the effect of Accent, results of ANCOVAs show that for /i#a/ there is a significant effect of Accent on cross-boundary U- and Y-distances ($F[1,67]=8/715$, $p<0.005$; $F[1,67]=25.686$, $p<0.0001$), but not X-distance, whereas for /a#i/, there is a weaker effect of Accent only on cross-boundary X-distance ($F[1,67]=4.138$, $p<0.05$), but no effect on U- and Y-distances. Overall, then, even if the durational influence is figured in, there is still accent-induced coarticulatory variation especially in the tongue height (y) dimension for /i#a/ (and in the tongue backness (x)

dimension for /a#i/, though weakly). This indicates that the durational variation is not the only factor responsible for the accent-induced variation in the reciprocal coarticulation.

Turning to the boundary effect, results of ANCOVAs show that there is no effect of Boundary Type on any cross-boundary distance for either vowel sequence. This suggests that the boundary-induced coarticulatory patterning and durational effect cannot be separated.

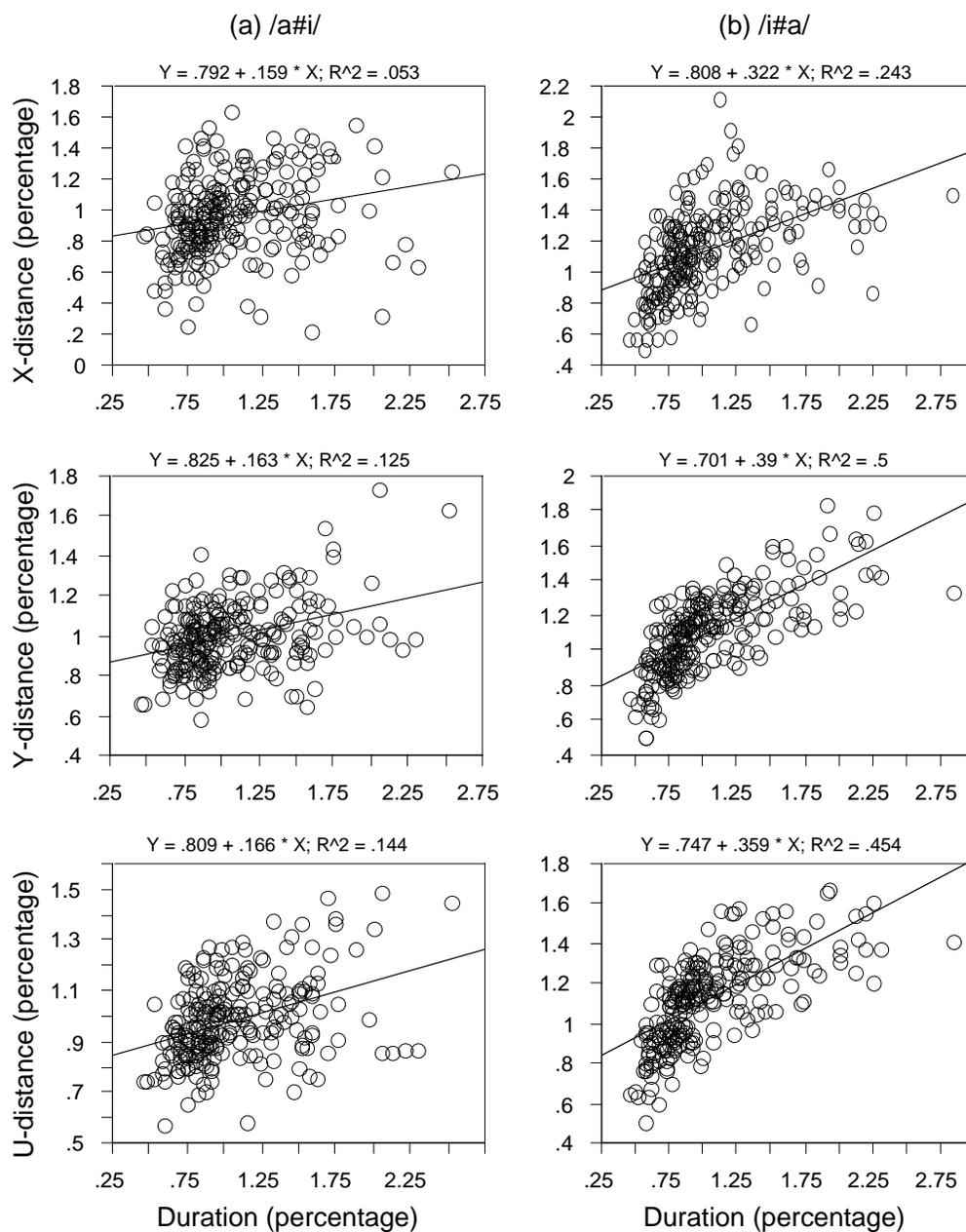


Figure 4.18. Regression plots with cross-boundary U-, X-, and Y-distances against temporal distance for the interval V_1 end- V_2 onset.

Table 4.6. R^2 values in regression analyses performed separately for (a) Vowel Sequence x Boundary Type and (b) Vowel Sequence x V2 Accent.

(a) Vowel Sequence x Boundary Type

Vowel Sequence	Boundary Type	U-distance	X-distance	Y-distance
/a#i/	IP	.283	.051	.099
	ip	.4	.121	.124
	Wd	.537	.223	.156
/i#a/	IP	.111	.056	.41
	ip	.193	.126	.534
	Wd	.283	.487	.428

(b) Vowel Sequence x V2 Accent sequence

Vowel Sequence	V2 Accent	U-distance	X-distance	Y-distance
/a#i/	ACC	.15	.098	.086
	UNACC	.116	.016	.151
/i#a/	ACC	.353	.14	.416
	UNACC	.282	.18	.317

4.4. General Discussion

4.4.1. Coarticulatory resistance as a function of accent

Coarticulatory patterns examined in this study generally support the hypothesis that vowels resist coarticulation when they occur in prosodically strong positions. We found that vowels under accent (sentence stress) are less coarticulated with (more resistant to) neighboring vowels than unaccented vowels are. This is generally true for both carryover and anticipatory coarticulation, as well as for reciprocal (syntagmatic) coarticulation in the case of Postboundary Accent (V_2) effect. It has previously been reported that within a word, lexically stressed vowels show less contextual variation than lexically unstressed ones (e.g., Fowler, 1981 for English; Nicolaidis, 1999 for Greek). The corpus of data studied here shows that sentence-level stress also induces such coarticulatory resistance in vowel-to-vowel coarticulation in English, supporting HYPOTHESIS 4.1—i.e., accented vowels are more resistant to coarticulation with neighboring vowels than unaccented

vowels are. The following three subsections discuss the linking between accent-induced coarticulatory resistance and strengthening effects found in Chapter 3, the relationship between duration and coarticulation, and potential contribution of accent-induced coarticulatory resistance to contrast maximization.

Accent-induced strengthening and coarticulatory resistance. Regarding the effect of Accent, at the outset of this chapter we also made a prediction in relation to the strengthening effects reported in Chapter 3: that is, the strengthening found in the tongue maximum position would lead to robust coarticulatory resistance. Recall, results in Chapter 3 showed that the accent-induced strengthening effect observed in the maximum tongue position was robust in the tongue height dimension for /a/, but in the tongue backness dimension for /i/.

Results regarding the domain-initial /a/ in carryover coarticulation showed that the ACC/UNACC differences for /i#a/ lie primarily in the Y-distance, i.e., in the tongue height dimension (see Figure 4.1), such that accented /a/ shows a lesser degree of coarticulation as compared to unaccented /a/. However, results regarding domain-final /a/ in anticipatory coarticulation for /a#i/ show no such effect (see Figure 4.6). These results suggest that at least the domain-initial vowel /#a/ shows coarticulatory resistance primarily in the height dimension being consistent with the strengthening pattern found in the maximum tongue position. Turning to the vowel /i/, both the domain-initial and domain-final /i/s show coarticulatory effects primarily in the tongue backness (x) dimension in which accented /i/ shows coarticulatory resistance (see Figure 4.4 for /#i/ and Figure 4.10 for /i#/).

Moreover, the results regarding the reciprocal coarticulation are consistent with the above-observed patterns, in that the effect of Postboundary (V2) Accent is robust primarily in the tongue height dimension for /#a/ but in the tongue backness dimension for /#i/. Overall results in this chapter suggest that the effect of Accent on coarticulation lies primarily in the tongue dimension for which the maximum tongue position also showed strengthening (except for the domain-final /a#/). From this, we can infer that accent-induced coarticulatory resistance is related to articulatory strengthening, such that accent-induced strengthening can be equated with coarticulatory resistance.

Duration and accent-induced coarticulatory resistance. In section 4.3.4, we observed that vowel-to-vowel temporal distance between the end V₁ end and V₂ onset varies with accent—i.e., it was longer when the domain-initial vowel is accented than unaccented. Regarding this, we found that there was a significant covariance between the duration and the cross-boundary spatial distance, indicating the longer the duration, the greater the coarticulatory resistance. That is, to some extent accented vowels resist coarticulation because they are further away (in time) from neighboring vowels, supporting HYPOTHESIS 4.5. However, results of ANCOVAs showed that the effect of V₂ Accent on coarticulation remains significant even after the durational influence is factored out. This suggests that duration is not the only factor responsible for accent-induced coarticulatory

resistance, and that coarticulatory resistance may be viewed as another type of accent-induced strengthening.

4.4.2. *Coarticulatory resistance across a prosodic boundary*

In this chapter, we also examined whether coarticulatory resistance varies across different prosodic boundaries. A general finding is that vowels are less coarticulated with each other across higher prosodic boundaries than across lower ones. This pattern is generally true for both carryover and anticipatory coarticulation, although carryover coarticulation shows a more robust coarticulatory effect than anticipatory coarticulation does. Further, the reciprocal coarticulation also showed that the spatial difference between vowels at edges of prosodic domains is larger across a higher boundary. Overall, the results show that vowels resist coarticulation with neighboring vowels across higher prosodic boundaries than across lower ones, lending support to the boundary-induced coarticulatory resistance hypothesis (HYPOTHESIS 4.2).

Asymmetry between domain-initial and domain-final vowels. Related to the boundary-induced coarticulatory resistance, it was predicted that since there was no strengthening effect on domain-initial vowel in #CV, as reported in Chapter 3, the domain-initial vowel (in the carryover direction) would show more coarticulation than domain-final vowels (in the anticipatory direction) (HYPOTHESIS 4.3). While the data in this chapter were examined separately for carryover and anticipatory coarticulations, we can qualitatively examine this by looking at mean values for Euclidean distance between the test and control conditions for the comparison between carryover and anticipatory coarticulations. As summarized in Table 4.7, the mean Euclidean distance is longer in the carryover coarticulation than in the anticipatory coarticulation in all cases. From this, we can infer that domain-initial vowels are more vulnerable to coarticulation than domain-final vowels, lending support to HYPOTHESIS 4.3. Seen from a different angle, the data suggest that domain-final vowels is more resistant to coarticulation than domain-initial vowels are. To the extent that this interpretation holds up, we can further posit that such coarticulatory vulnerability of domain-initial vowels is related to the lack of boundary-induced strengthening effect in domain-initial positions, whereas the lesser degree of coarticulation for domain-final vowels can be related to the strengthening effect in domain-initial positions reported in Chapter 3.

Another noteworthy point regarding the asymmetry between domain-initial and domain-final vowels in terms of coarticulation is that, although the overall degree of coarticulation is greater for domain-initial than for domain-final vowels, the variation as a function of Boundary Type is more robust in carryover coarticulation than in anticipatory coarticulation. Carryover coarticulation shows a significant boundary effect at three timepoints ($\frac{1}{2}B$, $\frac{3}{4}B$, v_2 onset) for U-, X-, and Y-distances (see Table 4.1b) whereas anticipatory coarticulation shows a significant boundary effect mainly for U-distance.

Furthermore, the boundary effect on the carryover coarticulation is far greater than on the anticipatory coarticulation as can be inferred from a greater F-ratio for the carryover coarticulation (ranging from 7.742 to 61.714), as compared to the anticipatory coarticulation (with F-ratios ranging from 0.56 to 10.239). This asymmetry between carryover and anticipatory coarticulation is further evident in the range of the mean Euclidean distances as shown in Table 4.7: the carryover coarticulation has a greater range of Euclidean distances than the anticipatory coarticulation, especially at edges of vowels. This observation allows us to infer that although there is no articulatory strengthening found in the maximum tongue position for domain-initial vowels (as reported in Chapter 3), domain-initial vowels *do* show systematic coarticulatory variation as a function of Boundary Type at their edges and during preceding consonant.

Table 4.7. Summary of Euclidean distances (mm) between the test and control conditions in carryover and anticipatory coarticulation at two different timepoints for each level of prosodic boundary.

Vowel	Boundary	At edges of vowels (V ₁ end vs. V ₂ onset)		At a quarter into the vowel ($\frac{3}{4}$ V ₁ vs. $\frac{1}{4}$ V ₂)	
		Anticipatory	Carryover	Anticipatory	Carryover
/a/	IP	13.5	14.2	8.6	10.9
	ip	16.1	19.8	8.8	12.0
	Wd	17.4	22.3	9.4	11.2
/i/	IP	7.2	11.5	6.1	10.8
	ip	7.8	13.5	6.5	11.1
	Wd	8.3	13.0	6.5	10.0

Duration and boundary-induced coarticulatory resistance. In this chapter, we observed that vowel-to-vowel temporal distance between the V₁ end and the V₂ onset varies with the level of prosodic boundary—it is longer across higher prosodic boundaries than across lower ones. Further, the results of ANCOVAs showed that when this durational factor is figured in, the effect of the prosodic boundary becomes non-significant. This suggests that both the boundary-induced coarticulatory resistance (as manifested by cross-boundary distances) and the elongated vowel-to-vowel interval can be taken to be the same effect, lending strong support to HYPOTHESIS 4.5, unlike the accent-induced coarticulatory resistance for which the durational variation is only partially responsible. However, the data do not tell us whether there is a causal relationship from duration to

coarticulation, or an acausal (correlational) relationship between coarticulation and duration. One possibility is that the observed coarticulatory patterning is due to boundary-induced durational variation (causal relationship). Another possibility is that the coarticulatory patterning and the durational variation are influenced independently but similarly by the prosodic boundary, showing covariance between the two variables.

4.4.3. *Accent- vs. boundary-induced coarticulatory resistance*

Accent- and boundary-induced coarticulatory patterns show a similar effect, in that they both support the coarticulatory resistance hypothesis. However, there are also some differences between the two factors. First, robust accent-induced coarticulatory resistance is generally found in the *x* dimension for /i/ and in the *y* dimension for /a/, whereas it is in the *y* dimension that both /a/ and /i/ show boundary-induced coarticulatory resistance. Second, accent-induced coarticulatory resistance lies primarily in the same tongue dimension in which the tongue maximum position also showed a robust strengthening effect (Chapter 3), whereas there is no clear evidence for this relationship regarding boundary-induced coarticulatory resistance. Finally, the accent-induced coarticulatory pattern cannot be fully accounted for by a duration factor, whereas the boundary-induced coarticulatory patterning and durational variation can be thought of as the same effect.

4.4.4. *Coarticulatory resistance vs. coarticulatory aggression*

Along with the coarticulatory resistance hypothesis, we also hypothesized that vowels under accent would exert a greater influence on neighboring vowels than vowels under no accent—i.e., vowels will be more vulnerable to coarticulation with accented than with unaccented neighboring vowels (HYPOTHESIS 4.4). In the corpus of data examined here, we found little evidence supporting this hypothesis. The only relevant finding that may favor this hypothesis was that the effect of accent of the target vowel on coarticulation tends to be stronger when the neighboring vowel is unaccented than when the neighboring vowel is accented. This indicates that the accentuation of the neighboring vowel *does* influence the target vowel's articulation at least to some degree. However, we found no main effect of the accent of the neighboring vowel on either carryover or anticipatory effects at any timepoint examined, showing that accented vowels do not especially influence neighboring vowels' articulation. Thus, the coarticulatory aggression effect previously observed for stressed vowels on neighboring unstressed vowels within a word (e.g., Fowler, 1981) is not observed for accented vowels across higher-level prosodic boundaries. This is incompatible with the view that coarticulatory resistance can be equated with coarticulatory aggression, as proposed under the window model (Keating, 1990). (See section 4.4.5 below for further discussion of the relationship between coarticulatory resistance and aggression in the window model.)

4.4.5. Inherent articulatory properties and coarticulatory resistance

Our data show that distances between the test ($V_1 \neq V_2$) and control ($V_1 = V_2$) conditions are significantly greater for /a/ than for /i/ in both the carryover and anticipatory directions. Figure 4.19 shows the mean difference in U-, X-, and Y-distances between /a/ and /i/. The mean difference is greater for the open /a/ than for the closed /i/ for all cases ($p < 0.0001$). That is, the open vowel /a/ is more vulnerable to coarticulation than the closed vowel /i/, lending support to the hypothesis that the coarticulatory resistance is inversely correlated with sonority (Lindblom, 1983). This hypothesis has been previously tested in terms of consonantal coarticulatory resistance (Lindblom, 1983; Recasens, 1984a, 1984b, 1985; Keating, et al., 1994). For example, it has been demonstrated that there is an inverse relationship between degree of coarticulation and the amount of linguopalatal contact required for the articulation of lingual consonants (Recasens, 1984a, 1984b, 1985), and that alveolar consonants show less coarticulation with vowels, and /h/ the most (Keating, et al., 1994). The current finding extends this relation to vowel-to-vowel coarticulation.

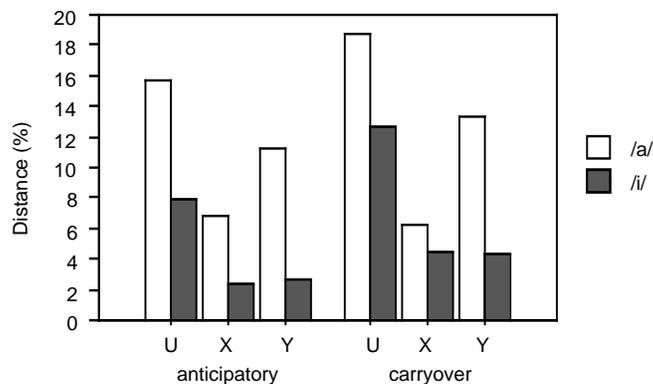


Figure 4.19. Mean U-, X-, and Y-distances between the test and control conditions for /a/ and /i/.

If we follow Lindblom (1983)'s hypothesis about the inverse relationship between degree of coarticulatory resistance and degree of sonority, a question arises as to why sonority matters. One explanation for this may be that less sonorous vowels such as the high vowel /i/ may require greater articulatory precision than more sonorous vowels such as the low vowel /a/. High vowels are produced with a relatively narrower channel between the tongue body and the palate than low vowels. The requirement of articulatory precision to make such a narrower channel for high vowels may also entail coarticulatory resistance to neighboring vowels.

Another possible account is that greater coarticulatory resistance in less sonorous vowels can be thought of as perceptual compensation for less loudness. More sonorous vowels are produced with an increase not only in acoustic intensity but also in duration as compared to less sonorous vowels. We know that perception of loudness usually integrates intensity over time (cf. Fry, 1965; Lehiste, 1970; Beckman, 1986). Thus, one can posit that a flexible range of variation may be allowed for more sonorous vowels to accommodate contextual influence presumably because such an articulatory variation can be made up for by sufficient loudness. On the contrary, more precise articulation (therefore, greater coarticulatory resistance) may be needed for less sonorous vowels in order to compensate for less loudness.

Alternatively, however, the observed vowel difference in the amount of coarticulation may have nothing to do with degree of sonority, but rather it may reflect constraints driven by the vowel system of English. That is, /i/ is associated with less degree of coarticulation than /a/, not because it is less sonorous than /a/, but perhaps because /i/ is spaced locally in a dense neighborhood of the English vowel space whereas /a/ is spaced in a relatively sparse neighborhood. This is reminiscent of Manuel (1990, 1999)'s proposal that coarticulatory resistance can be observable when coarticulation would result in blurring or confounding phonetic contrasts.

Whatever the underlying driving force for the inherent segmental difference in coarticulation may be, the fact is that there is coarticulatory variation due to segmental identity. In this connection, one additional point worth mentioning is that the difference in degree of coarticulation between /a/ and /i/ comes primarily from Y-distance, as can be seen in Figure 4.19. In carryover and anticipatory directions together, the mean difference between /a/ and /i/ is 8.84 (%) for Y-distance and 3.07 (%) for X-distance, suggesting that the vowel /a/ is more flexibly articulated than the vowel /i/, more so in the *y* dimension than in the *x* dimension of tongue movement.

Window model. This asymmetry due to segmental identity can be accounted for by the notion of “window.” As introduced in Chapter 1, Keating’s window model (1990) was proposed to relate contrast, coarticulatory resistance, and coarticulatory aggression by making phonetic targets vary within a specified range rather than simply having fixed values. Segments with a narrower window will have greater coarticulatory resistance whereas segments with a wider window will be more susceptible to coarticulation. Furthermore, a narrower window is assumed to influence position in wider windows of neighboring segments (coarticulatory aggression), such that the model equates at least weakly coarticulatory resistance and coarticulatory aggression.

In this framework, windows can be projected separately for the *x* and *y* dimensions of tongue movement. Figure 4.20 shows a hypothetical schematic of coarticulatory trajectories for /a#i/. Windows projected from /a/ are wider ((a) and (c) in the figure) than those projected from /i/ ((b) and (d) in the figure), resulting in greater degree of coarticulation for /a/ than for /i/. Likewise, the greater degree of coarticulation in the

tongue height (y) dimension results from a wider window for the y dimension ((a) and (b)), relative to the tongue backness (x) dimension ((c) and (d)). This hypothetical schematic can account for the asymmetry between /a/ and /i/, found in this chapter. Furthermore, we also found that /i/ (with a narrower window) is less coarticulated with /a/ (with a wider window) than the other way around, which is consistent with a view that coarticulatory resistance is equated with coarticulatory aggression, as far as the inherent segmental effects are concerned.

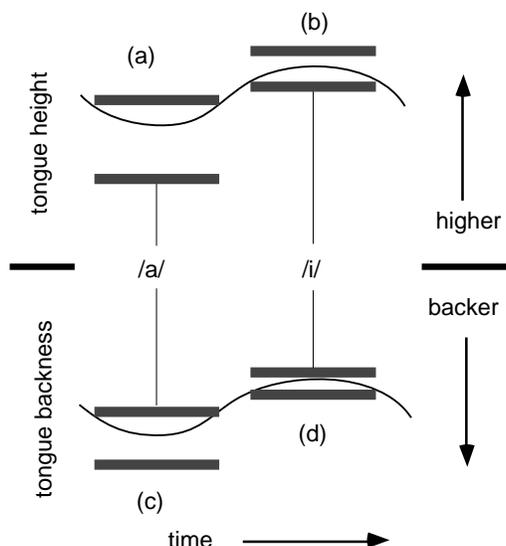


Figure 4.20. A schematic of coarticulatory trajectories for /a#i/ in the Window Model. (a) and (b) are windows specified for tongue height; (c) and (d) are windows specified for tongue backness.

While this model captures inherently-induced coarticulatory variations by relating coarticulatory resistance to coarticulatory aggression, the data presented in this chapter suggest several phenomena that should be taken into account in the current window model. First, the results in this chapter showed that coarticulatory resistance arising from a prosodic factor (i.e., accent) does not necessarily induce coarticulatory aggression, unlike coarticulatory resistance arising from an inherent segmental factor would do, as just mentioned above. This challenges the current window model in that it should devise a mechanism that dissociate prosodically-induced coarticulatory resistance from coarticulatory aggression while associating inherently-induced coarticulatory resistance with coarticulatory aggression.

Another factor that the original window model did not consider was coarticulatory variation which might come from prosodic variation, as was also noted later by Keating (1996). The original model allows only one fixed size window for a segment. Keating (1990, p.456) explains “Windows are determined empirically on the basis of context, but

once determined are not themselves contextually varied...Information about the possibilities for contextual variation is already built into that one window.” However, prosodically-conditioned coarticulatory variations, reported in this chapter, appear to require a flexible window such that the window size should vary depending on prosodic conditions, in a way that allows for narrowing a window for prosodically conditioned coarticulatory resistance. In the next section, I will discuss the directions that the current window model could be revised, paying particular attention to prosodically conditioned variations.

4.4.6. *Revised Window Model*

A possible solution to the problem regarding the prosodic influence on the size of the window has been proposed in Guenther (1995) in which the target range can vary depending on extralinguistic and linguistic factors. As introduced in Chapter 1, Guenther's computational model on speech production (called *DIVA*) specifies the vocal tract target for each speech sound in the form of *convex regions* in orosensory space that define the shape of the vocal tract. In the model, for each dimension of the orosensory target, a possible range of acceptable positions for that target (a kind of “window”) can vary as a function of various factors (e.g., speech rate, stress). As noted by Keating (1996), this model provides the basis for modifying Keating's window model in a way that allows re-sizing of the window to accommodate influences from various linguistic and extralinguistic factors.

In this section, I propose a revised window model in which window size varies as a function of prosodic factors that we already examined in this chapter. This is in the spirit of Byrd's (1996) Phase Window model. The phase window is the range of possible values in which intergestural overlap will be implemented. The phase window can be weighted by a variety of linguistic and extralinguistic factors, or *influencers*. Similarly, I propose that various influencers collectively affect the size of the window and determine the final active region of the window. Like the original model, the revised window model assumes that window size is empirically determined on the basis of context, having fixed maximum and minimum values. Then, postlexical optimization (or re-sizing) occurs on-line, depending on what kind of influencers are active, to determine the *active region* within a fixed window. It is this active region that varies with linguistic and extralinguistic conditions, setting the final trajectory.

Let's consider how prosodic factors may influence re-sizing of the window. First, consider the effect of accent. The results of the present study show that coarticulatory resistance is greater when a vowel is accented than when it is unaccented. This means that stress can serve as an influencer on the window, making the active region of the window smaller. As introduced earlier in Chapter 1, stress can be divided roughly into four degrees: no stress, word (lexical) stress, phrase stress, and sentence stress. The degree of

the stress then increase from lexical stress, to prenuclear pitch-accent, and to nuclear pitch-accent (cf. Liberman & Prince, 1977; Beckman, 1986; de Jong, Beckman & Edwards, 1993; Beckman & Edwards, 1994). Thus, it may not be unreasonable to assume that stress influences a window's active region in proportion to the relative strength of the stress as given in (1), although the present study suggested the difference only between pitch accent and lexical stress.

(1) Stress Hierarchy

Nuclear pitch-accent >> Pitch-accent >> Lexical stress >> No stress

According to this hierarchy, the active region of the window for vowels is smallest under nuclear pitch-accent, and largest under no stress.

Now let's consider the influence of prosodic boundary on the window. As discussed earlier, linguistic units are more prominent at the edges of higher prosodic domains, relative to the edges of lower prosodic domains. Our data also suggest that the degree of coarticulation becomes less around higher prosodic boundaries by and large in a cumulative way. This leads to a hierarchy for prosodic boundaries:

(2) Prosodic Boundary Hierarchy

Intonational Phrase >> Intermediate phrase >> Word >> Syllable

According to this hierarchy, the active region of the window is smallest around an IP boundary, and largest around a syllable boundary.

Figure 4.21 illustrates the hypothetical varying size of the window's active region as influenced by two influencers: stress and prosodic boundary. In the figure, the active region is narrowest when vowels occur under nuclear pitch-accent around an IP boundary, and widest when vowels occur under no accent around a syllable boundary.

Crucially, while Guenther's model does not have a mechanism that specifies the direction of the window's shrinking that may arise from prosodically-conditioned articulatory strengthening, the results of this study suggest that the window shrinks in a direction that leads to full achievement of segment's target. For example, the window for /a/ in the tongue vertical (y) dimension shrinks downwards, resulting in the hyperarticulation of [+low] and the resistance to the tongue raising; and the window for /i/ shrinks in an anterior direction, causing the hyperarticulation of [-back] and the resistance to the tongue backing.

I have outlined how two prosodic factors may influence the active region of the window. However, there must be numerous other factors that may also affect the window, involving many other unresolved issues. The most fundamental question is how the effects

of individual influencers combine to determine the final active region of the window. These interactions are likely to be more complex than in Figure 4.21. For instance, we have not considered at all the relationship between duration and prosodic conditions. As suggested by the results regarding duration, stress and prosodic boundary factors must not be treated the same, since they show different relationships between coarticulation and duration. Yet another question to be resolved is, as already mentioned above, how prosodically-induced coarticulatory resistance can be dissociated from coarticulatory aggression, while associating inherently-induced coarticulatory aggression to it. Answering these questions is beyond the scope of this work, and will require detailed computational modeling together with empirical data for many other influencing factors. However, it is hoped that the outline of the revised window model in this paper offers a framework from which further research on coarticulation can be developed.

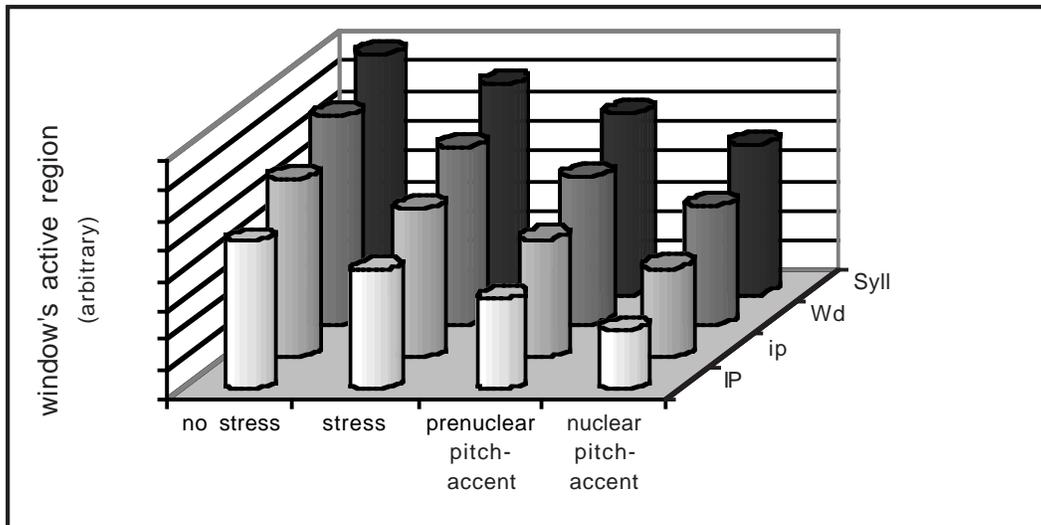


Figure 4.21. Hypothetical varying size of active window with two influencers, stress and prosodic boundary.

Chapter V

Effects of Prosody on Lip Movement Kinematics

In previous chapters, we observed prosodically conditioned articulatory strengthening as manifest in the maximum tongue position and coarticulatory resistance. This chapter continues to examine prosodically-induced articulatory strengthening by looking at the kinematics of the lip opening and closing movements occurring adjacent to prosodic boundary in a CV#CV sequence (where C = /b/). The major questions to be addressed in this chapter are what are the kinematic characteristics of prosodically conditioned strengthening, and how can prosodically-induced kinematic variations be accounted for by parameter settings in a mass-spring gestural model. The corpus designed for this dissertation allows for an examination of the kinematics of both the pre- and post-boundary lip opening gestures and cross-boundary lip closing gesture in a CV#CV sequence.

In what follows, I will first lay out specific hypotheses regarding these issues, followed by a section on experimental measurements and statistical procedures. In the results section (section 5.3), I will report on kinematic data and dynamical parameter settings, for domain-final lip opening gestures, domain-initial lip opening gestures, and V₁-to-V₂ lip closing gestures. Finally, section 5.4 will be devoted to general discussion.

5.1. Hypotheses

One of the underlying assumptions in a task dynamics model is that distinct kinematic patterns (as seen in the movement duration, displacement, and velocity) that might arise from various linguistic factors can be characterized by different settings of a specific dynamical parameter. Under this assumption, a hypothesis to be tested in this chapter concerns what dynamical parameter can best characterize accent-induced kinematic variation. As introduced in Chapter 1, several different observations have been reported in the literature regarding primary dynamical parameters underlying accented gestures. Some investigators (Edwards, et al., 1991; Beckman, et al., 1992; Harrington, et al., 1995) suggested that accent-induced kinematic variation in jaw opening movements is best captured by a single dynamical parameter, intergestural timing. Extending this to lip opening gestures, we test a hypothesis:

HYPOTHESIS 5.1: Accent-induced systematic kinematic variations in lip opening movements are governed by a change in intergestural timing.

To recall, the intergestural timing account predicts that under accent, the lip opening movements will be larger (in displacement), longer (in duration), but neither slower nor

faster (in movement velocity), as compared to unaccented counterparts. Furthermore, the acceleration duration (the time from the movement onset to the attainment of the peak velocity) will also be constant. (See section 1.3.3.1 in Chapter 1 for detailed descriptions of kinematic consequences of various mass-spring equation parameter manipulations.) This hypothesis will be tested separately for preboundary (domain-final) and postboundary (domain-initial) lip opening gestures, in order to examine whether the effects of Accent differ in different prosodic positions. Moreover, in testing this hypothesis, we will also look for the possibility that other dynamical parameter settings (e.g., a change in target or shrinking) underlie accent-induced kinematic patterning.

Relatedly, this chapter also tests whether the cross-boundary (V_1 -to- C_2) lip *closing* gesture shows a similar accent-induced kinematic patterning that can also be accounted for by a change in intergestural timing, testing an additional hypothesis:

HYPOTHESIS 5.2: Accent-induced kinematic variations for the cross-boundary (V_1 -to- C_2) lip closing gesture are governed by a change in intergestural timing.

