Prosodic strengthening in the articulation of English /æ/*

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Kim, Sahyang, and Taehong Cho. 2012. Prosodic strengthening in the articulation of English /æ/. *Studies in Phonetics, Phonology and Morphology* 18.2. 321-337. The current study investigates how prosodic strengthening induced by boundary and accent influences the articulation of English low front vowel /æ/ in *add*, *had*, and *pad*. Using Electromagnetic Articulograph (EMA), lip and jaw opening maxima, and tongue dorsum maxima in the horizontal (*x*) and vertical (*y*) dimensions were measured during the vocalic production. Boundary-induced strengthening was found in the tongue height (TD-y) dimension in all three words: /æ/ was lower domain-initially than -medially. In other measures, the boundary effect was conditioned by accent and the location of /æ/ within words. Domain-initial strengthening was found with the jaw opening maxima, with larger opening in a higher prosodic position, but it was only when the target words were unaccented. Also, the vowel in *add* tended to get fronted in a domain-initial position, but the same tendency was not observed in *had* and *pad*, suggesting the possibility that initial strengthening effect is conditioned by 'phonological' distance from the boundary edge. (*had* is phonologically similar to *pad* in that /h/ and /p/ occupy a phonological onset position.) Accent-induced strengthening was robust in all four articulatory measures. Results show that an accent-independent boundary effect is observed on vowels even in a language with lexical stress, and that the articulatory planning for the boundary-induced strengthening on vowels interacts with accent-induced strengthening. **(Hongik University and Hanyang University)**

Keywords: domain-initial strengthening, prosodic strengthening, vowel, EMA

1. Introduction

Prosodic structure conveys information structure of utterances by grouping words into informative units and by making important information prominent. These two functions are phonetically manifested in spoken utterances not only by suprasegmental features such as F0 (e.g., boundary tones) and duration (e.g., final lengthening), but by strengthening of segments in the vicinity of prosodic boundaries and prominence-lending locations. One of the well-known prosodic boundary-induced segmental changes is domain-initial strengthening (Fougeron and Keating 1997, henceforth DIS). This indicates a phenomenon that initial consonants of a prosodic domain exhibit articulatory strengthening (e.g., more articulatory contact, larger opening, faster movement) and lengthening (e.g., longer

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articulatory closure, longer acceleration/deceleration duration), compared to consonants in a prosodic domain-medial position (Bombien et al. 2007, Byrd and Saltzman 2003, Byrd et al. 2006, Cho 2005, 2006, Cho and Keating 2001, 2009, Fougeron and Keating 1997, Keating et al. 2003, Pierrehumbert and Talkin 1992, Tabain 2003, among others). The fine-phonetic details of domain-initially strengthened segments have been found to be exploited by listeners in spoken word recognition (Cho et al. 2007). Investigating the exact nature of DIS, therefore, would further our understanding of phonetics-prosody interface both in speech production and comprehension. The present study expands the attempt to explore the nature of DIS in speech production by investigating how DIS is phonetically realized in English vowel /æ/.

The domain-initial strengthening effect has been consistently found with consonants in both articulatory and acoustic dimensions, as introduced above; but the effect has been known to be rather inconsistent with vowels. In some studies, DIS effects on vowels were observed only with a few measures and with a subset of subjects (Byrd 2000, Byrd et al. 2006, Cho and Keating 2001, 2009, Fougeron and Keating 1997, Onaka et al. 2003); and other studies found no DIS effects on vowels (Barnes 2002, Fougeron 2001).

