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Prosodic Boundary Strengthening in the Phonetics–Prosody Interface

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Abstract

Prosodic structure has been assumed to serve as a frame for articulation, so that phonetic shaping of abstract phonological representations is fine-tuned as a function of the prosodic system of the language. The intricate relationship between phonetics and prosodic structure has been explored in the literature under the rubric of the phonetics–prosody interface. This paper reviews various aspects of the phonetics–prosody interface and discusses how prosodic structure modulates phonetic realization within and across languages. A particular attention is paid to boundary-related prosodic strengthening (i.e., spatial and/or temporal expansion of articulation that arises in the vicinity of prosodic junctures), especially in association with domain-initial positions (also known as domain-initial strengthening, DIS, effects). Prosodic boundary strengthening is further discussed in terms of how it is language-specifically fine-tuned, how it is understood in dynamical terms, and how it relates to linguistic functions (as syntagmatic vs. paradigmatic contrast enhancement) that are all further conditioned by other factors of the linguistic sound system of individual languages such as the prominence system and the phonetic feature system.

1. *Introduction*

For an utterance to be articulated, some kind of a "frame" for articulation is needed in order to specify the prosody and other phonetic detail of the utterance. Imagine, for example, that a string of words *when danger threatens your children call the police* is produced with no manipulation of prosodic features such as pitch, duration, and amplitude. The resulting speech signal will be ambiguous as it is interpretable in two different ways (Ladefoged 2001):

(1)
a. When danger threatens, your children call the police.
b. When danger threatens your children, call the police.

In an actual speaking context, however, the speaker is likely to plan the utterance with a particular "prosodic" frame or *prosodic structure* which provides a guideline about the intonation (the change of pitch) of the utterance, the rhythm (the timing or durational pattern of individual segments), and the stress (the relative prominence among segments) to be matched with the linguistic message as intended.

Figure 1 illustrates acoustic signals as possible outputs of two distinct prosodic structures for the otherwise ambiguous string of the words. As seen in the figure, they differ in how the words are grouped into major phrases (marked by square brackets), which are most notably demarcated by durational and intonational features. For example, the highlighted word "threatens" at the end of the first major phrase in Figure 1a is substantially longer relative to the same word which is non-final in Figure 1b, and the final word "threatens" in Figure 1a is further marked by a rising

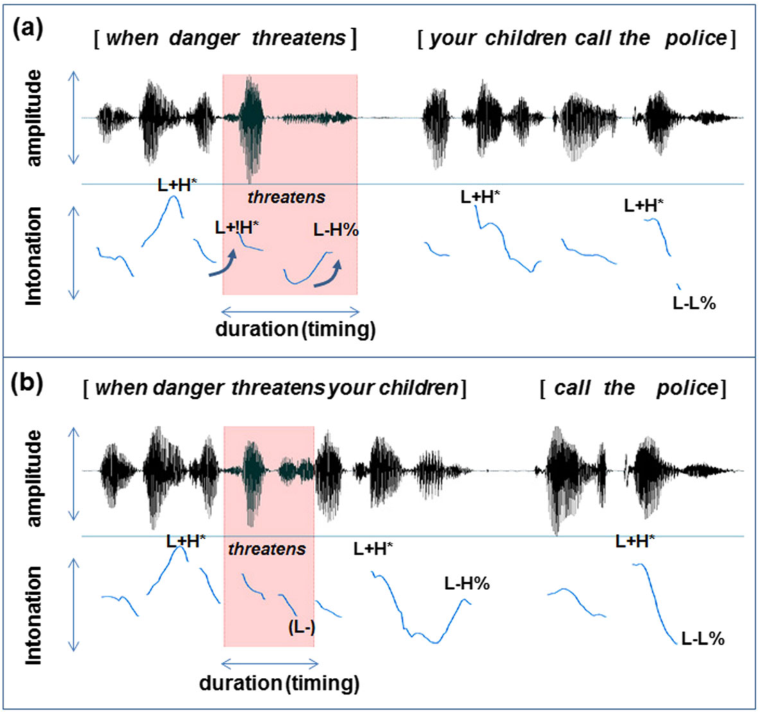

Fig. 1. Possible acoustic outputs of different syntactic parses for a string of words with the same segmental make-ups (recorded by P. Ladefoged 2001). The tonal transcriptions employed here follow the English ToBI conventions (Beckman and Ayers 1994; Beckman et al. 2005). See Endnote 1 for further explanation. Note that the parenthesized "(L-)" in (b) means that the presence of a phrase tone L- is likely but not entirely certain.

tone at the end (as indicated by H%) which characterizes the phrase-final intonation. Another important aspect of prosodic structure (as can also be observed in Figure 1) is prominence distribution – i.e., which part of the utterance is more prominent than others, which is generally indicated by a particular tonal pattern (rising or falling) often accompanied by an increase in duration and amplitude. For example, the stressed (first) syllable of "threatens" in Figure 1a is marked by a local pitch rise (as indicated by L+!H*) along with its waveform being wider (longer) and taller (louder) than the "unaccented" counterpart in Figure 1b. Note that the tonal transcriptions (e.g., H% or L + H*) used in this paper follow the English ToBI conventions (Beckman and Ayers 1994; Beckman, Hirschberg, and Shattuck-Hufnagel 2005; see Endnote 1 and Section 1.1 for further explanation).[1]

An important theoretical position assumed here is that the suprasegmental (prosodic) differences in Figure 1a,b, which roughly correspond to the distinct syntactic parses in (1), stem from different prosodic structures which serve as frames for articulation. More broadly, throughout the paper, it is assumed that the detailed suprasegmental and other phonetic information of the utterance is encoded in prosodic structure which is created prior to motor execution of the utterance, so that the abstract phonological (or segmental) representations that constitute the planned utterance are fleshed out with fine-grained phonetic content as specified by the prosodic structure (e.g., Keating and Shattuck-Hufnagel 2002; Cho 2011). The purposes of this paper are to introduce this structural view of prosody and to discuss how the prosodic structure modulates phonetic realizations of phonological representations (e.g., phonemes) in both suprasegmental and segmental dimensions within and across languages. The focus of the paper will be on phonetic modulation of prosodic structure with special reference to boundary-related phenomena and their interactions with prominence. The organization of this paper is as follows. For the remainder of this section, I will review a structural view of prosody (Section 1.1) and introduce the phonetics–prosody interface along with the notion of prosodic strengthening (Section 1.2). I will then briefly review preboundary lengthening as kind of boundary-related prosodic strengthening (Section 2) and engage in an in-depth discussion on post-boundary (domain-initial) strengthening effects within and across languages (Section 3). At the end, I will summarize the paper (Section 4).

1.1. A STRUCTURAL VIEW OF PROSODY

It is now a widely received view that "prosody" is a grammatical structure that has to be parsed in its own right (e.g., Beckman 1996). Under this structural view of prosody, the term prosody no longer refers merely to lower-order suprasegmental features such as pitch, duration, and amplitude, but it embraces an abstract notion of a higher-order grammatical structure definable as "a hierarchically organized structure of phonologically defined constituents and heads" (Beckman 1996:19). It therefore provides a "frame" for articulation with two functions: a *delimitative function* regarding how smaller phonological units or prosodic constituents (phonemes, syllables) are grouped together to form a larger prosodic constituent (a prosodic word or a phrase) and a *culminative function* regarding which of the prosodic constituents in the utterance should be the "head" of the phrase [e.g., the intermediate phrase (ip)] to be pronounced more prominently than others. A plausible prosodic structure that might stipulate the prosody of the utterance in (1b) (a possible phonetic output in Figure 1b) is given in Figure 2.