Another hypothesis with respect to accent effects is regarding whether and how V_1 -to- C_2 lip closing gestures are affected by an accent not only in the preboundary syllable (V_1 Accent) but also in the postboundary syllable (V_2 Accent). Byrd & Saltzman (1998) define the V_1 -to- C_2 lip closing gesture as being postboundary because it is activated in order to form a lip constriction for $\#C_2$ which belongs to the postboundary syllable. According to this account, the V_1 -to- C_2 lip closing gesture should perhaps be influenced only by V_2 Accent. However, we know from the results in Chapter 3 that V_1 Accent influences the realization of lip opening gestures for V_1 , resulting in a larger lip aperture. Such an increase in lip aperture would contribute to an increase in displacement of the V_1 -to- C_2 lip closing movement when V_1 is accented, and possibly an increase in movement duration as well, because all else being equal, the farther the articulator travels the longer it would take. Therefore, a working hypothesis to be tested is:

HYPOTHESIS 5.3: The gesture for postboundary C_2 lip closing is influenced not only by postboundary V_2 Accent but also by preboundary V_1 Accent.

Under this hypothesis, we expect that at least some kinematic measures (e.g., displacement, duration, peak velocity) for the V_1 -to- C_2 lip closing movement will be influenced by Accent in both V_1 and V_2 . In testing this hypothesis, we will also examine how the effects of V_1 and V_2 Accent on the V_1 -to- C_2 lip closing gestures differ in terms of kinematics.

Turning to hypotheses pertinent to the boundary effect on gestures adjacent to prosodic boundaries, researchers have agreed that boundary-induced kinematic characteristics can be best interpreted as a result of a lowered stiffness (e.g., see Edwards, et al. (1991) and Beckman, et al. (1992) for the jaw opening gesture, Byrd & Saltzman (1998) for the

domain-final lip opening and cross-boundary lip closing gesture; and Byrd (2000) for the cross-boundary tongue raising gesture). Nonetheless, a few researchers (Edwards, et al., 1991; Byrd & Saltzman, 1998) showed some evidence that the domain-final gestures may also be associated with an increase in articulatory displacement, which has not been considered in terms of a dynamical parameter setting. In theory, however, there must be some dynamical parameter setting (e.g., a change in target or intergestural timing) that explains a change in displacement as a function of boundary type. If gestures at edges of prosodic domains are indeed associated with not only a lowered stiffness, but also an increased gestural target position, a change by shrinking (or rescaling) of the gestural profile (i.e., duration and displacement are scaled proportionally) may be the likely account for boundary-induced kinematic variation. In fact, as introduced in Chapter 1, the shrinking mechanism has been considered as one of the possible dynamical parameters by researchers (e.g., Harrington, et al., 1995; Byrd, et al., 2000). Thus, in this chapter, we test a hypothesis:

HYPOTHESIS 5.4: All lip opening and closing gestures at edges of prosodic domains are best characterized by a decrease in the rescaling parameter value.

The shrinking hypothesis predicts that at a higher prosodic boundary, lip movements will be larger, longer, but neither faster nor slower, as compared to movements at a lower prosodic boundary. The difference between the shrinking and the intergestural timing hypotheses lies in that the former gives rise to a change in acceleration duration which is correlated with the total movement duration, whereas the latter does not. In testing this hypothesis, I will also pay attention to whether gestures at domain-edges show an increase in displacement regardless of Accent, in order to compare the results with those reported by Edwards, et al. (1991) who showed an increase in displacement only when the gestures being compared are unaccented.

Finally, departing from dynamical aspects of articulation, a hypothesis is formulated regarding lip opening and closing displacements. As introduced in Chapter 1, it has been suggested that one of the major articulatory signatures for edges of prosodic domain is an expanded C-to-V or V-to-C displacement adjacent to a prosodic boundary. For example, Fougeron & Keating (1997) suggested that expanded V#C and #CV displacement underlies domain-initial strengthening phenomena, which enhances V#C and #CV contrast, ultimately leading to the enhancement of syntagmatic or structural contrast. A similar idea has been proposed in Hsu & Jun (1998). However, this assumption has not been tested using kinematic data. This motivates us to test a hypothesis regarding not only domain-initial #CV and cross-boundary V#C, but also domain-final CV# :

HYPOTHESIS 5.5: Both the lip opening and the lip closing displacements in CV#, V#C, and #CV are greater at higher prosodic boundaries than at lower ones.

This hypothesis predicts that the spatial difference between the onset and the target of the movement (i.e., displacement) will be greater in the lip opening and closing movements at higher prosodic boundaries than at lower ones.

5.2. Measurements and Statistics

A detailed measurement procedure is given in section 2.4.3 in Chapter 2. In this section, I will simply re-list measurements used in this study: (a) *displacement*, (b) *total movement duration*, (c) *time-to-peak-velocity*, (d) *deceleration duration*, and (e) *peak velocity*. Based on these measured variables, the relationships between some of these variables are further examined, in order to investigate detailed dynamical aspect of prosodic effects. Kinematic relationships that are to be examined include: (f) *relationship between total movement duration and time-to-peak-velocity*, (g) *relationship between total movement duration and displacement/velocity ratio*; and (h) *relationship between peak velocity and displacement*.

The systematic influence of prosodic factors on lip opening and closing gestures will be evaluated, based on repeated measures Analyses of Variance (ANOVA). The within-subject factors considered for the analysis are V_1 Accent (ACC, UNACC), V_2 Accent (ACC, UNACC), and Boundary Type (IP, ip, Wd). The results are reported based on repeated measures three-way ANOVAs performed separately for /a/ and /i/. As before, in order to avoid violating the sphericity assumption (with the Boundary Type factor which has more than two levels), a Huynh-Feldt corrected degree of freedom was used in generating F ratio and p values. (See section 2.6 in Chapter 2 for general remarks on statistical procedures.)

Next, for relationships between various measured kinematic variables, simple regression analyses are performed. Since we are interested in overall patterns across speakers, and since each speaker has different magnitude of absolute measurements, data are normalized across speakers by transforming measured kinematic values into percentages. Such a conversion returns for each datapoint that datapoint's percentage contribution to the sum of the entire dataset, which makes the variables more comparable across speakers. (Note that regressions that are run either on the raw data or on the converted data for each speaker separately result in the same significance and regression values.) In examining the relationship between measured kinematic variables, qualitative observations will be employed to see whether the observed distribution of datapoints can correspond to an idealized patterning in Figure 1.2, which is an analysis technique also employed by Fowler (1995).

5.3. Results

This section reports on the effects of Accent and Boundary Type on the kinematic characteristics of a preboundary (domain-final) C_1 -to- V_1 lip opening gesture (section 5.3.1), a postboundary (domain-initial) C_2 -to- V_2 lip opening gesture (section 5.3.3), and a

cross-boundary V_1 -to- C_2 lip closing gesture (section 5.3.5). Following each of these sections, a summary of prosodically conditioned kinematic variation is provided, followed by discussion of whether and how the observed kinematic variations can be accounted for in the framework of the mass-spring task dynamical model (sections 5.3.2, 5.3.4, 5.3.6).

5.3.1. Domain-final C_1 -to- V_1 lip opening gesture

5.3.1.1. Displacement

Effect of Accent. As seen in Figure 5.1a, C_1 -to- V_1 displacement is significantly greater when accented than when unaccented, for both /ba#/ and /bi#/ ($F[1,5]=19.982$, $p<0.01$ for /ba#/; $F[1,5]=88.184$, $p<0.001$ for /bi/).

Effect of Boundary Type. /bi#/ shows an increased displacement before a higher prosodic boundary ($F[1.1,5.8]=6.404$, $p<0.05$), whereas /ba#/ does not ($F[1.2,6.0]=0.705$, $p=0.461$). However, there is a significant Accent by Boundary interaction ($F[1.3,6.4]=5.99$, $p<0.05$) for /ba#/. *Posthoc* comparisons show that the interaction is because there is a pattern of IP>(ip=Wd) only when /ba#/ is unaccented. (Examining individual speakers' mean differences suggest that one speaker (S5) showed a unique pattern, while the other five speakers showed the same pattern.)

5.3.1.2. Peak Velocity

Effect of Accent. The accented CV# is associated with a higher peak velocity than the unaccented CV for both /ba#/ and /bi#/ ($F[1,5]=15.921$, $p<0.01$; $F[1,5]=62.582$, $p<0.001$, respectively), as can be seen in Figure 5.1b.

Effect of Boundary Type. Neither a main effect of Boundary Type nor a significant interaction among Boundary Type and other factors is obtained for both /ba#/ and /bi#/ , as can be seen in Figure 5.1b. (Note, however, that in the case of /ba#/ under accent, C_1 -to- V_1 peak velocity tends to be higher for Word than IP ($p<0.05$, weak evidence). Two speakers (S1, S2) showed a pattern opposite of this trend, while four speakers showed the same direction in accord with this trend.)

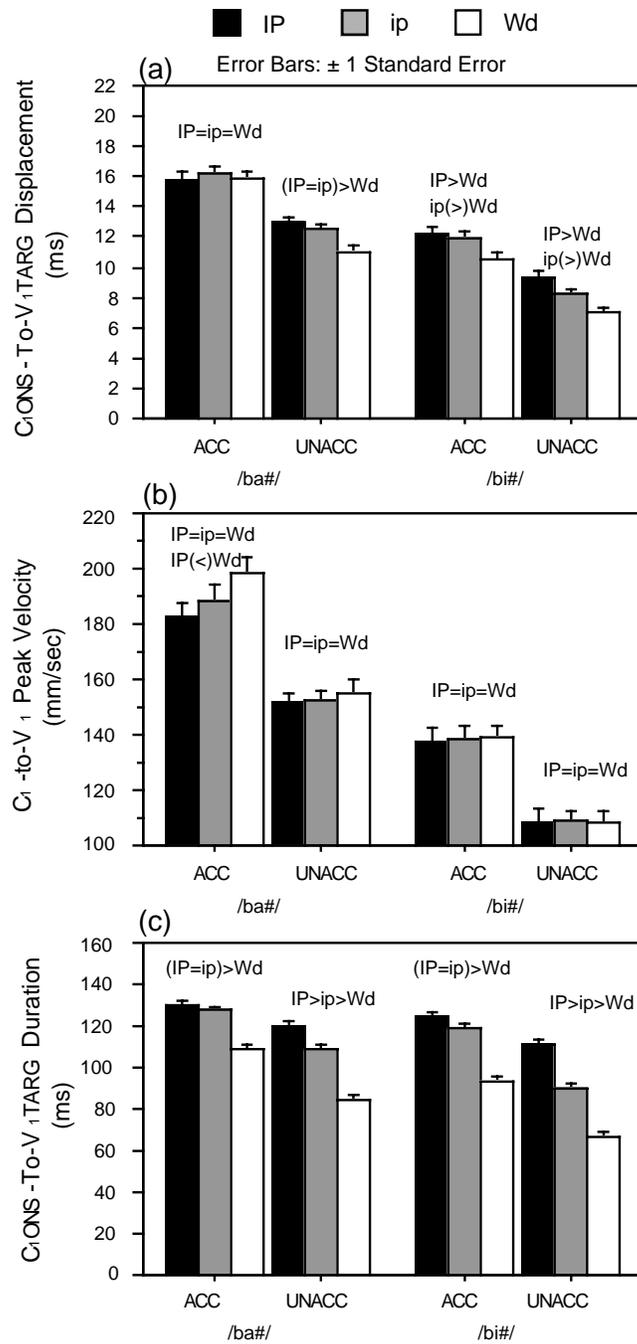


Figure 5.1. Effects of Accent and Boundary Type on (a) C₁-to-V₁ displacement, (b) C₁-to-V₁ peak velocity, and (c) on C₁-to-V₁ movement duration C₁ONS-TO-V₁TARG, separated by V₁ Type. Results of pairwise comparisons (Bonferroni/Dunn) are provided with '>' referring to p<0.01, '>)', p<0.05.

5.3.1.3. Total Movement Duration: $C_{1ONS-TO-V_{1TARG}}$

Effect of Accent. $C_{1ONS-TO-V_{1TARG}}$ is significantly longer when accented than when unaccented, regardless of V_1 Type and Boundary Type (main effects: $F[1,5]=37.405$, $p<0.005$ for /ba#/; $F[1,5]=74.754$, $p<0.001$ for /bi#/), as shown in Figure 5.1c.

Effect of Boundary Type. Both /ba#/ and /bi#/ show a Boundary Type effect on $C_{1ONS-TO-V_{1TARG}}$ ($F[1.1,5.6]=23.852$, $p<0.005$ for /ba#/; $F[1.6,8.0]=66.137$, $p<0.001$ for /bi#/). As shown in Figure 5.1c, $C_{1ONS-TO-V_{1TARG}}$ generally increases progressively as the boundary type becomes higher from Word to IP. There is a significant Boundary Type by Accent interaction ($F[2,10]=5.838$, $p<0.025$ for /ba#/; $F[2,10]=4.369$, $p<0.05$ for /bi#/), due to the fact that the effect is more robust for unaccented CV# (IP>ip>Wd) than for accented CV# (IP=ip>Wd). No other interactions are found.

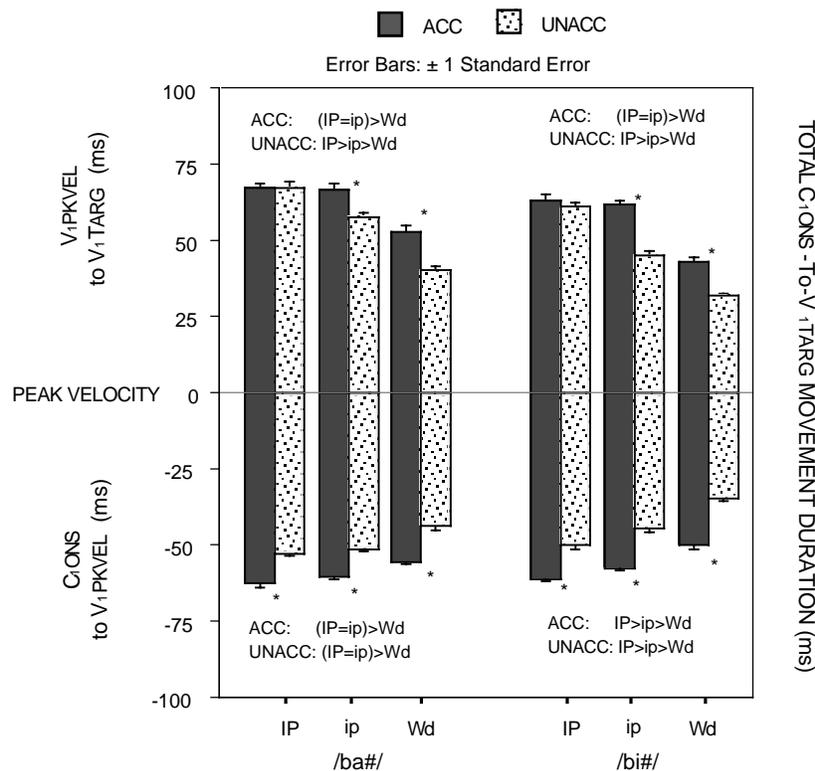


Figure 5.2. Effects of Accent and Boundary Type on two component durations $C_{1ONS-TO-V_{1PKVEL}}$ (time-to-peak-velocity) and $V_{1PKVEL-TO-V_{1TARG}}$ (deceleration duration), separated by V_1 Type. Bar graphs are aligned at the attainment of peak velocity. Results of pairwise comparisons (Bonferroni/Dunn) are provided with '>' and '*' referring to $p<0.01$.

5.3.1.4. $C_{1\text{ONS-TO-}V_{1\text{PKVEL}}}$ (time-to-peak-velocity) and $V_{1\text{PKVEL-TO-}V_{1\text{TARG}}}$ (deceleration duration)

Effect of Accent. Both /ba#/ and /bi#/ show a main effect of Accent on $C_{1\text{ONS-TO-}V_{1\text{PKVEL}}}$ ($F[1,5]=44.183$, $p<0.001$ for /ba#/; $F[1,5]=103.815$, $p<0.001$ for /bi#/) and $V_{1\text{PKVEL-TO-}V_{1\text{TARG}}}$ ($F[1,5]=16.320$, $p<0.01$ for /ba#/; $F[1,5]=38.075$, $p<0.005$ for /bi#/). This means that the two component durations (acceleration and deceleration) of the total movement interval ($C_{1\text{ONS-TO-}V_{1\text{TARG}}}$) both contribute to the Accent effect on the total movement duration. This effect is shown in Figure 5.2.

Effect of Boundary Type. Boundary Type has a main effect on $C_{1\text{ONS-TO-}V_{1\text{PKVEL}}}$ ($F[1.2,5.9]=8.630$, $p<0.025$ for /ba#/; $F[1.8,9.1]=49.293$, $p<0.001$ for /bi#/) and $V_{1\text{PKVEL-TO-}V_{1\text{TARG}}}$ ($F[2,10]=8.051$, $p<0.01$ for /ba#/; $F[1.3,6.6]=38.791$, $p<0.001$ for /bi#/). As shown in Figure 5.2, both component durations are longer at a progressively higher prosodic boundary, showing either a two-way ((IP=ip)>Wd) or a three-way (IP>ip>Wd) distinction.

There is no Boundary Type by Accent interaction on $C_{1\text{ONS-TO-}V_{1\text{PKVEL}}}$, but $V_{1\text{PKVEL-TO-}V_{1\text{TARG}}}$ shows a Boundary Type by Accent interaction ($F[2,10]=8.051$, $p<0.01$ for /ba#/; $F[2,10]=9.529$, $p<0.01$ for /bi#/). This interaction is due to the fact that the ACC/UNACC difference is not significant when CV# precedes IP, and that $V_{1\text{PKVEL-TO-}V_{1\text{TARG}}}$ (the second component) shows a more robust effect of Boundary Type when unaccented than when accented. This interaction is consistent with what was found for the total movement duration ($C_{1\text{ONS-TO-}V_{1\text{TARG}}}$) which also showed a more robust effect of Boundary Type when unaccented.

5.3.2. Discussion about dynamics underlying kinematic differences for $C_{1\text{-to-}V_{1}}$ lip opening gesture

Thus far, we have examined how various kinematic variables for the $C_{1\text{-to-}V_{1}}$ lip opening gesture are influenced by Accent and Boundary Type. The results are summarized in Table 5.1. The basic findings are that the $C_{1\text{-to-}V_{1}}$ lip opening movement is longer, larger and faster under accent, and it is longer, sometimes larger, but not necessarily faster before a higher prosodic boundary. In what follows, based on these results and regression analyses, we discuss whether and how kinematic differences due to Accent and Boundary Type can be accounted for by various dynamical parameter manipulations.

Table 5.1. Summary of kinematics for domain-final C₁-to-V₁ lip opening gestures.

Kinematic measures	When accented		At a higher boundary	
	/ba#/	/bi#/	/ba#/	/bi#/
Displacement	larger	larger	ACC: no change UNACC: larger (excl. S5)	larger
Total Movement Duration	longer	longer	longer	longer
C ₁ ONS-To-V ₁ PKVEL (TIME-TO-PEAK-VELOCITY)	longer	longer	longer	longer
V ₁ PKVEL-To-V ₁ TARG (DECELERATION DURATION)	longer	longer	longer	longer
Peak Velocity	higher	higher	ACC: lower (excl. S1,S2) UNACC: no change	no change

5.3.2.1. Dynamical aspect of accent effects on C₁-to-V₁ (C₁V₁#) lip opening gesture

Regarding ACC/UNACC differences in lip opening gestures, we found that an accented C₁V₁# lip opening gesture is associated with an increase in all kinematic parameter values: that is, an increase in displacement, duration, time-to-peak-velocity (C₁ONS-To-V₁PKVEL), and peak velocity, showing larger, longer, and faster movement, as summarized in Table 5.1. When these results are compared to the summary chart for kinematic consequences of various mass-spring parameter manipulations (see Table 1.1 in Chapter 1), there seems to be no single specific mass-spring parameter that can account for ACC/UNACC differences. If intergestural timing were the only dynamical parameter, we would have observed an increase in both displacement and duration but no change in time-to-peak-velocity and peak velocity. If gestural target (or underlying amplitude) were the only dynamical parameter, there would have been no change in total movement duration and time-to-peak-velocity. In a pure change in stiffness, there would have been no change in displacement but a decrease in peak velocity for accented gesture. Finally, in a pure change by shrinking, there would have been no change in peak velocity. However, none of these idealized descriptions match the results presented here. In what follows, I further explore kinematic relationships in order to see if there is any dynamical account that is favored by the present data.

Temporal Relationships. One way of testing the stiffness hypothesis is the technique employed by Byrd & Saltzman (1998), and Byrd (2000) by examining the relationship between total movement duration and time-to-peak-velocity (C₁ONS-To-

V_{1PKVEL}). As reported earlier, time-to-peak-velocity is influenced by Accent, such that a longer time-to-peak-velocity is associated with accented lip opening gestures. Consequently, if there is a close relationship between duration and time-to-peak-velocity kinematic measures, it is likely that the elongated total movement duration under accent is due to a decrease in stiffness. In fact, regression analyses show that there is generally quite a robust and positive relationship between duration and time-to-peak-velocity ($R^2 = 0.366$ to 0.734 for /#ba/; $R^2 = 0.468$ to 0.939 for /bi#/) (see Table A.1 in Appendix II).

However, considering the nature of part-whole correlation (which generally shows a relatively high correlation because the independent variable, time-to-peak-velocity, is part of the dependent variable, total movement duration), some cases with smaller R^2 values (e.g., /ba#/, IP, $R^2=0.366$; /ba#/, ip, $R^2=0.435$; /bi#/, IP, $R^2=0.468$) do not seem to fully support the stiffness account.

In contrast, the total movement duration and the deceleration duration (the second durational component of the total movement duration) are even more highly related ($R^2 = 0.676$ to 0.901 for /#ba/; $R^2 = 0.747$ to 0.928 for /bi#/) (see Table A.1 in Appendix II). In the current mass-spring dynamical model, variation in deceleration can be achieved by three different mechanisms. The first possibility is simply a change in stiffness. The second possibility is a change in intergestural timing, given the assumption that deceleration duration is correlated with the timing of the initiation of the following gesture. (To recall, an earlier or later timing of the following gesture would affect only the second durational component.) The third possibility is shrinking, with stiffness and target being proportionally scaled. Since the variation in total movement duration is much more closely related to the deceleration duration than to time-to-peak velocity, one might gather that a change in intergestural timing is likely to be the primary source as far as the temporal relationships are concerned. However, this intergestural timing account is critically weakened by a significant change in peak velocity (the-larger-the-faster pattern), which would not be observable in a pure change in intergestural timing. Likewise, in a pure change by shrinking, there should be no change in peak velocity either. Thus, we can posit that a change in stiffness is the most likely source for variation in the deceleration duration.

In short, the results regarding temporal relationships suggest that durational differences as a function of accent may be due not only in part to variation in time-to-peak-velocity but also in even larger part to variation in deceleration duration, both of which are presumably due to a change in stiffness.

Relationship between duration and displacement/velocity ratio. Turning to the duration-displacement/velocity-ratio relationship, Figure 5.3 shows results for this relationship for each vowel type (/ba#/ vs. /bi#/), separately by Boundary Type (IP, ip, Wd). Each plot shows in general quite a close fit of points to the regression line, with R^2 ranging from 0.51 to 0.97 (in all cases, $p < 0.001$). The first point to be made is that the relationship between duration and displacement/velocity ratio does not support either the

amplitude (target) account or the intergestural timing account. Recall that if target is a major parameter, there should be no separation among points (see Figure 1.2d for an idealized pattern in a change in target); and if truncation or intergestural timing is a major parameter, there should be no correlation between duration and displacement/velocity ratio (see Figure 1.2f). Thus, the possibilities are reduced to the stiffness and the shrinking parameters, given the fact that there is a relatively close fit of points to the regression line (see Figures 1.3b and h). Further, there is quite a remarkable separation among points distinguishing ACC from UNACC, lending support to both the stiffness and the shrinking accounts, especially when comparisons are made at a word boundary for both /ba#/ and /bi#/ and at an ip boundary for /bi#/.

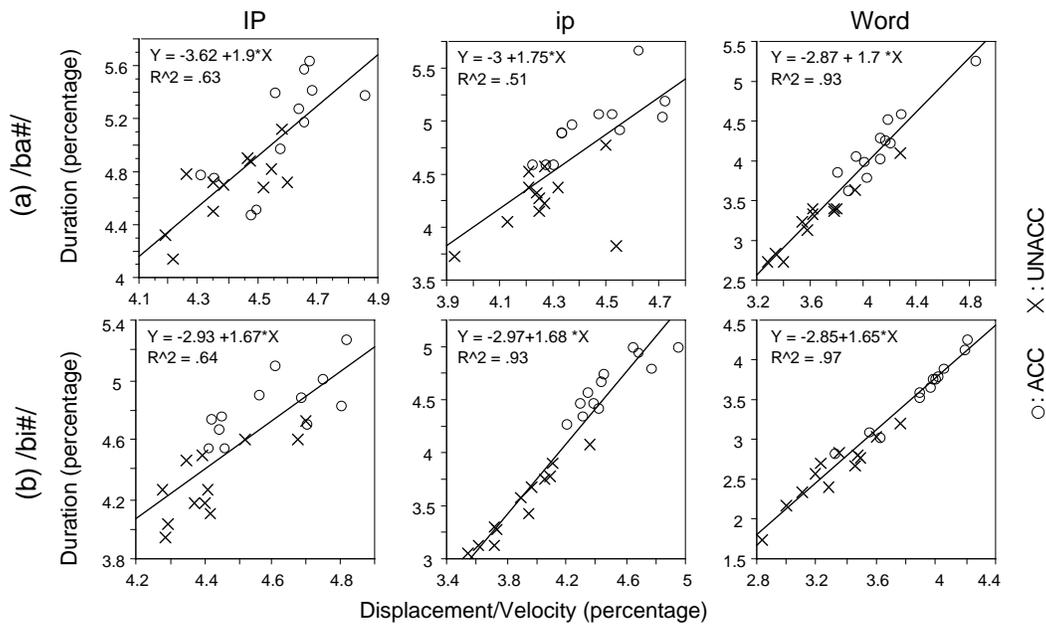


Figure 5.3. Effect of Accent on relationship between duration and displacement/velocity ratio for C1-to-V1 lip opening gesture, separated by V1 Type and Boundary Type. (a) /ba#/ in upper panels and (b) /bi#/# in lower panels with results of regression analyses.

Relationship between displacement and peak velocity. Now, if a change either in stiffness or by shrinking is a major dynamical mechanism underling the accent-induced kinematic patterning, we would be able to single out one of the two possibilities by examining the relationship between displacement and peak velocity, which would show a pattern matching either Figure 1.2a (showing vertical distribution of the datapoints in the case of the stiffness account) or Figure 1.2g (showing horizontal distribution of the datapoints in the case of the shrinking account). Let's now look at Figure 5.4. Each plot in the figure matches neither idealized picture. Instead, the figure shows a highly close fit of datapoints to the regression line with at least $R^2 > 0.81$ ($p < 0.001$), showing a proportional relationship between peak velocity and displacement (i.e., diagonal distribution of the

datapoints). Further, there is quite a noticeable separation between ACC and UNACC. This pattern best matches the idealized picture in Figure 1.2c which is predicted under a change in target.

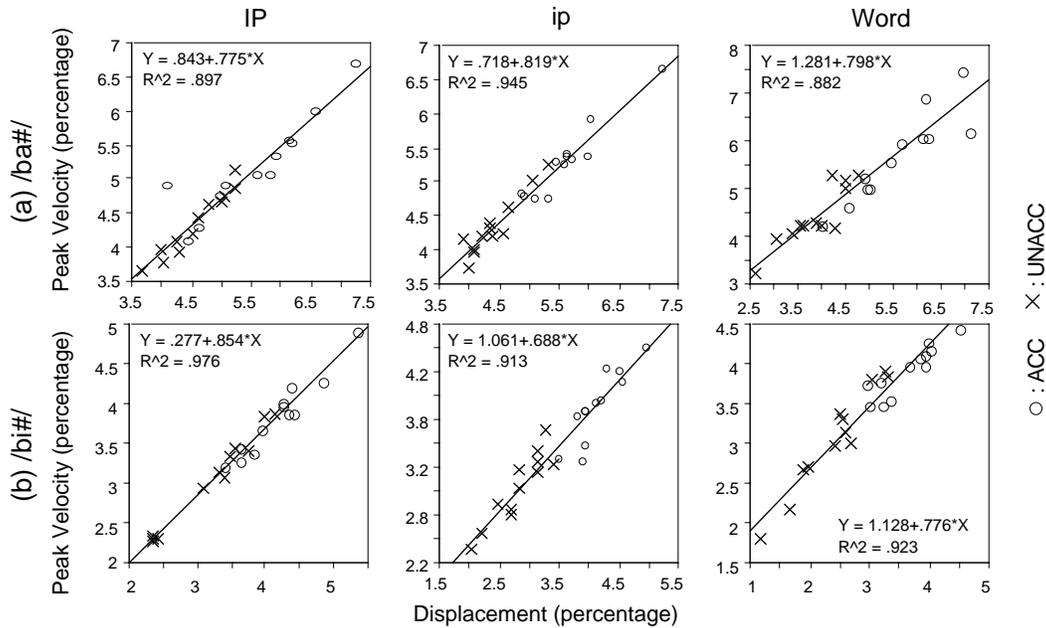


Figure 5.4. Effect of Accent on relationship between peak velocity and displacement for C_1 -to- V_1 lip opening gesture, separated by V_1 Type and Boundary Type. (a) /ba#/ in upper panels and (b) /bi#/ in lower panels with results of regression analyses.

Thus far, we have examined whether and how the kinematic pattern of larger, longer and faster movements for accented C_1 -to- V_1 lip opening gestures can be accounted for by a single dynamical parameter setting. However, we found that no single dynamical account could successfully explain the accent-induced kinematic pattern observed here. It appears that we need at least more than one dynamical parameter to account for one single prosodic phenomenon, Accent. For example, the larger and faster movement requires a change in target, and the longer movement a change in stiffness.

5.3.2.2. Dynamical aspect of boundary effects on C_1 -to- V_1 lip opening gesture

As summarized in Table 5.1, the patterning of kinematics in common to both /ba#/ and /bi#/ is that a C_1 -to- V_1 lip opening gesture at a higher boundary is associated with an increase in total movement duration, time-to-peak-velocity (C_1 ONS-TO- V_1 PKVEL) and deceleration duration, with no increase in peak velocity, i.e., showing a longer, but not faster movement.

There are also kinematic differences due to a Vowel Type and Accent interaction. For /ba#/ when accented, boundary-induced kinematic variation appears to best match descriptions for a change in stiffness (see Table 1.1 in Chapter 1): the lip opening gesture is longer (both in total movement duration and time-to-peak-velocity) and slower, but not larger. However, for other cases (/ba#, UNACC; /bi#, ACC or UNACC), the lip opening gesture at a higher prosodic boundary is associated with an increase not only in duration and time-to-peak velocity, but also in displacement with no change in peak velocity. This pattern does not match descriptions for a pure change in stiffness. If anything, the longer and larger kinematic pattern (with an increase in both total movement duration and time-to-peak-velocity and no change in peak velocity) appears to be consistent with shrinking.

To sum up, the kinematic patterns observed so far favor the stiffness account for accented /ba#/ but the shrinking account for other cases (/ba#, UNACC; /bi#, ACC or UNACC).

Both the stiffness and shrinking accounts are further evident in (1) a close relationship between total movement duration and time-to-peak-velocity ($R^2 = 0.73$ to 0.78 for /ba#/; $R^2 = 0.86$ to 0.96 for /bi#, see Table A.2 in Appendix II) and (2) a close relationship between duration and displacement/velocity ratio with a remarkable separation among boundary types (see Figure 5.5 in comparison with Figures 1.3b and h in Chapter 1).

Turning to the relationship between peak velocity and displacement, if the boundary-induced kinematic pattern found for accented /ba#/ were due to a pure change in stiffness, datapoints would be vertically scattered, showing a distinct separation between ACC and UNACC (see the idealized picture in Figure 1.2a), and if the kinematic pattern found for other cases is due to a pure change in shrinking, datapoints would be horizontally scattered (see the idealized picture in Figure 1.2g). Contrary to these predictions, however, each plot shown in Figure 5.6 matches neither idealized picture, lending no real support to either the stiffness account or the shrinking account. Instead, there is an interesting pattern emerging from the plots in Figure 5.6. The datapoints are generally scattered diagonally with the datapoints for IP clustering beneath the regression line to the right, and the datapoints for Wd clustering above the regression line to the left.²

² Since the datapoints are pooled across speakers, one might wonder if each speaker actually shows either the horizontal or the vertical scattering of datapoints, but speaker-dependent varying magnitude results in such a diagonal distribution of datapoints. However, the examination of individual speakers revealed no such situation.