Two different accounts have been proposed in order to explain this sparse domain-initial strengthening effect on vowels. One is related to the fact that another type of strengthening, i.e., accent-induced strengthening, can be realized on vowels. Vowels are potential prominence-lending locations, and therefore can be prominent when it is accented and stressed. Barnes (2002), for example, examined the domain initial acoustic lengthening of English /æ/ in domain initial (#C**V**…) and domain-medial (#V_1C$\underline{\mathbf{V}}_2$…) position in three different prosodic domains. The target vowel received a secondary stress, in order to avoid any effect due to accentuation with a primary stress. He also examined Turkish /a/ in the same environment. The results showed that acoustic lengthening due to domain initial strengthening was found in Turkish, but not in English. He argued that the results are attributable to different stress system in the two languages. That is, stress is correlated with acoustic duration in English, while it is not the case in Turkish. He further claimed that when the vowel duration is reserved for another prominence marking like English stress, the vowel is not subject to domain-initial lengthening. A similar language-dependent DIS effect was found in a French and German corpus study by Gendrot and Gerdes (2011). They examined the acoustic space of vowels in #CV and #V contexts and found that vowel space shows progressive expansion as the vowels appear in stronger prosodic positions in both languages. German, however, showed weaker effect of the prosodic hierarchy than French. They attributed it to the fact that German has lexical stress which French does not have. In fact, an acoustic study on Korean (Cho et al. 2011), which does not have lexical stress like Turkish and

French, reported that domain-initial strengthening (as manifested by acoustic vowel duration) is quite robust in #CV position. These studies therefore suggest that vowels show weak DIS effect especially in languages with lexical stress, because vowels in those languages are reserved for marking another important prosodic function, i.e., stress.

An alternative account for the weak and inconsistent DIS effect on vowel is that it is mainly attributable to the distance between the boundary and vowels (Fougeron 2001, Cho and Keating 2009, among others). The vowels in most studies cited above were not located in strictly domain-initial position (i.e., #V), but they were the second segment from a given prosodic boundary in #CV context. If domain-initial strengthening affects only the initial segment of a given boundary, as has been argued by Fougeron and Keating (1997) and others (e.g., Cho and Jun 2000, Keating, Cho et al. 2003), a vowel in #CV would not be strengthened, and, even when it is strengthened, the effect should be smaller than the effect on the initial consonant that occurs right after the boundary. This is also in line with the pi-gesture theory, which claims that the boundary effect is attenuated as segments are farther away from the boundary (e.g., Byrd and Saltzman 2003).

The two possible accounts and the limitation of previous studies suggest that at least two conditions should be met in order to study the DIS effect on vowels: 1) they should be examined purely in the phrase-initial position (#V) and 2) the DIS effect should be examined without the confounding accent effect. The current study is part of a larger project which aimed to examine the prosodic effects on articulation of various English vowels, with these two conditions in mind. First, in order to observe how the DIS effect is conditioned by the distance of the vowel from the boundary edge, we compared vowels in strictly domain-initial position (#V) with those in domain-initial #CV position. For this purpose, various target vowels were placed in /#V…/(e.g., *add*), /#pV…/ (e.g., *pad*), and /#hV…/ (e.g., *had*) contexts. The /#pV/ context was chosen because a bilabial stop would yield minimum coarticulation between the consonant and the vowel. The /#hV/ context was included in order to see whether the DIS effect on vowel is dependent on the phonological or phonetic distance from the vowel. That is, /#hV/ is phonologically similar to /#pV/ in that there is a phonological timing slot before a vowel, but it is phonetically similar to /#V/ in that there is no supralaryngeal articulation for /h/ (and this, of course, guarantees no supralaryngeal coarticulation between the consonant and the vowel). If the DIS effect is affected by phonological distance from the boundary, the vowels in /#pV/ and /#hV/ would show similar strengthening effects, but they would show different effects from the vowels in /#V/. On the other hand, if the DIS effect is influenced by phonetic (physical) distance from the boundary, the vowels would behave similarly in /#V/ and /#hV/, as in both cases vowels would be free from phonetic interference from the consonant's oral constriction. It is therefore expected that the three contexts would reveal how the DIS effect is realized on vowels depending on varying distance from the prosodic boundary.

It should be noted that our study is not the first which examined DIS on vowels in #V position. Lehnert-LeHouillier et al. (2010) examined tongue traces with ultrasound to test DIS on English /ɛ/ and /ɔ/ in both #CV and #V positions, and found that domain-initial vowels in #V are produced with greater articulatory magnitude (as shown by tongue tracing), suggesting that strictly initial vowels do undergo articulatory domain-initial strengthening. Their results, however, should be taken with caution because the target words in their study (both C-initial and V-initial) were placed in contexts where they can easily receive phrasal accent. (Their target monosyllabic words were either a first-mention topic or a member in a list.) Phrasal accent has been known to strongly influences the phonetic realization of segments, and the accent-induced strengthening has been consistently found both with vowels and consonants (e.g., Beckman et al. 1992, Cho 2005, Cho and Keating 2009). Cho and Keating (2009), for example, showed that accent influences various acoustic and articulatory (EPG) vowel measures in a way that vowels with primary accents are strengthened and lengthened when accented. It is, therefore, highly likely that the domain initial effect they found were confounded with the accent effect, or it may just be the accent effect itself.