The delimitative function of prosodic structure is reflected in Figure 2 in terms of how phonologically units are hierarchically organized: The segments at the bottom of the hierarchy are grouped into an immediately next-higher unit, the syllable (σ) and further into a progressively higher unit in the order of the prosodic word (PWd), the ip, and the Intonational Phrase (IP). It is worth noting at this point that prosodic constituents are also referred to as *prosodic domains* as they often serve as domains of tonal distribution and of applications of phonological rules (cf. Selkirk 1984, 1995; Jun 1998). For the sake of completeness, IP recursion is introduced in the figure, so that an IP can dominate one or more IPs (Krivokapić and Byrd 2012), although

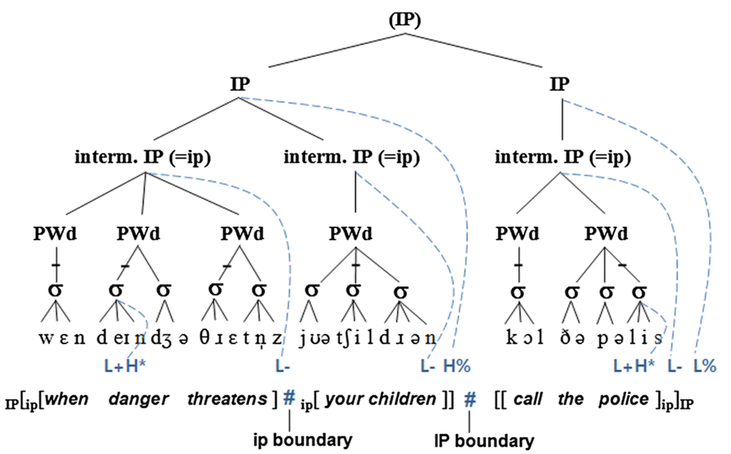

Fig. 2. A prosodic structure of *When danger threatens your children, call the police*. It depicts a hierarchically-nested organization of phonological units of the utterance in terms of phrasing (or prosodic grouping) and prominence distribution. [Here, an Intonational Phrase (IP) is assumed to be recursive (following Krivokapić and Byrd 2012), so that an IP may govern one or more IPs]. Note that '-' in the association line indicates stressed syllables; H* refers to an H-tone pitch accent as a phrase-level stress; L-, a phrase tone at the end of an intermediate phrase (ip); and L% or H%, a boundary tone at the end of an IP. (The Foot as a possible prosodic unit above the syllable is omitted.)

the IP is often assumed to be the non-recursive highest prosodic unit (Beckman and Pierrehumbert 1986; Beckman et al. 2005; but see Nespor and Vogel 1986 in which the utterance is treated as the highest prosodic unit above the IP). An important notion in connection with prosodic grouping is *prosodic boundary strength* (henceforth boundary strength), which refers to the degree of prosodic disjunction between abutting prosodic units, roughly in proportion to the level of the units in the constituent hierarchy (e.g., as shown in Figure 2). Prosodic structure supplements information about the boundary strength with tonal markings, especially for the highest two prosodic boundaries, the IP and ip boundaries, so that phrase tones (e.g., L- or H-) and boundary tones (e.g., L% or H%) are associated with the right edge of the ip and the IP, respectively (see Endnote 1 for further explanation of tonal transcriptions).

Along with the delimitative function, the distribution of the relative prominence among prosodic constituents (the culminative function) is also assumed to be stipulated by the prosodic structure. In Figure 2, the diacritic "-" in the association line between the PWd and the syllable (σ) indicates that the syllable is lexically stressed (following Keating and Shattuck-Hufnagel 2002), so that it is more prominent than neighboring unstressed syllables. The L + H* (a starred tone) in the figure is associated with a stressed syllable (as marked by a dashed association line in the figure), indicating that the syllable (or the word that contains the syllable) receives a higher-level (phrase-level) stress, thus being more prominent than the rest in the phrase. This higher-level stress is called a *pitch accent*, highlighting the fact that the accentuation is associated with a salient pitch movement as indicated by a starred tone. The accented syllable is assumed to serve as the head of the ip, and the pitch accent associated with the head is referred to as a *nuclear* pitch accent.

Finally, prosodic structure stipulates the global intonation of the utterance. As explained earlier, prominence marking is assigned with a particular tonal type of pitch accent (e.g., L + H*) and boundary marking with a particular type of phrase and boundary tones (e.g., L-L%). While these tonal markings of prosodic structure are specified locally in a stressed syllable and at the right edge of a prosodic domain, when they are put together, the global "tune" of the utterance is generated (e.g., "L+H*L-L%" for the phrase "call the police" in Figure 2). In phonetic implementation, the assigned tones may be assumed to serve as F0 targets which are phonetically interpolated, giving rise to a continuous F0 contour at the surface (Pierrehumbert 1980; Pierrehumbert and Beckman 1988; see Ladd 2008 for further discussion about different theoretical assumptions).

Thus far, I have introduced how prosodic structure is hierarchically organized and serves as a frame for articulation, focusing on suprasegmental variation of an utterance. Converging evidence accumulated over the past decades, however, suggests that the influence of prosodic structure on phonetic implementation is not limited to the suprasegmental level, but it is indeed pervasive over the segmental level. The extensive view of phonetic modulation of prosodic structure across segmental and suprasegmental levels has been vigorously explored by many researchers under the rubric of the *phonetics–prosody interface*, which is the topic of the next section.

1.2. THE PHONETICS–PROSODY INTERFACE AND PROSODIC STRENGTHENING

Past decades have witnessed significant progress in our understanding of the linguistic sound system, keeping abreast with the advancement of scientific experimental methodologies adopted in language research. In particular, there has been increasing awareness of the role of scalar and gradient aspects of speech in the grammar of the language (see Cho 2015 for a review). Research on speech prosody has been in the vanguard of exploring the linguistic function of phonetic granularity that goes beyond suprasegmental variation and operates at various levels of the sound system of the language. It has now become a "norm" that an understanding of the linguistic sound system can never be completed without making reference to the phonetics–prosody interface – i.e., the interaction of sounds and sound patterns with prosodic structure in the grammatical system of the language (e.g., Shattuck-Hufnagel and Turk 1996; Fletcher 2010; Cho 2011). The phonetics–prosody interface is concerned with two interrelated questions: how the phonetic implementation of the phonological (or segmental) representations is modulated by abstract prosodic structure (from the perspective of speech production) and how fine-grained phonetic detail, in turn, informs high-order prosodic structure (which should be decoded in speech comprehension) (e.g., Cho, McQueen, and Cox 2007; see Cutler 2012, for a comprehensive review on the roles of prosodically driven fine-phonetic detail in speech comprehension).

Researchers have explored these questions by making reference to the delimitative and culminative functions of prosodic structure whose phonetic reflexes are largely associated with important prosodic landmark locations such as edges of prosodic domains and stressed/accented syllables. Such phonetic manifestations of prosodic structure have been investigated in terms of *prosodic strengthening*, which is used as a cover term for "strong" articulation characterized by a spatial and/or temporal expansion that may rise with boundary and prominence markings (e.g., Cho 2011, 2015; Mücke and Grice 2014). The remainder of the paper will be devoted to discussing the phonetics–prosody interface with particular reference to prosodic strengthening as a function of boundary strength, exploring fine-grained phonetic modulation of speech production at prosodic junctures (i.e., before and after a prosodic boundary). Prominence-induced prosodic strengthening will also be discussed when necessary, especially in relation to how it may interact with boundary-induced strengthening.