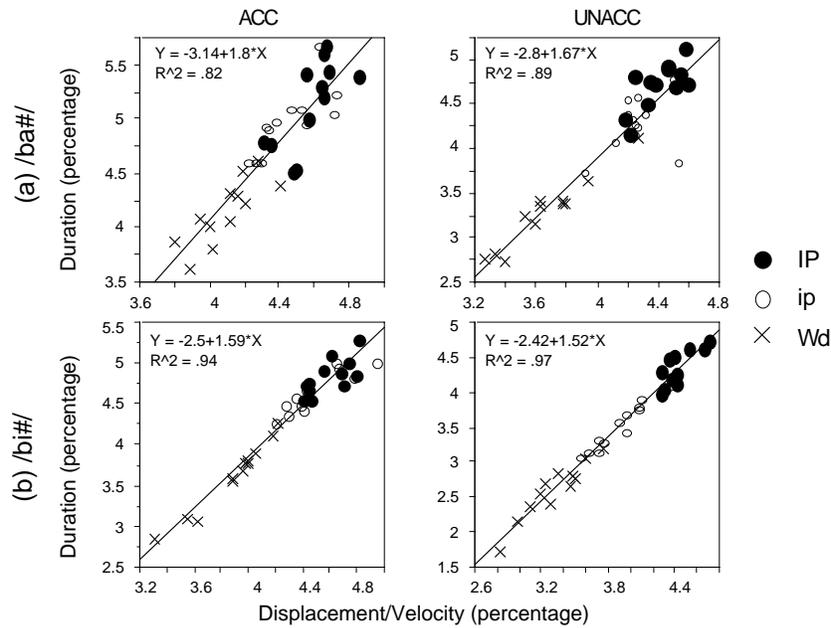


Figure 5.5. Effect of Boundary Type on relationship between duration and displacement/velocity ratio for C₁-to-V₁ lip opening gesture, separated by V₁ Type and Accent. (a) /ba#/ in upper panels and (b) /bi#/ in lower panels with results of regression analyses.

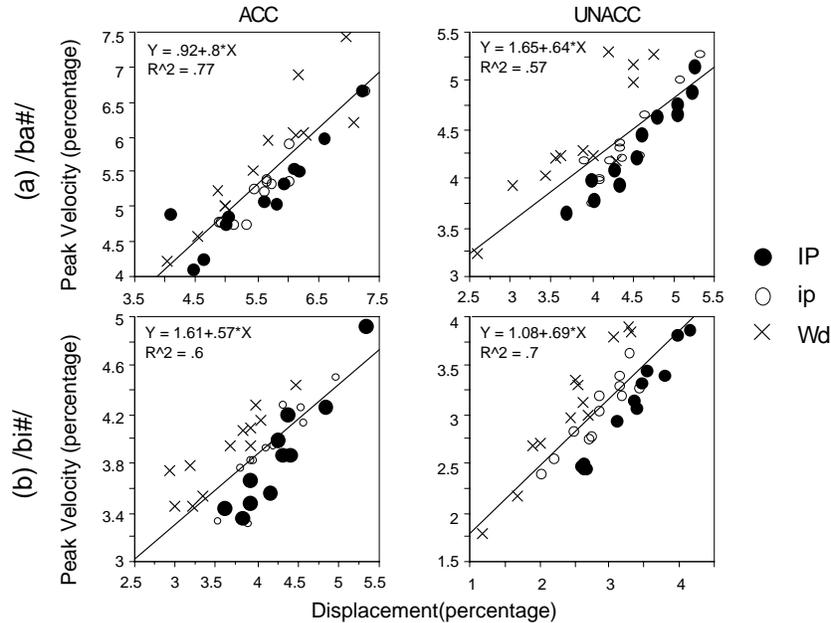


Figure 5.6. Effect of Boundary Type on relationship between duration and displacement/velocity ratio for C₁-to-V₁ lip opening gesture, separated by V₁ Type and Accent. (a) /ba#/ in upper panels and (b) /bi#/ in lower panels with results of regression analyses.

To sum up, while the stiffness (for /ba#/ACC) and shrinking accounts (for /ba#/, UNACC; /bi#/, ACC or UNACC) for the boundary-induced kinematic variation are favored by the categorical patterns suggested by ANOVA, and by the relationship between duration and displacement/velocity ratio, the relationship between peak velocity and displacement suggests that the kinematic patterns are not fully accounted for by either the stiffness or the shrinking parameter setting.

5.3.3. Domain-initial C₂-to-V₂ lip opening gesture

5.3.3.1. Displacement (#C₂V₂)

Effect of Accent. As shown in Figure 5.7a, an accented C₂V₂ has a significantly greater displacement than an unaccented one for both /#ba/ and /#bi/ (F[1,5]=29.541, p<0.005 for /#ba/; F[1,5]=41.823, p<0.005 for /#bi/).

Effect of Boundary Type. There is no systematic boundary-induced variation in C₂-to-V₂ displacement for either /#ba/ or /#bi/. However, there is a significant Boundary Type by Accent interaction for both /#ba/ and /#bi/ (F[1.6,8.1]=6.345, p<0.025 for /#ba/; F[2,10]=4.650, p<0.05 for /#bi/). As can be seen in Figure 5.7a, although there is no consistent effect of Boundary Type, one noteworthy point is that unaccented /#ba/ shows a pattern of IP>Wd (p<0.01), whereas unaccented /#bi/ shows an inconsistent pattern of IP>ip and ip<Wd (p<0.01).

5.3.3.2. Peak Velocity (#C₂V₂)

Effect of Accent. Peak velocity of C₂-to-V₂ lip opening movement is significantly higher for accented than for unaccented C₂V₂ (F[1,5]=17.813, p<0.01 for /#ba/; F[1,5]=37.696, p<0.005 for /#bi/), as can be seen in Figure 5.7b.

Effect of Boundary Type. There is no main effect of Boundary Type on peak velocity. However, there is a Boundary Type by Accent interaction for /#bi/ (F[1.9,9.8]=5.519, p<0.025). This interaction is because unaccented /#bi/ shows inconsistent patterns of IP>ip and of ip<Wd (p<0.01) while accented /#bi/ shows no differences due to boundary types at all (Figure 5.7b).

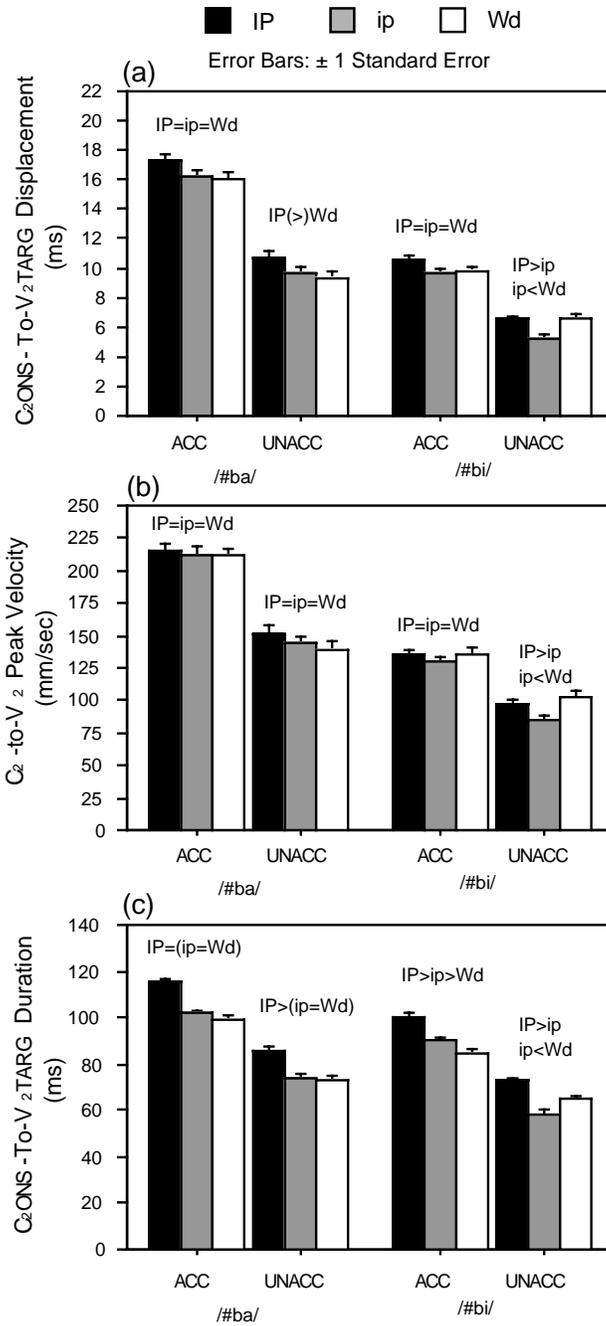


Figure 5.7. Effects of Accent and Boundary Type on (a) C₂-to-V₂ displacement, C₂-to-V₂, (b) peak velocity, and (c) C₂-to-V₂ movement duration C₂ONS-To-V₂TARG, separated by V₂ Type. Results of pairwise comparisons (Bonferroni/Dunn) are provided with '>' referring to p<0.01.

5.3.3.3. Total Movement Duration: $C_{2ONS-T0-V_{2TARG}}$ ($\#C_2V_2$)

Effect of Accent. As can be seen in Figure 5.7c, accented C_2V_2 is associated with a longer $C_{2ONS-T0-V_{2TARG}}$, as compared to unaccented counterpart ($F[1,5]=79.403$, $p<0.001$ for $\#ba/$; $F[1,5]=60.779$, $p<0.001$ for $\#bi/$).

Effect of Boundary Type. C_2 -to- V_2 lip movement duration also shows a main effect of Boundary Type ($F[1.8,9.3]=16.527$, $p<0.005$ for $\#ba/$; $F[2,10]=9.913$, $p<0.005$ for $\#bi/$) such that it is generally longer for a higher boundary type (especially IP) than a lower boundary type (Word), as seen in Figure 5.7c. There is also a Boundary Type by Accent interaction for $\#bi/$, in that accented $\#bi/$ shows a pattern of $IP>ip>Wd$, while unaccented $\#bi/$ shows a pattern of $IP>ip$ and $ip<Wd$ (consistent with findings for displacement and peak velocity).

5.3.3.4. $C_{2ONS-T0-V_{2PKVEL}}$ and $V_{2PKVEL-T0-V_{2TARG}}$ ($\#C_2V_2$)

Effect of Accent. There are main effects of Accent on both $C_{2ONS-T0-V_{2PKVEL}}$ and $V_{2PKVEL-T0-V_{2TARG}}$ for both $\#ba/$ and $\#bi/$ (main effects on the former: $F[1,5]=51.613$, $p<0.001$ for $\#ba/$; $F[1,5]=61.274$, $p<0.001$ for $\#bi/$; main effects on the latter: $F[1,5]=54.861$, $p<0.001$ for $\#ba/$; $F[1,5]=43.987$, $p<0.001$ for $\#bi/$). In other words, the elongated lip opening movement duration for accented $\#C_2V_2$ is due to the lengthening of not only the time-to-peak velocity ($C_{2ONS-T0-V_{2PKVEL}}$), but also the deceleration interval ($V_{2PKVEL-T0-V_{2TARG}}$). This effect is shown in Figure 5.8, in which accented C_2V_2 is significantly longer than unaccented C_2V_2 in the intervals both preceding and following the moment of peak velocity.

Effect of Boundary Type. For the deceleration interval ($V_{2PKVEL-T0-V_{2TARG}}$), there is no significant main effect of Accent. On the other hand, time-to-peak-velocity ($C_{2ONS-T0-V_{2PKVEL}}$) shows a main effect of Accent ($\#ba/$, $F[1.9,9.4]=25.847$, $p<0.001$; $\#bi/$, $F[2,10]=17.024$, $p<0.005$). Thus, boundary-induced variation in total movement duration of C_2 -to- V_2 lip opening gesture is mainly due to the durational variation in time-to-peak-velocity. As shown in Figure 5.8, $C_{2ONS-T0-V_{2PKVEL}}$ is longer for IP than for ip or Wd at $p<0.01$, showing a pattern of $IP>(ip=Wd)$ in all cases. There is no Boundary Type by Accent interaction on any variables.

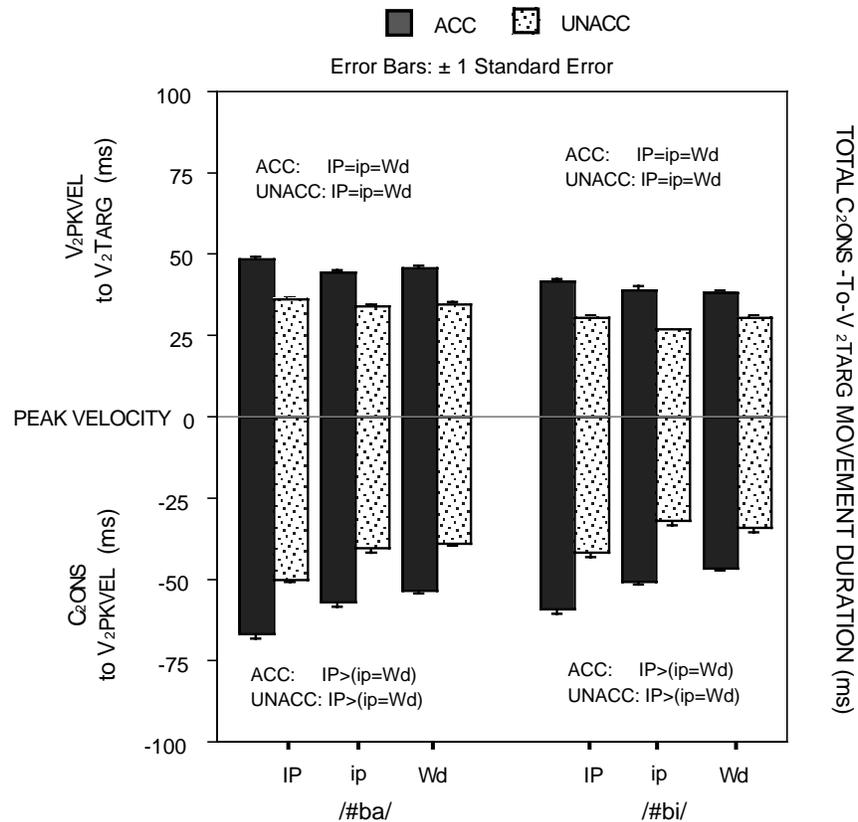


Figure 5.8. Effects of Accent and Boundary Type on two component durations C_1 ONS-To- V_1 PKVEL and V_1 PKVEL-To- V_1 TARG, separated by V_1 Type. Bar graphs are aligned at the attainment of peak velocity. Results of pairwise comparisons (Bonferroni/Dunn) are provided with ‘>’ and ‘*’ referring to $p < 0.0$

5.3.4. Summary and discussion about dynamics underlying kinematic differences for C_2 -to- V_2 lip opening gesture

Thus far, we have examined how various kinematic measures for # C_2V_2 lip opening gestures are influenced by Accent and Boundary Type. The results are summarized in Table 5.2. To recapitulate briefly, under accent the domain-initial (C_2 -to- V_2) lip opening movement is longer, larger and faster (being consistent with the findings for the domain-final C_2V_2 #); and after a higher prosodic boundary, it is generally longer but not necessarily faster and larger. A larger displacement after a higher boundary is found only for /#ba/ when it is *unaccented*. In what follows, as was the case in the previous section, we examine these results and regression analyses, and explore whether and how prosodically conditioned kinematic differences in domain-initial lip opening gestures can be accounted for in terms of various dynamical parameter manipulations.

Table 5.2. Summary of kinematics for domain-initial C₂-to-V₂ lip opening gestures.

Kinematic measures	When accented		At a higher boundary	
	/#ba/	/#bi/	/#ba/	/#bi/
Displacement	larger	larger	ACC: no change UNACC: larger	ACC: no change UNACC: <i>inconsistent</i>
Total Movement Duration	longer	longer	longer	ACC: longer UNACC: <i>inconsistent</i>
C ₂ ONS-T ₀ -V ₂ PKVEL	longer	longer	longer	longer
V ₂ PKVEL-T ₀ -V ₂ TARG	longer	longer	no change	no change
Peak Velocity	higher	higher	no change	ACC: no change UNACC: <i>inconsistent</i>

5.3.4.1. Dynamical aspect of accent effects on C₂-to-V₂ (#C₂V₂) lip opening gesture

As was the domain-final case (C₁V₂#), we found that accented domain-initial #C₂V₂ is associated with an increase in all kinematic measures such as displacement, duration, time-to-peak-velocity (C₁ONS-T₀-V₁PKVEL), and peak velocity. These results suggest no single specific mass-spring parameter that can account for ACC/UNACC differences. Two possibilities emerges from the results. First, the increase in time-to-peak-velocity for an accented gesture indicates an increase in stiffness. Second, the increase in displacement along an increase in peak velocity is suggestive of a potential increase in target. Again, neither the shrinking account nor the intergestural timing account is fully supported due to a change in peak velocity.

Next, relationships among various kinematic measures are further discussed, with the same analysis techniques employed in sections for domain-final lip opening gestures. (Note that for the sake of simplicity, this section summarizes results, without a full discussion for each relationship.)

First, two possibilities, a change in stiffness and a change by shrinking, are evident in (1) a close durational relationship between total duration and time-to-peak-velocity (with R² ranging from 0.85 to 0.92 for /#ba/, and from 0.92 to 0.95 for /#bi/, see Table A.3 in Appendix II) and (2) a close relationship between duration and displacement/velocity ratio with substantial separation among points distinguishing ACC from UNACC as shown in Figure 5.9, which is consistent with two idealized patterns in Figure 1.2b (a change in stiffness) and Figure 1.2h (a change by shrinking).

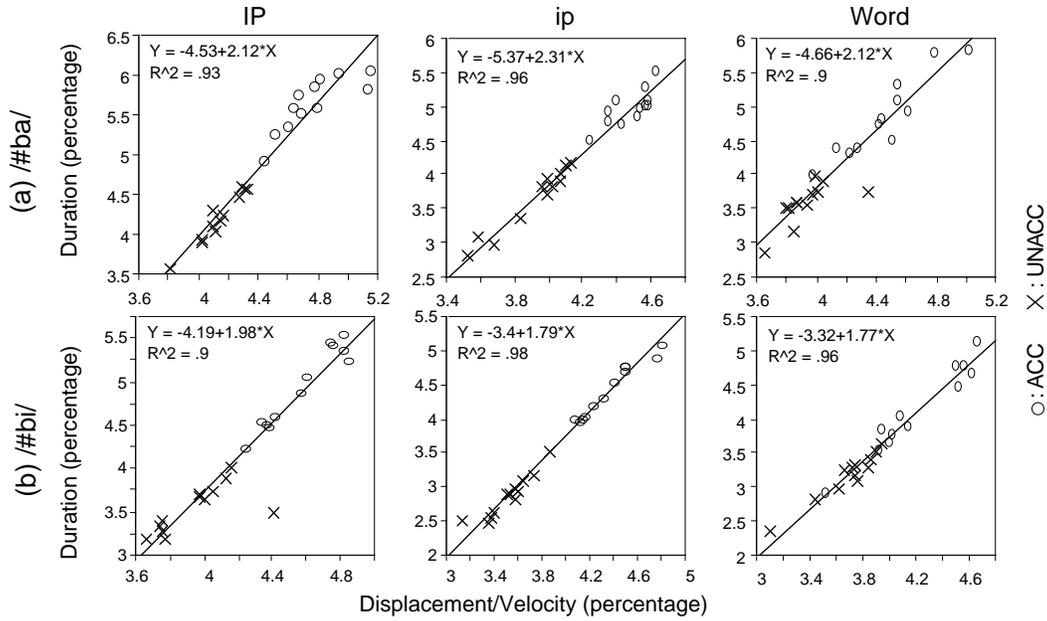


Figure 5.9. Effect of Accent on relationship between duration and displacement/velocity ratio for C₂-to-V₂ lip opening gesture, separated by V₂ Type and Boundary Type. (a) /#ba/ in upper panels and (b) /#bi/ in lower panels with results of regression analyses.

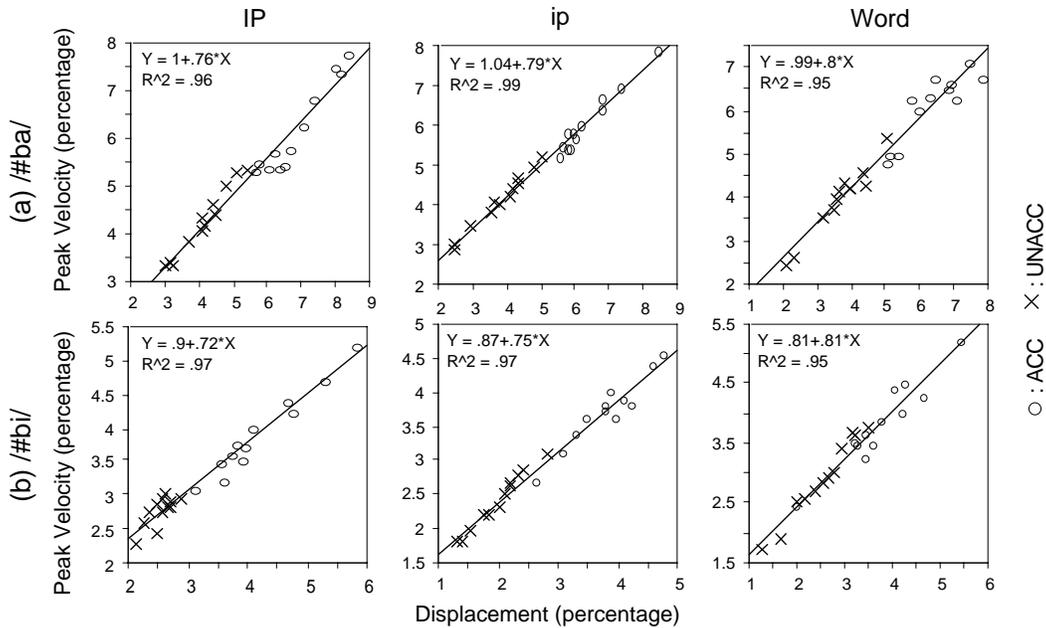


Figure 5.10. Effect of Accent on relationship between peak velocity and displacement for C₂-to-V₂ lip opening gesture, separated by V₂ Type and Boundary Type. (a) /#ba/ in upper panels and (b) /#bi/ in lower panels with results of regression analyses.

However, as was the case for the domain-final C_1V_2 lip opening, these two possibilities are not supported by the relationship between peak velocity and displacement. As can be seen in Figure 5.10, there is a close relationship between peak velocity and displacement (with datapoints being separated into ACC and UNACC groups), which favors a change in target (compare Figure 5.10 with the idealized pattern in Figure 1.2c in Chapter 1).

To sum, as was the case for domain-final CV# lip opening gestures, no particular dynamical parameter setting can be singled out as an absolute dynamical mechanism underling ACC/UNACC kinematic differences.

5.3.4.2. Dynamical aspect of boundary effects on C_2 -to- V_2 ($\#C_2V_2$) lip opening gesture

As summarized in Table 5.2 in the previous section, /#ba/ and /#bi/ show somewhat different kinematic results, depending on Accent conditions. Consider first the case when the gestures being compared are accented. When accented, C_2 -to- V_2 lip opening gestures after a higher prosodic boundary are associated with an increase in duration and time-to-peak velocity ($C_{2ONS-T0-V_2PKVEL}$), but with no change in displacement and peak velocity. According to the chart in Table 1.1, a dynamical parameter change that most closely matches these results is a change in stiffness, which predicts an increase in both duration and time-to-peak velocity. However, no change in peak velocity weakens the stiffness account. (In a pure change in stiffness, peak velocity should also change (the less stiff, the lower the peak velocity.) On the other hand, the intergestural timing account is favored by no change in peak velocity, but critically weakened by the fact that the deceleration duration is not influenced by Boundary Type. (Recall that the second durational component, deceleration duration, must change substantially as the timing of the following gesture varies.) The shrinking account is also ruled out because, if it held, there would be a change in displacement.

Turning to the cases in which the gestures being compared are unaccented, /#ba/ shows an increase in displacement, duration and time-to-peak-velocity with no change in peak velocity after a higher prosodic boundary. This pattern best matches a change in shrinking (see Table 1.1 in Chapter 1). Unlike /#ba/, /#bi/ shows inconsistent variation, as summarized in Table 5.2 above. On the one hand, comparing only the higher two boundary types (IP vs. ip), IP is associated with an increase in duration and time-to-peak-velocity as well as an increase in displacement and peak velocity. On the other hand, comparing only the lower two boundary types (ip vs. Wd), it is not the higher boundary type ip, but the lower boundary type Wd that shows an increase in displacement, duration and peak velocity with no change in time-to-peak-velocity. Such an inconsistency renders dynamical parameter accounts for unaccented /#bi/ difficult to identify.

Relationships among various kinematic measures do not show clear evidence supporting any dynamical account, either, except that a close relationship between total movement duration and time-to-peak-velocity ($R^2 = 0.73$ to 0.78 for /#ba/; $R^2 = 0.86$ to 0.96 for /#bi/, see Table A.4 in Appendix II) suggests either a change in stiffness or a change by shrinking. The relationship between duration and displacement/velocity ratio (Figure 5.11) shows quite a substantial overlapping among points belonging to different boundary types. Similarly, the relationship between peak velocity and displacement (Figure 5.12) does not show any clear evidence supporting any dynamical account.

To sum up, as was the case for domain-final CV# lip opening gestures, boundary-induced kinematic differences cannot be accounted for by any particular dynamical parameter setting.

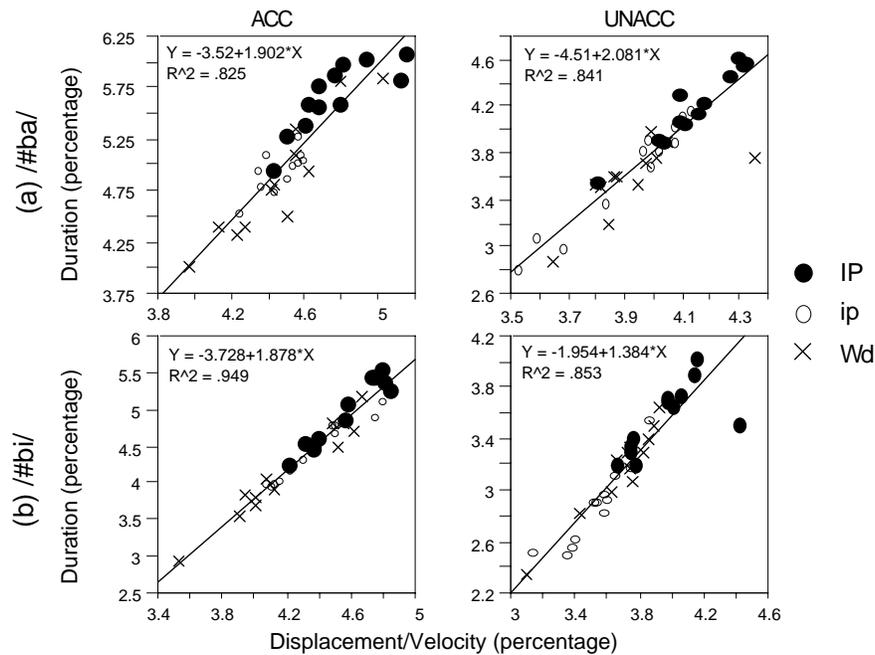


Figure 5.11. Effect of Boundary Type on relationship between duration and displacement/velocity ratio for C₂-to-V₂ lip opening gesture, separated by V₂ Type and Accent. (a) /#ba/ in upper panels and (b) /#bi/ in lower panels with results of regression analyses.

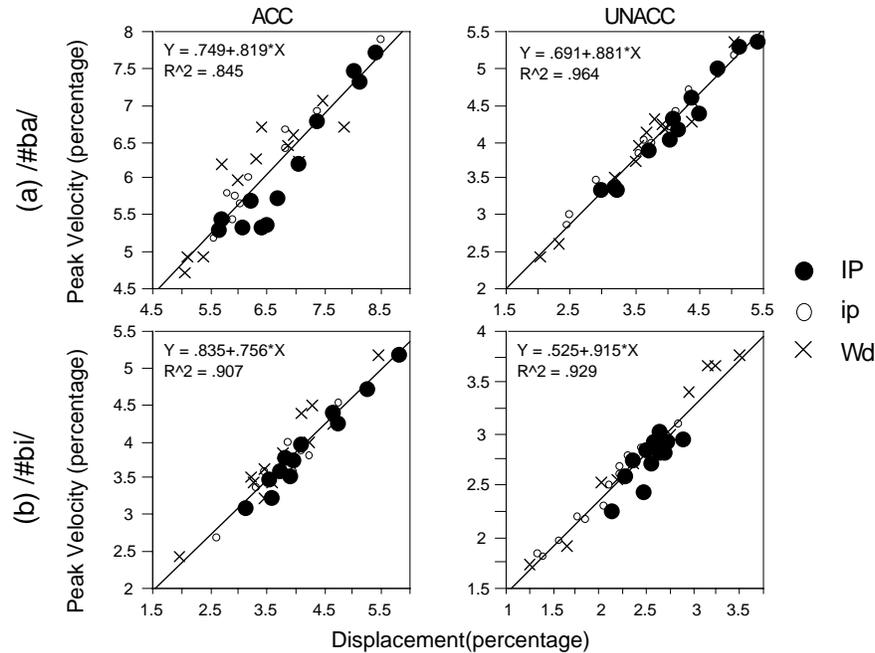


Figure 5.12. Effect of Boundary Type on relationship between peak velocity and displacement for C₂-to-V₂ lip opening gesture, separated by V₂ Type and Accent. (a) /#ba/ in upper panels and (b) /#bi/ in lower panels with results of regression analyses.

5.3.5. V₁-to-C₂ Closing Gestures

In this section, we examine V₁-to-C₂ lip *closing* movements and discuss possible dynamical accounts for the observed kinematic patterns. Further, as mentioned at the outset of this chapter, effects of both V₁ Accent and V₂ Accent will be examined to see how the accent condition on either side of the boundary affects the V₁-to-C₂ lip closing gesture.

5.3.5.1. Displacement (V₁#C₂)

Effect of Accent. There are main effects of both V₁ Accent and V₂ Accent on V₁-to-C₂ lip closing displacement for both /a#b/ and /i#b/ (main effects of V₁ Accent: F[1,5]=8.944, p<0.05 for /a#b/; F[1,5]=37.882, p<0.005 for /i#b/; main effects of V₂ Accent: F[1,5]=28.251, p<0.005 for /a#b/; F[1,5]=8.691, p<0.05 for /i#b/). These effects are shown in Figure 5.13. (Note that for the sake of simplicity, Figure 5.13 shows graphs only for main effects, since there are no interactions among V₁ Accent, V₂ Accent, and Boundary Type in most cases.) As can be seen in Figures 5.13a-b, there is a larger V₁-to-C₂ displacement for V₁ACC than for V₁UNACC, regardless of V₁ Type. Similarly V₁-to-C₂ displacement is also larger for V₂ACC than for V₂UNACC. The reason for effects of both V₁

Accent and V_2 Accent is presumably because the maximum lip aperture for V_1 is significantly larger for V_{1ACC} than for V_{1UNACC} ($p < 0.01$) and the minimum lip aperture for C_2 is significantly smaller for V_{2ACC} than for V_{2UNACC} ($p < 0.01$). No V_1 Accent by V_2 Accent interaction was found.

Effect of Boundary Type. V_1 -to- C_2 lip closing displacement shows a main effect of Boundary Type for both /a#b/ and /i#b/ ($F[1.3,6.6]=9.05$, $p < 0.05$ for /a#b/; $F(1.4,7.1)=15.771$, $p < 0.005$ for /i#b/), such that V_1 -to- C_2 displacement is larger for a higher prosodic boundary than for a lower prosodic boundary, as shown in Figure 5.13c. No interactions among factors are found.

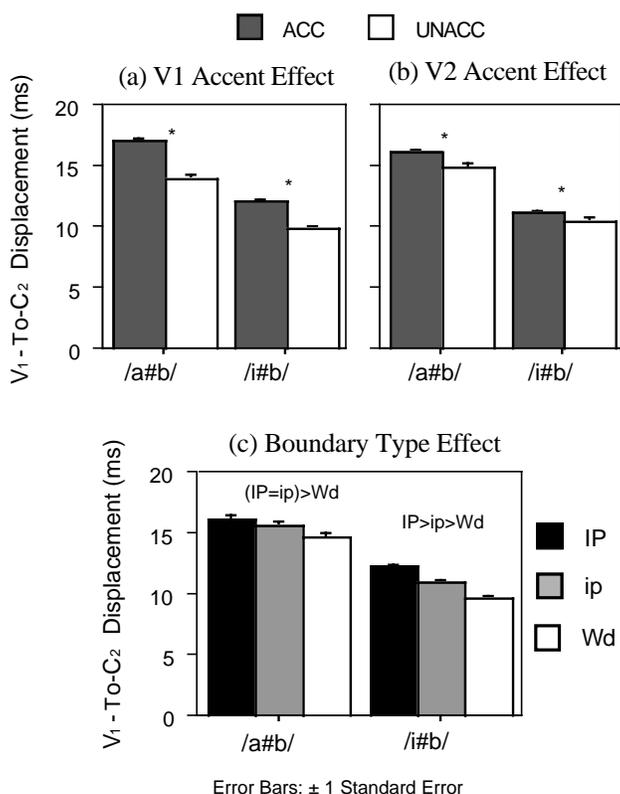


Figure 5.13. Effects of (a) V_1 Accent, (b) V_2 Accent, and (c) Boundary Type on V_1 -to- C_2 lip closing displacement. Results of pairwise comparisons (Bonferroni/Dunn) are provided with '>' and '*' referring to $p < 0.01$.