Thus, the second condition that we considered for the current study was to minimize the confounding accent effect. In this study, target words were placed in positions where they are accented (by contrastive focus) or unaccented in both phrase-initial and phrase-medial positions (See Table 1 for details). Since the target words were monosyllabic, the target vowels naturally bore lexical stress. But note that English unstressed vowels in word-initial position are almost always reduced to a schwa and that it would not be possible to examine the prosodic strengthening effect on a schwa. By controlling phrasal accent, the boundary-induced strengthening (i.e., DIS) could still be observed independently from the accent-induced prominence (i.e., phrasal accent).

With the sentential contexts that were designed to satisfy the two conditions, the current study examines articulatory characteristics of English low front vowel /æ/ in various prosodic positions, using an EMA (Electromagnetic Articulography). Through this study, we aim to provide a new set of descriptive data on the articulatory strengthening of English vowel /æ/, which has not yet been examined..It seems that different vowels show prosody-induced strengthening in different directions, which seem to be due to intrinsic features of given vowels. Cho (2005), for example, found that English /i/ in the #CV context showed higher tongue-mid position (i.e., TM vertical movement), smaller jaw opening, and larger lip opening in higher prosodic domain, but that English /ɑ/ in the same context only showed larger lip opening in higher domains. The articulatory differences are also context-dependent. For instance, Kim and Cho (2011b) found that English /i/ and /ɪ/ in #V context showed boundary-induced strengthening only in tongue dorsum (TD-y) (i.e., higher tongue position in a higher prosodic domain), while the same vowels did not show the same effect in #CV context. Moreover, the accent effect varied depending on vowels and their contexts as well. For the two English high front vowels in #V contexts, the tongue was more fronted (tongue dorsum horizontal movement), higher (tongue dorsum vertical movement), and lip and jaw openings were larger when accented (Kim and Cho 2011b) than unaccented; but the accent effect was observed in TD-x, and Lip and Jaw Opening Maximum (and not in TD-y) in #CV contexts both in Cho (2005) and Kim and Cho (2011b). As for English /ɑ/ in #CV, accent affected TD-y, jaw and lip opening (Cho 2005). The previous studies therefore suggest that the articulatory dimensions that are affected by prosody-induced strengthening differ depending on the vowels, the contexts where they occur, and the sources of prosodic strengthening. That said, it is descriptively important to investigate how different vowels show articulatory strengthening in different contexts. The current study therefore explores how place features (i.e., [+low, -back]) and sonority features (as realized by lip and jaw opening) of the vowel /æ/ are articulatorily realized by boundary and accent in #V and #CV contexts. This will further allow us to address the question about how boundary-induced prominence and accent-induced prominence are similarly or differentially encoded in the articulatory planning. For instance, it has been claimed that the presence of an accent enhances a segment's intrinsic sonority (the Sonority Expansion Hypothesis, Beckman et al. 1992) such that vowels become more vowel like, with larger vocal tract opening. de Jong (1995) proposed that stress results in hyperarticulation, and hence featural enhancement of vowels, in order to maximize lexical distinctions. Farnetani and Vayra (1996), however, claimed that accent-induced prominence leads to hyperarticulation and that boundary-induced prominence leads to sonority expansion. In subsequent studies, it was found that accent-induced strengthening results in sonority expansion, as well as hyperarticulation while boundary-induced strengthening show somewhat different pattern than accent-inducedd strengthening (Cho 2005, Kim and Cho 2011b). This study will, therefore, give us more insights about how the two types of prosodic strengthening are manifested on different English vowels.

2. Experiment

2.1 Subjects

Seven (4 male, 3 female) native speakers of American English participated in the experiment. They were either English teachers or exchange students in their 20s, residing temporarily in Korea at the time of recording. They did not have any known speaking or hearing disorder, and they were paid for participation.