2. Preboundary Lengthening

A well-known boundary-induced phonetic fine-tuning that is observed across languages is a temporal modulation of domain-final phonological units before a prosodic boundary (known as phrase-final or preboundary lengthening) (e.g., Edwards, Beckman, and Fletcher 1991; Wightman et al. 1992; Gussenhoven and Rietveld 1992; Berkovits 1993, 1994; Byrd 2000; Cambier-Langeveld 2000; Byrd, Krivokapić, and Lee 2006; Cho 2006; Turk and Shattuck-Hufnagel 2007; see also Fletcher 2010 or Cho 2015 for a review). As was briefly introduced above, for example, the phrase-final word "threatens" in Figure 1a ("when danger threatens, your children call the police") is longer than the one in Figure 1b ("when danger threatens your children, call the police"), reflecting a degree of boundary strength that follows – i.e., an IP boundary vs. an ip boundary.

Given that preboundary lengthening is a cross-linguistically recurrent phenomenon, a viable assumption is that the effect is attributable to universally applicable low-level phonetic constraints. Preboundary lengthening is likely to involve a relaxation of articulatory gestures following a natural physical tendency – i.e., the articulatory movement has to slow down approaching the end of the utterance before the cessation of the movement (e.g., Lindblom 1968). In a similar vein, preboundary lengthening, as noted by Fletcher (2010), may also be understood as a kind of supralaryngeal declination over the course of an utterance (Fowler 1988; Vayra and Fowler 1992; Berkovits 1994; Krakow, Bell-Berti, and Wang 1995; Tabain 2003). An example which is fit with this putatively physiologically driven slowing-down effect is found in Hebrew in which the degree of lengthening increases progressively from the beginning to the end of a phrase-final disyllabic word (Berkovits 1993, 1994), reflecting a gradual temporal declension.

One might then ask whether the preboundary lengthening effect should be understood simply as stemming from physiological and biomechanical constraints imposed on the human speech production system. As discussed by Cho (2015), however, there is in fact ample evidence that the seemingly physiologically driven slowing-down effect is likely under the speaker's control: Many languages show language-specific granular lengthening effects which interact with other linguistic factors such as lexical stress (e.g., English), mora (e.g., Japanese), and vowel quantity (Finish). For example, while preboundary lengthening in English is generally observed in a final syllable or a final rhyme of a phrase-final word (e.g., Klatt 1975; Edwards et al. 1991; Wightman et al. 1992; Byrd and Saltzman 2003), a recent paper by Turk and Shattuck-Hufnagel (2007) showed multiple targets of preboundary lengthening: the final syllable and the stressed non-final antepenultimate syllable, indicating that preboundary lengthening may skip the intervening penultimate unstressed syllable and be extended to a stressed antepenultimate syllable (e.g., *Michigan*). A small-scaled recent paper by Cho, Kim, and Kim (2013) showed that the effect can be extended even beyond the non-final stressed syllable to the initial unstressed syllable in the trisyllabic test word *banana*. A similar interaction of preboundary lengthening with stress is found in other languages but in a language-specific way. For example, in Italian, preboundary lengthening is extended to a non-final stressed syllable but only when it is penultimate (D'Imperio 2011). In Northern Finnish, it is extended to the non-final stressed syllable but with restriction on a phonologically long vowel which is not lengthened when next to another long vowel, presumably to avoid obscuring the long-long syntagmatic relationship between phonologically long vowels (Nakai, Kunnari, Turk, Suomi, and Ylitalo 2008). Yet another type of language-specific preboundary lengthening is found in Japanese in which the domain of preboundary lengthening is localized to the final mora rather than to the final vowel (Shepherd 2008).

The cross-linguistically available results taken together provide some implications. First, preboundary lengthening comes about as a consequence of a universally applicable temporal modulation of domain-final articulation before a boundary. It may be seen as a kind of prosodic strengthening in the temporal dimension as a function of boundary strength, which is assumed to help in encoding the higher-order prosodic structure of the language. Crucially, however, it is language-specifically fine-tuned in terms of its domain of influence and in the way that it interacts with other phonological factors of the language such as stress and vowel quantity. This supports the view, as suggested by Cho (2015), that preboundary lengthening is under the speaker's control and so must be specified in a linguistic description of the phonetics–prosody interface as part of the phonetic grammar of the language (e.g., Keating 1984, 1990; Cho and Ladefoged 1999). Here, the phonetic grammar is assumed to modulate phonetic implementation by making reference to various levels of linguistic structure including prosodic structure.

3. Domain-initial (Post-boundary) Strengthening

Another important aspect of boundary-related phonetic modulation is *domain-initial strengthening* (henceforth DIS), which characterizes prosodically conditioned phonetic realization of segments at the left edge of prosodic domains. That is, a given segment is produced with "stronger" articulation after a higher than a lower prosodic boundary – i.e., when it occurs at the initial (left) edge of a higher-level prosodic domain than at the initial edge of a lower one (e.g., Fougeron and Keating 1997; Cho and Keating 2001, 2009; Fougeron 2001; Keating, Cho, Fougeron, and Hsu 2003; Cho and McQueen 2005; Kuzla, Cho, and Ernestus 2007; Cho, Lee, and Kim, 2011, 2014, *inter alia*).

In exploring why segments are strengthened domain-initially, Fougeron (1999) suggested an explanation from a physiological point of view: DIS is ascribable to "articulatory force" (cf. Straka 1963) associated with the initial position, which can be defined as "the amount of energy necessary to the realization of all the muscular effort involved in the production of a consonant" (Delattre 1940, translated). Furthermore, just like prominence-induced strengthening may involve an increase in the respiratory force as shown in EMG (electromyographic) studies by Ladefoged and his colleagues (e.g., Ladefoged 1967; Ladefoged and Loeb 2002), a greater respiratory force may be associated with the initial position of a larger prosodic domain. That is, given that a larger prosodic domain may serve as a breath group, the speaker is likely to reset his/her respiration cycle and initiate a new phrase with an augmented respiratory power which may be responsible at least partially for some of the acoustic correlates of DIS effects such as an elongated VOT and an increase in acoustic amplitude. Whatever the mechanism underlies the DIS effect, a large body of phonetic studies (e.g., Fougeron and Keating 1997; Cho and Keating 2001, 2009; Keating et al. 2003; Kuzla et al. 2007) have demonstrated that phonetic variation associated with domain-initial positions is systematically related to the boundary strength in the prosodic hierarchy, so that it is likely that the speaker delivers some linguistically relevant message (with respect to a higher-order prosodic structure) to the listener by virtue of DIS (e.g., Gow, Melvold, and Manuel 1996; Cho, McQueen, and Cox 2007).

In the following subsections, I will review phonetic characteristics of DIS (Section 3.1) and its scope (domain) of influence (section 3.2), followed by discussions on how DIS is understood in dynamical terms (Section 3.3), in terms of its universal applicability and language specificity (Section 3.4) and, finally, in terms of its linguistic functions and contrast enhancement (Section 3.5).

3.1. PHONETIC CHARACTERISTICS OF DOMAIN-INITIAL STRENGTHENING

Here, "strengthening" refers to "strong" articulation in both spatial and temporal dimensions, so that a given segment is longer in duration and its assumed spatial target is attained in full. For example, a voiceless aspirated stop /t/ in English is produced with longer closure duration (temporal expansion) and more constriction (spatial expansion) when in the initial position of a higher domain (e.g., IP-initially) than of a lower one (e.g., PWd-initially). Similar consonantal strengthening patterns have been observed across other consonant types such as fricatives and nasals and across languages including Korean, Japanese, French, Taiwanese, and German (see Cho 2011, 2015 for a review).