5.3.5.2. Peak Velocity ($V_1 \# C_2$)

Effect of Accent. With respect to effect of V_1 Accent on V_1 -to- C_2 peak velocity, there is a main effect on /i#b/ ($F[1,5]=8.923$, $p < 0.05$), with /a#b/ showing a *ns* trend ($F[1,5]=4.924$, $p < 0.075$ for /a#b/), such that V_1 -to- C_2 peak velocity is higher when V_1 is

accented than unaccented. (The failure to reach significance for /a#b/ is due to one speaker (S6) who shows a direction different from the rest of the speakers.)

As for V_2 Accent, a main effect is obtained only for /a#b/ ($F[1,5]=11.431$, $p<0.025$), but not for /i#b/. No V_1 Accent by V_2 Accent interaction is found. (See note below for V_1 Accent by Boundary Type interaction.)

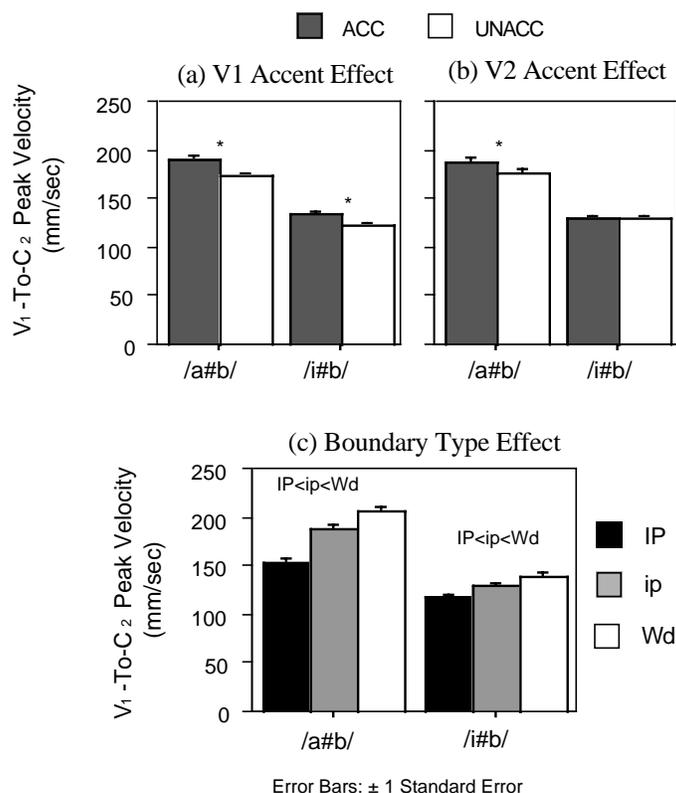


Figure 5.14. Effects of (a) V_1 Accent, (b) V_2 Accent, and (c) Boundary Type on V_1 -to- C_2 lip closing peak velocity. Results of pairwise comparisons (Bonferroni/Dunn) are provided with ‘>’ and ‘*’ referring to $p<0.01$.

Effect of Boundary Type. There are main effects of Boundary Type on both /a#b/ and /i#b/ ($F[1.7,8.7]=32.754$, $p<0.001$, $F[2,10]=5.978$, $p<0.025$, respectively). Interestingly, however, unlike the case for Accent effect, a higher boundary which is associated with a larger displacement shows a decrease in peak velocity, as shown in Figure 5.14c. Pairwise *posthoc* comparisons show that there is a three-way distinction ($IP<ip<Wd$) ($p<0.01$, Bonferroni/Dunn) for both /a#b/ and /i#b/.

There is a significant V_1 Accent by Boundary Type interaction for both /a#b/ and /i#b/ ($F[1.3,6.3]=5.602$, $p<0.05$; $F(2,10)=9.095$, $p<0.01$, respectively). This interaction is due to two facts. First, V_1 Accent effect is more robust when the prosodic boundary is the Word. Second, there is a three-way distinct pattern of $IP<ip<Wd$ when V_1 is accented, but

only a two-way distinct pattern of IP<(ip=Wd) when V₁ is unaccented. No other interactions are found.

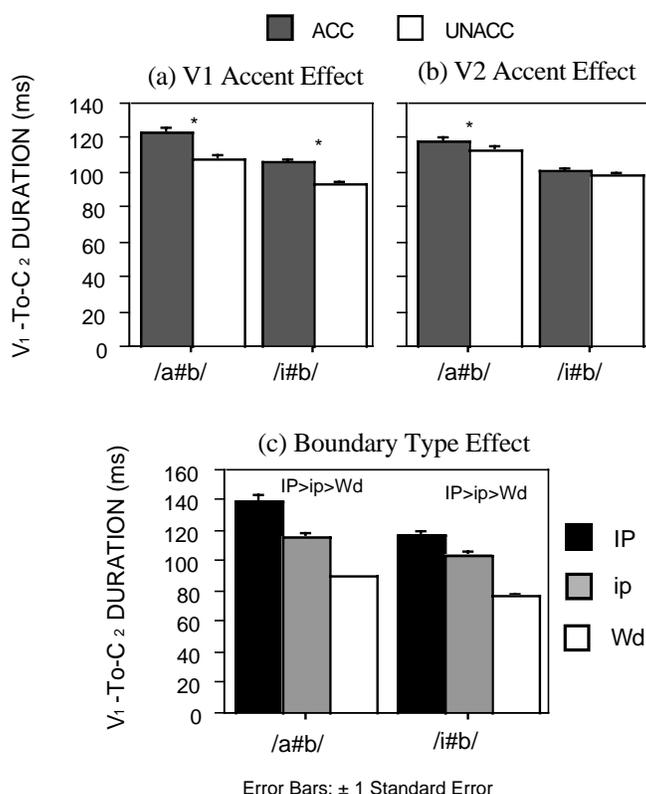


Figure 5.15. Effects of (a) V₁ Accent, (b) V₂ Accent, and (c) Boundary Type on V₁-to-C₂ lip closing total movement duration (V₁ONS-TO-C₂TARG). Results of pairwise comparisons (Bonferroni/Dunn) are provided with ‘>’ and ‘*’ referring to p<0.01.

5.3.5.3. Total Movement Duration: V₁ONS-TO-C₂TARG

Effect of Accent. Lip closing total movement duration (V₁ONS-TO-C₂TARG) for both /a#b/ and /i#b/ is influenced by V₁ Accent (F[1,5]=6.354, p<0.05 for /a#b/; F(1,5)=20.384, p<0.01 for /i#b/). Figure 5.15a shows that the movement duration is significantly longer when V₁ is accented than unaccented for both /a#b/ and /i#b/. However, as for v₂ Accent, /a#b/ shows a main effect (F[1,5]=6.414, p<0.05), but not /i#b/ (Figure 5.15b). There is no v₁ Accent by v₂ Accent interaction.

Effect of Boundary Type. There is a main effect of Boundary Type on both /a#b/ and /i#b/ (F[1.4,7.1]=20.018, p<0.001 for /a#b/; F[1.2,6.6]=66.654, p<0.001 for /i#b/), such that the lip closing duration is longer for a higher prosodic boundary. As shown in Figure 5.15c, variation in the lip closing duration yields a pattern of IP>ip>Wd for both /a#b/ and /i#b/ (p<0.01, Bonferroni/Dunn).

There is a Boundary Type by V_1 Accent interaction ($F[2,10]=11.058$, $p<0.025$) for /i#b/, due in part to a more robust boundary type effect when V_1 is unaccented than when it is accented: there is a three-way distinction ($IP>ip>Wd$) when V_1 is unaccented but a two-way distinction ($IP=ip>Wd$) when V_1 is accented. This interaction is also partly due to the fact the ACC/UNACC comparisons reach significance ($p<0.01$) for lower boundaries ip and Wd, but not for IP. No other interactions are found.

5.3.5.4. $V_{1ONS-T0-C_2PKVEL}$ and $C_{2PKVEL-T0-C_2TARG}$

Effect of Accent. V_1 Accent and V_2 Accent have different effects on different components of the total V_1 -to- C_2 movement duration. V_1 Accent influences only the first durational component, time-to-peak-velocity ($V_{1ONS-T0-C_2PKVEL}$) ($F[1,5]=6.567$, $p<0.05$ for /a#b/; $F[1,5]=19.172$, $p<0.01$ for /i#b/), whereas V_2 Accent influences only the second durational component, the deceleration interval ($C_{2PKVEL-T0-C_2TARG}$) ($F[1,5]=32.477$, $p<0.005$ for /i#b/; $F[1,5]=11.833$, $p<0.025$). As shown in Figure 5.16, time-to-peak-velocity is longer when V_1 is accented (Figure 5.16a), but not when V_2 is accented (Figure 5.16b). In contrast, the deceleration interval $C_{2PKVEL-T0-C_2TARG}$ is longer when V_2 is accented (Figure 5.16b), but not when V_1 is accented (Figure 5.16a). No V_1 Accent by V_2 Accent interaction is obtained.

Effect of Boundary Type. Both the first and the second durational components are significantly influenced by Boundary Type (main effects on $V_{1ONS-T0-C_2PKVEL}$: $F[1.4,6.7]=15.289$, $p<0.005$ for /a#b/ $F(1.2,6.1)=55.448$, $p<0.001$; main effects on $C_{2PKVEL-T0-C_2TARG}$: $F(2,10)=35.001$, $p<0.001$ for /a#b/; $F(2,10)=37.049$, $p<0.001$ for /i#b/). As shown in Figure 5.16c, both $V_{1ONS-T0-C_2PKVEL}$ and $C_{2PKVEL-T0-C_2TARG}$ show a three-way distinction ($IP>ip>Wd$) in both /a#b/ and /i#b/, indicating that variation in the total movement duration as a function of Boundary Type is ascribable to variation in both durational components.

There are no interactions among factors, except that /i#b/ shows a Boundary Type by V_1 Accent interaction on both $V_{1ONS-T0-C_2PKVEL}$ ($F[1.1,5.5]=9.699$, $p<0.025$) and $C_{2PKVEL-T0-C_2TARG}$ ($F[2,10]=5.019$, $p<0.05$). These interactions are because the ACC/UNACC comparison reaches significance for lower boundaries ip and Wd, but not for a higher boundary IP, and that the effect of Boundary Type is more robust when V_1 is unaccented.

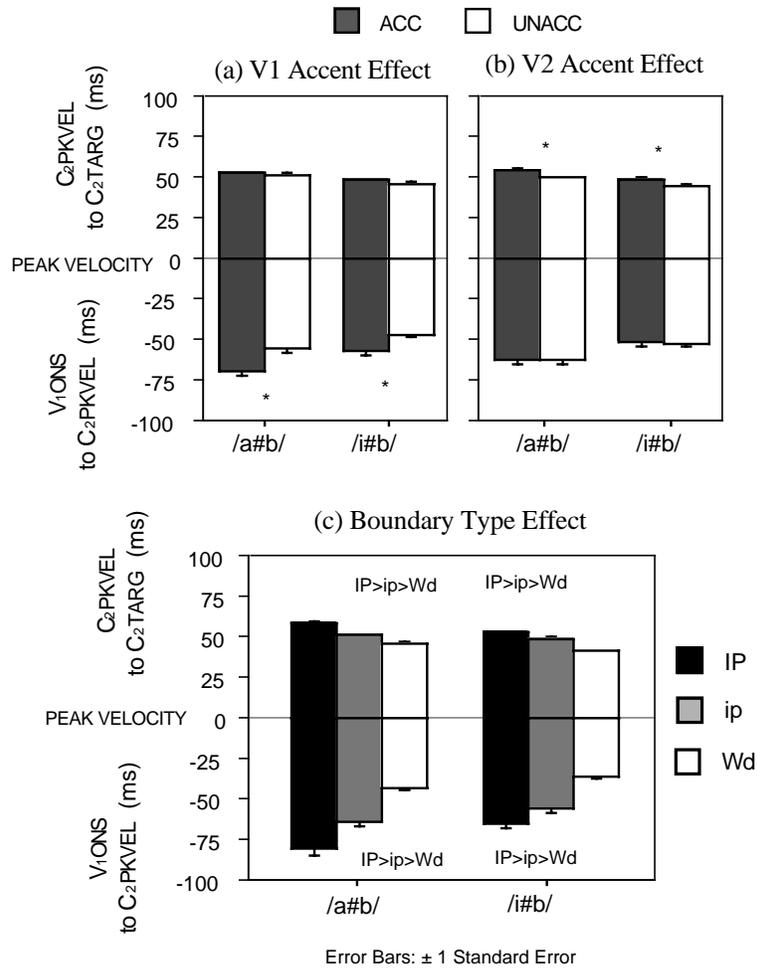


Figure 5.16. Effects of (a) V₁ Accent, (b) V₂ Accent and (c) Boundary Type on two component durations C₁ONS-To-V₁PKVEL and V₁PKVEL-To-V₁TARG, separated by VOWEL TYPE. Bar graphs are aligned at the attainment of peak velocity. Results of pairwise comparisons (Bonferroni/Dunn) are provided with '>' and '*' referring to p<0.01.

5.3.6. Summary and discussion about dynamics underlying kinematic differences for V₁-to-C₂ lip closing gesture

In the previous section, we examined various kinematic measures for V₁-to-C₂ lip closing gestures. The results are summarized in Table 5.3. As before, this section discusses how prosodically conditioned kinematic differences in V₁-to-C₂ lip closing gestures can be accounted for by various dynamical parameter manipulations.

5.3.6.1. Dynamical aspect of V_1 Accent effects on V_1 -to- C_2 lip closing gesture

As summarized in Table 5.3, V_1 -to- C_2 lip closing gestures are influenced by both V_1 and V_2 Accent factors. With respect to the V_1 Accent effect, when V_1 is accented, V_1 -to- C_2 lip closing gestures are associated with an increase in displacement, duration, time-to-peak-velocity, and peak velocity (showing a larger, longer, and faster movement). This means, as was the case for lip opening gestures, that no single dynamical parameter can be identified as a primary source for V_1 ACC/UNACC differences in kinematic measures (See Table 1.1 in Chapter 1).

Table 5.3. Summary of kinematics for V_1 -to- C_2 lip closing gestures. 'tr' refers to a non-significant trend, and '>,' to $p<0.01$ (Bonferroni/Dunn), '—,' to non-significance.

	When V_1 accented		When V_2 accented		Boundary Effect	
	/a#b/	/i#b/	/a#b/	/i#b/	/a#b/	/i#b/
Displacement	larger	larger	larger	larger	(IP=ip)>Wd	IP>ip>Wd
Total Duration	longer	longer	longer	—	IP>ip>Wd	IP>ip>Wd
V_1 ONS-To- C_2 PKVEL	longer	longer	—	—	IP>ip>Wd	IP>ip>Wd
C_2 PKVEL-To- C_2 TARG	—	—	longer	longer	IP>ip>Wd	IP>ip>Wd
Peak Velocity	higher	higher	higher	—	IP<ip<Wd	IP<ip<Wd

Now, consider the relationships between various kinematic variables. Both the stiffness and the shrinking accounts are supported by (1) a close relationship between total duration and time-to-peak-velocity ($R^2=0.66$ to 0.95 for /a#b/; $R^2=0.77$ to 0.96 for /i#b/, see Table A.5 in Appendix II); and (2) separation between ACC and UNACC in the regression plot that relates duration and displacement/velocity ratio, especially true for the gestures at lower boundaries (see Figure 5.17 in comparison with Figure 1.2b in Chapter 1). In contrast, the relationship between displacement and peak velocity suggests that the target account is favored, as evident in a close relationship between the two measures with clear separation between ACC and UNACC for Wd (see Figure 5.18 in comparison with Figure 1.1c), although no such evidence is found for higher boundaries, IP and ip.

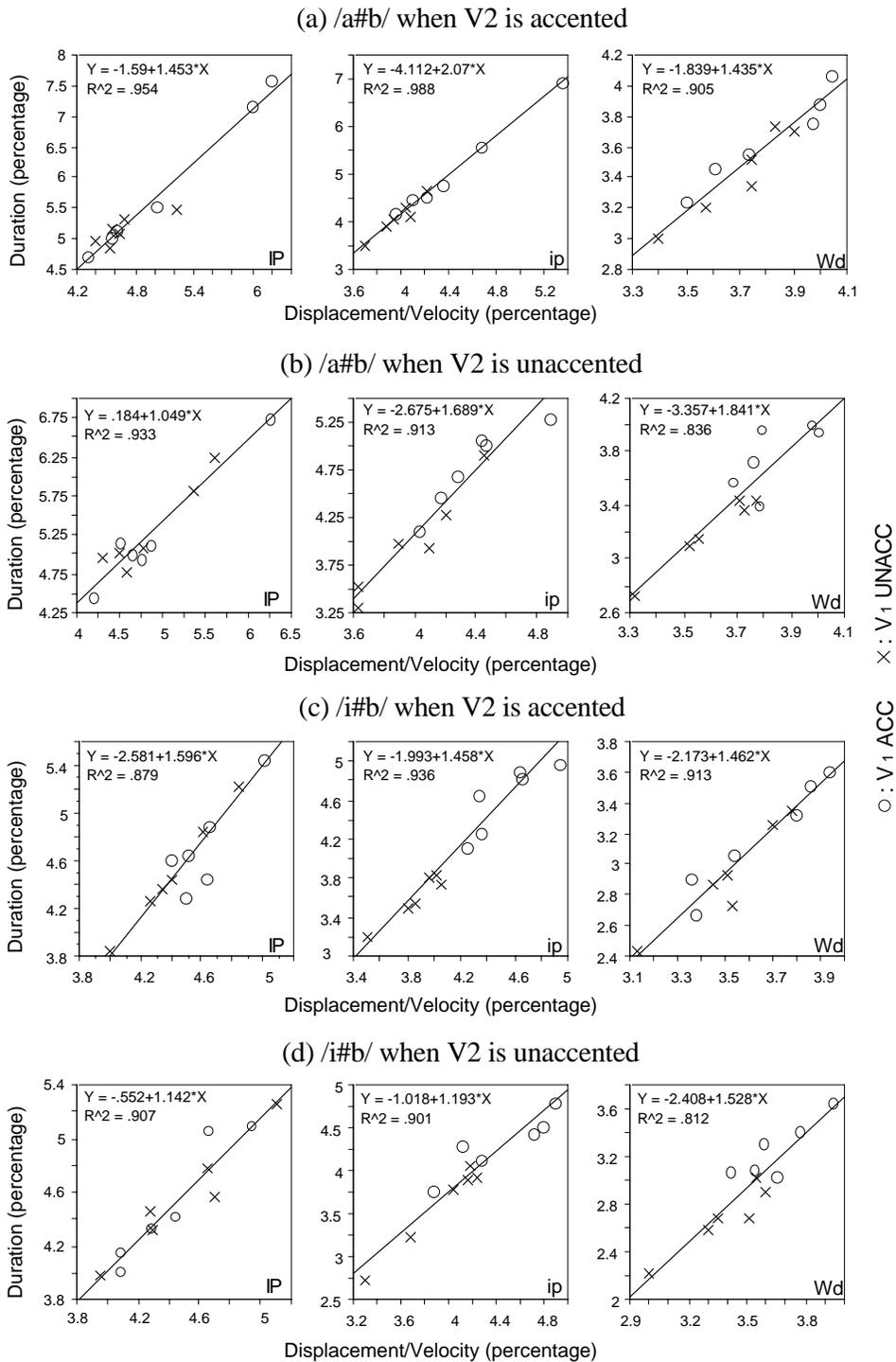


Figure 5.17. Effect of V₁ Accent on relationship between duration and displacement/velocity ratio for V₁-to-C₂ lip closing gesture, separated by (following) V₂ Type and Boundary Type.

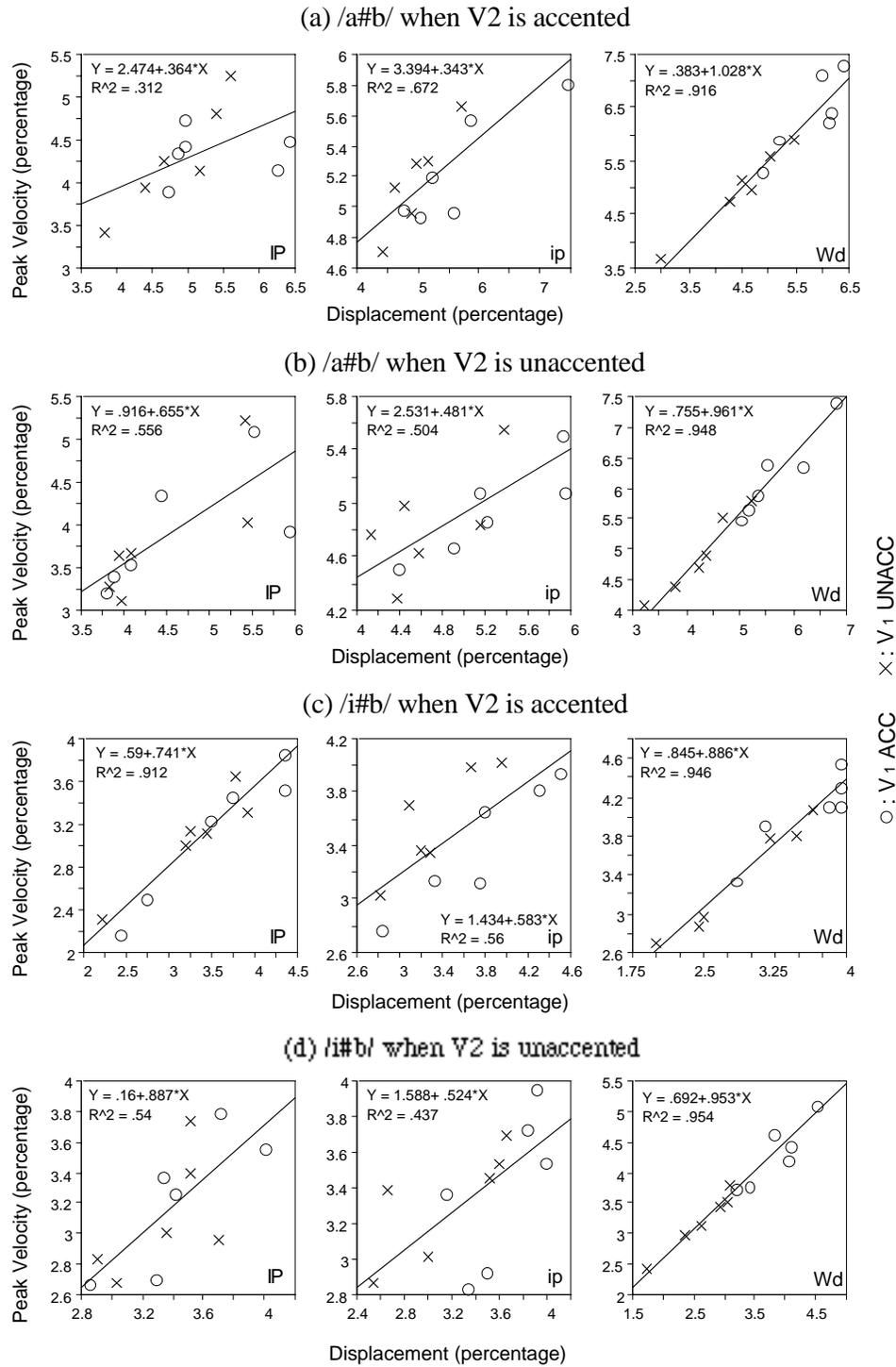


Figure 5.18. Effect of V₁ Accent on relationship between peak velocity and displacement for V₁-to-C₂ lip closing gesture, separated by (following) V₂ Type and Boundary Type.

In short, as was the case with the lip opening gesture, various kinematic relationships further reinforce the complexity of the accent-induced kinematic variation, such that the effect of V_1 Accent on the V_1 -to- C_2 lip closing movement is not clearly accounted for by any particular dynamical parameter setting.

5.3.6.2. *Dynamical aspect of V_2 Accent effects on V_1 -to- C_2 lip closing gesture*

V_2 Accent also influences V_1 -to- C_2 lip closing gestures with respect to several kinematic measures, but in a way that is somewhat different from V_1 Accent. First, V_1 -to- C_2 lip closing gestures with V_2 under accent are larger, but not faster, showing an increase in displacement for both /a#b/ and /i#b/, but this time with no change in time-to-peak-velocity, as opposed to the effect of V_1 Accent. Second, there is a significant change in deceleration duration as a function of V_2 Accent, which was not the case for the effect of V_1 Accent. Finally, the total movement duration is not consistently longer when V_2 is accented. Only /a#b/ shows an accent-induced increase in total movement duration together with an increase in peak velocity, whereas /i#b/ shows no change either in total movement duration or in peak velocity.

From the standpoint of task dynamical parameter settings, no change in time-to-peak-velocity immediately rules out the possibility that a change in stiffness is a major source of durational variation, even for /a#b/ which shows significant durational variation due to V_2 Accent. On the other hand, the fact that only the second component of the total duration is influenced by V_2 Accent lends support to the intergestural timing account, which is especially true for /i#b/ with no change in peak velocity and time-to-peak-velocity. (Recall that the patterning of no change in peak velocity along with an increase in displacement best fits the descriptions of a delayed intergestural timing (see Table 1.1 in Chapter 1)). However, this intergestural timing account is critically weakened for /a#b/ which shows a change in peak velocity (the larger, the faster).

Now, let us further explore the intergestural timing account for /i#b/ by examining the relationships between various kinematic measures. As can be seen in Figures 5.19 and 5.20, there is substantial overlapping between ACC and UNACC datapoints, not matching Figures 1.3c-d in Chapter 1 that show idealized pictures for a pure change in intergestural timing. (The examination of individual speakers also revealed that speakers showed either such overlapping or at least patterns that do not fully conform to the intergestural timing account.)

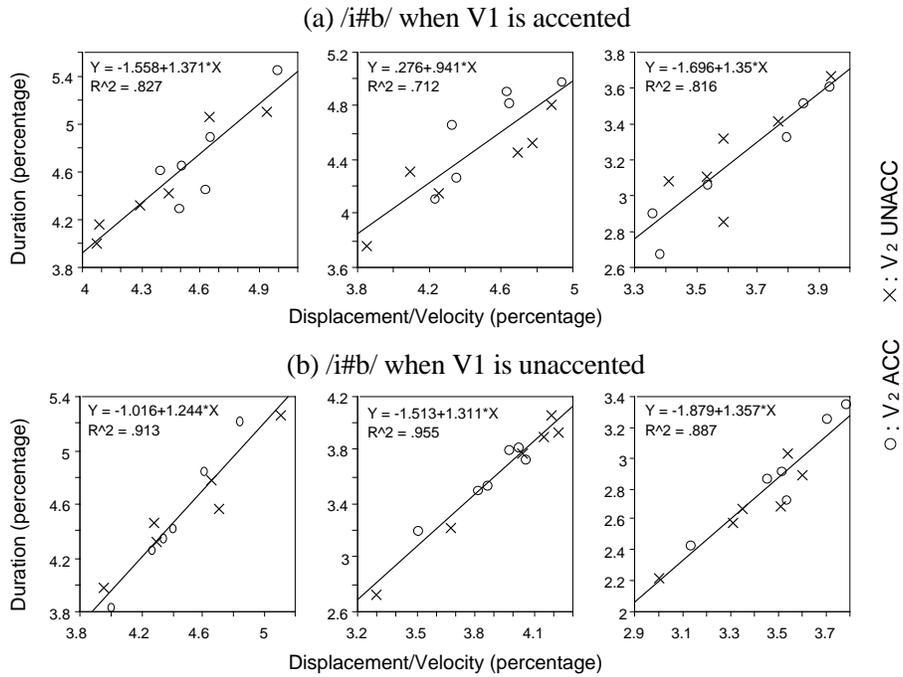


Figure 5.19. Effect of V₂ Accent on relationship between duration and displacement/velocity ratio for the /i#b/ lip closing gesture, separated by (preceding) V₁ Type and Boundary Type.

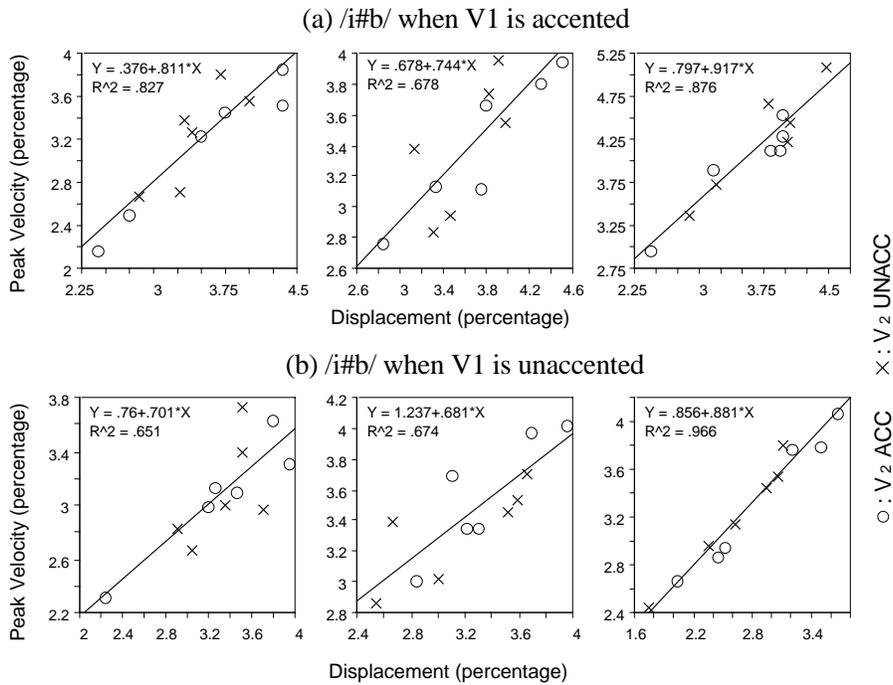


Figure 5.20. Effect of V₂ Accent on relationship between peak velocity and displacement for the /i#b/ lip closing gesture, separated by (preceding) V₁ Type and Boundary Type.

To sum up, the accent of V_2 affects V_1 -to- C_2 lip closing gestures in ways that differ from the effect of V_1 Accent. The most obvious finding is that only the deceleration duration is influenced by V_2 Accent (a long deceleration duration for V_2 ACC). Although the results of ANOVAs suggested that the patterning of an increase in displacement with no change in peak velocity and time-to-peak-velocity favors a change in intergestural timing, especially for /i#b/, no further evidence was found in the relationship between kinematic variables, which weakens the intergestural timing account.

5.3.6.3. Dynamical aspect of boundary effects on V_1 -to- C_2 lip closing gesture

As summarized above in Table 5.3, there is systematic boundary-induced kinematic variation in all measured kinematic variables. V_1 -to- C_2 lip closing gestures at a higher prosodic boundary show progressive increase in displacement, total movement duration, time-to-peak-velocity and deceleration duration, but a progressive decrease in peak velocity. This pattern holds for both vowel types. The pattern of a larger, longer, and slower movement does not single out any particular dynamical parameter as an underlying mechanism. For example, while the patterning of the longer duration with a lowered peak velocity favors the stiffness account, the systematic variation in displacement requires a further dynamical mechanism which cannot be pinpointed here.

Relationships between various kinematic measures show evidence favoring only the stiffness account. In other words, the longer and slower movement for V_1 -to- C_2 lip closing gestures at a higher prosodic boundary can be best accounted for by a decrease in stiffness, as evident in (1) a close relationship between total movement duration and time-to-peak-velocity ($R^2=0.88 - 0.97$, see Table A.7 in Appendix II), (2) a close relationship between duration and displacement/velocity ratio with datapoints for a higher prosodic boundary gathering towards the upper right corner of the regression space (see Figure 5.21 in comparison with Figure 1.2b), and (3) datapoints for a higher prosodic boundary being scattered in the lower side of the regression space that relates peak velocity and displacement (see Figure 5.22 in comparison to Figure 1.2a). However, while various kinematic measures suggest that a change in stiffness is favored as a major underlying mechanism for the boundary-induced kinematic differences, the systematic change in displacement (the higher the prosodic boundary, the larger the movement) cannot be explained in the framework of the mass-spring dynamical model, which makes it difficult to pinpoint a unified dynamical account.