2.2 Speech materials

Three words (*add*, *had*, *pad*) containing the target vowel /æ/ were inserted in IP-initial and IP-medial positions in carrier sentences. There were two sentences for each prosodic condition, in order to control for accent by inducing a contrastive focus or non-focus on the test syllable. The target words always appeared in the second sentence. Table 1 shows how boundary and accent factors were manipulated across test sentences with *add*. Note that when *add* was the accented target word in the second sentence, the contrasting word was *had* in the first sentence, as shown in the Accented conditions in Table 1. When the target words were *had* and *pad*, the contrasting words in the first sentence were *pad* and *add*, respectively. Contrary to the Accented conditions, both the first and the second sentences contained the target words (e.g., *add* in Table 1) in the Unaccented conditions, because the target words were not supposed to have a contrastive focus in these conditions.

Table 1. A list of carrier sentences with four prosodic conditions. (Accented words are capitalized and marked in bold. The target word (in this case, 'add') is underlined. '#' indicates an IP boundary in IP-initial conditions and an IP-medial word boundary in IP-medial conditions)

<table>
<tr><th>Boundary</th><th>Accent</th><th>Carrier sentences</th></tr>
<tr><td rowspan="2">IP-initial</td><td>Accented</td><td>After I say 'Diana,' 'HAD again' will be the next phrase to say.
But after THEY say 'Diana,' # 'ADD again' will be the next phrase to say.</td></tr>
<tr><td>Unaccented</td><td>After I say 'Diana,' 'add again' will be the NEXT phrase to say.
But after THEY say 'Diana,' # 'add again' will be the FINAL phrase to say.</td></tr>
<tr><td rowspan="2">IP-medial</td><td>Accented</td><td>To say 'Diana HAD again' with me is going to be difficult.
But to say 'Diana # ADD again' with me is going to be easy.</td></tr>
<tr><td>Unaccented</td><td>To say 'Diana add again' with JOHN is going to be difficult.
But to say 'Diana # add again' with ME is going to be easy.</td></tr>
</table>

2.3 EMA data collection

The 2D Electromagnetic Midsagittal Articulography (Carsten AG200) was used to track sensors adhered to the tongue tip, the tongue body, the tongue dorsum (the rearmost point when the tongue was pulled out; approximately 4.5cm from the tongue tip sensor), the jaw (at the lower gumline of the mandibular incisor), and the upper and lower lips (at the vermilion borders). Two reference sensors were attached to the upper front gum line and bridge of the nose. Figure 1 shows the locations of sensor coils on the articulators. In addition, two extra sensors on a bite plate were used to obtain the occlusal plane, to which the data was rotated. The occlusal plane was *x*-axis, and perpendicular to the occlusal plane was *y*-axis. Entire articulatory movement data were sampled at 200Hz and low-pass filtered at a cut-off frequency of 20Hz. All the filtering and rotation processes were performed by the TAILOR (Carsten's data processing program).

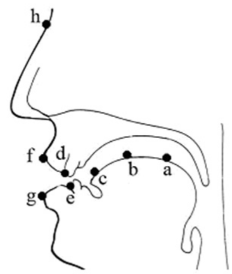


Figure 1. Locations of sensor coils: (a) the tongue dorsum; (b) the tongue body (c) the tongue tip; (d)-(e) the maxillary (upper) and mandibular (lower) central incisors; (f)-(g) the upper and lower lips; and (h) the nose bridge.
(This figure was adopted from Figure 1 in Son and Cho (2010).)

Among the recorded articulatory data, the current study only reports spatial measures obtained from the extreme points of the lip, the jaw, and the tongue dorsum during the production of the target vowel. To examine the lip and jaw opening maximum point, the articulatory landmarks were taken from the vertical dimension of the articulators. In addition, the extreme points of the tongue dorsum (TD) were examined. The extrema in the horizontal (*x*) and vertical (*y*) dimensions were taken separately at different time points. These points were cross-checked by inspecting a sagittal display of the tongue movement trajectories where "turn-around" points could be found. The following list summarizes the four spatial measures taken for this study.