Figure 3 illustrates a DIS effect in Korean, showing variation of linguopalatal contact for initial /n/ reported in an electropalatography (EPG) paper (Cho and Keating 2001). Some important observations can be made. First, the area in the palate contacted by the tongue (or linguopalatal contact) becomes progressively larger as the level of the domain moves up in the prosodic hierarchy – i.e., a cumulative articulatory strengthening effect roughly in proportional to the boundary strength. Second, there is a shift in place of articulation. The nominal place seen in IP-initial position moves back in lower prosodic positions in which the front denti-alveolar contact of /n/ is progressively lost. This suggests that the assumed articulatory target for place of articulation (in this case, the denti-alveolar for /n/) is fully attained at the initial edge of the highest prosodic domain, the IP, whereas the target is "undershot" in lower prosodic positions. As there is a strong correlation between spatial and temporal variations, Cho and

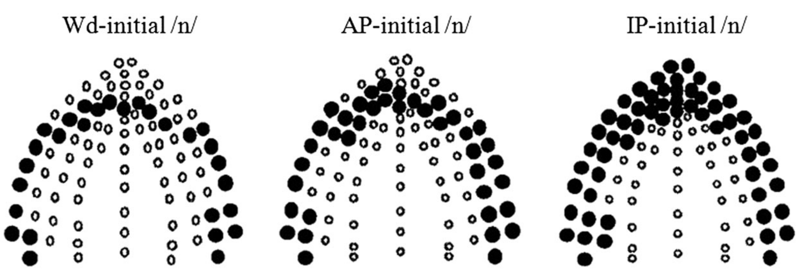

Fig. 3. Variation of linguopalatal contact for Korean /n/ as a function of boundary strength (redrawn based on Figure 3 in Cho and Keating 2001). The filled ovals refer to electrodes in an electropalatography (EPG) that are contacted by the tongue during the occlusion of the stop. Here, AP refers to accentual phrase, which is an intermediate level of prosodic domain assumed in a prosodic model of Korean (Jun 1993, 1995).

Keating (2001) propose that "strengthening" and "lengthening" associated with domain-initial positions is a single effect in Korean. The effect can be understood with the notion of *articulatory undershoot*: Enough time is given to the consonant in domain-initial position for executing the articulatory action to fully attain the assumed articulatory target, whereas the target is undershot in domain-medial positions due to insufficient durations associated with the positions. Third, although /n/ is a sonorant sound, the increase in consonantal constriction goes against enhancing its sonority, but rather it is its consonantality that is enhanced in domain-initial positions. This is further supported by the finding that the degree of nasality (as reflected in acoustic nasal duration and amplitude) indeed decreases in domain-initial position. Similar domain-initial reduction of nasality, again interpretable as enhancement of consonantality, has been reported in English and French (e.g., Fougeron and Keating 1997; Fougeron 2001; Cho, Kim, and Kim 2015). This point will be discussed further in Section 3.5 in conjunction with the relationship between boundary strength and featural enhancement.

Another well-known phonetic reflex of DIS found across languages is an increase in VOT for voiceless aspirated stops in domain-initial positions (in English, Pierrehumbert and Talkin 1992; Cole, Kim, Choi, and Hasegawa-Johnson 2007; Cho and Keating 2009; Cho, Lee, and Kim 2014; in Korean, Jun 1993, 1995; Cho and Jun 2000; Cho and Keating 2001; Cho, Lee, and Kim 2011; in Japanese, Onaka 2003; Onaka, Watson, Palethorpe, and Harrington 2003; in Taiwanese, Hsu and Jun 1998; Hayashi, Hsu, and Keating 1999). Given that a larger glottal abduction gesture is likely to give rise to a longer VOT (Cooper 1991), the DIS effect on VOT is often interpreted as coming from strengthening of the glottal abduction gesture (Pierrehumbert and Talkin 1992; Cho and Keating 2001). Jun, Beckman, and Lee (1998) indeed found that aspirated stops in Korean were produced with larger glottal apertures in AP-initial position than in AP-medial position [where AP stands for an accentual phrase, which is a kind of "minor" phrase assumed in Korean (e.g., Jun 1993, 1995)].

The DIS effect on VOT in English, however, is often found to be constrained by the stress (prominence) factor. For example, some recent studies have reported that VOTs for voiceless stops in English are reliably longer IP-initially than IP-medially only when the initial syllable does not receive a nuclear pitch accent, while the effect often disappears when the syllable is accented (Cole et al. 2007; Cho and Keating 2009; Cho et al. 2014). Such a *prominence-dependent* DIS effect on VOT may be due to the ceiling effect of prominence on VOT. The rationale is as follows. Although VOT is often considered as part of the consonant from the acoustic point of view (as it contains aperiodic frication and aspiration noises), it is part of the vowel from the articulatory point of view (as the vocalic gesture starts from the release of consonantal constriction). Given that the vowel is the primary locus of prominence, VOT, as part of the vowel, is effectively lengthened under prominence, leaving no room for further temporal expansion due to DIS. Contrary to the view that the DIS effect involves articulatory strengthening of the laryngeal (glottal abduction) gesture as a longer VOT is likely to be caused by a larger glottal abduction gesture (see Fougeron 1999, 2001 for further discussion), the prominence-dependent variation of VOT suggests that strengthening of the laryngeal abduction gesture may not be an invariant characteristic of DIS, while strengthening of the supralaryngeal gesture is (as reflected in constriction degree of consonants). See Section 3.5.1 for related discussion on language-specific modulation of VOT.

3.2. THE SCOPE OF DIS

One of the important questions at the central issue of DIS is how far the DIS effect may be extended to the right beyond the initial segment. The DIS effect has generally been assumed to be largely localized to the initial syllable, most robustly on the very initial segment. But researchers have endeavored to define its precise domain of influence as it would not only illuminate the nature of boundary-induced strengthening phenomena, but it would also inform theories of speech production as to how boundary strengthening effects may be incorporated into a speech production model.

Some previous studies showed that the DIS effect in English on the vowel beyond the initial consonant in CV is generally limited or often nonexistent (Fougeron and Keating 1997; Barnes 2002; Cole et al. 2007; Cho and Keating 2009; Cho et al. 2014). At least in the acoustic dimension, no previous paper indeed showed a consistent temporal expansion of the vowel in initial CV in English. As Barnes (2002) explains, it may be because the vowel should be reserved for stress marking especially when the first syllable is stressed. But later studies by other researchers suggest that although the scope of DIS may be constrained by the stress factor in English, the lack of the DIS effect on the vowel in CV may not be entirely due to the functional load of the vowel for stress marking, but more likely due to the locality condition of DIS – i.e., the vowel in CV is not strictly local to the boundary (but the consonant is), so that the DIS effect is attenuated or non-observable on the non-initial vowel. For example, Kim and Cho (2012) demonstrated that lip opening duration from a schwa to /æ/ was indeed longer IP-initially than IP-medially when /æ/ occurred in "add" (a vowel-initial word), while the effect disappeared in "pad" in which /æ/ is not strictly initial. Furthermore, in an acoustic paper, Kim, Kim, and Cho (2014) (and Cho, Kim and Kim, in preparation) tested whether the vowel in CV would undergo DIS when the test word was iambic so that the initial syllable was free from the stress influence as in "banal" or "panache." In the paper, no DIS effect was observed on the vowel in the initial unstressed syllable of an iambic word (i.e., even in the absence of the functional load for stress marking in the first syllable), suggesting that the lack of DIS on the vowel in CV has more to do with the locality condition of DIS rather than being driven by the functional load of the vowel.

There are, however, other pieces of evidence that the DIS effect is not altogether nonexistent in the vowel in CV in English. Several articulatory studies have indeed revealed boundary-induced temporal expansion of C-to-V vocalic movement in the articulatory dimension (Byrd 2000; Cho 2006, 2008; Byrd et al. 2006). For example, Cho (2006) reported lengthening of vocalic gestures in domain-initial CV lip opening movement along with a spatial expansion (an increase in CV displacement), and Byrd et al. (2006) found a similar lengthening effect of the C-to-V articulatory opening movement from two out of four speakers who participated in the study. Moreover, Cho and Keating (2009) reported that the DIS effect was evident in the vowel intensity in CV, though limited to when the syllable was not accented. What has therefore emerged from the available studies on the DIS effect in English is that the effect is not "strictly" local to the edge, but it is gradient in nature and so varies depending on the segment's proximity to the prosodic juncture and the prominence system of the language.