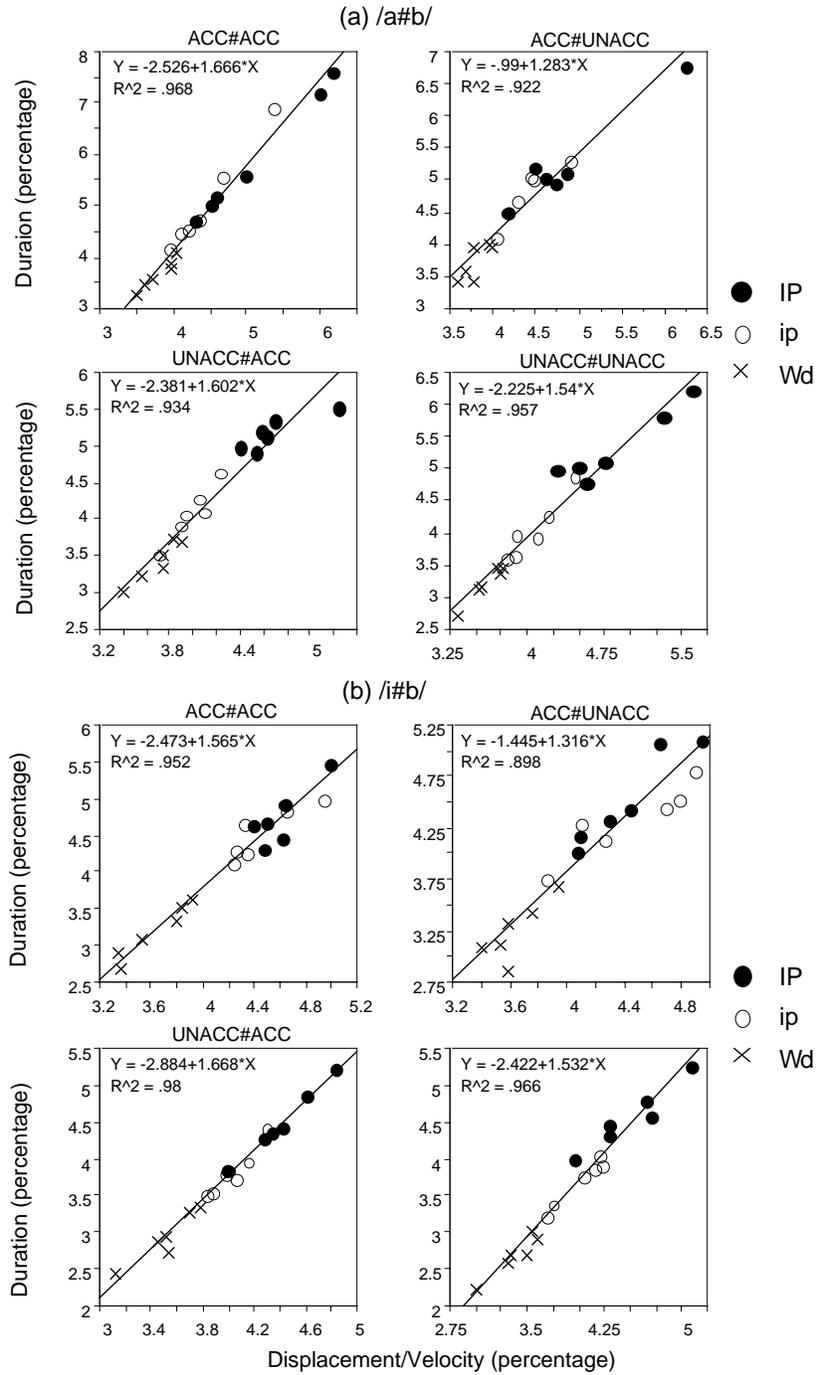


Figure 5.21. Effect of Boundary Type on relationship between duration and displacement/velocity ratio for V_1 -to- C_2 lip closing gesture, separated by V_1 Accent and V_2 Accent.

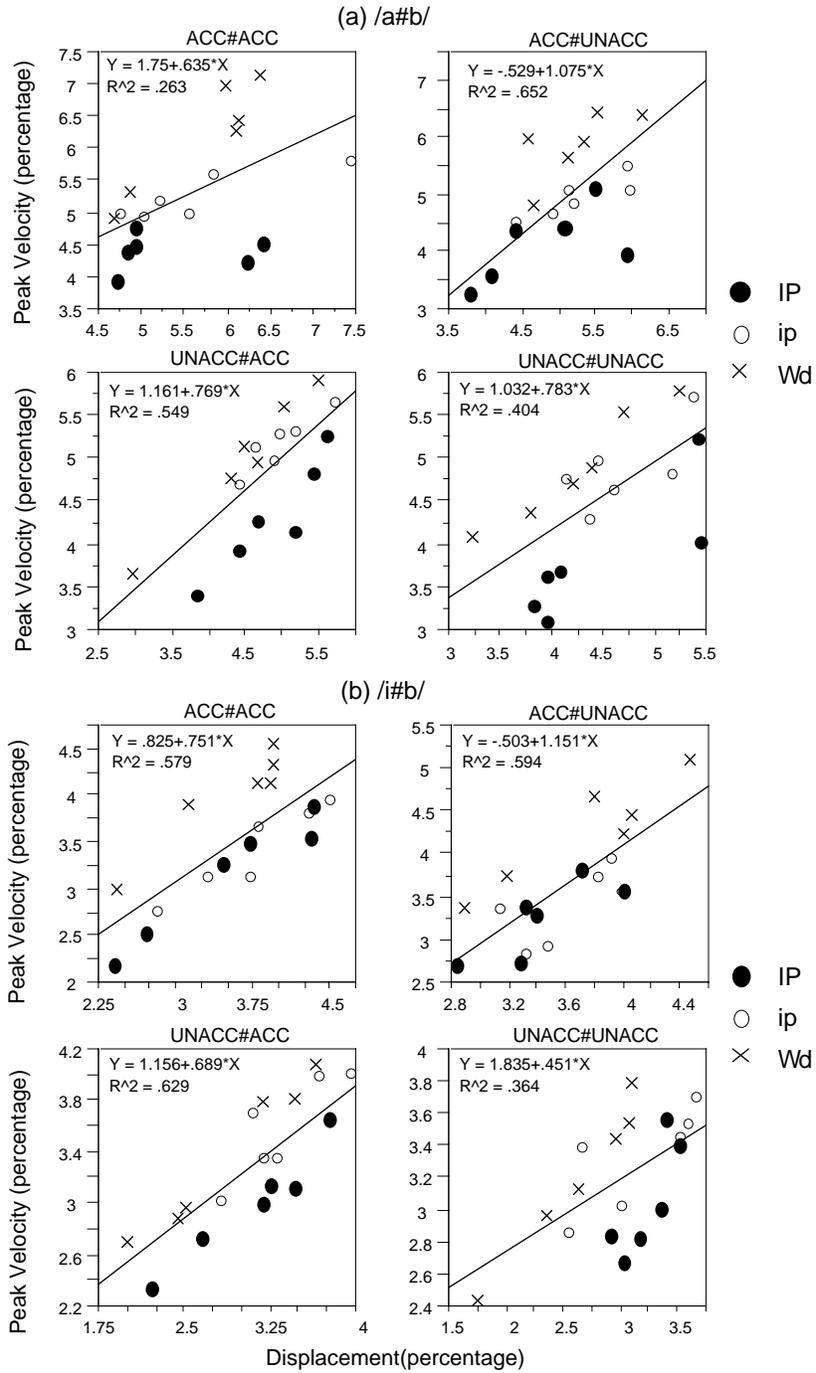


Figure 5.22. Effect of Boundary Type on relationship between peak velocity and displacement for V₁-to-C₂ lip closing gesture, separated by V₁ Accent and V₂ Accent.

5.4. General Discussion

5.4.1. What are the accent-driven kinematic characteristics underlying lip opening and closing gestures?

In Chapter 3, we found that the maximum lip opening was greater when CV syllables are accented than unaccented, showing accent-induced articulatory strengthening. In this chapter, we found that the lip opening gesture under accent is associated with an increase in almost all measured kinematic variables including displacement, total movement duration, time-to-peak-velocity, deceleration duration, and peak velocity, regardless of whether it is domain-initial or domain-final. This kinematic patterning indicates that the articulatory strengthening can be further characterized with a larger, longer, and faster lip opening movement. This result is consistent with findings for jaw opening gestures under accent reported in the literature (as in English *put* reported in de Jong 1991; and in *Pope* and *pipe* in Fowler, 1995). The ACC/UNACC differences are also consistent with kinematic differences due to lexical (word-level) stress (Kelso, et al., 1985 for jaw and lower lip movements for reiterant /ba/).

Turning to the cross-boundary V_1 -to- C_2 lip closing gesture, one of the significant findings is that the V_1 -to- C_2 lip closing gesture is influenced not only by postboundary accent (V_2 Accent) but also by preboundary accent (V_1 Accent), supporting HYPOTHESIS 5.3. Some measured variables are affected primarily by preboundary accent and some, by postboundary accent, while yet others are affected by both. For example, spatial displacement is significantly affected by both V_1 Accent and V_2 Accent, such that lip closing displacement is larger for ACC than for UNACC, regardless of whether accent comes from the preboundary or the postboundary syllables. As for durational variation, the preboundary accent affects primarily the first durational component (time-to-peak-velocity) of the total movement duration, whereas the postboundary accent affects only the second component (deceleration duration) of the total movement duration. Finally, while peak velocity is consistently influenced by preboundary (V_1) accent such that it is higher for ACC than for UNACC, there is no consistent effect of postboundary (V_2) accent on peak velocity. In short, although there are some compounding effects of Accent arising from both sides of the boundary, all six speakers behaved similarly, showing that the effects of both V_1 and V_2 Accents converge on a larger and longer lip closing movement, while a faster movement comes primarily from V_1 Accent. This is generally consistent with accent-induced kinematic characteristics for the lip opening gesture.

As an aside, one more noteworthy point is regarding an issue about whether the V_1 -to- C_2 lip closing gesture should be considered solely as a postboundary phenomenon. As mentioned earlier, Byrd and Saltzman (1998) define V_1 -to- C_2 lip closing gesture as a postboundary phenomenon, presumably because the lip closing gesture is activated for the postboundary consonant # C_2 . What is at issue here is whether such terminology can be

justified by the kinematic characteristics of V_1 -to- C_2 lip closing gesture. A short answer is probably no. The fact that some measured kinematic variables are affected only by preboundary accent and some, only by postboundary accent suggests that kinematic variation for the V_1 -to- C_2 lip closing gesture may be better defined as a *transboundary* phenomenon. Taking all the results and dynamical interpretations into consideration, we can make a generalization that the V_1 -to- C_2 lip closing gesture can be thought of as consisting of two components, with the timepoint of peak velocity as a landmark. First, the articulation during the time course from V_1 onset to the peak velocity landmark may be characterized as a preboundary phenomenon which is governed by the preboundary accent. Second, the articulation during the time course from the peak velocity landmark to the C_2 target attainment may be thought of as a postboundary phenomenon which is governed by the postboundary accent. (Note also that if we apply this transboundary nature of the C_2 lip closing gesture to the framework of syllable structure, we can further posit that the C_2 lip closing gesture is “ambisyllabic” in that the first half of it belongs to the preceding syllable and the second half of it, to the following syllable.)

5.4.2. *Can accent-driven kinematic variations be modeled by a particular dynamical parameter setting?*

With respect to dynamical accounts for kinematic variation as a function of Accent, at the outset of this chapter it was hypothesized, based on Edwards, et al. (1991) and Harrington, et al. (1995), that the intergestural timing (or the truncation) mechanism underlies accent-induced kinematic variation in the lip opening gesture (HYPOTHESIS 1.1) and in the lip closing gesture (HYPOTHESIS 1.2). However, when the kinematic findings regarding lip opening gestures were compared to predictions of the mass-spring task dynamic model, no single dynamical parameter setting could be singled out as an absolute underlying mechanism. With respect to the lip opening gesture, the data suggested that if anything a change in both stiffness and target was the more probable account for accent-induced kinematic differences, with a change in intergestural timing as the least likely dynamical mechanism. (Note that findings reported by de Jong (1991) and Fowler (1995) also suggested that if anything an increase in target is the most likely source for an increased displacement.)

Turning to the cross-boundary V_1 -to- C_2 lip closing gesture, kinematic patterns are different depending on the source of Accent (preboundary vs. postboundary) and Vowel Type. On the one hand, the effect of preboundary (V_1) accent shows a pattern similar to the effect of accent on the lip opening gesture, favoring no dynamical account. On the other hand, when it comes to the postboundary (V_2) accent effect, the results of ANOVAs suggested that the longer and larger articulation (with no change in peak velocity and time-to-peak-velocity) due to postboundary (V_2) accent for /i#b/ is ascribable to a change in

intergestural timing. However, relationships between various kinematic variables did not show any evidence, weakening the intergestural timing account.

Taking all these into account, what emerges from the data is that no single dynamical mechanism can account for accent-induced kinematic variations, contrary to what has previously been assumed among researchers who have attempted to characterize prosodically-conditioned kinematic variations in terms of a mass-spring dynamical parameter setting.

Now, a rather fundamental question arises as to the validity of the current mass-spring dynamical model. Given the failure to single out any particular dynamical parameter setting that may underlie the accent-induced kinematic variations, one radical view may be that the current mass-spring dynamical model is not adequate to account for the accented-induced kinematic patterning. As mentioned in Chapter 1, Fowler (1995) proposed that gestural behaviors under accent may not be best described in terms of dynamical parameter settings, but rather they are most consistent with the “global effect” hypothesis that stress consists of a global increase in *production effort* in order to maximize prominence in the stressed syllable. It may be possible that such prominence maximization can be obtained simply by the larger, longer, and faster lip opening and closing movements.

A less radical view, the position that I take here, is that speech mechanisms may not be as simple as has been assumed by researchers who adopt the mass-spring dynamical model in explaining certain speech phenomena. The observed data could be explained under a mass-spring dynamical model, if we further explore the possibility that more than one dynamical parameter governs the accent-induced kinematic patterning. For example, our data suggest that it is likely that both stiffness and target changes govern the lip opening movements under accent, and the lip closing movement under V_1 accent, and that both stiffness and intergestural timing changes likely underlie the lip closing movement under V_2 accent. Further, we cannot entirely reject the possibility that all the dynamical parameters are interactively influential on kinematic realizations with different degrees of effect, such that breaking down such compounding effect into individual dynamical parameter settings would be extremely difficult without fine-grained computational modeling. Thus, it is hoped that the findings in the present study motivate future studies to look for the complexity of dynamical parameter settings, rather than seeking what particular dynamical parameter setting 'best' matches speech phenomena.

5.4.4. *What are the boundary-driven kinematic characteristics underlying lip opening and closing gestures?*

The one obvious kinematic characteristic for lip opening and closing gestures at edges of prosodic domains is that they are consistently longer, but this time, not necessarily faster (as opposed to the accent-induced faster movement). However, there is an inconsistent

boundary effect on spatial displacement in lip opening and closing gestures. The larger displacement was found consistently for the cross-boundary V₁-to-C₂ lip closing gesture, showing a progressive increase in displacement as the prosodic boundary moves up in the prosodic hierarchy. This is consistent with results reported in Byrd & Saltzman (1998). On the other hand, domain-edge lip opening gestures show some interaction between Accent and Vowel Type.

As for the domain-final lip opening gestures, /bi#/ shows an increase in displacement before a higher prosodic boundary regardless of accent, but /ba#/ shows such an effect only when it is *unaccented*. Turning to the domain-initial lip opening gesture, there is an increased displacement after a higher prosodic boundary only when /ba#/ is *unaccented*. Considering both domain-initial and domain-final effects, what emerges is that there is an increased displacement at least when the target gestures are unaccented. This is presumably because of some sort of ceiling effect due to accent. Put differently, when gestures are accented, articulation is already expanded such that an expanded articulation would not leave much room for an additional articulatory expansion from boundary type. At a first glance, this result appears to be consistent with findings in Edwards, et al. (1991) whereby an expanded jaw opening displacement at domain-final positions only when the gestures being compared are *unaccented*. Recall, however, that our results about domain-final lip opening gestures for /bi#/ and transboundary lip closing gestures for both /a#b/ and /i#b/ show a larger displacement at a higher prosodic boundary for both ACC and UNACC, suggesting that boundary-induced spatial expansion is not limited to the unaccented gestures only.

All in all, the boundary-induced kinematic variations found in this chapter show that there is some sort of articulatory strengthening as evident by the longer and sometimes larger lip opening and closing gestures. However, the boundary-induced strengthening pattern manifest in kinematics is somewhat different from that arising from accent in that the latter is associated with a faster movement whereas the former is not. An additional point worth emphasizing here is that this pattern, especially the longer movement duration, is found not only in domain-final but also in domain-initial positions. As mentioned in Chapter 1, Byrd & Saltzman (1998) did not consider this domain-initial lip opening gesture as a boundary-adjacent phenomenon, presumably because the domain-initial lip opening gesture in #CV is not strictly domain-initial, in that the V₁-to-C₂ lip closing gesture is defined as a postboundary (i.e., domain-initial) movement preceding C₂-to-V₂ lip opening gesture. The present study, however, suggests that the domain-initial lip opening gesture has temporal characteristics much the same as the domain-final lip opening gesture.

5.4.5. *Can boundary-driven kinematic variations modeled by a particular dynamical parameter setting?*

At the outset of this chapter, we hypothesized that a proportional change in stiffness and target (the shrinking account) underlies boundary-induced kinematic variations (HYPOTHESIS 5.4). When the results of various kinematic measures were compared to the mass-spring dynamical model, we found that the boundary-induced kinematic variations were not fully accounted for by any single dynamical parameter setting, including a change by shrinking. There were some close cases (/ba#/ , UNACC; /bi#/ , ACC or UNACC; /#ba/ , UNACC) in which the kinematic patterns suggested by ANOVA best matched the shrinking account, showing the requisite larger and longer movement with no change in peak velocity. However, a close examination of the relationship between peak velocity and displacement revealed that the shrinking account is not an absolute fit to the observed pattern (see Figure 5.6).

If we consider only temporal kinematic measures, the total movement duration and time-to-peak-velocity, as Byrd & Saltzman (1998) did, the boundary-induced durational difference is likely ascribable to a change in stiffness, given the proportional change in the total movement duration and time-to-peak-velocity as a function of prosodic boundary for both lip opening and closing gestures. At a first glance, this appears to be consistent with previous proposals that the boundary-induced kinematic variation is governed by the stiffness parameter (Edwards, et al., 1991; Beckman, et al., 1992; Byrd & Saltzman, 1998; Byrd, 2000).

However, when we consider additional kinematic measures, the stiffness hypothesis is seriously undermined. For instance, when peak velocity (which was not included in Byrd & Saltzman) is considered, only the lip closing gesture shows a slower movement (with lowered peak velocity) at a higher prosodic boundary, favoring the stiffness account, whereas no change in peak velocity in the case of the lip opening gestures weakens the stiffness account. Moreover, when the variation in displacement is figured in, it is obvious that a change in stiffness, even for the lip opening gesture, is not the only dynamical mechanism underlying the boundary-induced longer, larger, and sometimes slower movement.

As discussed in section 5.4.2 regarding the dynamical accounts of accent-induced kinematic variations, considering multiple dynamical parameters appears more promising than looking for a single dynamical parameter, in order for a mass-spring gestural model to successfully account for the complex boundary-induced kinematic patterning. For example, the consistently larger displacement in the lip closing movement at a higher prosodic boundary must be dealt with by either the target or the intergestural timing parameters. Again, given possible complex interactions between parameters, the task of identifying underlying individual parameters will require fine-grained modeling.

The π -gesture. As introduced in Chapter 1, in an effort to characterize boundary-adjacent kinematic variation, Byrd and Saltzman (Saltzman, 1995, Byrd, et al., 2000; Byrd, 2000; Byrd & Saltzman, 2000) have suggested that there might be abstract and non-tract variable prosodic boundary gestures that are governed by prosodic constituency in a mass-spring dynamical model. The so-called ‘ π -gesture’ is hypothesized to affect stiffness in tract variable articulatory gestures over its activation period, roughly in proportion to the strengths of the boundary: the higher the level of the prosodic boundary, the stiffer the articulatory gestures that are adjacent to the boundary. In this framework, the boundary-induced temporal variation found in this chapter can be interpreted as a change in stiffness, as an effect of the π -gesture. In other words, the temporal activation interval of the π -gesture overlaps with the activation interval of articulatory gestures adjacent to prosodic boundaries, such that the boundary-adjacent articulation lengthen in proportion to degree of the π -gesture’s strength, which is again roughly proportional to level of prosodic boundary.

The degree of lengthening is also influenced by the temporal extent of the π -gesture, in addition to the π -gesture’s strength. Byrd (2000) suggested that the π -gestures’ domain of influence is local at edges of prosodic domains—i.e., “only the constriction gestures within the π -gesture’s temporal field of activation are directly affected, not gestures remote from the phrasal boundary (p.14).” Thus, Byrd hypothesized that for the sequence $C_1V_1\#C_2V_2$, articulations that are closest to the prosodic boundary are most influenced by the π -gesture, resulting in the maximal elongation. In this chapter, we found that not only V_1 -to- C_2 movement but also C_1 -to- V_1 and C_2 -to- V_2 movements are all significantly affected by boundary type: domain-final lip opening gesture, transboundary lip closing gesture and domain-initial lip opening gesture. Of course, it is likely that the lengthening of C_1 -to- $V_1\#$ comes from the effect of the π -gesture on $V_1\#$ and the lengthening of $\#C_2$ -to- V_2 , from the effect of the π -gesture on C_2 . It is also possible that articulations for the rather remote C_1 and V_2 are still within the activation field of the π -gesture but presumably with somewhat reduced degree of the π -gesture’s influence, under the assumption that the π -gesture’s strength tapers out towards edges of its temporal activation interval. However, it is not entirely clear what are the exact mechanisms that underlie lengthening of gestures that are not immediately next to a prosodic boundary. Specifically, it is hoped that future studies provide us with more information not only about the precise temporal extent of the π -gesture (as noted by Byrd (2000)) but also about its relationship with the declining nature of the π -gesture’s strength towards the edges of the activation interval

Another issue regarding the π -gesture model is whether the π -gesture influences degree of spatial magnitude directly or not. The only available information with respect to variation in spatial magnitude is some preliminary results from simulations (Byrd & Saltzman, 2000) which demonstrate that a clock-slowness implementation of π -gestures may entail variation in displacement. The basic idea is that boundary strength determines degree of clock slowing, such that the gestures adjacent to a prosodic boundary will get

slower, and possibly spatially larger. This would account for why we could not single out a dynamical parameter (target vs. intergestural timing) that is responsible for the boundary-adjacent V₁-to-C₂ lip closing gesture. It remains to be seen whether this model can account for the full range of results presented here.

5.4.6. Articulatory signature of prosodic structure

Departing from the dynamical accounts, one of the central issues with respect to boundary-induced kinematic variation is whether it is a linguistically significant phenomenon. At the outset of this chapter, it was hypothesized that contrasts between consonants and vowels are enhanced at edges of prosodic domains, such that there is an increase in both the lip opening and closing displacement in CV#, V#C, and #CV (HYPOTHESIS 5.5). This hypothesis was formulated based on previous proposals (Fougeron & Keating, 1997; Hsu & Jun, 1998) that expanded #CV or V#C displacement adjacent to a prosodic boundary would serve as an articulatory signature for marking prosodic boundary. The results reported in this chapter are generally supportive of this hypothesis. In particular, the V#C lip closing gesture shows the most robust boundary effect on displacement with a pattern of IP>ip>Wd. A similar result was found for domain-final (CV#) lip opening gesture, whereas the domain-initial (#CV) lip opening gesture did not show a consistent effect. This is compatible with Fougeron & Keating's observation that the domain-initial consonantal strengthening as measured by linguopalatal contact induces a greater V#C displacement at edges of prosodic domains, while such an effect is less evident in degree of #CV displacement. This observation is reinforced by kinematic data reported in this chapter. Further, the results presented in this chapter show that even the domain-final CV# displacement is expanded at higher prosodic boundaries, which Fougeron & Keating did not find in their EPG data.

Chapter VI

Effects of Prosody on V₁-to-V₂ Tongue Movement Kinematics

The previous chapter examined prosodically-conditioned kinematic patterns observed in lip opening and closing movements. This chapter further examines tongue movement kinematics and explores how articulatory strengthening is manifested in the tongue movement kinematics, and whether and how prosodically-conditioned kinematic variation can be accounted for in the framework of a mass-spring dynamical model. To this end, I will investigate effects of both V₂ Accent and Boundary Type on transboundary V₁-to-V₂ vocalic gestures, based on the tongue movement kinematics in both the *x* and the *y* dimensions (i.e., the dimensions of the horizontal and vertical vocalic movements) for both /i/-to-/a/ and /a/-to-/i/. Note that with respect to the effect of accent, the focus of this chapter will be on V₂ Accent because, in gestural terms, V₁-to-V₂ movements occur to form a constriction of V₂.

6.1. Hypotheses

Results regarding the kinematic study of the lip opening and closing movements reported in Chapter 5 suggest that gestures under accent are generally associated with a larger, longer, and faster movement. Thus, it is reasonable to expect vocalic V₁-to-V₂ gestures to show a comparable kinematic pattern, which leads to the first hypothesis to be tested:

HYPOTHESIS 6.1: Accented vocalic V₁-to-V₂ gestures are associated with an increase in duration, displacement, and velocity not only in the vertical (*y*) movement but also in the horizontal (*x*) movement regardless of the vowel type.

With respect to dynamical accounts, some investigators (Edwards, et al., 1991; Beckman, et al., 1992; Harrington, et al., 1995) suggested that accent-induced kinematic variation is ascribable to a change in intergestural timing. On the other hand, results regarding lip opening and closing gestures reported in Chapter 5 suggest, though not conclusively, that intergestural timing is the most likely source for only the effects of postboundary (V₂) accent on the transboundary V₁-to-C₂ lip closing gestures, while no dynamical mechanism for the lip opening gestures (C₁V₁# and #C₂V₂) was reliably identified by the kinematic patterns. The V₁-to-V₂ movement data being examined in this chapter are somewhat similar to those for the transboundary V₁-to-C₂ lip closing gestures, in that both gestures span a prosodic boundary and the accent effect in question comes from the postboundary (V₂) accent. Thus, it is not unreasonable to predict that kinematic

patterns for these two transboundary gestures would be comparable, which leads to the formulation of a hypothesis:

HYPOTHESIS 6.2: Accent induced kinematic variation is primarily ascribable to a change in intergestural timing.

This hypothesis predicts that under accent, the tongue movement will be larger and longer than under no accent. Furthermore, the movement velocity and acceleration duration (the time from the movement onset to the attainment of the peak velocity) will be constant.

Turning to issues related to effects of prosodic boundary, Byrd (2000) showed that a change in stiffness is the major dynamical mechanism that underlies boundary-induced kinematic variation in V_1 -to- V_2 vocalic gestures in her data, as was the case for lip opening and closing gestures at domain-edges. Although Byrd examined only /ə/-to-/i/ tongue raising movement in the vertical (y) dimension, it is conceivable that the same effect applies regardless of whether the movement is upward or downward in the y dimension and whether it is forward or backward in the x dimension. Thus, the following hypothesis is tested:

HYPOTHESIS 6.3: A change in stiffness underlies durational variation due to boundary type, regardless of vowel type and directionality of movements.

This hypothesis predicts that the movement will be longer and slower, but neither larger nor smaller in displacement at higher prosodic boundaries than at lower ones. Furthermore, the total movement duration will be highly correlated with its first durational component acceleration duration. In connection to this hypothesis, Byrd (2000) showed that variation in the movement duration was more closely related to the preboundary (V_1) lengthening than to the postboundary (V_2) lengthening. In this chapter, I re-examine this by looking at both vertical and horizontal tongue movement, testing a hypothesis regarding kinematic variation.

HYPOTHESIS 6.4: Boundary-induced variation in the total movement duration for the transboundary V_1 -to- V_2 vocalic gesture comes primarily from durational variation due to preboundary (V_1) lengthening, regardless of vowel type and tongue movement directionality.

Another issue regarding boundary-induced kinematic variation is whether the V_1 -to- V_2 vocalic gestures at higher prosodic boundaries are associated with an increase in displacement. Although Byrd (2000) did not discuss this possibility, results reported in Chapter 5 with respect to the transboundary lip closing gestures suggest an increased displacement at higher prosodic boundaries. Thus, we test a hypothesis:

Hypothesis 6.5: V_1 -to- V_2 vocalic gestures at higher prosodic boundaries are associated with an increase in displacement—i.e., a larger movement.

In testing this hypothesis, I will examine what dynamical parameter settings may underlie variation in displacement as a function of boundary type, including the discussion of the π -gesture hypothesis as a potential account, as was discussed in Chapter 5.

6.2. Measurements and Statistics

As fully explained in the methodology section 2.4.4 in Chapter 2, the corpus examined in this chapter includes only /bi#ba/ and /ba#bi/ (opposite vowel) sequences (where # is IP, ip, or Wd) in order to examine vocalic gestures for /i/-to-/a/ and /a/-to-/i/. Further, in examining the effect of Accent, since we are mainly interested in the effects of Accent on the target vowel (V_2), only the subset of the corpus is considered in which the preboundary (V_1) syllable is always unaccented, in order to control for V_1 accent type.

Measures are calculated based on timepoints of movement onset, target, and peak velocity for each tongue movement dimension (x and y), and for each vowel sequence (raising and fronting gestures for /a/-to-/i/ and lowering and backing gestures for /i/-to-/a/). Basic measured variables include: (a) displacement (mm), (b) total movement duration ($V_{1\text{ONS-TO}}-V_{2\text{TARG}}$), (c) time-to-peak-velocity ($V_{1\text{ONS-TO}}-V_{2\text{PKVEL}}$), (d) deceleration duration ($V_{2\text{PKVEL-TO}}-V_{2\text{TARG}}$), (e) peak velocity. (Recall that for the sake of clarity, ‘X’ and ‘Y’ are attached to each variable to show whether the measurement is made in the x or y dimension (e.g., X-displacement, Y-peak velocity), and the variable name $V_{1\text{ONS}}$ refers to the onset of V_1 -to- V_2 movement away from V_1 .) Based on these measurements, kinematic relationships are examined, including: (f) the relationship between total movement duration and time-to-peak-velocity, (g) the relationship between total movement duration and deceleration duration, (h) the relationship between total movement duration and displacement/velocity ratio, and (i) the relationship between peak velocity and displacement.

6.3. Results

6.3.1. Effects of Accent

6.3.1.1. Effect of Accent on vertical (y) tongue movement

Effect of Accent on Y-displacement. There is no main effect of V_2 Accent on V_1 -to- V_2 displacement. However, a significant V_2 Accent by V_2 Type interaction is obtained ($F[1,5]=9.834$, $p<0.05$) due to the fact that displacement for /i/-to-/a/ (downward movement) is influenced by V_2 Accent (greater for ACC than for UNACC, $p<0.01$) whereas no such effect is found for /a/-to-/i/ (upward movement), as can be seen in Figure 6.1a.

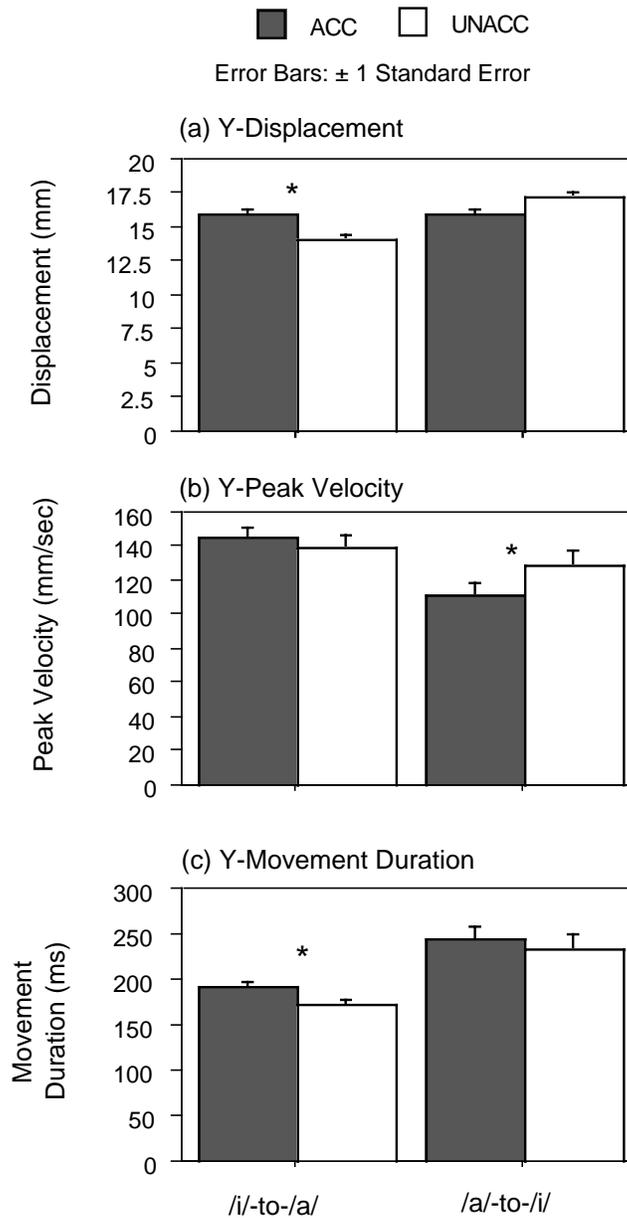


Figure 6.1. Effects of Accent on (a) displacement, (b) peak velocity, and (d) total movement duration for the vertical (y axis) tongue movement, separated by V₂ Type. Results of pairwise comparisons (Bonferroni/Dunn) are provided with ‘*’ referring to $p < 0.01$.

Effect of Accent on Y-peak velocity. No main effect of V₂ Accent is obtained, but there is a significant V₂ Accent by V₂ Type interaction ($F[1,5]=12.273$, $p < 0.025$). As shown in Figure 6.1b, only /a/-to-/i/ upward movement is associated with a significantly

lower peak velocity ($p < 0.01$) when /i/ is accented than unaccented, while no such effect is found for /i/-to-/a/ downward movement.

Effect of Accent on the total Y-movement duration. There is no main effect of V_2 Accent on the movement duration, but as was the case for displacement, a significant V_2 Accent by V_2 Type interaction is found ($F[1,5]=12.714$, $p < 0.025$): while accent does not influence the upward movement duration for /a/-to-/i/, it *does* have a significant influence on the downward movement duration for /i/-to-/a/—it is longer for the accented /a/ than for the unaccented one. This effect is shown in Figure 6.1c.