(1) *Lip Opening Maximum*: the maximum point of the lip aperture
(2) *Jaw Opening Maximum*: the maximum point of the jaw aperture
(3) *TD-x Extremum*: the horizontal extreme point of the tongue dorsum
(4) *TD-y Extremum*: the vertical extreme point of the tongue dorsum

Subjects read the carrier sentences three times in a pseudo-randomized order. They did not have much difficulty in producing intended renditions. The collected data were screened by two ToBI transcribers (the authors). When there was a disagreement between them, the token was excluded from the data analysis. Tokens with abnormal velocity trajectory patterns were also excluded. Through these procedures, 25 tokens were excluded from 252 (2 boundaries x 2 accent conditions x 3 words x 3 repetitions x 7 speakers), and hence 227 tokens were analyzed.

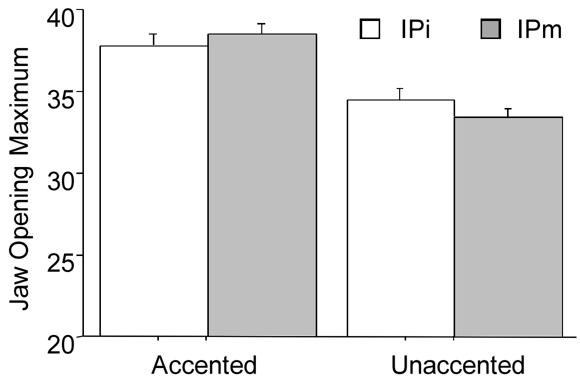
3. Results

A three-way repeated measures Analyses of Variance was conducted with three within-subject factors: Boundary (IP initial, IP medial), Accent (Accented, Unaccented), and Initial Segment (/p/, /h/, /æ/). Since the Initial Segment factor had three-levels, Huynh-Feldt corrected degrees of freedom were used in generation of F ratios and p values (Huynh and Feldt 1970). In addition, post-hoc pair-wise comparisons with Bonferroni/Dunn corrections were conducted whenever necessary. In all statistical analyses, p-values less than 0.05 were considered significant, and p-values between 0.05 and 0.08 were treated as non-significant trends.

Among the four articulatory measures, a significant effect of Boundary was found only with TD-y Extremum values. TD-y Extremum results showed that the tongue position was significantly lower when target words were in IP-initial than in IP-medial positions ($F(1,6) = 6.903$, p=.039).

The effect of Accent, on the other hand, was significant in all four measures. Jaw Opening Maximum and Lip Opening Maximum showed that there are more jaw and lip opening when target words were accented than when unaccented ($F(1,6)=179.304$, p=.000 for Jaw Opening Maximum; $F(1,6)=138.173$, p=.000 for Lip Opening Maximum). Both TD-x Extremum and TD-y Extremum values were significantly lower when the words were accented than when they were unaccented, indicating the tongue was more fronted ($F(1,6)=16.375$, p=.007, TD-x Extremum) and lowered ($F(1,6)=7.283$, p=.036, TD-y Extremum) when target words are accented than unaccented.

More importantly, significant interactions were found between Boundary and Accent on Jaw Opening Maximum ($F(1,6)=8.381$, p=.028), and Lip Opening Maximum ($F(1,6)=7.444$, p=.034). Post-hoc t-tests showed that, in both cases, the Boundary effect was not observed when the target words were accented. When they were unaccented, however, Jaw Opening Maximum values were significantly higher in IP-initial than in IP-medial positions ($t(6)=2.715$, p=.035) (Figure 2) and Lip Opening Maximum values showed a similar but non-significant trend effect ($t(6)=2.126$, p=.078) (Figure 3).



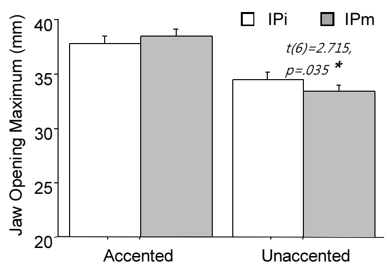


Figure 2. Jaw Opening Maxima

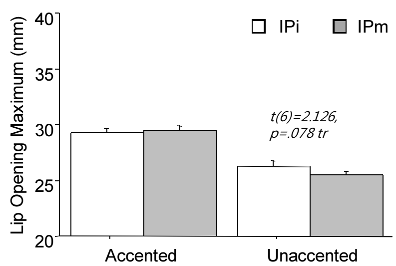


Figure 3. Lip Opening Maxima

In addition, a regression analysis revealed a close relationship between Jaw Opening Maxima and Lip Opening Maxima (R^2=.171, F(1, 221)=45.638, p=.000) in the production of English /æ/, showing that the larger the jaw opening, the larger the lip opening.