An informative case that illustrates the gradient locality condition and its interaction with prominence is found in the way initial consonant clusters are produced under the influence of boundary and accent. An articulatory paper by Byrd and Choi (2010) showed a robust DIS effect on the initial (post-boundary) stop C in s#CV in English (especially in the temporal dimension), but an attenuated effect on the same stop as the second member of the consonant cluster in #sCV. A more recent acoustic paper on the English /s/-stop cluster (as in "scan") by Cho et al. (2014) further revealed that the DIS effect on the first segment /s/ remains independent of prominence – i.e., being invariantly robust regardless of the prominence condition on the following vowel (whether accented or unaccented). On the other hand, the effect on the stop as the second member of the cluster was found to be prominence dependent, so that, for example, the closure duration of the stop was reliably longer only when in the absence of the influence of prominence (i.e., when the syllable was unaccented). A similar result with German consonant clusters was reported by Bombien, Mooshammer, Hoole, and Kühnert (2010) and Bombien, Mooshammer, and Hoole (2013). They showed that the DIS effect in German was robust on the first consonant, but the effect on the second consonant was limited to either a certain cluster type to an attenuated degree or non-observable at all, which was arguably because the second member being adjacent to the vowel was subject to the lengthening effect of lexical stress.

Taken all together, results of previous studies on DIS in English suggest that the boundary effect is strongest on the first segment of the initial syllable and its effect on the following segments becomes gradually weaker as a function of the segment's proximity to the boundary (e.g., Byrd and Saltzman 2003; Byrd et al. 2006; Krivokapić and Byrd 2012; cf. Cho and Keating 2009). The prominence effect, on the other hand, has been found to be centered at the vowel (the nucleus), and its "leftward" effect on the preceding consonants is gradually attenuated as well (e.g., Turk and White 1999; White and Turk 2010). Thus, there appears to be a kind of "competition" relationship between boundary and prominence in determining each other's domain of influence. In the next section, I will discuss how prosodic strengthening can be understood in dynamical terms, and consider the competition between the two different prosodic strengthening factors (i.e., boundary and prominence) in the framework of a dynamical model of speech production.

3.3. A DYNAMICAL ACCOUNT OF DIS AND ITS INTERACTION WITH PROMINENCE

In a recent special issue on the theme of "Dynamics of Articulation and Prosodic Structure" in the Journal of Phonetics, Mücke, Grice, and Cho (2014) pitched the need for dynamical approaches to understand the human communicative sound system. The principle tenet of the exposition is that speech is continuously and gradually changing over time, which comes from a dynamically time-varying articulatory behavior, such that the sound system cannot be understood simply by studying "magic moments" (or static snapshots) of speech. They explain this as below:

> The lowest common denominator across different dynamical approaches is the notion that systems are not made up of static entities such as symbols and rules, but that their behavior is best studied in terms of change over time. This makes variation and context-dependency an important part of a description. Context-dependent variation in speech production often stems from interactions between various subcomponents of linguistic structure in the grammar. In this regard, a dynamical approach deals with the interdependency between levels of linguistic structure that gives rise to systematic variation in speech production (Mücke, Grice, and Cho 2014:2).

One such dynamical approach is a critically damped mass–spring gestural (task dynamic) model (Saltzman and Munhall 1989). In the model, a gesture is defined as a dynamical system in which its articulatory motor execution is determined by a particular setting of dynamical parameters such as target (which determines the spatial expansion of the articulatory movement), stiffness (which determines the speed of articulatory movement), and activation time (which determines the time during which a given gesture remains activated) (see Hawkins 1992 for an overview for non-specialists). In such a system, the articulatory movement is modeled in terms of the behavior or "task" of the abstract "mass" to which a "spring" and a "damper" are attached. One end of the spring is assumed to be fixed to the mass and the other end to the gestural point attractor. As the gestural point attractor moves to the assumed target location (as defined by the target parameter), the spring is stretched, and therefore, the mass is pulled towards the target (and the stiffness of the spring determines the speed of the movement: the stiffer, the faster). The mass–spring system, however, is critically damped (due to the damper attached to the system), so that the mass does not oscillate. It never reaches the target or moves beyond it nor does it return to its original position. Instead, it stays in the target region and asymptotes towards the target (i.e., continuously and slowly reaching the equilibrium position of the spring). Articulatory phonology is a theoretical framework that assumes such dynamically defined gestures as phonological primitives, so that phonological contrasts are directly expressed by coordination of articulatory gestures in temporal and spatial dimensions (e.g., Browman and Goldstein 1992).

In an effort to understand the nature of the boundary-related modulation of phonetic realization within the frameworks of the task dynamic model and articulatory phonology, Byrd and her colleagues (e.g., Byrd 2000, 2006; Byrd et al. 2000; Byrd and Saltzman 1998, 2003, Byrd, Krivokapić, and Lee 2006) advanced the theory of "π-gesture" (the prosodic gesture). The theory assumes that boundary-related temporal variation does not come about as a direct consequence of settings of the dynamical parameters such as the target and the stiffness, but as a result of modulation of a so-called π-gesture which is governed by the prosodic constituency. The π-gesture is a "non-tract variable" gesture in the sense that it is not actually realized with a vocal-tract constriction. A π-gesture is assumed to be anchored at a prosodic boundary and modulate the rate of the "clock" that controls articulatory temporal activation of constriction gestures in the vicinity of the prosodic juncture. The boundary-induced temporal expansion (at both edges of a prosodic constituent) is therefore understood as a slowing-down effect of the clock at a prosodic juncture under the influence of a π-gesture. The degree of influence of the π-gesture is assumed to be roughly in proportional to boundary strength, and its effect is strongest at the juncture and becomes gradually attenuated as it gets farther away from the juncture.

The concept of the π-gesture as a temporal modulation gesture has been extended to a more general modulation gesture, the μ-gesture (e.g., Saltzman, Nam, Krivokapić, and Goldstein 2008). Two sets of the μ-gesture are considered: a temporal modulation gesture (a "μ_t-gesture") and a spatial modulation gesture (a "μ_s-gesture"). The two types of modulation gestures may operate interactively, giving rise to the prominence-related strengthening pattern in English that generally involves both the spatial variation and the temporal variation of the articulation movement of constriction gestures.

The interaction of DIS and prominence effects on the temporal realization of the consonant cluster in English may then be seen as a "competition" of the two temporal modulation gestures, a π-gesture and a μ_t-gesture, which have different "docking" sites – i.e., the initial segment at the prosodic juncture for the former and the vowel of the stressed syllable for the latter. Figure 4a illustrates this relationship. On the one hand, the robust prominence-independent DIS effect on C1 in the cluster C1C2 in English (and German) is interpreted as coming from the strongest influence of the π-gesture on the boundary-adjacent C1,

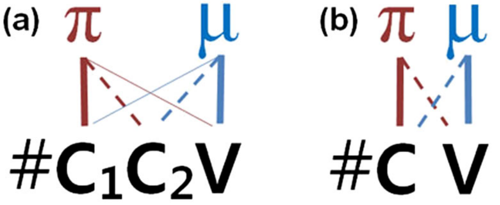

Fig. 4. Schema for segmental associations of the π-gesture vs. the μ-gesture. The segment linked by a thick solid line refers to a "docking site" of a modulation gesture, and dotted and hairy lines are used to indicate the degree of the influence of a modulation gesture on adjacent segments (the thinner, the weaker).

whereas the influence of the μ-gesture on C1 is minimal (as indicated by a hairy line) as C1 is distal from V, the docking site of the μ-gesture. On the other hand, the prominence-dependent DIS effect on C2 (which was reliable only in the absence of accent) may be accountable by a greater influence of the μ-gesture on C2 than that of the π-gesture, although C2 is flanked by both modulation gestures – i.e., the μ-gesture takes precedence over the π-gesture on the non-initial C2 in the "competition." For the case with a simplex onset in CV, as schematized in Figure 4b, the opposite may be true. The influence of the π-gesture on C is stronger (as the initial C is directly under the influence of the π-gesture as marked by a thick solid line) than that of the μ-gesture, which does not exercise a direct influence on C (as marked by a dotted line), thus possibly accounting for the robust and prominence-independent DIS effect on C in CV in English.