Effect of Accent on $V_{1ONS-TO-V_2PKVEL}$ and $V_{2PKVEL-TO-V_2TARG}$. Turning to the V_2 Accent effect on $V_{1ONS-TO-V_2PKVEL}$ (time-to-peak-velocity), there is no main effect, but a significant V_2 Accent by V_2 Type interaction ($F[1,5]=6.910$, $p < 0.05$). The interaction is due to the fact that only /i/-to-/a/ has a significantly longer $V_{1ONS-TO-V_2PKVEL}$ when V_2 is accented than when it is unaccented ($p < 0.01$), as can be seen in the lower part of Figure 6.2. On the other hand, for $V_{2PKVEL-TO-V_2TARG}$ (deceleration duration), there is neither a main effect of V_2 Accent nor a V_2 Accent by V_2 Type interaction. These results indicate that the accent-induced difference in the total Y-movement duration ($V_{1ONS-TO-V_2TARG}$) for /i/-to-/a/ is largely due to lengthening of time-to-peak-velocity.

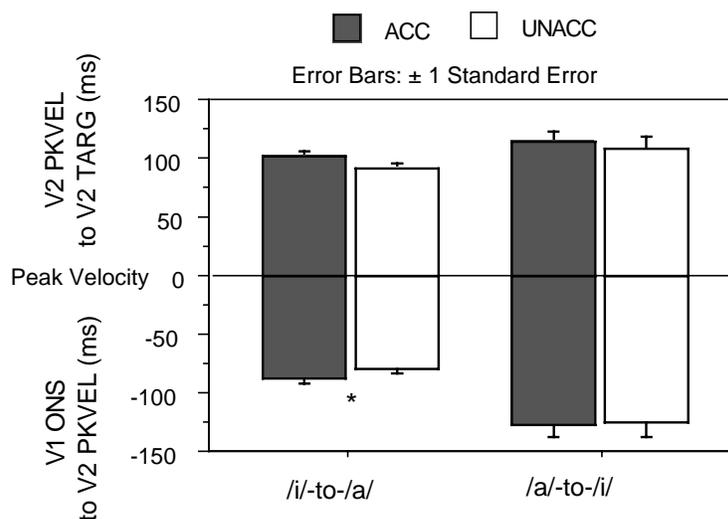


Figure 6.2. Effects of V_2 Accent on two component durations $V_{1ONS-TO-V_2PKVEL}$ and $V_{2PKVEL-TO-V_2TARG}$ for the vertical (y axis) tongue movement, separated by V_2 Type. Bar graphs are aligned at the attainment of peak velocity. Results of pairwise comparisons (Bonferroni/Dunn) are provided with ‘*’ referring to $p < 0.01$.

6.3.1.2. Effect of Accent on horizontal (x) tongue movement

Effect of Accent on X-displacement. There is no main effect of V_2 Accent on X-displacement, but a trend for the interaction between V_2 Accent and V_2 Type

($F[1,5]=6.153$, $p<0.75$), which is due to the fact that accented V_2 /i/ has a significantly larger displacement than unaccented V_2 /i/ while /a/ shows no such effect. (For /i/, five out of six speakers (excluding S3) showed a larger displacement for ACC than for UNACC, whereas for /a/, no consistent pattern was found among speakers.)

Effect of Accent on X-peak velocity. There is neither a main effect of V_2 Accent on X-displacement, nor an interaction between V_2 Accent and V_2 Type.

Effect of Accent on the total X-movement duration. There is no main effect of V_2 Accent on the total X-movement duration, but a non-significant trend (longer for ACC than for UNACC) is found ($F[1,5]=5.753$, $p<0.75$). The failure to reach significance is due to the fact that /a/ shows inconsistent patterns among speakers while /i/ shows longer duration consistently among speakers. (This observation was confirmed by a significant ACC/UNACC difference for /i/ at $p<0.01$.)

Effect of Accent on $V_{1ONS-TO-V_{2PKVEL}}$ and $V_{2PKVEL-TO-V_{2TARG}}$. There is no main effect of V_2 Accent either on $V_{3ONS-TO-V_{2PKVEL}}$ (time-to-peak-velocity) or on $V_{2PKVEL-TO-V_{2TARG}}$ (deceleration duration). However, while there is no interaction between factors for $V_{1ONS-TO-V_{2PKVEL}}$, a significant V_2 Accent by V_2 Type interaction is obtained for $V_{2PKVEL-TO-V_{2TARG}}$ ($F[1,5]=12.662$, $p<0.025$), such that $V_{2PKVEL-TO-V_{2TARG}}$ for /i/ is significantly longer when accented than unaccented, whereas /a/ shows no such difference in $V_{2PKVEL-TO-V_{2TARG}}$, as shown in Figure 6.4. This suggests that the difference in the total X-movement duration for /i/ is not due to the lengthening of time-to-peak-velocity, but rather due to the lengthening of the deceleration interval. This is the opposite of the case for the Y-movement duration for /a/, in which lengthening of time-to-peak-velocity is a primary factor contributing to variation in the total Y-movement duration.

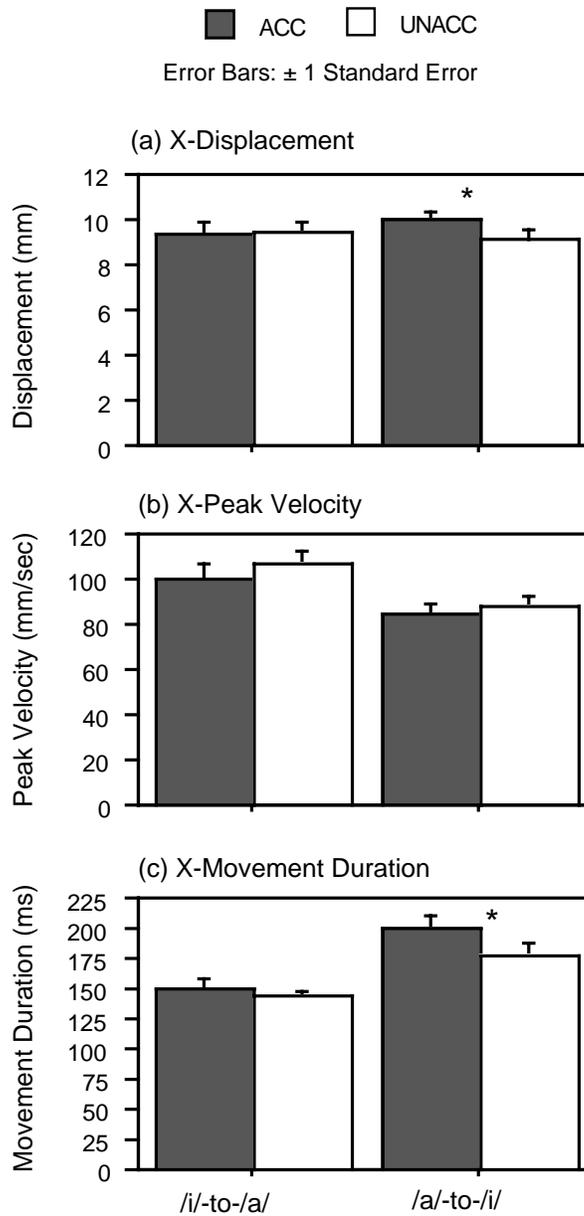


Figure 6.3. Effects of V_2 Accent on (a) X-displacement, (b) X-peak velocity, and (d) total X-movement duration for the vertical (x axis) tongue movement, separated by V_2 Type. Results of pairwise comparisons (Bonferroni/Dunn) are provided with '*' referring to $p < 0.01$.

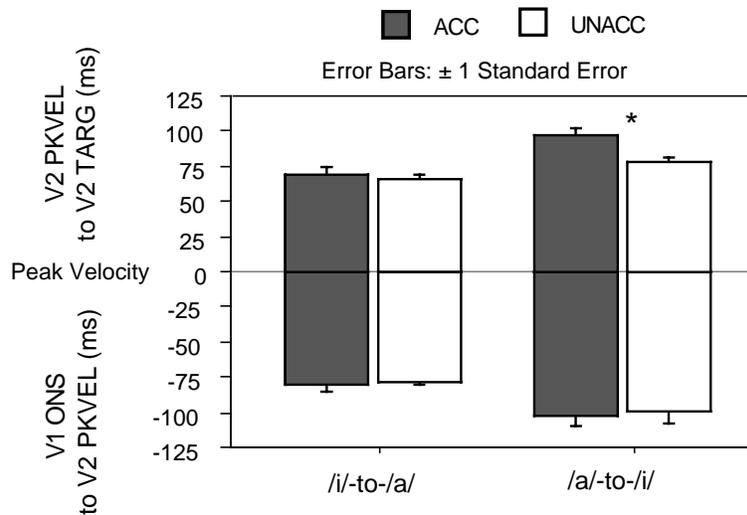


Figure 6.4. Effects of V_2 Accent on two component durations V_1 ONS-TO- V_2 PKVEL and V_2 PKVEL-TO- V_2 TARG for the horizontal (x axis) tongue movement, separated by V_2 Type. Bar graphs are aligned at the attainment of peak velocity. Results of pairwise comparisons (Bonferroni/Dunn) are provided with ‘*’ referring to $p < 0.01$.

6.3.2. Discussion of dynamics underlying ACC/UNACC differences in kinematics

Thus far, we have examined how various kinematic variables for V_1 -to- V_2 vocalic gestures are influenced by Accent. Results are summarized in Table 6.1. Before considering the dynamical parameter settings that may underlie ACC/UNACC differences in kinematics, a brief note about the asymmetry between /i/-to-/a/ and /a/-to-/i/ vocalic gestures is necessary. As can be seen in Table 6.1, the /i/-to-/a/ vocalic gesture shows quite robust accent-induced variation in kinematic variables only in the y dimension, whereas /a/-to-/i/ vocalic gesture shows such variation primarily in the x dimension. Put differently, the vocalic gesture for /i/-to-/a/ is sensitive to accentuation only in the vertical dimension of the tongue movement whereas the vocalic gesture for /a/-to-/i/ is so only in the horizontal dimension of the tongue movement.

This is consistent with results reported in Chapter 3 in that the maximum tongue position for /a/ is lower but not necessarily backer when accented (showing the effect of Accent in the y dimension), whereas the maximum tongue position for /i/ is fronter but not necessarily higher when accented (showing the effect of Accent in the x dimension). In what follows, based on these results and regression analyses, the vertical (y) tongue movement will be examined only for /i/-to-/a/ and the horizontal (x) movement, only for /a/-to-/i/, in order to discuss how significant kinematic differences due to Accent can be accounted for by various dynamical parameter manipulations.

Table 6.1. Summary of kinematics descriptions for V₁-to-V₂ vocalic gestures when V₂ is accented. ‘—’ refers to no significance.

Kinematic measures	/i/-to-/a/		/a/-to-/i/	
	y dimension	x dimension	y dimension	x dimension
Displacement	larger	—	—	larger (excl. S3)
Total Movement Duration	longer	—	—	longer
Time-to-peak-velocity	longer	—	—	—
Deceleration duration	—	—	—	longer
Peak Velocity	—	—	lower	—

6.3.2.1. Dynamical aspects of accent for the /i/-to-/a/ vocalic gesture in the y dimension.

As summarized in Table 6.1, when V₂/a/ is accented, the /i/-to-/a/ tongue lowering gesture is associated with an increase in displacement, total movement duration and time-to-peak-velocity, but with no change in peak velocity and deceleration duration. In other words, the movement for accented V₂/a/ is larger and longer, but not necessarily faster. This pattern does not support any dynamical parameter setting as an underlying mechanism (see Table 1.1 in Chapter 1 for various dynamical parameters). The stiffness account is weakened because of lack of variation in peak velocity; the target account is weakened because of variation in duration; and both the intergestural timing and shrinking accounts are weakened because of lack of variation in deceleration.

Now, let's further examine relationships between kinematic variables. First, a close and positive relationship between the total movement duration and time-to-peak-velocity (with R² values ranging from 0.42 to 0.67) favors two possibilities, the stiffness account and the shrinking account.

Turning to the relationship between the total Y-movement duration and Y-displacement/velocity ratio, Each plot in Figure 6.5a shows quite a close fit of datapoints to the regression line, with R² ranging from 0.68 to 0.816 (p<0.001). The first point to be made is that the relationship between duration and the displacement/velocity ratio does not support either the target or the intergestural timing accounts. Recall that if target is a major parameter, there should be no separation among points (see Figure 1.2d in Chapter 1); and if intergestural timing is a major parameter, there should be no correlation between duration and displacement/velocity ratio (see Figure 1.2f in Chapter 1). This reduces the possibilities to either the stiffness account or the shrinking account (see Figure 1.2b and h). In fact, in Figure 6.5a, datapoints for accented gestures are spaced, by and large, at the upper right corner of the plot, being separated from datapoints for unaccented gestures,

suggesting that, if anything, accented gestures are associated with either less stiffness or less shrinking.

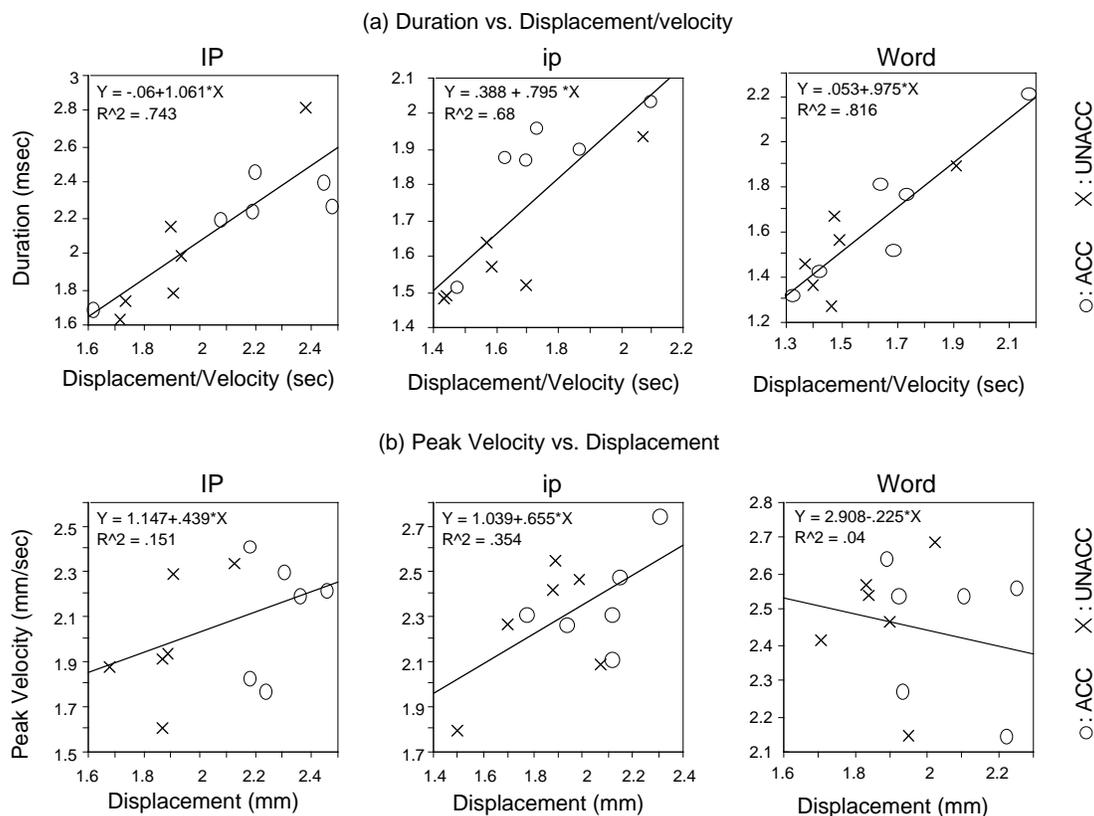


Figure 6.5. Effect of V_2 Accent on relationships (a) between duration and displacement/velocity ratio, and (b) between peak velocity and displacement for /i/-to-/a/ tongue lowering gestures in the y dimension, separated by Boundary Type.

Now, let's examine which one of these two accounts is supported by the pattern in the relationship between Y-displacement and Y-peak velocity. Recall that a pure change in stiffness predicts a vertical distribution of datapoints, and a pure change by shrinking a horizontal one. In fact, the pattern in Figure 6.5b shows no perfect fit to either case. However, we find some weak evidence that may favor the shrinking account, in (1) that there is no close relationship between the variables, and (2) that datapoints for ACC are scattered by and large in the right side of the plot (compare this with Figure 1.2e in Chapter 1).

To sum up, considering all the kinematic differences and the relationship between kinematic measures, a dynamical mechanism that most closely explains the accent-induced kinematic pattern is a change by shrinking. The shrinking account is evident in (1) a change in displacement and duration with no change in peak velocity, and (2) a close

relationship between duration and displacement/velocity ratio, and (3) datapoints for ACC being clustered by and large in the right side of the displacement-peak-velocity relation plot, though weakly so. However, one piece of evidence that disfavors the shrinking account is the lack of systematic variation in the second durational component (deceleration duration). If a change by shrinking were the only dynamical mechanism that underlies accent-induced kinematic variation, we would have seen systematic variation in deceleration duration as was the case in time-to-peak-velocity (acceleration duration). This weakens the shrinking account.

6.3.2.2. *Dynamical aspects of accent for the /a/-to-/i/ vocalic gesture in the x dimension.*

As mentioned earlier, for the /a/-to-/i/ tongue raising gesture, robust accent-induced kinematic variations are found only in the horizontal (x) dimension of the tongue movement. As summarized in Table 6.1, accented /a/-to-/i/ tongue fronting gestures are associated with an increase in displacement, total movement duration and deceleration duration ($V_{2PKVEL-T0}-V_{2TARG}$), and with no change in peak velocity. Note that unlike the case for the /i/-to-/a/ tongue lowering gestures, this /a/-to-/i/ tongue fronting gesture show a change not in time-to-peak-velocity, but in deceleration duration.

Comparing these results with the chart for kinematic consequences of various mass-spring parameter manipulations (Table 1.1 in Chapter 1), both the stiffness and shrinking accounts are ruled out because of lack of variation in time-to-peak-velocity; and the target account is ruled out because of a change in total movement duration and deceleration duration. Now, the remaining possibility is the intergestural timing account which is in fact supported by systematic patterns observed so far: the larger and longer movement which accompanies longer deceleration duration with no change in time-to-peak-velocity and peak velocity. In order to explore this possibility, we examine relationships between kinematic variables.

First consider the relationship between duration and the displacement/velocity ratio. Each plot shows a close fit of points to the regression line with R^2 ranging from 0.855 to 0.926. Furthermore, there is quite a noticeable separation between ACC and UNACC, especially for ip and Wd . Recall that these characteristics best match either the stiffness or the shrinking account (see Figures 1.3b and 1.3h in Chapter 1). However, the observed pattern cannot entirely rule out the intergestural timing account, insofar as there is separation between ACC and UNACC groups (see Figure 1.2f).

Given this possibility, let's now consider the relationship between displacement and peak velocity, as shown in Figure 6.6b. Datapoints in the figure tend to be scattered rather vertically with some points for ACC being in the lower region of the plot and some points for UNACC in the upper region of the plot. Although there is quite a substantial overlapping, such a tendency suggests that, if anything, the /a/-to-/i/ tongue fronting

gesture under accent is by and large associated with lowered stiffness, taking support away from the intergestural timing account.

To sum up, when we consider the kinematic patterns suggested by ANOVAs, the intergestural timing account appears to be the best dynamical mechanism that may underlie accent-induced kinematic variation. However, relationships between kinematic variables give no support to the intergestural timing account.

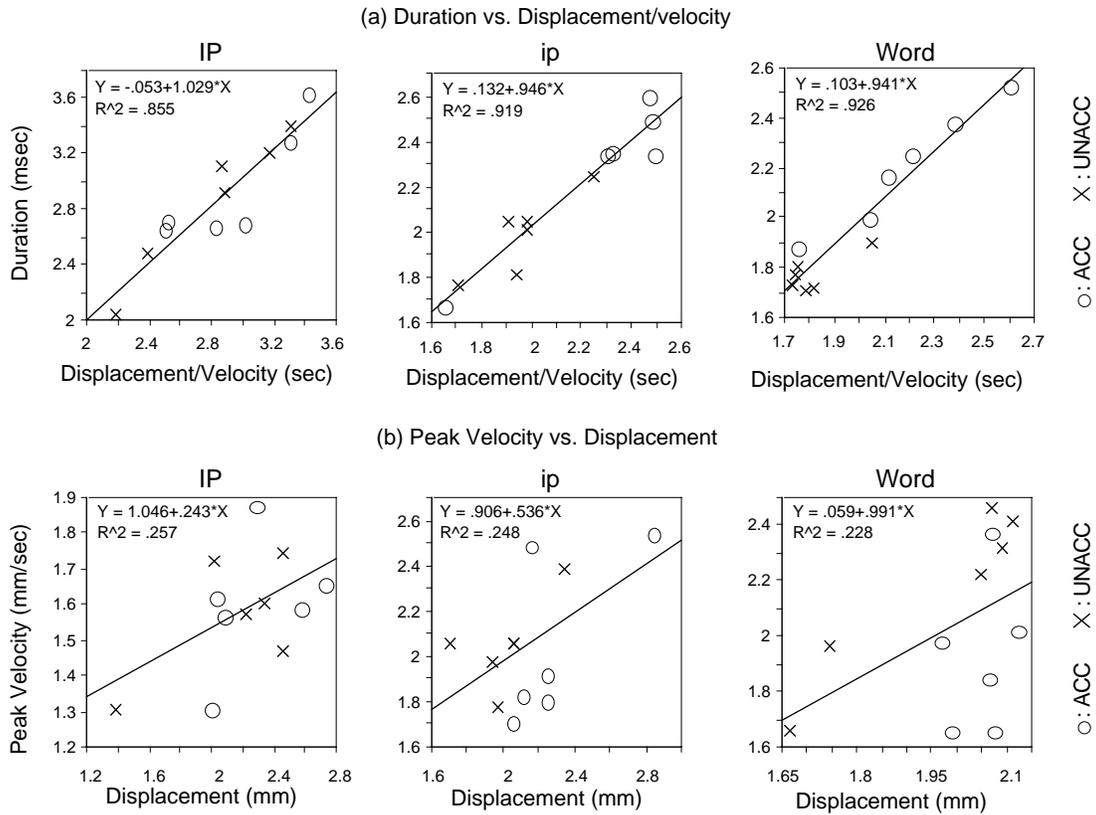


Figure 6.6. Effect of V_2 Accent on relationships (a) between duration and displacement/velocity ratio, and (b) between peak velocity and displacement for /a/-to-/i/ tongue fronting gestures in the x dimension, separated by Boundary Type.

6.3.3. Effects of Boundary Type

6.3.3.1. Effects of Boundary Type on the vertical (y) tongue movement

Effect on Y-displacement. There is a main effect of Boundary Type on Y-displacement ($F[2,10]=7.235$, $p<0.025$). As can be seen in Figure 6.7a, Y-displacement is greater across IP than across Wd, regardless of V_2 Type. There is no interaction among other factors, showing that this effect is consistent across Accent and V_2 Type.

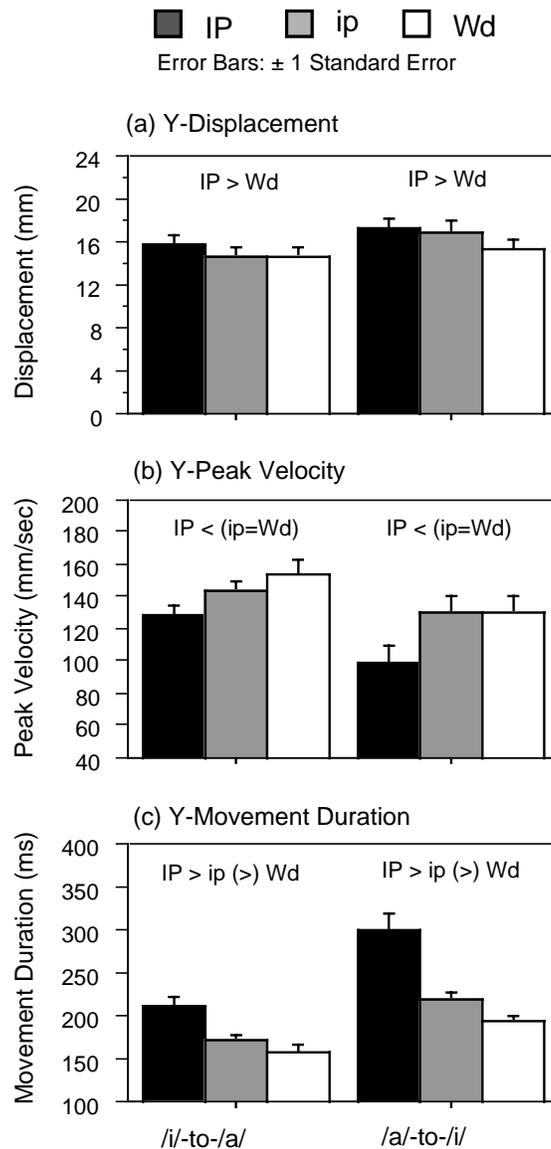


Figure 6.7. Effects of Boundary Type on (a) Y-displacement, (b) Y-peak velocity, and (d) total Y-movement duration, separated by V_2 Type. Results of pairwise comparisons (Bonferroni/Dunn) are provided with '<' referring to $p < 0.01$, '<(),' to $p < 0.05$.

Effect on Y-peak velocity. Y-peak velocity shows a significant main effect of Boundary ($F[2,10]=10.549$, $p < 0.005$), as can be seen in Figure 6.7b. Peak velocity is significantly lower for IP than for the other two boundaries ($p < 0.01$), but no significant difference between ip and Word boundaries is obtained. There is no interaction among factors.

Effect on the total Y-movement duration. A significant main effect of Boundary Type on the total Y-movement duration is obtained ($F[1.8,9.2]=31.922$, $p<0.001$). As shown in Figure 6.7c, Y-movement duration is significantly longer for IP than for the other two boundaries ($p<0.001$), whereas there is weak evidence of significance for the difference between ip and Word ($p<0.05$). No significant interactions are found.

Effect on $V_{1ONS-TO-V_2PKVEL}$ and $V_{2PKVEL-TO-V_2TARG}$. For the interval $V_{1ONS-TO-V_2PKVEL}$ (time-to-peak-velocity), there is a main effect of Boundary Type ($F[1.6,8.0]=13.856$, $p<0.005$), and a significant Boundary Type by V_2 Type interaction ($F[1.4,6.8]=9.556$, $p<0.025$). As shown in the lower part of Figure 6.8, this interaction is due to the fact that there is a three-way distinction (IP > ip > Wd) for /i/, but a two-way distinction (IP > (ip=Wd)) for /a/ at the level of $p<0.01$.

Turning to the interval $V_{2PKVEL-TO-V_2TARG}$ (deceleration duration), there is also a main effect ($F[1.1,5.7]=6.754$, $p<0.05$) with no other significant interactions among factors, showing a pattern of IP > (ip=Wd), as can be seen in the upper part of Figure 6.8.

One more noteworthy point here is that there is a more robust boundary effect on $V_{1ONS-TO-V_2PKVEL}$ than on $V_{2PKVEL-TO-V_2TARG}$, as can be inferred from the fact that the F -ratio (and p -value) is larger for the interval $V_{1ONS-TO-V_2PKVEL}$, in which there is also a boundary-induced three-way distinction for the case of /i#/. This suggests that the observed difference in the total movement duration due to boundary type is attributable more to the preboundary lengthening than to the postboundary lengthening, as can also be seen in the right panel of Figure 6.8.

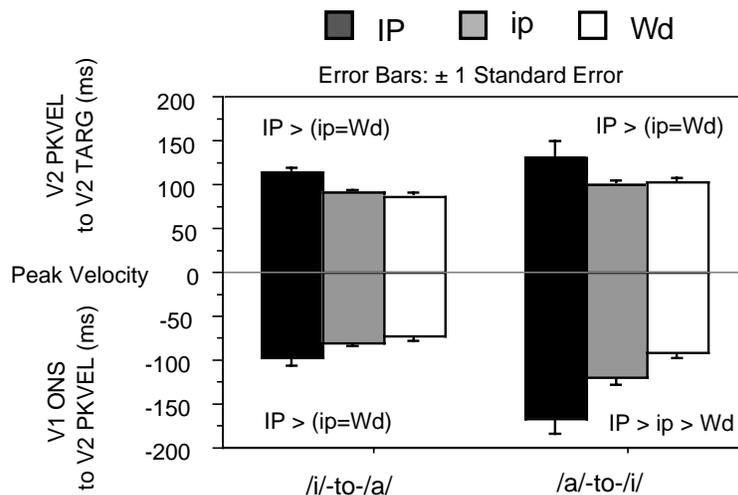


Figure 6.8. Effects of Boundary Type on two component durations $V_{1ONS-TO-V_2PKVEL}$ and $V_{2PKVEL-TO-V_2TARG}$ for the vertical (y axis) tongue movement, separated by V_2 Type. Bar graphs are aligned at the attainment of peak velocity. Results of pairwise comparisons (Bonferroni/Dunn) are provided with '>' referring to $p<0.01$.

6.3.3.2. Effects of Boundary Type on the horizontal (x) movement

Effect on X-displacement. There is no main effect of Boundary Type on X-displacement, with no significant Boundary Type by V_2 Type interaction.

Effect on X-peak velocity. A significant main effect of Boundary Type is obtained for X-peak velocity ($F[1.9,9.3]=11.715$, $p<0.005$). As shown in Figure 6.9b, *posthoc* comparisons show a pattern of $(IP=ip)>Wd$ for /a/, and $IP>(ip=Wd)$ for /i#/ ($p<0.01$). No interactions among factors involving Boundary Type are found.

Effects on the total X-movement duration. A main effect of Boundary Type on the total X-movement duration is obtained ($F[1.8,9.2]=17.337$, $p<0.001$), showing a pattern of $IP>(ip=Wd)$ for both vowel types, as shown in Figure 6.9c. There is a significant Boundary Type by V_2 Type interaction ($F[1.2,5.9]=9.780$, $p<0.025$), which is due to the fact that /i/ has a progressively increasing mean duration across higher prosodic boundaries, whereas /a/ does not show such a progressively increasing pattern.

Effect on $V_{1ONS-T0}-V_{2PKVEL}$ and $V_{2PKVEL-T0}-V_{2TARG}$. Boundary Type has a main effect on the interval $V_{1ONS-T0}-V_{2PKVEL}$ ($F[1.7,8.6]=19.787$, $p<0.001$) with no significant interactions among factors, showing a pattern of $IP>(ip=Wd)$, as can be seen in the lower panel of Figure 6.10.

There is also a main effect on the second interval of the total X-movement duration, $V_{2PKVEL-T0}-V_{2TARG}$ ($F[1.5,6.] = 7.539$, $p<0.025$), and again a pattern of $IP>(ip=Wd)$, as shown in the upper panel of Figure 6.10.

Given that both $V_{1ONS-T0}-V_{2PKVEL}$ and $V_{2PKVEL-T0}-V_{2TARG}$ show significant effects of Boundary Type, the boundary-induced variation in the total X-movement duration seems to be due to durational variation in both durational components. That is, the boundary-induced lengthening appears to be due to both preboundary lengthening for V_1 and postboundary lengthening for V_2 .

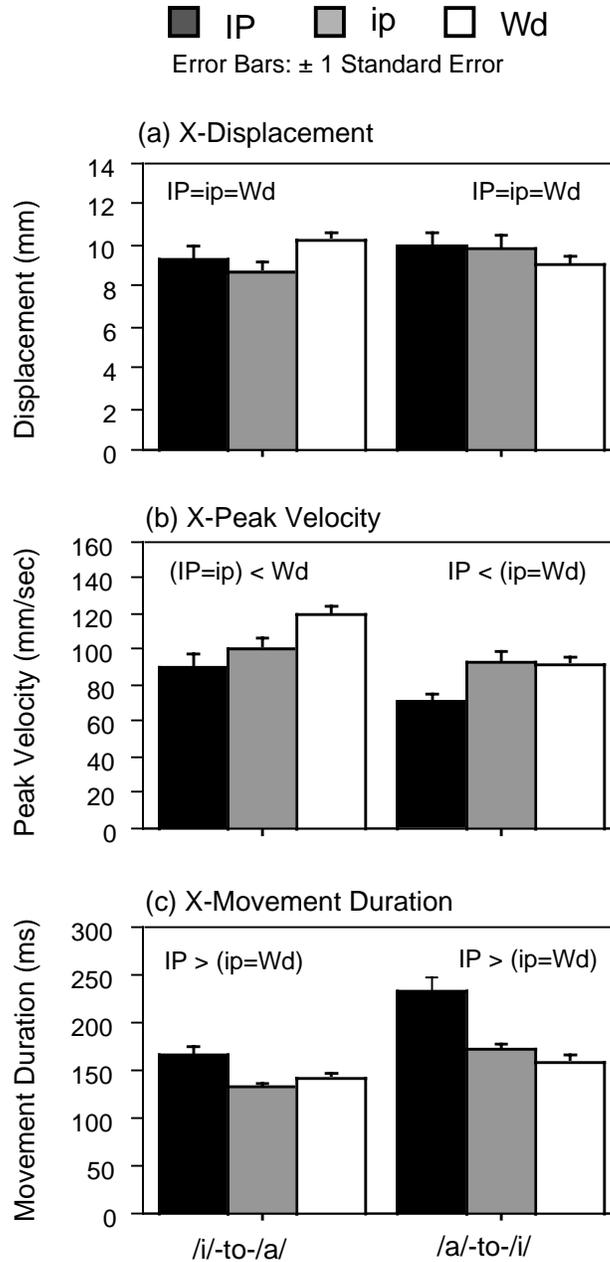


Figure 6.9. Effects of Boundary Type on (a) X-displacement, (b) X-peak velocity, and (d) total X-movement duration, separated by V_2 Type. Results of pairwise comparisons (Bonferroni/Dunn) are provided with '<' referring to $p < 0.01$, '<(')', to $p < 0.05$.