There were significant effects of Initial Segment in three out of four measurements: Jaw Opening Maximum (F(2,12)=21.111, p=.000), Lip Opening Maximum (F(2,12)=14.295, p=.001), and TD-x Extremum (F(2,12)=4.696, p=.039). Post-hoc pairwise comparisons showed that Jaw and Lip Opening Maximum values were significantly higher for *add* and *had* than for *pad* (Jaw Opening Maximum: add>pad, p=.003; had>pad, p=.01; Lip Opening Maximum: add>pad, p=.011; had>pad, p=.045), but that *add* and *had* did not differ. As for the TD-x Extremum values, the three target words did not differ significantly from each other, despite the fact that the Initial Segment effect was significant. The average TD-x values show that, *add* and *had* tended to be more fronted (though not significantly so), showing lower mean values (137mm, SD 4.4 vs. 137.1mm, SD 4.4) than *pad* (138.3mm, SD 4.7). Interestingly, the TD-x Extremum measure showed a Initial Segment x Boundary interaction (F(2,12)=7.178, p=.009) in such a way that the Boundary effect was observed as a near-significant trend effect with *add* (t(6)=-2.371, p=.055), but not observed with *had* and *pad*, as illustrated in Figure 4.

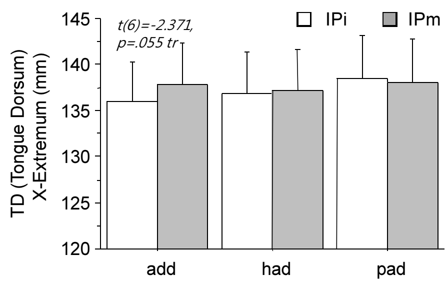


Figure 4. Initial Segment x Boundary interaction: TD-x Extremum

The main effects and interactions are summarized in Table 2 below.

Table 2. The summary of the results

	Boundary	Accent	Initial Segment	Interactions
Lip opening maximum		Acc > Unacc* more opening	add, had > pad * more opening	B x A (tr)
Jaw opening maximum		Acc > Unacc* more opening	add, had > pad * more opening	B x A* IPi>IPm when unacc.
TD-x extremum		Acc > Unacc* more fronted	Significant effect *	B x Ini.Seg* IPi>IPm with 'add' (*tr*)
TD-y extremum	IPi > IPm* lower	Acc > Unacc* lower		

4. Discussion

The current study examined four articulatory maximum points (i.e., Tongue dorsum x- and y- extrema, lip and jaw opening maxima) during the production of English /æ/. With the articulatory data obtained via an EMA, the present study aimed to investigate how boundary-induced and accent-induced strengthening were realized on the vowel /æ/ in a strictly domain-initial vowel (as in *add*) versus in domain-initial CV (as in *had* and *pad*). In the following, our findings will be discussed in connection with the findings from previous studies.