3.4. UNIVERSAL APPLICABILITY VS. LANGUAGE SPECIFICITY OF THE π-GESTURE

The task dynamic model assumes that the communicative sound system of any given language should be understood in dynamical terms although specific dynamical parameter settings may differ from language to language. Likewise, given that the boundary-related lengthening phenomena recur across languages, the π-gesture model should in principle be universally applicable. However, just as the detail of boundary-related lengthening (as discussed above regarding language-specific preboundary lengthening patterns) differs between languages, so does the detail of how the π-gesture operates between languages.

Cho (2015) discusses cross-linguistic differences in boundary-related timing patterns by considering two possible (but rather speculative) parameters regarding the scope of the π-gesture that may vary across language-specific prosodic systems. The first parameter is the coordination of the π-gesture with constriction gestures. Although the center of the π-gesture is assumed to be anchored to the prosodic boundary, so that the effect is symmetrical on both sides of the boundary, its effects may differ, depending on the coordination of the π-gesture with constriction gestures (Byrd and Saltzman 2003). For example, an activation curve of π-gesture being shifted to the left relative to the prosodic juncture would result in an extended preboundary but a reduced post-boundary lengthening effect. The reverse would be true when the activation curve is shifted to the right. The second parameter is the variable activation interval (or the time domain) of the π-gesture which itself may stretch or shrink depending on the boundary strength. Languages may differ in terms of how these two parameters are set in the language. For example, although the scope of boundary-related lengthening effects have not been systematically tested yet, acoustic data reported in Cho et al. (2011) indicate that Korean may have quite a narrow preboundary lengthening effect presumably limited to the last syllable of the phrase-final word, while the post-boundary effect may be extended to the second syllable of the phrase-initial word (although these possibilities are subject to further corroboration). On the other hand, English shows an opposite boundary-related lengthening pattern: Preboundary lengthening may be extended to the non-final stressed syllable (e.g., Turk and Shattuck-Hufnagel 2007), while post-boundary lengthening appears to be localized to the first segment as discussed above. The cross-linguistically reversed pattern of boundary-related lengthening may be modeled by regulating the two parameters. The function of the left-shifted or right-shifted coordination of π-gesture (the first parameter) may account for the asymmetrical temporal expansion of the preboundary vs. post-boundary effect in English and Korean, respectively, and the actual activation interval of π-gesture (the second parameter) may determine precisely how far the effect should be extended.

Another interesting difference in dynamical terms is found in the way the boundary-related articulation varies kinematically between languages. In English, for example, the "transboundary" V-to-V articulatory movement (that spans the intervening prosodic juncture in /V#CV/ context) is longer and *slower*, presumably under a direct or the strongest (slowing-down) influence of the π-gesture. The consonantal closing and opening gestures are also produced with a longer and *slower* articulatory movement again in line with the assumptions made by the π-gesture theory (Byrd 2000; Byrd et al. 2006; Cho 2006, 2008). However, in Korean, some different patterns have been observed: The "transboundary" V-to-V vocalic gesture was found to be produced with a longer but *faster* movement (Shin, Kim, and Cho 2015); whereas the (consonantal) lip closing movement in #CV was larger, longer, and *slower* (similar to a pattern found in English under the influence of the π-gesture), the (#C-to-V) lip opening movement was found to be larger and *faster* (Cho et al. in press). That is, the transboundary tongue movement is "slower" in English, but "faster" in Korean, and the lip opening movement is "slower" in English, but "faster and larger" in Korean.

The results in Korean clearly demonstrate that the boundary strength gives rise to not only a temporal expansion as found in English (and other languages) but also a spatial expansion, which is largely comparable to the prominence-induced prosodic strengthening pattern in English. There is therefore some degree of inseparability of boundary- and prominence-driven strengthening in Korean unlike English in which the two kinds of prosodic strengthening are distinct. The cross-linguistic difference is interpreted as stemming from different prosodic systems of the languages. With no functional demands that may come from the lexical stress system, Korean appears to have more freedom to strengthen articulation at prosodic junctures in a way that is comparable to prominence marking (Cho et al. in press; cf. Keating et al. 2003). This is consistent with the observation that focus marking in Korean is more likely accompanied by prosodic phrasing headed by the focused word in the domain-initial position (Jun 2003; Schafer and Jun 2002). It is therefore plausible that prominence marking is intricately related to boundary marking in Korean with one being inseparable from the other, such that DIS goes hand in hand with some degree of prominence.

As Cho et al. (in press) suggest, while a spatial modulation gesture (a μ_s-gesture) may modulate prominence-induced spatial variation in English largely independently of prosodic phrasing (as proposed by Saltzman et al. 2008), a similar type of μ_s-gesture may underlie the seemingly boundary-induced spatial variation in Korean. More specifically, the boundary-induced spatial expansion in Korean may be explained by phasing relationships of constriction gestures with a temporal modulation gesture (a π-gesture) vs. a spatial modulation gesture (a μ_s-gesture) both of which are mediated by prosodic boundary strength. Alternatively, a unified account might be that the prosodic gesture (π-gesture) is divided into a temporal modulation prosodic gesture (a π_t-gesture) and a spatial modulation prosodic gesture (a π_s-gesture) whose activation is specified in the grammar of the phonetics–prosody interface of a given language. So in the case of Korean, both the π_t-gesture and the π_s-gesture influence domain-initial constriction gestures with the former being coupled with a boundary-adjacent consonantal constriction gesture (explaining its slower movement) and the latter with the post-boundary vocalic opening (out of the consonant) gesture (being responsible for its larger and faster movement). Under this scenario, cross-linguistic variation in boundary-induced strengthening may be understood in terms of how the non-tract-variable temporal and spatial modulation gestures are phased with tract-variable constriction gestures in relation to boundary marking and prominence marking. It remains to be seen whether and how these possibilities can be modeled and computationally implemented in a dynamical system (e.g., Byrd and Saltzman 2003; Goldstein, Byrd, and Saltzman 2006; Saltzman et al. 2008; Nam, Goldstein, and Saltzman 2009).

3.5. LINGUISTIC FUNCTIONS OF DOMAIN-INITIAL STRENGTHENING

Up until now, I have discussed some basic phonetic correlates of prosodic structure in acoustic and articulatory dimensions and their dynamical interpretations, focusing on the effects of DIS as a function of boundary strength. In this section, I will discuss how the DIS effects can be understood in terms of their linguistic functions, especially with respect to linguistic contrast enhancement.

As briefly discussed above, the initial position should be phonetically rich, so that the poorer contextual information associated with the initial position can be compensated for (e.g., Keating 2006). In fact, some phonologists (e.g., Beckman 1998; Steriade 1999; Barnes 2002) have considered initial positions as "privileged" or "licensing" positions in which phonological contrasts are frequently maintained and segments often trigger phonological alteration of neighboring segments while they themselves resist such an alteration. V-to-V coarticulatory resistance associated with the domain-initial position in English, as reported in Cho (2004), also implies the propensity of contrast maintenance in initial positions. An important question from the perspective of phonological theories, which is beyond the scope of our discussion here, is whether such a positional privilege is phonetically grounded (so that it is purely attributable to the richness of the phonetic cues associated with that position; e.g., Steriade 1999) or structurally driven (so that phonetic strengthening arises to mark the position itself; Beckman 1998). With this question set aside, what has emerged from research on DIS suggests that if segments are strengthened in line with the phonetics–prosody interface that should be specified in the grammar of a given language (Cho 2015), the resulting speech signal must contain some linguistic information possibly linked to maintenance or maximization of phonological contrasts of the sound system of a given language, which in turn should be eventually exploited by the listener in speech comprehension (e.g., Gow et al. 1996; Fougeron and Keating 1997; Cho et al. 2007).