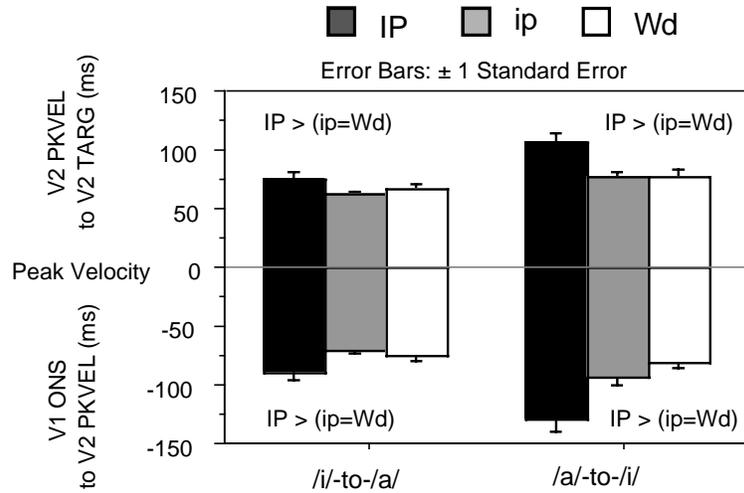


Figure 6.10. Effects of Boundary Type on two component durations $V_1\text{ONS-To-}V_2\text{PKVEL}$ and $V_2\text{PKVEL-To-}V_2\text{TARG}$ for the horizontal (x axis) tongue movement, separated by V_2 Type. Bar graphs are aligned at the attainment of peak velocity. Results of pairwise comparisons (Bonferroni/Dunn) are provided with ‘>’ referring to $p < 0.01$.

6.3.4. Discussion of dynamics underlying boundary-induced differences in kinematics

Thus far, we have examined how various kinematic variables for V_1 -to- V_2 vocalic gestures are influenced by Boundary Type. The results are summarized in Table 6.2. Unlike the case for ACC/UNACC differences, we found similar patterns for /i/-to-/a/ and /a/-to-/i/ vocalic gestures in both the x and y dimensions. However, x and y differ in displacement, such that in the y dimension, an increased displacement is found for a higher prosodic boundary (with a pattern of $\text{IP} > \text{Wd}$), whereas no variation in displacement is observable in the x dimension. In the y dimension, V_1 -to- V_2 vocalic gestures are longer, larger, and slower at a higher boundary than at a lower one; and in the x dimension, they are longer and slower, but not larger.

As before, in the following subsections these kinematic patterns and results from regression analyses are considered in order to discuss whether and how boundary-induced kinematic differences in V_1 -to- V_2 vocalic gestures can be accounted for by a particular dynamical parameter setting.

Table 6.2. Summary of kinematic descriptions for V₁-to-V₂ vocalic gestures. '>' refers to p<0.01 and '>)',' to p<0.05 (Bonferroni/Dunn), '—,' to no main effect.

Kinematic measures	y dimension		x dimension	
	/i/-to-/a/	/a/-to-/i/	/i/-to-/a/	/a/-to-/i/
Displacement	IP>Wd	IP>Wd	—	—
Total Movement Duration	IP>ip(>)Wd	IP>ip(>)Wd	IP>(ip=Wd)	IP>(ip=Wd)
V ₁ ONS-To-V ₂ PKVEL	IP>(ip=Wd)	IP>ip>Wd	IP>(ip=Wd)	IP>(ip=Wd)
V ₂ PKVEL-To-V ₂ TARG	IP>(ip=Wd)	IP>(ip=Wd)	IP>(ip=Wd)	IP>(ip=Wd)
Peak Velocity	IP<(ip=Wd)	IP<(ip=Wd)	(IP=ip)<Wd	IP<(ip=Wd)

6.3.4.1. Dynamics of boundary-induced kinematic differences in the y dimension

As summarized in Table 6.2, V₁-to-V₂ vocalic gestures in the y dimension at higher prosodic boundaries are associated with an increase in most kinematic variables including displacement, duration, time-to-peak-velocity, and V₂PKVEL-To-V₂TARG, except for peak velocity which shows a decrease. In comparison with the kinematic consequences of dynamical parameter manipulations (see Table 1.1 in Chapter 1), these observations do not single out any particular dynamical parameter that underlies boundary-induced kinematic differences. (This is consistent with results about boundary-adjacent lip opening and closing gestures, as reported in Chapter 5.) However, relationships between various kinematic variables suggest that the stiffness account is the most likely dynamical mechanism that best explain the observed pattern. The stiffness account is further evident in:

- (1) a close relationship between total movement duration and time-to-peak-velocity, with R² ranging from 0.54 to 0.68 for both /i/-to-/a/ and /a/-to-/i/;
- (2) a close fit of datapoints to regression lines of duration to displacement/velocity ratio, with datapoints clustering in the upper right corner of the plot (see Figure 6.11 in comparison with Figure 1.2c); and
- (3) no close fit of datapoints to regression lines in the displacement-peak velocity relationship, with points for IP being scattered together in the lower part of the plot (see Figure 6.12 in comparison with Figure 1.2a)

However, when we figure in the increased displacement at a higher prosodic boundary, the stiffness hypothesis cannot solely account for the observed data.

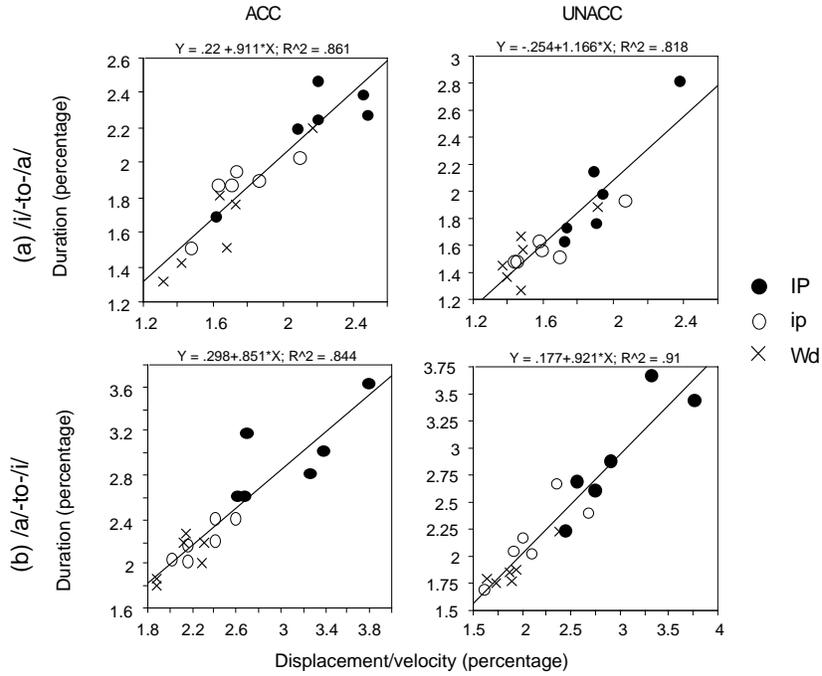


Figure 6.11. Effect of Boundary Type on relationship between duration and displacement/velocity ratio for the tongue lowering and raising gestures in the y dimension, separated by V₂ Type and Accent. (a) /i/-to-/a/ in upper panels and (b) /a/-to-/i/ in lower panels with results of regression analyses.

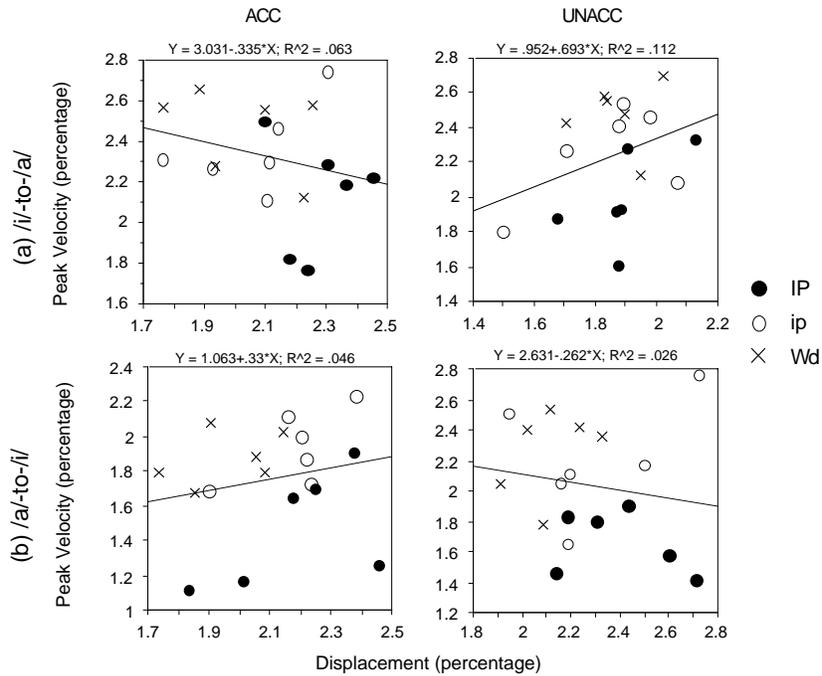


Figure 6.12. Effects of Boundary Type on relationship between peak velocity and displacement for the tongue lowering and raising gestures in the y dimension, separated by V₂ Type and Accent. (a) /i/-to-/a/ in upper panels and (b) /a/-to-/i/ in lower panels with results of regression analyses.

6.3.4.2. Dynamics of boundary-induced kinematic differences in the *x* dimension

As mentioned above, V_1 -to- V_2 vocalic gestures in the *x* dimension are characterized by kinematic patterns similar to those in the *y* dimension, except that there is no change in displacement as a function of Boundary Type. In other words, V_1 -to- V_2 vocal gestures at higher prosodic boundaries show an increase in total movement duration, time-to-peak-velocity, and V_2 PKVEL-TO- V_2 TARG, but a decrease in peak velocity, and not necessarily an increase in displacement. Both the target and the shrinking accounts are immediately ruled out because of lack of change in displacement; the intergestural timing account is also weakened by the fact that there is a change in both peak velocity and time-to-peak-velocity (see Table 1.1 in Chapter 1). The only possible account for the observed kinematic variations is the stiffness hypothesis, which predicts a longer and slower but not larger articulation at higher prosodic boundaries (less stiff).

The stiffness account is further supported by various kinematic relationships:

- (1) there is a close relationship between total movement duration and time-to-peak-velocity, with R^2 ranging from 0.54 to 0.801 (/i/-to-/a/, ACC, $R^2=0.801$; /i/-to-/a/, UNACC, $R^2=0.547$; /a/-to-/i/, ACC, $R^2=0.615$; /a/-to-/i/, UNACC, $R^2=0.742$).
- (2) the relationship between peak velocity and displacement shows no close fit of points to regression lines, but with datapoints for IP gathering towards the lower part of the regression plot (see Figure 6.13 in comparison with Figure 1.2a)
- (3) there is a close relationship between duration and the displacement/velocity ratio, with quite a clear separation between datapoints for IP (clustering towards the upper right corner of the plot) and for lower boundaries (see Figure 6.14 in comparison with Figure 1.2b).

Overall, all kinematic measures and the relationships between them converge on a change in stiffness as a reliable dynamical mechanism underlying boundary-induced kinematic variation in the horizontal (*x*) tongue movement dimension.

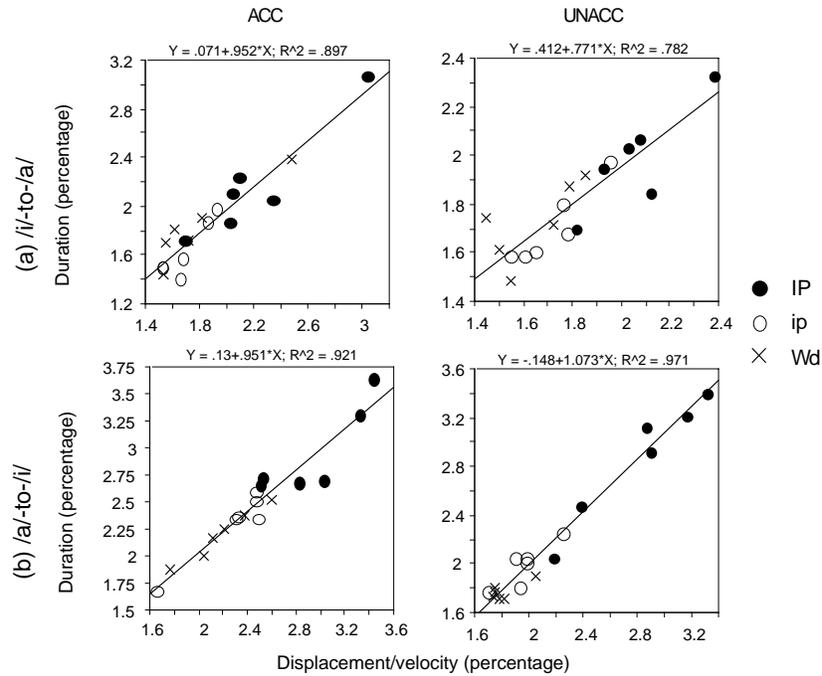


Figure 6.13. Effect of Boundary Type on relationship between peak velocity and displacement for the tongue fronting and backing gestures in the x dimension, separated by V₂ Type and Accent. (a) /i/-to-/a/ in upper panels and (b) /a/-to-/i/ in lower panels with results of regression analyses.

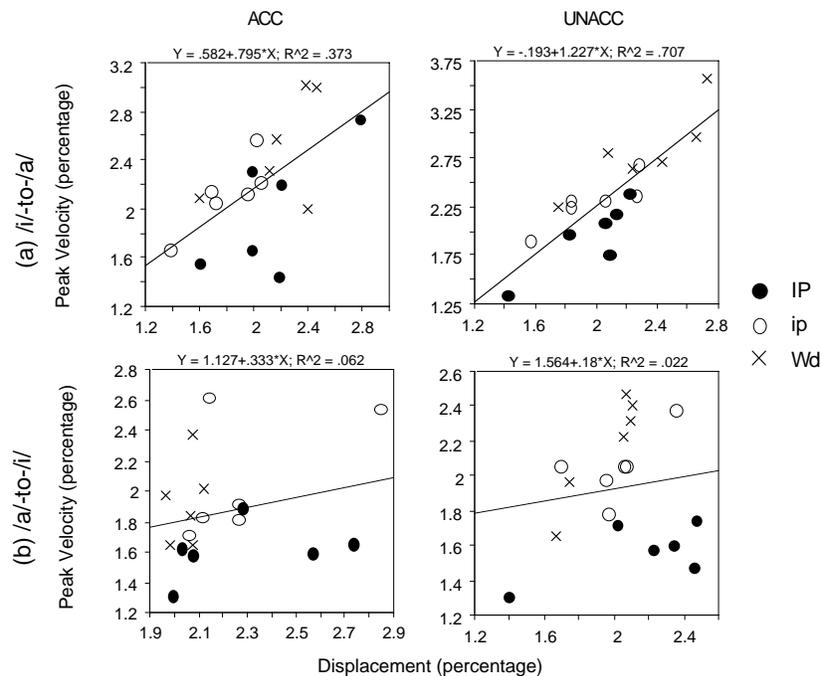


Figure 6.14. Effect of Boundary Type on the relationship between peak velocity and displacement for tongue fronting and backing gestures in the x dimension, separated by V₂ Type and Accent. (a) /i/-to-/a/ in upper panels and (b) /a/-to-/i/ in lower panels with results of regression analyses.

6.4. General Discussion

In this chapter, we examined effects of Accent and Boundary Type on V_1 -to- V_2 vocalic movements, and discussed how dynamical parameter values that control kinematic patterns may be modulated by prosodic context. This section is devoted to a summary of results, followed by discussion in connection with the hypotheses set forth at the outset of this chapter.

6.4.1. Accent-induced kinematic variation and task dynamics

6.4.1.1. Accent-induced kinematic variation and strengthening

With respect to the V_2 Accent effect on kinematic variables, we found an asymmetry between /i/-to-/a/ and /a/-to-/i/ vocalic gestures. On the one hand, /i/-to-/a/ gestures are influenced by V_2 Accent only in the y dimension, showing a larger, longer, but not faster movement. The elongated /i/-to-/a/ total movement duration is ascribable primarily to a change in time-to-peak-velocity (i.e., the interval that is closely related to V_1 /i/), given that there is no variation in the deceleration duration. On the other hand, /a/-to-/i/ gestures under accent show a longer, slower, but not larger movement, but this time only in the x dimension. Further, the lengthening of the /a/-to-/i/ total movement duration comes mainly from the lengthening of the deceleration duration (i.e., the interval that is closely related to V_2 /i/), as opposed to /i/-to-/a/ gestures. As mentioned earlier, the asymmetry is consistent with the findings in Chapter 3 that effects of Accent on maximum tongue body position are robust primarily in the y dimension for V_2 /a/ but in the x dimension for V_2 /i/—i.e., the tongue body was lower but not necessarily further back for accented V_2 /a/ but it was fronter but not necessarily higher for accented V_2 /i/. Overall, these results show that spatially V_2 Accent affects V_1 -to- V_2 movement (just as it affects V_2 's maximum position, seen in Chapter 3), but temporally, it affects the interval that is closely related to the vowel /i/ whether it is V_1 or V_2 .

These results do not fully support HYPOTHESIS 6.1, which postulates that accented vocalic V_1 -to- V_2 gestures are associated with a larger, longer, and faster movement, irrespective of vowel type and tongue movement (x or y) dimension. For example, expanded spatial magnitude was found only for tongue lowering gestures for /a/ but not for other gestures, including tongue backing gestures for /a/, or tongue raising and fronting gestures for /i/. In addition, accented gestures are not necessarily faster, in contrast to lip opening gestures.

Overall, the data presented in this chapter suggest that articulatory strengthening of accent as seen in the maximum tongue position is further evident in the kinematics, which show a longer and larger movement pattern.

6.4.1.2. Dynamical accounts

With respect to dynamical accounts, at the outset of this chapter we hypothesized that accent-induced kinematic variation is ascribable to a change in intergestural timing, based on earlier studies regarding jaw movements (Edwards, et al., 1991; Beckman, et al., 1992; Harrington, et al., 1995) (HYPOTHESIS 6.2). However, the results presented in this chapter support this hypothesis only partially and weakly.

As far as the kinematic patterns suggested by ANOVAs are concerned in comparison with descriptions of kinematic consequences of dynamical parameter settings given in Table 1.1 (Chapter 1), two dynamical accounts appear to best explain accent-induced gestural behavior. On the one hand, accent-induced variation in /a/-to-/i/ tongue fronting movement is best accounted for by the intergestural timing account, supporting the intergestural timing hypothesis (see section 5.3.2.2). On the other hand, the /i/-to-/a/ tongue lowering movement (in the *y* dimension) is best accounted for by the shrinking account, taking support away from the intergestural timing account (see section 5.3.2.1).

However, the intergestural timing account for /a/-to-/i/ tongue fronting movement is undermined by the pattern shown in the relationship between peak velocity and displacement, which favors the stiffness account only (see Figure 6.6b in comparison with Figure 1.2a in Chapter 1). In contrast, the shrinking account for /i/-to-/a/ tongue lowering movement is further underpinned by the pattern shown in relationships not only between duration and displacement/velocity ratio but also between duration and peak velocity (see Figures 6.5a-b in comparison with Figures 1.3g-h).

The tongue movement data reported in this chapter with respect to effects of accent show clearer evidence that favors a certain dynamical mechanism, as compared to the lip movement data reported in Chapter 5. In particular, as far as the /i/-to-/a/ tongue lowering gesture is concerned, all the kinematic measures and relationships between them converge on one dynamical parameter setting—i.e., a change by shrinking that governs the accent-induced kinematic variations. In just this one case, the mass-spring task dynamical model successfully captures the speech phenomena arising from accentuation.

However, there appear to be some potential problems arising from kinematic patterns regarding the /a/-to-/i/ tongue fronting gesture. First, as already mentioned, although accent-induced kinematic variations in the /a/-to-/i/ tongue fronting movement can be captured most closely by the intergestural timing account, this account was not completely supported by relationships between kinematic measures. Second, even if intergestural timing is responsible for /a/-to-/i/ tongue fronting, it would still not be able to explain the lowering observed in /i/-to-/a/, and an additional mechanism would be required, lacking a unified explanation.

6.4.2. *Boundary-induced kinematic variation and task dynamics*

6.4.2.1. *Boundary-induced kinematic variation and strengthening*

As for boundary effects, V_1 -to- V_2 vocalic gestures show a longer and slower movement at higher prosodic boundaries, regardless of V_2 Accent, V_2 type, and tongue movement (x or y) dimension, which is consistent with the boundary-induced kinematic patterns reported in Byrd (2000). Regarding variation in displacement, gestures in only the y dimension show an increased displacement at higher prosodic boundaries for both vowel types, suggesting that only the vertical tongue movement (raising or lowering) is sensitive to Boundary Type. There is no significant Boundary Type and Accent interaction, indicating that the observed pattern is consistent across accent conditions (ACC/UNACC). These results, combined with the lack of spatial expansion in the x dimension, lend partial support to the hypothesis that spatial expansion occurs at higher prosodic boundaries (Hypothesis 6.5). (However, it is not entirely clear why only the vertical (y) tongue movement dimension shows such spatial expansion, unlike the case under accent in which /i/ shows an increase in displacement in the x dimension.)

Now, these results can be considered in terms of boundary-induced articulatory strengthening. Recall that the results regarding maximum tongue positions reported in Chapter 3 indicated no spatial expansion for the domain-initial vowels after a higher prosodic boundary, showing no strengthening effect. However, the pattern of longer and larger movement at higher prosodic boundaries found in this chapter can be thought of as boundary-induced articulatory strengthening. This asymmetry between the maximum tongue position and the kinematics may be at least partially due to the difference in the data samples analyzed. The maximum tongue position data were extracted from identical vowel sequences (where $V_1 = V_2$), whereas the tongue movement data were extracted from opposite vowel sequences. Thus, we can further posit that the contrast between opposite vowels across a boundary is further enhanced at a higher prosodic boundary via an expanded spatio-temporal articulatory magnitude, a syntagmatic enhancement that may help mark the prosodic boundary.

6.4.2.2. *Dynamical accounts*

When the observed kinematic patterns are considered in terms of a mass-spring dynamical model, the boundary-induced kinematic variation is best accounted for by a change in stiffness, supporting the stiffness hypothesis (HYPOTHESIS 6.3). This is evident in (1) a decreased peak velocity for an increased duration, (2) a close relationship between total movement duration and time-to-peak-velocity, (3) a close relationship between total movement duration and the displacement/velocity ratio, with a clear separation between boundary types; and (4) no close fit of displacement to peak velocity, but with datapoints for a higher prosodic boundary gathering towards the lower part of the plot. The results generally hold for both /i/-to-/a/ and /a/-to-/i/ in both the x and y dimension. However, as for the increased displacement at higher prosodic boundaries in the y dimension, no obvious dynamical account can be singled out, weakening the stiffness account.

6.4.2.3. *The π -gesture and pre- and postboundary lengthening*

As proposed in Byrd (2000), variation in stiffness value as a function of Boundary Type can be modeled by an abstract non-tract variable, the π -gesture: The strength of π -gestures at a higher prosodic boundary is greater, which has the effect of lowering the stiffness in boundary-adjacent articulatory gestures, leading to a longer duration. More recently, Byrd & Saltzman (2000) attribute such boundary-induced kinematic variation to their clock slowing mechanism. As discussed in Chapter 5, the clock slowing mechanism can possibly explain as well an increased displacement at a higher prosodic boundary (see section 5.4.5 in Chapter 5 for further discuss of the π -gesture model).

With respect to the relative contribution of pre- and post-boundary lengthening to the variation in the total movement duration, based on Byrd (2000) we hypothesized that the lengthening of the total movement duration was due primarily to preboundary lengthening (HYPOTHESIS 6.4). Byrd claimed it to be a consequence of a stronger effect of the π -gesture on the preboundary V_1 : that is, in a $C_1V_1\#C_2V_2$ sequence V_1 is closer to the prosodic boundary than V_2 is, so that V_1 is more heavily influenced by the π -gesture than V_2 is. However, the results in this chapter show that boundary-induced durational variation is evident quite equally in both the preboundary and the postboundary lengthening, lend no support to HYPOTHESIS 6.4. There is at least a two-way distinction among boundary types, showing a pattern of $IP > (ip = Wd)$ in both the time-to-peak-velocity (an index of preboundary lengthening) and the deceleration duration (an index of postboundary lengthening). Given that there is a significant boundary effect on the deceleration duration, the durational variation in time-to-peak-velocity cannot be attributed entirely to lowered stiffness affecting the preboundary V_1 gesture only. This means that the lengthening of the total movement duration at higher prosodic boundaries is likely to be due to lowered stiffness affecting both pre- and postboundary movement, whose compounding effects cannot be broken down into individual effects. Thus, our data is not compatible with the

idea that the V_1 gesture is influenced more by the π -gesture than the V_2 is simply because V_1 is closer to the boundary (#) than V_2 is in $C_1V_1\#C_2V_2$ sequence.³

6.4.3. *Accent- vs. boundary-induced kinematic patterns and articulatory strengthening*

In Chapter 3, we found that accent-induced articulatory strengthening is manifested in the maximum tongue position, especially in tongue fronting for /i/ and tongue lowering for /a/. In this chapter, we observed that accent-induced articulatory strengthening can be further characterized by a larger displacement, longer duration, and faster movement velocity, primarily in the same tongue movement dimension that also showed articulatory strengthening with respect to maximum tongue positions. As for boundary effects, although the maximum tongue position data reported in Chapter 3 showed no spatial expansion in domain-initial position, results in this chapter show that boundary-induced articulatory strengthening is observable in the kinematic pattern of a longer and sometimes larger V_1 -to- V_2 movement at higher prosodic boundaries. However, the boundary-induced strengthening pattern manifest in movement kinematics cannot be considered to be the same effect as the one arising from accent, in that the latter is associated with a faster movement whereas the former is not, and that there is not as consistent boundary-induced spatial expansion as accent-induced spatial expansion.

³ A comment to be made regarding the π -gesture model is that it is not clear whether V_1 is indeed closer to the boundary than V_2 is in $C_1V_1\#C_1V_2$ sequence. In *Articulatory Phonology* (Browman & Goldstein, 1989, 1990, 1992), it is assumed that vocalic and consonantal gestures are on separate tiers such that consonantal gestures are superimposed on vocal gestures, allowing for overlap between the two gestures (an idea based on Öhman, 1966 and Fowler, 1980). Under this assumption, there appears to be no reason to say that the C_2 gesture precedes V_2 gestures, and that V_2 is farther away from the prosodic boundary.

Chapter VII

Conclusion

This dissertation has investigated how segmental phonetic realizations are conditioned by various prosodic factors, by examining articulation in three kinds of prosodically strong locations. These prosodically strong locations included accented syllables, domain-initial syllables, and domain-final syllables. The primary goal of this dissertation was to understand how the articulatory strengthening that may arise from these prosodically strong locations is manifested in the articulatory maximum positions, vowel-to-vowel coarticulation, and movement kinematics. To accomplish this, three articulators, the tongue, the jaw, and the lips, were examined, with data collected from six speakers of American English using electromagnetic articulography (EMA). In what follows, I will summarize results of this dissertation, with some implications of the study.

Articulatory strengthening in accented syllables

The results regarding the maximum articulatory positions reported in Chapter 3 show that accented vowels are associated with a more open vocal tract, evident in the larger lip and jaw openings, as compared to unaccented vowels. Both low /a/ and high /i/ show this, consistent with sonority expansion. On the other hand, the results regarding the maximum tongue position show only partial enhancement of vowel features: /a/ is lower (but not backer) and /i/ is fronter (but not higher). These results suggest that accented syllables are characterized primarily by sonority expansion, and only secondarily by the enhancement of vowel features, when doing so does not conflict with sonority expansion. Thus /i/, which is featurally high and front, is enhanced by tongue fronting, since that does not conflict with sonority expansion, but it is not enhanced by tongue raising, since that would conflict with the greater mouth opening of sonority expansion. This result, which is quite consistent in this study across six speakers, differs from what Harrington, et al. (2000) found for /i/ in Australian English for one of the two speakers: namely, that under accent, the jaw lowers while the tongue raises, so that different articulators enhance different features. The result of the present study, in contrast, is that sonority expansion dominates, and the tongue defers to the jaw/lips in this regard, seen also in the second speaker in Harrington, et al. (2000).

The strengthening effect found in the maximum tongue position is further evident in vowel-to-vowel coarticulation. In Chapter 4, it was shown that accented vowels generally resist coarticulation with neighboring vowels, while unaccented vowels are vulnerable to coarticulation. In particular, the effect of Accent on coarticulation lies primarily in the same tongue dimension for which the maximum tongue position also shows strengthening. However, the data did not show any evidence that the accent-induced articulatory strengthening can be related to coarticulatory aggression, suggesting

that strongly articulated segments under accent do not necessarily have strong influence on the articulation of neighboring segments.

Accent-induced articulatory strengthening can be further characterized by larger, longer, and faster lip opening and closing movements (in Chapter 5). This finding is found robustly for all the speakers in this study. Furthermore, it is a result that makes intuitive sense: under accent, vowel movements are simply bigger in all ways – in distance, time, and speed. Nonetheless, unlike previous proposals (e.g., Edwards, et al., 1991, Harrington, et al, 1995), these kinematic characteristics cannot be accounted for by any particular dynamical parameter setting in the framework of a mass-spring gestural model.

Finally, accent-induced articulatory strengthening is also manifested in V_1 -to- V_2 tongue movement kinematics. The results in Chapter 6 indicate that /i/-to-/a/ tongue gestures are influenced by V_2 Accent only in the vertical (y) dimension (lowering), showing a larger, longer, but not faster movement, while /a/-to-/i/ gestures show a larger, longer, and slower movement only in the horizontal (x) dimension (fronting). This asymmetry also is consistent with the patterns found in the maximum tongue position and vowel-to-vowel coarticulation, in that accent-induced kinematic variations are robust in the same tongue movement dimension that also shows robust articulatory strengthening effects. Thus, for example, in an /i/-to-/a/ sequence, accent on V_2 /a/ results not only in larger and longer lowering movement, but also in lower maximum tongue position and robust coarticulatory resistance in the vertical (y) dimension.

The tongue movement kinematic data show relatively clear evidence that favors a dynamical mechanism (as compared to the lip movement data). For the /i/-to-/a/ tongue lowering gesture, kinematic measures strongly suggest that a change by shrinking underlies accent-induced kinematic patterns, which contradicts proposals supporting the intergestural timing account. On the other hand, for the /a/-to-/i/ tongue fronting gesture, the intergestural timing account is favored, though not conclusively. This suggests a failure for the model to provide a unified account for the same linguistic factor, accent.

Articulatory Strengthening at Domain-edges

The results regarding articulatory maxima reported in Chapter 3 suggest that boundary-induced articulatory strengthening is found only in domain-final positions, showing an increase in the lip opening and in the tongue lowering, but not in the jaw opening, for both /a#/ and /i#/. No strengthening was found in the articulatory maxima in domain-initial positions, suggesting that perhaps initial vowels in #CV do not strengthen. Another possibility is that vowels in #CV are not strictly initial since they follow the domain-initial consonant.

The coarticulatory patterns (Chapter 4) suggest that vowels show greater coarticulatory resistance across higher than lower prosodic boundaries, which can be interpreted as one type of articulatory strengthening. However, the data indicate that

domain-initial vowels, which show no strengthening effect on the maximum tongue position, are also more susceptible to coarticulation than domain-final vowels, which show a robust strengthening effect. Again, weaker coarticulatory resistance associated with domain-initial vowels in #CV may be because the vowel in #CV is not strictly initial.

Boundary-induced strengthening effects are further evident in the lip opening and closing movement kinematics (Chapter 5), which show longer, but this time slower, articulation (as opposed to accent-induced kinematic patterns) both in domain-final positions and in domain-initial positions. The spatial expansion (i.e., increased displacement) is found quite consistently when the gestures being examined are *unaccented*, but cross-boundary V₁-to-C₂ lip closing gestures shows a consistent increase in displacement regardless of accent. All in all, the boundary-induced articulatory strengthening is further evident in longer, slower, but only sometimes larger lip opening and closing gestures. With respect to dynamical accounts of these kinematic patterns, no single dynamical parameter setting was able to account for all of the observed boundary-induced lip movement patterns. Although the stiffness account was preferred to other dynamical accounts, the complex patterns evident in the kinematic relationships weakened the stiffness account. The ' π -gesture' model was considered as a possible solution to the problem, but it remains to be seen whether the full range of results presented here can be accounted for by this model.

Finally, boundary-induced articulatory strengthening is also shown in V₁-to-V₂ tongue movement kinematics (Chapter 6), characterized by longer movement duration in both the x and y dimension, and larger displacement in the y dimension only. Considering that the target vowel V₂ in the V₁-to-V₂ movement belongs to the domain-initial position, this result can also be thought of as domain-initial articulatory strengthening. With respect to dynamical accounts, the stiffness account was supported as a dynamical mechanism, especially for the tongue gesture in the x dimension. However, the stiffness account was weak when it comes to the tongue gesture in the y dimension.

Accent- vs. Boundary-induced Articulatory Strengthening

As just summarized above, in this dissertation we have observed articulatory strengthening effects both in accented syllables and at edges of prosodic domains. One of the main questions that this dissertation has tried to answer is whether the strengthening effects arising from these two prosodically strong locations can be considered the same. The results suggest that there are some differences between accent-based and boundary-based articulatory characteristics, especially in the dimension in which the tongue is expanded, the involvement of the lips and the jaw, and movement velocity. The differences are recapitulated here:

- (1) Accent-induced strengthening is associated with an increase in both lip and jaw openings, but boundary-induced strengthening is associated with an increase only in the lip opening, and only domain-finally at that.