One of the main purposes of the current study was to observe how DIS is realized on the articulation of English low front vowel /æ/, which has not been documented until now. Results revealed that the boundary-induced strengthening (DIS) was observed only with TD-y extremum, showing lower tongue height in IP-initial than in IP-medial position. Furthermore, the fact that the Boundary effect did not interact with either the Initial Segment or the Accent factors on the TD-y measure indicates that DIS is realized in the form of articulatory tongue lowering for /æ/ regardless of its distance from the boundary (viz., both strictly domain initial (i.e., /#æd/) and in domain-initial syllable (i.e., /#pæd/ or /#hæd/)), and independent of accent-induced strengthening. Along with previous articulatory studies on English /i, ɪ/ in #V (Kim and Cho 2011b), the current study therefore allows us to conclude that at least three English front vowels (/i, ɪ, æ/) show the DIS effect that is independent of accent-induced strengthening, in /#V/ and sometimes in /#CV/ contexts. Additionally, in all of the three front vowels, the boundary-induced strengthening resulted in the featural enhancement of [+/- high] as reflected in TD-y values, in such a way that high front vowels (/i, ɪ/) become higher and a low front vowel (/æ/) becomes lower in a higher position. Note also that, unlike high vowels in #V and low vowel /æ/ the enhancement of tongue dorsum height was not observed either by boundary or accent for high vowels in #CV in both Cho (2005) and Kim and Cho (2011b). This discrepancy might be partially explained by the fact that vowel height is less variable because /i/ allows small vocal tract opening, which becomes yet smaller due to the presence of /p/ closure (e.g., Stevens and House 1963, Recasens 1985). Both high vowels in #V (with no preceding consonant) and the vowel /æ/ (with higher degree of vocal tract opening), are free from such coarticulatory resistance, and this seems to contribute to boundary-induced tongue dorsum lowering. This explanation based on coarticulation, however, cannot tell us why /#hV/, with lack of supralaryngeal constriction, behaved like /#pV/ in terms of tongue lowering. In order to explain this and other related phenomenon, we resort to the phonological distance from the boundary, as will be discussed later in this section.

Our results also confirm that the boundary-induced strengthening is not as robust as accent-induced strengthening when it comes to the articulation of vowels, since only one measure showed a significant boundary effect while all four articulatory measures (TD-x, TD-y, the lip and the jaw maxima) showed significant accent effects. The results accord with previous studies, which showed that vowels are more susceptible to accent-induced than boundary-induced strengthening, since many more acoustic and articulatory measures are affected by the presence of accent than that of boundary (e.g., Cho 2005, Cho and Keating 2009, among others). Along with previous studies (Cho 2005, Kim and Cho 2011b), the current study showed that the Accent effect is always observed in TD-x (more fronted), Jaw opening and Lip opening (although the direction may vary) dimensions in the articulation of English front vowels. The current study showed that accent not only facilitated enhancement of phonological features of the vowel (cf. de Jong 1995) in tongue place dimensions (i.e., lower and more fronted tongue position in accented position), but also expanded sonority of the vowel (cf. Beckman et al. 1992) by enlarging the size of vocalic opening as reflected in larger lip and jaw opening in higher domains. Our results thus provide more counterexamples to the claim that the accent-induced strengthening and boundary-induced strengthening would be differentially characterized in the vowel articulation with the former being characterized by hyperarticulation and the latter by sonority expansion (Farnetani and Vayra 1996).

The Boundary x Accent interaction found in the jaw and lip opening measures provides an interesting piece of evidence for the accent-independent DIS effect on vowels. The jaw opening movement revealed a significant boundary effect in unaccented condition only (a similar non-significant trend was found with lip opening movement). The result seems to suggest that the boundary effect is overridden by the accent effect when the initial word is accented, but that it may come up to the surface in the absence of accent on initial words. The result implies that the domain initial strengthening found in Lehnert-LeHouillier et al. (2010) for vowels in #VC could in fact be the combined effects of boundary and accent. The effects from accent should therefore be carefully factored out when investigating the DIS effect on vowels. The observed DIS effect suggests that the boundary-induced strengthening contributes to the sonority expansion of English vowel /æ/ in the absence of accent on the vowel.

Although three out of four articulatory measures showed a significant initial segment effects, the effects are predictable and can be naturally accounted for by articulatory limitations and characteristics of different segments. First, Jaw and Lip Opening Maximum showed that *add* and *had* showed significantly higher values than *pad*. This is due to a coarticulatory effect from /p/. That is, *pad* requires a lip closing gesture for the bilabial stop before the vowel, and hence the lip and jaw movement is naturally limited. A significant TD-x extremum value, with a lower mean value (=more fronted) for *add* and *had* than *pad* (though the three did not significantly differ from each other), is also explainable by the fact that the tongue may not have been more fronted in case of *pad* due to the presence of lip closure for /p/. The fact that TD-y extremum did not show the effect of Initial Segment indicates that the tongue lowering required for the target vowel /æ/ was successfully reached in all contexts, and this is not surprising considering that none of the target words had consonantal tongue movement which could potentially interfere with the vocalic tongue movement. In other words, unlike three other articulatory dimensions, TD-y dimension did not show a blocking effect due to the consonant /p/ because TD-y dimension is free from articulatory constraints due to the closure for /p/, because the tongue lowering movement for /æ/ co-occurs with the jaw and lip movement toward the same downward direction,.