3.5.1. Syntagmatic and Paradigmatic Contrast Enhancement

Possible linguistic functions of DIS have been discussed in terms of linguistic contrast enhancement – i.e., *syntagmatic* and *paradigmatic* contrast enhancement (see Fougeron 1999 and Cho 2011 for a review). The term *syntagmatic* pertains to the structural relationships between neighboring linguistic elements that form a sequence in speech. The boundary-marking function of prosodic structure is often construed to be syntagmatically, or structurally, motivated, so that the contrast between neighboring segments (or the syntagmatic contrast) at the prosodic junctures is enhanced. The frequently observed strengthening of initial consonants as reflected in constriction degree and duration may have an effect of heightening its consonantality (e.g., the longer the closure duration, the more consonant like) by virtue of which #CV displacement of the initial syllable and V#C displacement across a prosodic juncture may be enhanced. Note that an increased VOT may also be seen as heightening the consonantality as a longer aspiration makes the consonant more consonant like (cf. Pierrehumbert and Talkin 1992). As also mentioned above, the reduced nasal flow and nasal energy (e.g., Fougeron 2001; Cho and Keating 2009; Cho et al. 2015) are also in line with the enhancement of consonantality by reducing the sonority feature of the nasal consonant, so that its contrast in sonority with neighboring vowels can be augmented. The spatial expansion of a vocalic articulation often (though not always) observed in association with both preboundary and post-boundary positions (e.g., in English, Byrd et al. 2006 and Cho 2006, 2008; in French, Tabain 2003 and Tabain and Perrier 2005; in Korean, Shin et al. 2015; Cho et al. in press) may also contribute to the enhancement of #CV and V#C contrast.

Fougeron and Keating (1997) predicted that the increased articulatory #CV and/or V#C contrast in the vicinity of prosodic juncture would help listeners parse the continuous incoming speech signal into words and thus in facilitating lexical segmentation. In a later cross-modal identity priming study, Cho et al. (2007) indeed tested the role of DIS in lexical segmentation of a two-word sequence (e.g., *mill#company).* The results revealed that the presence of DIS in the onset of the post-boundary word (e.g., *company*), even in the absence of preboundary lengthening of the preceding word (e.g., *mill*) serves as a cue to lexical segmentation via resolving lexical ambiguity that arises temporally at the juncture (*milk* is a competitor of *mill* in the *mill#company* sequence). This result implies that the fine-grained phonetic detail of DIS even in the absence of other prosodic cues to the boundary is exploited by listeners in speech comprehension, warranting further studies that explore roles of DIS in various other aspects of speech comprehension across languages (e.g., Kim, Cho, and McQueen 2012).

The term *paradigmatic*, on the other hand, pertains to the relationship among linguistic units such as phonemes (or words) that can substitute for each other in a given context. The paradigmatic contrast enhancement used here generally refers to the maximization of phonemic distinction of contrastive sounds in a given prosodic landmark location such as a domain-initial position or an accented syllable. The enhancement of paradigmatic contrast in English has often been thought to come from prominence, which de Jong refers to as a "localized" hyperarticulation: The prominence-induced strengthening effect is generally localized to the stressed syllable as opposed to a communicatively driven hyperarticulation in the sense of Hyper- & Hypo-articulation (H & H) theory (Lindblom 1990), which is assumed to be extended globally to the whole utterance.

Such a paradigmatic enhancement involves an enhancement of distinctive features of accented segments. For example, in an articulatory paper, de Jong (1995) showed that the English vowel /ʊ/ is produced not only with a lowered jaw and tongue, which effectively increases the sonority feature (making the sound louder), but also with a more retracted tongue body, which is interpretable as an enhancement of the [+back] feature of the vowel. Similarly, in an articulatory and acoustic paper, Cho (2005) observed that English /i/ under accent is produced with a more advanced tongue body along with a higher F2, again showing an enhancement of the [−back] feature for the vowel. The prominence-induced featural enhancement may also be found in a case where the feature is a derived one as a result of an allophonic rule. Cho et al. (2014), for example, showed that VOT for a voiceless stop in the /s/-stop cluster that is already shortened due to the allophonic rule (i.e., a voiceless stop becomes unaspirated after /s/) is shortened even more under accent. They interpreted the shortened VOT as an enhancement of the allophonically derived phonetic feature {voiceless unaspirated}. Following Keating (1984), curly brackets "{}" refer to phonetic features (see below for further discussion on a related point).

As exemplified above, there is ample evidence of the paradigmatic contrast enhancement due to prominence in English, but one may wonder whether the boundary-induced DIS effect in English also gives rise to a similar paradigmatic contrast enhancement. A commonly observed lengthening of VOT for a domain-initial voiceless stop in English is in fact ambiguously interpretable either as a paradigmatic featural enhancement of {voiceless aspirated} or as a syntagmatic contrast enhancement of consonantality (i.e., the more aspirated, the more consonant like). Results of a recent acoustic paper that explored prosodic strengthening of English nasal consonants (Cho, Kim, and Kim 2015) suggest that the nature of linguistic enhancement may vary depending on the source of prosodic strengthening. They showed that the duration of nasal murmur for nasal consonants was lengthened under accent (interpretable as a paradigmatic featural enhancement of [+nasal]) but shortened domain-initially (interpreted as a syntagmatic enhancement of consonantality). Thus, as far as prosodic strengthening in English is concerned, a line may be drawn quite clearly between prominence and boundary with respect to paradigmatic and syntagmatic enhancement contrast.

The relatively clear dichotomy in the linguistic functions between the two kinds of prosodic strengthening in English may be seen as coming from the fact that English is a stress-timed language in which lexical stress is integrated into a higher-order prominence system, which dissociates prominence marking from boundary marking (e.g., Keating et al. 2003; Cho 2011; Cho and Keating 2009; Cho et al. 2011, 2014). The dichotomy, however, becomes less clear-cut when we consider a language like Korean whose prominence system is rather "loosely" defined: Korean does not specify lexically defined stressed syllables, so that higher-order prominence is not superimposed on a lexically specified location.

In an acoustic–aerodynamic paper of the DIS effect on three-way contrastive stops in Korean (lenis, fortis, aspirated; e.g., Cho, Jun, and Ladefoged 2002), Cho and Jun (2000) demonstrated a kind of a combined effect that is consistent with both syntagmatic and paradigmatic enhancements: VOT and the amount of airflow for aspirated stops were greater domain-initially than domain-medially, whereas fortis stops showed the opposite pattern, produced with reduced VOT and airflow. These results were interpreted as enhancements of different laryngeal features: [spread glottis] for the aspirated and [constricted glottis] for the fortis. At the same time, the increased VOT/airflow for the aspirated stop (along with the increase in constriction duration, as reported in Cho and Keating 2001) was also interpreted as being at least partially syntagmatically driven (enhancing the CV contrast). Furthermore, the lenis stop was also produced with an increase in VOT and airflow in domain-initial positions, but this time, it was interpreted as being purely syntagmatically driven under the assumption that the lenis stop is unspecified for any laryngeal feature. Interestingly, although the total ranges of variation in VOT and airflow overlapped between the lenis and aspirated stops, they seldom overlapped in an initial position of the same level, so that the paradigmatic contrast between the two stop categories was still maintained. This case of the DIS effects on Korean stops therefore suggests that boundary-related prosodic strengthening may involve both paradigmatic and syntagmatic contrast enhancements.[2]

Another case of a language-specific effect of DIS on enhancement of phonetic features is documented in a paper of Dutch stops by Cho and McQueen (2005). In the paper, the Dutch voiceless stop /t/ was found to be produced with a shorter VOT when in domain-initial position than in domain-medial position, showing the opposite of the DIS effect on the voiceless stop /t/ in English, although the voiceless stop in both languages may be specified with the same phonological feature [−voice] (e.g., Keating 1984, 1990; Kingston and Diehl 1994). Cho and McQueen interpreted the asymmetrical boundary-induced modulation of VOT between the two languages as being attributable to language-specific constraints on how the phonological feature [−voice] is specified with a phonetic feature: {−spread glottis} for the Ducth voiceless stop vs. {+spread glottis} for the English voiceless stops. They proposed that it would not be the phonological feature but the phonetic feature with phonetic content that would be enhanced under prosodic strengthening.