- (2) Accent-induced strengthening is associated with some enhancement of place features (fronting of /i/, lowering of /a/), but boundary-induced strengthening with lowering of both /i/ and /a/, i.e., enhancement of sonority.
- (3) Accent-induced coarticulatory resistance is related to strengthening: it lies primarily in the same tongue dimension for which the tongue maximum position showed a robust strengthening effect (e.g., /i/ resists backing and /a/ resists lowering), whereas there is no clear evidence for this relationship in boundary-induced coarticulatory resistance.
- (4) The accent-induced coarticulatory patterning cannot be fully accounted for by a duration factor, whereas the boundary-induced coarticulatory patterning is fully accounted for by a duration factor.
- (5) Accent-induced kinematic variations are characterized by longer, larger, and faster movement, but boundary-induced kinematic variations by longer, sometimes larger, and not necessarily faster movement.
- (6) There were two clear cases in which a particular dynamical mechanism can be identified: one *accent-induced* kinematic pattern can be fully accounted for by a change by shrinking (in the case of the /i/-to-/a/ tongue lowering gesture) and one *boundary-induced* kinematic pattern by a change in stiffness (in the case of the /i/-to-/a/ backing and /a/-to-/i/ fronting gestures). If we consider just these two cases, only the accented vowels show strengthening due to less shrinking, whereas vowels at higher boundaries show not strengthening but lengthening due to less stiffness. However, in other cases dynamical accounts of the prosodically-conditioned kinematic variations are not fully supported by all the observed data, which are too complex to explain in a unified way.

Consonantal vs. vocalic domain-initial strengthening

As introduced in Chapter 1, a series of electropalatographic studies from the UCLA Phonetics Lab showed that in general consonants are produced with an increased constriction degree and longer constriction duration (as measured by linguopalatal contact) in domain-initial positions at each level (e.g., IP, ip, Wd) than in domain-medial positions at that level. In this dissertation, we also found that the V₁-to-C₂ lip closing movement for the domain-initial consonant /b/ is larger and longer, showing domain-initial consonantal strengthening in terms of kinematics.

Now, the question is how such domain-initial *consonantal* strengthening can compare the domain-initial *vocalic* strengthening in #CV examined in this dissertation. The articulatory maxima data of the jaw, the tongue, and the lips (Chapter 3) showed little evidence for such vocalic strengthening. However, V₁-to-V₂ movement kinematics showed that there is robust spatial expansion (i.e., increased displacement) associated with

the domain-initial target vowel V_2 , accompanied by elongated duration, showing larger and longer movement domain-initially (Chapter 6). Furthermore, the $\#C_2V_2$ lip opening movement also suggested robust domain-initial lengthening with occasional spatial expansion, especially when syllables are unaccented (Chapter 5). From these results, we can conclude that the domain-initial vocalic strengthening in $\#CV$ is compatible with domain-initial consonantal strengthening in $V\#C$ in terms of kinematics. However, with respect to the positional extremity observed in the articulatory maxima, domain-initial vocal articulation shows no strengthening effect, as opposed to the domain-initial consonantal articulation. This is presumably because the vowel in $\#CV$ is further from the boundary, such that the strengthening effect is weaker at the timepoint of the maximum tongue position.

Articulatory strengthening and its linguistic significance

This study has shown that articulations are prosodically strengthened, albeit in different ways, in three prosodically strong locations. The question is then what is the linguistic function of prosodically-conditioned articulatory strengthening? In the discussion of results in each chapter, we tried to answer this question. The prosodically-conditioned articulatory strengthening found for various articulatory variables examined in this dissertation can be interpreted in terms of the prominence maximization.

One way to maximize prominence is by heightening phonetic clarity. The phonetic clarity can be heightened articulatorily in various ways. One way is by opening the vocal tract larger and longer, and by fully reaching each feature's assumed target, which will ultimately make the relevant sound acoustically clear. In this dissertation, we found that both accent- and boundary-induced articulatory patterns showed evidence for larger mouth opening, longer movement duration, and positional extremity, which indicates an enhancement of phonetic clarity associated with prosodically strong locations. Furthermore, coarticulatory resistance can also be interpreted as adding to phonetic clarity, which would otherwise be obscured by contextual influence.

The prominence achieved via such heightened phonetic clarity can be interpreted as enhancing linguistic contrast, both syntagmatically (structurally) and paradigmatically (lexically or phonemically). For example, heightened phonetic clarity can render a sound more distinct from neighboring segments (an enhancement of syntagmatic contrast), and it can also make the sound distinct from other contrastive sounds in the sound system of the language (an enhancement of paradigmatic contrast). These two effects appear to be compatible. It is possible that phonetic clarity arising from strengthening can render the segment in prosodically strong locations more prominent than neighboring segments and, at the same time, make the segment maximally distinctive among contrastive sounds.

Developing further the idea of prosodically-conditioned articulatory strengthening as a prominence enhancing strategy, articulatory strengthening can be thought of as facilitating lexical processing and sentence comprehension. It has been suggested in the

literature that words under accent are processed more efficiently than words with no accent (Shields, et al., 1974; Cutler, 1976; Cutler & Foss, 1977). We can posit that this is because phonetic clarity arising from accent-induced articulatory strengthening may facilitate lexical processing.

As for boundary effects, Fougeron & Keating (1997) suggested that domain-initial *consonantal* strengthening can facilitate lexical processing and sentence comprehension. The present study suggests that such prosodically-driven facilitation of speech comprehension can be further achieved via strengthening not only in domain-initial *vocalic* articulation but also in domain-final *vocalic* articulation, providing additional cues to listeners about hierarchically-nested prosodic structure, hence presumably facilitating sentence comprehension. In fact, psycholinguistic studies have suggested that appropriate prosodic cues for boundaries facilitate sentence comprehension (e.g., Sanderman, 1996; Sanderman & Collier, 1997; Schafer, 1997; Schafer, Kjelgaard & Speer, 1999 to name a few). Moreover, it has also been shown that lexical access is facilitated when a word occurs phrase-initially, as opposed to when it occurs phrase-medially (e.g., Christophe, Gout & Morgan, 2001). It remains to be seen whether lexical access is also facilitated when a word occurs phrase-finally, as well.

All in all, the present study suggests that the speaker signals prosodic structure and accent via articulatory strengthening, and the listener could make use of such an articulatory signature (in addition to lexical information) in speech comprehension.

Other implications

In this dissertation, I have also made a few other suggestions that provide the basis from which existing phonetic theories can further develop. First, based on the results regarding prosodically-driven coarticulatory resistance, I suggested an outline of the revised window model in which the size of the window can vary to accommodate prosodic conditions such as accent and prosodic boundary. It is hoped that such an outline motivates future research to further develop the theory of coarticulation, reflecting speech variations coming from various linguistic factors.

Second, the results regarding movement kinematics suggest that speech mechanisms are more complex than has generally been assumed by researchers who have adopted a mass-spring gestural model in explaining certain speech phenomena. It was proposed that in order to account for prosodically-conditioned kinematic patterns in the framework of a mass-spring gestural model, one should look for a combination of settings for multiple dynamical parameters, rather than seeking one particular dynamical mechanism governing kinematic patterns arising from each prosodic condition. Alternatively, the best solution to the problem might be to find an integrated dynamical parameter, if existent, that allows the facts to be modeled in a unified way.

Closing remarks

In this dissertation, I have attempted to provide a relatively comprehensive account of effects of prosody on articulation in English in terms of prosodically-conditioned articulatory strengthening. All in all, this dissertation suggest that the phonetic realization is systematically governed by high level prosodic conditions, and the prosodically-conditioned phonetic patterns, in turn, could signal high level prosodic structures. Much remains to be done in terms of psycholinguistic and cross-linguistic work. Nevertheless, it is hoped that this dissertation will contribute to theories of the phonetics-prosody interface, making progress towards gaining better insight into prosodically-driven speech phenomena.

= Intermediate or Intonational Phrase boundaries (ip or IP):

- (e) *Acc.-Unacc.* A: Did you say "Donna **D.** beeped at **Ann** last night"?
 B: No, "Donna **B.** # beeped at **Al** "
renditions : H*L-(L%) H* L- L%
- (f) *Unacc.-Acc.* A: Did you say "**Anna B.** **peeped** at him last night"?
 B: No, "**Donna B.** # beeped at him "
renditions : H* L-(L%) H* L- L%
- (g) *Acc.-Acc.* A: Did you say "Donna **D.** **peeped** at him last night"?
 B: No, "Donna **B.** # beeped at him "
renditions : H*L-(L%) H* L- L%
- (h) *Unacc.-Unacc.* A: Did you say "**Anna B.** beeped at **Ann** last night"?
 B: No, "**Donna B.** # beeped at **Al** "
renditions: H* L-(L%) H* L- L%

C. [ba#bi] sequence

= Word boundary:

- (a) *Acc.-Unacc.* A: Did you say "Little **Boo** beeped at him last night"?
 B: No, "Little **Bah** # beeped at him "
rendition : H* L- L%
- (b) *Unacc.-Acc.* A: Did you say "Little Bah **peeped** at him"?
 B: No, "Little **Bah** # beeped at him "
rendition : H* L- L%
- (c) *Acc.-Acc.* A: You know what? Little **Bah** # beeped at him.
rendition : H* H* L- L%
- (d) *Unacc.-Unacc.* A: Did you say "**Big** Bah beeped at him last night"?
 B: No, "**Little Bah** # beeped at him "
rendition : H* L- L%

= Intermediate or Intonational Phrase boundaries (ip or IP):

- (e) *Acc.-Unacc.* A: Did you say "Little **Boo** beeped at **Ann** last night"?
 B: No, "Little **Bah** # beeped at **Al** "
renditions : H*L-(L%) H* L-L%
- (f) *Unacc.-Acc.* A: Did you say "**Big** Bah **peeped** at him last night"?
 B: No, "**Little Bah** # beeped at him "
renditions : H* L-(L%) H* L- L%
- (g) *Acc.- Acc.* A: Did you say "Little **Boo** **peeped** at him last night "?
 B: No, "Little **Bah** # beeped at him "
renditions : H*L-(L%) H* L- L%
- (h) *Unacc.-Unacc.* A: Did you say "**Big** Bah beeped at **Ann** last night "?
 B: No, "**Little Bah** # beeped at **Al** "
renditions: H* L-(L%) H* L- L%

Appendix II: R^2 Values for Lip Movement Temporal Relationships

This section reports R^2 values for the relationship (1) between the total lip movement duration and the first durational component, time-to-peak-velocity and (2) between the total lip movement duration and the second durational component, deceleration duration.

Table A.1. C_1 -to- V_1 lip opening movement, separated by Boundary Type

	/ba#/			/bi#/		
	IP	ip	Wd	IP	ip	Wd
duration vs. time-to-peak-velocity	.366	.435	.734	.468	.741	.939
duration vs. deceleration duration	.676	.781	.901	.737	.897	.918

Table A.2. C_1 -to- V_1 lip opening movement, separated by Accent

	/ba#/		/bi#/	
	ACC	UNACC	ACC	UNACC
duration vs. time-to-peak-velocity	.782	.727	.961	.856
duration vs. deceleration duration	.838	.911	.955	.911

Table A.3. C_2 -to- V_2 lip opening movement, separated by Boundary Type

	/#ba/			/#bi/		
	IP	ip	Wd	IP	ip	Wd
duration vs. time-to-peak-velocity	.85	.92	.91	.92	.95	.94
total duration vs. deceleration duration	.72	.81	.87	.76	.88	.89

Table A.4. C_2 -to- V_2 lip opening movement, separated by Accent

	/#ba/		/#bi/	
	ACC	UNACC	ACC	UNACC
duration vs. time-to-peak-velocity	.78	.73	.96	.86
duration vs. deceleration duration	.84	.91	.96	.91

Table A.5. V_1 -to- C_2 lip closing movement, separated by Boundary Type and V_2 Accent

	V_2 Accent	/a#b/			/i#b/		
		IP	ip	Wd	IP	ip	Wd
duration vs. time-to-peak-velocity	ACC	.937	.941	.662	.911	.894	.773
	UNACC	.882	.947	.898	.844	.878	.957
total duration vs. deceleration duration	ACC	.389	.599	.493	.736	.493	.776
	UNACC	.357	.529	.616	.113	.458	.913

Table A.6. V₁-to-C₂ lip closing movement, separated by Boundary Type and V₁ Accent

	V ₁ Accent	/a#b/			/i#b/		
		IP	ip	Wd	IP	ip	Wd
duration vs. time-to-peak-velocity	ACC	.945	.961	.85	.889	.831	.902
	UNACC	.805	.621	.593	.789	.788	.706
total duration vs. deceleration duration	ACC	.505	.737	.476	.389	.439	.817
	UNACC	.241	.482	.663	.434	.612	.827

Table A.7. V₁-to-C₂ lip closing movement, separated by V₁ Accent and V₂ Accent

	duration vs. time-to-peak-velocity		total duration vs. deceleration duration	
	/a#b/	/i#b/	/a#b/	/i#b/
ACC-ACC	.97	.941	.689	.712
ACC-UNACC	.951	.913	.621	.419
UNACC-ACC	.878	.915	.626	.762
UNACC-UNACC	.914	.918	.502	.692

References

- Beckman, M.E. (1986) *Stress and Non-stress Accent*. Dordrecht: Foris Publications.
- Beckman, M.E. & Edwards, J. (1994) Articulatory evidence for differentiating stress categories. In *Papers in Laboratory Phonology III: Phonological Structure and Phonetic Form* (P.A. Keating, editor), pp. 7-33. Cambridge: Cambridge University Press.
- Beckman, M.E. & Edwards, J., and Fletcher, J. (1992) Prosodic structure and tempo in a sonority model of articulatory dynamics. In *Papers in Laboratory Phonology II: Gesture, Segment, Prosody* (G. Docherty & D.R. Ladd, editors), pp. 68-86. Cambridge: Cambridge University Press.
- Beckman, M.E. & Pierrehumbert, J. (1986) Intonational structure in Japanese and English. *Phonology Yearbook*, 3, 255-309.
- Bladon, R.A.W. & Al-Bamerni, A. (1976) Coarticulation resistance in English /l/. *Journal of Phonetics*, 4, 137-150.
- Bladon, R.A. & Nolan, F. (1977) A video-fluorographic investigation of tip and blade alveolars in English. *Journal of Phonetics*, 5, 185-193.
- Bolinger, D. (1958) A theory of pitch accent in English. *Word*, 14, 109-149.
- Browman, C. & Goldstein, L. (1989) Articulatory gestures as phonological units. *Phonology*, 6: 201-252.
- Browman, C. & Goldstein, L. (1990) Tiers in Articulatory Phonology, with Some Implications for Casual Speech. In *Papers in Laboratory Phonology I: Between the Grammar and the Physics of Speech* (J. Kingston and M.E. Beckman, editors), pp. 341-376. Cambridge: Cambridge University Press.
- Browman, C. & Goldstein, L. (1992) Articulatory phonology: an overview. *Phonetica*, 49, 155-180.
- Browman, C. & Goldstein, L. (1998) Competing constraints on intergestural coordination and self-organization of phonological structures. Paper presented at the meeting of Current Trends in Phonology. Royaumont France. June, 1998. (To appear in *Bulletin de la Communication Parle*.)
- Byrd, D. (1996) A phase window framework for articulatory timing. *Phonology* 13: 139-169.

- Byrd, D. (2000) Articulatory vowel lengthening and coordination at phrasal junctures. *Phonetica*, 57, 3-16
- Byrd, D. & Saltzman, E. (1998) Intra-gestural dynamics of multiple prosodic boundaries. *Journal of Phonetics*, 26, 173-200.
- Byrd, D., Kaun, A., Narayanan, S. & Saltzman, E. (2000) Phrasal signatures in articulation. In *Acquisition and the Lexicon: Papers in Laboratory Phonology V* (M. Broe & J. Pierrehumbert, editors), pp. 70-88. Cambridge, UK: Cambridge University Press.
- Cho, T. (1998) Domain-initial articulatory strengthening in the prosodic hierarchy in Korean: an EPG study. In *Proceedings of the 11th International Conference on Korean Linguistics (ICKL)*, pp. 363-372.
- Cho, T. (1999) Effect of prosody on vowel-to-vowel coarticulation in English. In *Proceedings of the 14th International Congress of Phonetic Sciences* (J.J. Ohala, Y. Hasegawa, M. Ohala, D. Granville & A.C. Bailey, editors), pp. 459-462. New York: American Institute of Physics.
- Cho, T. (2001) Effects of morpheme boundaries on intergestural timing. Evidence from Korean. *Phonetica*, 58, 129-162.
- Cho, T. & Jun, S. (2000) Domain-initial strengthening as featural enhancement: Aerodynamic evidence from Korean. In *Chicago Linguistics Society*, 36(1), 31-44.
- Cho, T. & Keating, P. (2001) Articulatory and acoustic studies of domain-initial strengthening in Korean. *Journal of Phonetics*, 29, 155-190.
- Christophe, A., Gout, A. & Morgan, J. (2001) Infants and adults exploit phonological phrase boundaries on-line to drive lexical access. A paper presented in Workshop Prosody in Processing, Utrecht Institute of Linguistics OTS, Utrecht University, 5-6 July 2001.
- Cooper, A. (1991) *Glottal Gestures and Aspiration in English*. Ph.D. Dissertation, Yale University.
- Cooper, W. E. & Paccia-Cooper, J. (1980) *Syntax and speech*. Cambridge, MA: Harvard University Press.
- Couper-Kuehlen, E. (1986) *An introduction to English prosody*. London: Edward Arnold.
- Cutler, A. (1976) Phoneme-monitoring reaction time as a function of preceding intonation contour. *Perception and Psychophysics*, 20, 55-60.
- Cutler, A. & Foss, D.J. (1977) On the role of sentence stress in sentence processing. *Language and Speech*, 20, 1-10.
- De Jong, K. (1991) *The Oral Articulation of English Stress Accent*. Unpublished Ph.D. Dissertation. Ohio State University.
- De Jong, K. (1995a) The supraglottal articulation of prominence in English: Linguistic stress as localized hyperarticulation. *JASA*, 97 (1), 491-504.
- De Jong, K. (1995b) On the status of redundant features: the case of backing and rounding in American English. In *Phonology and phonetic evidence: Papers in Laboratory Phonology IV* (B. Connell & A. Arvaniti, editors), pp. 68-86. Cambridge, UK: Cambridge University Press.
- De Jong, K., Beckman, M.E. & Edwards, J. (1993) The interplay between prosodic structure and coarticulation. *Language and Speech*, 36 (2, 3), 197-212.
- Dilley, L., Shattuck-Hufnagel, S. & Ostendorf, M. (1996) Glottalization of word-initial vowels as a function of prosodic structure. *Journal of Phonetics*, 24, 423-444.
- Edwards, J. & Beckman, M.E. (1988) Articulatory timing and the prosodic interpretation of syllable duration. *Phonetica*, 45, 156-174.

- Edwards, J. E., Beckman, M.E. & Fletcher, J. (1991) The articulatory kinematics of final lengthening. *Journal of the Acoustical Society of America*, 89, 369-382.
- Farnetani, E. (1990) V-C-V lingual coarticulation and its spatiotemporal domain. In *Speech production and speech modeling* (W.J. Hardcastle & A. Marchal, editors), pp. 93-130. Dordrecht: Kluwer Academic Publishers
- Farnetani, E. (1997) Coarticulation and connected speech processes. In *A Handbook of Phonetic Science* (W.J. Hardcastle and J. Laver, editors), pp. 371-404. Oxford: Blackwell.
- Farnetani, E. & Recasens, D. (1993) Anticipatory consonant-to-vowel coarticulation in the production of VCV sequences in Italian. *Language and Speech*, 36, 279-302.
- Farnetani, E. & Recasens, D. (1999) Coarticulation models in recent speech production theories. In *Coarticulation: Theory, Data and Techniques* (W.J. Hardcastle & N. Hewlett, editors). pp.31-65. Cambridge, UK: Cambridge University Press.
- Farnetani, E. & Vayra, M. (1996) The role of prosody in the shaping of articulation in Italian CV syllables. *Proceedings of the 1st ESCA Workshop on Speech Production Modeling, 4th Speech Production Seminar*, 9-12. Autrans, France.
- Fougeron, C. (1998) *Variations Articulatoires en Début de Constituants Prosodiques de Différents Niveaux en Français*. Ph.D. Dissertation, Université Paris III - Sorbonne Nouvelle.
- Fougeron, C. (1999) Prosodically conditioned articulatory variations: a review. *UCLA Working Papers in Phonetics*, 97, 1-74.
- Fougeron, C. (2001) Articulatory properties of initial segments in several prosodic constituents in French. *Journal of Phonetics*, 29, 109-135.
- Fougeron, C. & Keating, P.A. (1996) Variations in velic and lingual articulation depending on prosodic position: Results for two French speakers. *UCLA Working Papers in Phonetics*, 92, 88-96.
- Fougeron, C. & Keating, P.A. (1997) Articulatory strengthening at edges of prosodic domains. *JASA*, 106 (6), 3728-3740.
- Fowler, C.A. (1980) Coarticulation and theories of extrinsic timing. *Journal of Phonetics*, 8, 113-133.
- Fowler C.A. (1981) Production and perception of coarticulation among stressed and unstressed vowels. *Journal of Speech and Hearing Research*, 46, 127-139.
- Fowler, C.A. (1995) Acoustic and kinematic correlates of contrastive stress accent in spoken English. In *Producing Speech: Contemporary Issues: For Katherine Safford Harris* (F. Bell-Berti and J.J. Raphael, editors), pp.355-373.
- Fry, D.B. (1965) Experiments in the perception of stress. *Language and Speech*, 1, 126-152.
- Fujimura, O. (1990) Methods and goals of speech production research. *Languages and Speech*, 33 (3), 195-258.
- Guenther, F. H. (1995) Speech sound acquisition, coarticulation, and rate effects in a neural network model of speech production. *Psychological Review*, 102, 594-621.
- Harrington, J., Fletcher, J. & Roberts, C. (1995) Coarticulation and the accented/unaccented distinction: Evidence from jaw movement data. *Journal of Phonetics*, 23, 305-322.
- Harrington, J., Fletcher, J. & Beckman, M.E. (2000) Manner and place conflicts in the articulation of accent in Australian English. In *Acquisition and the Lexicon: Papers in Laboratory Phonology V* (M.B. Broe and J.B. Pierrehumbert, editors), pp. 70-87. Cambridge: Cambridge University Press.
- Hawkins, S. (1992) An introduction to task dynamics. In *Papers in Laboratory Phonology II: Gesture, Segment, Prosody* (G. Docherty & D.R. Ladd, editors), pp. 9-25. Cambridge: Cambridge University Press.

- Hayashi, W., Hsu, C. & Keating, P. (1999) Domain-initial strengthening in Taiwanese: a follow-up study. *UCLA Working Papers in Phonetics*, 97, 152-156.
- Hayes, B. (1989) The prosodic hierarchy in meter. In *Phonetics and phonology, vol.I: Rhythm and meter* (P. Kiparsky & G. Youmans, editors), pp. 47-96. New York: Academic Press.
- Hoole, P. (1996) Issues in the acquisition, processing, reduction and parameterization of articulographic data. *Forschungsberichte des Instituts für Phonetik und Sprachliche Kommunikation, München*, 34, 158-173.
- Hsu, C.-S. & Jun, S.-A. (1998) Prosodic strengthening in Taiwanese: Syntagmatic or paradigmatic?. *UCLA Working Papers in Phonetics*, 96, 69-89.
- Huynh, H. & Feldt, L.S. (1970) Conditions under Which Mean Square Ratios in Repeated Measurements Designs Have Exact F-Distributions. *Journal of the American Statistical Association*, 65, 1582 -1589.
- Inkelas, S. (1990) *Prosodic Constituency in the Lexicon*. New York: Garland Publishing.
- Jones, D. (1940) *An outline of English phonetics*. New York: Dutton.
- Jun, S.-A. (1993) *The Phonetics and Phonology of Korean Prosody*. Ph.D. Dissertation. Ohio State University.
- Jun, S.-A. (1995) Asymmetrical prosodic effects on the laryngeal gesture in Korean. In *Phonology and phonetic evidence: Papers in Laboratory Phonology IV* (B. Connell & A. Arvaniti, editors), pp. 235-253. Cambridge, UK: Cambridge University Press.
- Jun, S.-A. (1998) The accentual phrase in the Korean prosodic hierarchy. *Phonology*, 15(2), 189-226.
- Keating, P.A. (1990) The window model of coarticulation: articulatory evidence. In *Papers in Laboratory Phonology I: Between the Grammar and the Physics of Speech* (J. Kingston and M.E. Beckman, editors), pp. 451-470. Cambridge: Cambridge University Press.
- Keating, P.A. (1996) The Phonology-Phonetics Interface. In *Interfaces in Phonology* (U. Kleinhenz, editor), pp. 262-278. *Studia grammatica* 41, Akademie Verlag, Berlin.
- Keating, P.A., Cho, T., Fougeron, C. & Hsu, C. (1999, to appear) Domain-initial strengthening in four languages. *UCLA Working Papers in Phonetics*, 97, 139-151. (Also to appear in *Papers in Laboratory Phonology 6*, Cambridge, UK: Cambridge University Press.
- Keating, P.A., Lindblom, B., Lubker, J. & Kreiman, J. (1994) Variability in jaw height for segments in English and Swedish VCVs. *Journal of Phonetics*, 22, 407-422.
- Kelso, Vatikiotis-Bateson, Saltzman & Kay, (1985) A qualitative dynamic analysis of reiterant speech production: phase portraits, kinematics, and dynamic modeling. *Journal of the Acoustical Society of America*, 77, 266-280.
- Kirk, R.E. (1995) *Experimental Design: Procedures for the Behavioral Sciences*. Pacific Grove, CA: Brooks/Cole Publishing Company.
- Klatt, D.H. (1975) Vowel lengthening is syntactically determined in connected discourse. *Journal of Phonetics*, 3, 129-140.
- Kühnert, B. & Nolan, F. (1999) The origin of coarticulation. In *Coarticulation: Theory, Data and Techniques* (W.J. Hardcastle & N. Hewlett, editors), pp.1-30. Cambridge, UK: Cambridge University Press.
- Lehiste, I. (1970). *Suprasegmentals*. Cambridge, Mass.: MIT Press.
- Lieberman, M. & Prince, A. (1977) On stress and linguistic rhythm. *Linguistic Inquiry*, 8, 29-336.
- Lindblom, B. (1963) Spectrographic study of vowel reduction. *Journal of the Acoustical Society of America*, 35, 1773-1781.
- Lindblom, B. (1983) Economy of speech gestures. In *The Production of Speech* (P.F. MacNeilage, editor), pp.217-245. New York, NY: Springer-Verlag.

- Lindblom, B. (1990) Explaining phonetic variation: a sketch of the H&H theory. In *Speech Production and Speech Modeling* (W.J. Hardcastle and A. Marschal, editors), pp. 403-439. Dordrecht: Kluwer.
- Löfqvist, A. (1999) Interarticulator phasing, locus equations, and degree of coarticulation. *Journal of the Acoustical Society of America*, 106 (4), 2022-2030.
- Löfqvist, A., Gracco, V.L. & Nye, P.W. (1993) Recording speech movements using magnetometry: One laboratory's experience. *Forschungberichte des Instituts für Phonetik und Sprachliche Kommunikation der Universität München*, 31, 143-162
- Macchi, M.J. (1985) *Segmental and Suprasegmental Features and Lip and Jaw Articulators*. Unpublished doctoral dissertation. New York University.
- Manuel, S. (1990) The role of contrast in limiting vowel-to-vowel coarticulation in different languages. *Journal of the Acoustical Society of America*, 88(3):1286-1298.
- Manuel, S. (1999) Cross-language studies: relating language-particular coarticulation patterns to other language-particular facts. In *Coarticulation: Theory, Data and Techniques* (W.J. Hardcastle & N. Hewlett, editors), pp.179-198. Cambridge, UK: Cambridge University Press.
- Max, L. & Onghena, P. (1999) Some issues in the statistical analysis of completely randomized and repeated measures designs for speech, language, and hearing research. *Journal of Speech, Language, and Hearing Research*, 42, 261-270.
- Nespor, M. & Vogel, I. (1986) *Prosodic Phonology*. Dordrecht: Foris Publications.
- Nicolaidis, K. (1999) The influence of stress on V-to-V coarticulation: An electropalatographic study. In *Proceedings of the 14th International Congress of Phonetic Sciences* (J. J. Ohala, Y. Hasegawa, M. Ohala, D. Granville & A. C. Bailey, editors), pp.1087-1090. New York: American Institute of Physics.
- Öhman, S.E.G. (1966) Coarticulation in VCV utterances: Spectrographic measurements. *Journal of the Acoustical Society of America*, 39, 151-168.
- Öhman, S.E.G. (1967) Numerical model of coarticulation. *Journal of the Acoustical Society of America*, 41, 310-320.
- Ostry, D.J., Keller, E. & Parush, A. (1983) Similarities in the control of speech articulators and the limbs: Kinematics of tongue dorsum movement in speech. *Journal of Experimental Psychology: Human Perception and Performance*, 9, 622-636
- Perkell, J. S., Cohen, M.H., Svirsky, M.A., Matthies, M.L., Garabieta, I. & Jackson, M.T.T. (1992) Electromagnetic midsagittal articulometer systems for transducing speech articulatory movements. *Journal of the Acoustical Society of America*, 92: 3078-3096.
- Pierrehumbert, J. & Talkin, D. (1992) Lenition of /h/ and glottal stop. In *Papers in Laboratory Phonology II: Gesture, Segment, Prosody* (G. Docherty and D.R. Ladd, editors), pp. 90-117. Cambridge, UK: Cambridge University Press.
- Recasens, D. (1984a) Vowel-to-vowel coarticulation in Catalan VCV sequences. *Journal of the Acoustical Society of America*, 76, 1624-1635.
- Recasens, D. (1984b) V-to-C coarticulation in Catalan VCV sequences: An articulatory and acoustical study. *Journal of Phonetics*, 12, 61-73.
- Recasens, D. (1985) Coarticulatory patterns and degrees of coarticulatory resistance in Catalan CV sequences. *Language and Speech*, 28, 97-114.
- Recasens, D. (1987) An acoustic analysis of V-to-C and V-to-V coarticulatory effects in Catalan and Spanish VCV sequences. *Journal of Phonetics*, 15, 299-312.
- Saltzman, E. (1995) Intergestural timing in speech production: Data and modeling. In *Proceedings of the XIII International Congress of Phonetic Sciences*, 2, 84-91.

- Saltzman, E. & Munhall K.G. (1989) A dynamical approach to gestural patterning in speech production. *Ecological Psychology*, 1, 333-82.
- Saltzman, E. & Byrd, D. (2000) Demonstrating effects of parameter dynamics on gestural timing. Presented at the May 2000 meeting of the Acoustical Society of America, Atlanta, Georgia. *Journal of the Acoustical Society of America*, 107(5,2): 2904.
- Sanderman, A. (1996) *Prosodic phrasing: production, perception, acceptability and comprehension*. Ph.D. Dissertation. Technische Universiteit Eindhoven.
- Sanderman, A. & Collier, R. (1997) Prosodic phrasing and comprehension. *Language and Speech*, 40, 391-409.
- SAS (1998) *StatView* (Version 5) SAS Institute Inc.
- Schoenle, P.W. (1988) *Elektromagnetische Artikulographie*, Berlin: Springer-Verlag.
- Schoenle, P.W., Mueller, C. & Wenig, P. (1989) Echtzeitanalyse von Orofacialen Bewegungen mit Hilfe der Elektromagnetischen Artikulographie. *Biomedizinische Technik*, 34: 126-130.
- Selkirk, E. (1984) *Phonology and syntax: the relation between sound and structure*. MIT Press.
- Selkirk, E. (1986) On derived domains in sentence phonology. *Phonology Yearbook*, 3, 371-405.
- Shattuck-Hufnagel, S. & Turk, A.E. (1996) A prosody tutorial for investigators of auditory sentence processing. *Journal of Psycholinguistic Research*, 25(2), 193-247.
- Shields, J.L., McHugh, A. & Martin, J.G. (1974) Reaction time to phoneme targets as a function of rhythmic cues in continuous speech. *Journal of Experimental Psychology*, 102, 250-255.
- Shin, J. (1997) *Consonantal Production and Coarticulation in Korean*. Ph.D. Dissertation, University of London.
- Silverman, K. Beckman, M., Pitrelli, J., Ostendorf, M., Wightman, C., Price, P., Pierrehumbert, J. & Hirschberg, J. (1992) TOBI: A Standard for Labeling English Prosody. In *Proceedings of the 1992 International Conference on Spoken Language Processing*, vol. 2, pp. 867-870.
- Stone, M. (1981) Evidence for a rhythm pattern in speech production: observations of jaw movement. *Journal of Phonetics*, 9, 109-120.
- Tuller, B., Shao, S. & Kelso, J. A.S. (1990) An evaluation of an alternating magnetic field device for monitoring tongue movements. *Journal of the Acoustical Society of America*, 88, 674-679.
- Wightman, C.W., Shattuck-Hufnagel, S., Ostendorf, M. & Price, P.J. (1992) Segmental durations in the vicinity of prosodic phrase boundaries. *Journal of the Acoustical Society of America*, 91, 1707-1717.