What is more informative regarding the segmental context effect is that there was an Initial Segment x Boundary interaction on TD-x measure. This leads us to a question as to whether the manifestation of DIS on vowels is influenced by the phonological or phonetic distance from the boundary edge. Recall that the Initial Segment x Boundary interaction was not found in TD-y for /æ/, indicating that at least for the tongue height dimension, the vowel /æ/ is strengthened domain-initially regardless of its distance from the boundary (i.e., both in #V and #CV). The interaction between the initial segment and the boundary factors in TD-x, however, showed that the boundary-induced strengthening was observed as a near significant trend effect for /æ/ in the /#V/ context (*add*), with the vowel more fronted in higher positions, but that no boundary effect was observed on the same vowel in /#CV/ context (*had*, *pad*). A similar context-dependent effect was indeed found in Kim and Cho (2011b), but in terms of TD-y dimension for English high front vowels. (As aforementioned, TD-y boundary effect was only found with the vowel-initial context (*eat*-*it*), but not with either of the consonant-initial context (*heat*-*hit*, *Pete*-*pit*) in Kim and Cho (2011b).) Taken together, Kim and Cho (2011b) and the present study appear to indicate that, although the affected articulatory dimensions are different, the vocalic tongue movement shows differential boundary-induced strengthening depending on the segmental contexts in which it occurs. For some measures, the boundary-induced strengthening on vowels seems to be strong enough, so that DIS is observed regardless of the vowels' distance from the boundary (as in TD-y for the current study). For other measures, however, the boundary-induced strengthening is not so robust, such that DIS is observed on vowels that are strictly adjacent to the boundary (#V), but not on those that are not (#CV, as in *had* and *pad*) (as in TD-x for the current study, and in TD-y for Kim and Cho (2011b)). Furthermore, insofar as a DIS effect is not observed in #CV, the distance from the boundary which is relevant in determining the domain of DIS is phonological, not phonetic distance, given that both the consonants with and without supralaryngeal articulation (/p/ and /h/) blocked the spreading of DIS effect on vowels in the current study, as well as Kim and Cho (2011b).

5. Conclusion

The current study investigated how two types of prosodic strengthening (i.e., boundary- and accent-induced strengthening) are articulatorily manifested on the production of English /æ/ both in strictly domain-initial position (#V) and in #CV position. The horizontal (TD-x) and vertical (TD-y) maxima of the tongue, and the lip and jaw maxima were measured during the vocalic opening.

Results revealed that boundary-induced strengthening (DIS) was observed independent of accent-induced strengthening, but that the effect was somewhat limited, compared to strengthening due to accent. First, only one articulatory measure, TD-y, showed accent-independent domain-initial strengthening both in strictly domain-initial position (#V) and in #CV position. The vertical tongue maximum point was lower in domain-initial than in domain-medial position, indicating the enhancement of [+/-high] feature. Second, the DIS effect on the vowel seemed to contribute to sonority expansion (as indicated by the jaw opening), but only when the target words were unaccented. Third, the [-back] feature of /æ/ showed a tendency to be enhanced (as indicated by a near-significant trend found in TD-x value) only when the vowel was in strictly domain initial position (as in 'add'), suggesting that, at least for this specific feature, the phonological distance from the boundary plays a role in the realization of DIS on vowels. The accent-induced strengthening was observed in all four measures, regardless of the location of /æ/ within the target word. Both lip opening and jaw opening were larger when the words were accented than unaccented, expanding the sonority of the vowel; and the tongue was more fronted and lowered when the words were accented than unaccented, enhancing the [-back] and [+low] features. Overall, the results of the current study suggest that the two important prosodic functions are manifested differentially in the articulatory domain. When speakers deliver their intended prosodic structure, the encoding of the boundary on vowels seems to be done in a more subtle and intricate way than the encoding of accent is, such that the boundary marking on vowels are conditioned by other factors in the surroundings, such as its phonological distance from the boundary edge and the presence of prominence.

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