An interesting question regarding the modulation of VOT is how the shortening of VOT of an initial voiceless stop may come about counter to the general assumption that the glottal abduction gesture is strengthened as a function of boundary strength, which would, all else being equal, induce lengthening rather than shortening of VOT. In accounting for this seemingly paradoxical modification of VOT, Cho and colleagues (Cho and McQueen 2005; Cho et al. 2014) introduced the notion of articulatory VOT (Cho and Ladefoged 1999; Ladefoged and Cho 2001), definable as the intergestural timing between the stop release gesture and the laryngeal gesture responsible for vocal fold vibrations. Articulatory VOT, defined as such, is a controllable parameter rather than something that is passively determined as a result of the laryngeal abduction–addition cycle and the magnitude of the abduction (cf. Browman and Goldstein 1986). It is this articulatory VOT that is fine-tuned according to prosodic strengthening by making reference to the phonetic content provided by the language-specific phonetic feature system. Thus, prosodically conditioned shortening of VOT observed across languages (e.g., for domain-initial voiceless stops in Dutch and voiceless stops in #sC in English) may ensue from a direct modulation of articulatory VOT even in an environment in which the glottal abduction gesture is strengthened.

Taken together, the results from different languages imply that the detailed linguistic function of prosodic strengthening and its enhancement pattern of linguistic contrast is language-specifically determined by making reference to other components of the linguistic system of the language such as the prominence system, the allophonic rules, and the phonetic/phonological feature system.

4. Conclusion

Studies reviewed in this paper have illuminated detailed aspects of the phonetics–prosody interface with particular reference to boundary-related prosodic strengthening (e.g., preboundary lengthening and DIS), which ensue from the delimitative function of prosodic structure. The discussion in this paper, however, was primarily based on English and Korean, and thus more research on typologically diverse languages (see Jun 2014 for an overview of prosodic typology) is certainly called for before we can obtain a solid understanding of the universality vs. the language-specificity of boundary-driven strengthening. But the crux of the discussion is that some kind of boundary-related prosodic strengthening appears to be employed in encoding prosodic structure across languages, but it is fine-tuned in a language-specific way as it is likely to be specified in the phonetic grammar of individual languages. It was also suggested that prosodic strengthening is rooted in the linguistic contrast system, so that it engenders enhancement of both syntagmatic and paradigmatic contrasts. Here again, the detailed enhancement patterns are taken to be determined in a language-specific way in interaction with various other linguistic factors of the language such as the prominence system and the phonetic feature system. Finally, it was discussed how boundary-related strengthening effects could be understood in dynamical terms (within the framework of a mass–spring gestural model) and how language-specific effects could be modeled by using the notion of temporal and spatial modulation gestures (such as π-gesture and μ-gesture), which must operate by making reference to a higher-order prosodic structure of the language.

All these observations on boundary-driven strengthening boil down to support for an overarching theoretical assumption regarding the phonetics–prosody interface with which this paper started off: Prosodic structure provides a "frame" for articulation based on which abstract phonological representations whose phonetic detail is rather coarsely specified by the phonology of the language are fleshed out with fine-grained phonetic content in both segmental and suprasegmental dimensions. Boundary-driven strengthening then arises as a corollary of such a prosodic structuring process. Seen from another angle, this assumption entails that the prosodic structure of an utterance is phonetically "encoded" into the speech signal and the listener in turn decodes the structural information from the signal and exploits it in speech comprehension. Our understanding of the phonetics–prosody interface is still at an embryonic stage, given its intricate interaction with various levels of linguistic structure and the complexity of the interplay between them. It is hoped that this review paper has provided kernels from which further research on the phonetics–prosody interface may proliferate, exploring linguistic mechanisms of encoding and decoding prosodic structure, which will ultimately illuminate linguistic roles played by prosody in the grammar of the language.

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Short Biography

Taehong Cho's research focuses on the interplay between phonetics, phonology, and prosody in speech production and speech comprehension, articulatory phonology, and language effects on timing. He has authored or co-authored papers in these areas in a variety of international journals including *Journal of Phonetics, Journal of the Acoustical Society of America, Phonetica, Journal of the International Phonetic Association, Journal of Memory and Language, and Studies in Second Language Acquisition*. Cho currently serves as Editor-in-Chief for *Journal of Phonetics* (Elsevier), book series co-editor for "Studies in Laboratory Phonology" (Language Science Press), and Executive Councilor for Association for Laboratory Phonology (ALP). Cho earned his PhD degree in Phonetics at the University of California, Los Angeles (UCLA) and worked at the Max Planck Institute for Psycholinguistics. Cho is a Professor of Linguistics in the Department of English Language and Literature and the director of Hanyang Phonetics and Psycholinguistics Lab (HPPL) at Hanyang University, Seoul, Korea.

Notes

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[1] The tonal transcriptions employed in this paper follow the conventions of the English ToBI (tones and break indices) (Beckman and Ayers 1994; Beckman, Hirschberg, and Shattuck-Hufnagel 2005), which has been developed on the basis of Pierrehumbert's intonation-based model (e.g., Pierrehumbert 1980; Beckman and Pierrehumbert 1986). The interested reader is also referred to Selkirk (1984, 1986) and Nespor and Vogel (1986) for syntactically motivated models of prosodic structure. In ToBI, a tone with "%" (e.g., H% or L%) is called a "boundary" tone, which refers to a phrase-final tone that characterizes the end of a major phrase called the intonational phrase (the largest prosodic unit assumed in the model); a tone with "-" (e.g., L-) is called a phrase tone that is associated with the end of the intermediate size phrase called the intermediate phrase (roughly comparable with the phonological phrase assumed in Selkirk (1984, 1986)); and a tone with "*" or a starred tone (e.g., H* or L+H*) refers to a pitch accent that falls on a lexically stressed syllable along with a higher-level (phrasal) stress. A pitch accent can be bitonal, so that, for example, L+H* means that the starred high tone (H*) is realized primarily on a lexically stressed syllable preceded by a low tone. Note that !H (a "downstepped" high tone), as used in L+!H* in Figure 1a, refers to a high tone which is lower relative to a high tone that precedes it.

[2] It should be noted, however, that paradigmatic relations among Korean stops may have changed over time, given that the role of VOT has been reduced in making a distinction between the lenis and the aspirated stop, whereas F0 has obtained its primacy in cue weighting at least among young Korean speakers (e.g., Silva 2006; Kang and Guion 2008; Kang 2014; cf. Schertz, Cho, Lotto, and Warner 2015). Further research on the contemporary Korean produced by young speakers is needed to examine how phonetic realization of the tonal (F0) feature vs. VOT is modulated by DIS and to what extent the DIS effect on F0 relative to VOT can be understood as syntagmatically vs. paradigmatically driven.

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