PHONETIC ENCODING OF PROSODIC STRUCTURE

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INTRODUCTION

Prosody has been defined as the "grouping and relative prominence of the elements making up the speech signal" (Pierrehumbert, 1999). That is, prosody serves both a grouping function and a prominence-marking function in speech. As examples of the grouping function, some ways in which smaller units are combined to form larger ones (perhaps via intermediate groupings) include: segments combine to form syllables, syllables combine to form words, and words combine to form phrases. As examples of the prominence-marking function, there are at least two levels of prominence in English: lexical stress, or prominence at the word level, and pitch accent, or prominence at a phrasal level.

Some prosodic constituents:	**Some levels of prominence:**
• Utterance • Intonational Phrase • Smaller phrases: Phonological Phrase/ Intermediate Phrase /Accentual Phrase • Phonological Word • Foot • Syllable • Mora	• Nuclear accent • Pitch accent • Lexical primary stress • Lexical secondary stress

The grouping function and the prominence-marking function can be seen together in a prosodic tree of an utterance. Figure XXX.1 is a partial prosodic tree of the phrase “that new propaganda” as part of some larger utterance, showing 4 levels of prosodic domains (leaving out several other levels): it shows a single Intonational Phrase (IP), containing 2 intermediate phrases (ip), the first of which contains 3 prosodic words (Wd) corresponding to the 3 lexical words in “that new propaganda”. The third word has the phrasal accent or prominence, and it contains 4 syllables (sigma), of which the third has the lexical stress or prominence. This partial tree has syllables as its smallest prosodic units. Each syllable contains some segments, and the features of the segments are the terminal nodes of the prosodic tree. A few of these segmental features are included in the figure. As can be seen, each segment and thus each feature has a position in the tree relative to the domains and prominences.

- Figure XXX.1 about here –

For the purposes of this paper, we can consider any one interval of speech that is grouped into a single prosodic domain and ask, At what level of prosodic structure does this domain occur? What speech events occur at the beginning and end of this domain? How prominent is this domain relative to its neighbors? All of this information will be relevant phonetically.

The phonetic dimensions that are most obviously connected with prosody are pitch, duration, and loudness, which are generally thought of as the suprasegmental dimensions. But the phonetic dimensions that are typically thought of as more segmental than suprasegmental also serve to realize prosodic distinctions. For

example, it is well-known that vowel quality varies not only with phonemic vowel identity, but also with such traditional suprasegmental factors as stress and length (Lehiste, 1970). This classic observation can be generalized to all of prosody as now understood, including its hierarchical structure. Put generally, then, the phonetic realization of an individual speech segment (vowel or consonant)'s phonological properties depends in part on that segment's position in the entire prosodic structure (Pierrehumbert & Talkin, 1992; Hawkins & Smith, 2001). The exact pronunciation of any one feature will depend on the other features in that segment, features of neighboring segments, and the position of the feature in the overall tree. Thus segmental phonetic dimensions, though they convey segmental contrasts, are influenced by prosody in much the same way as are the traditional suprasegmental dimensions (dimensions not involved in conveying segmental contrasts).

In Levelt, Roelofs & Meyer (1999)'s important model of planning for speech production, a distinction is made between (1) phonological encoding, or generating a complete phonological representation, including prosody, from lexical entries and syntactic structure; and (2) phonetic encoding, which specifies the surface phonetic shape of the phonological representation. At each of these stages, Levelt et al., relying on the traditional distinction between segmental and suprasegmental phonological representations and speech parameters, envision segmental and prosodic planning as virtually independent. Phonetic encoding of segments is thought to operate at the level of the word, and it consists largely of retrieval of stored syllable plans. Segmental and prosodic planning interact in only a minor fashion, at the end of the encoding process, when the results of these two independent processes are brought together.

As discussed at length in Keating & Shattuck-Hufnagel (2002), the missing ingredient from their model (and similarly, from the model in Levelt, 1989) is the close link between prosodic structure and segmental phonetic properties. We outlined instead an opposing view, according to which segmental and prosodic planning are not independent, since planning segmental articulation depends crucially on prosody. We stressed that even if phonetic encoding relies on stored syllable plans, the work of phonetic encoding has just begun with their retrieval, as adjustments to them are required on the basis of all kinds of prosodic information; and even if phonetic encoding relies on stored exemplars, then that retrieval operation itself must be highly sensitive to prosodic structure and the retrieved exemplar may still require further processing. The present chapter, like Keating & Shattuck-Hufnagel (2002), defends this claim, by reviewing a variety of ways in which phonetic encoding must be sensitive to prosodic structure, focusing especially on results from my own laboratory. In particular, I will review results of experiments suggesting a strength relation between prosodic positions and phonetic realizations.

The general idea of a strength relation is that prosodic positions are stronger or weaker**;** segment/feature phonetic realizations are also stronger or weaker; and segment strength matches position strength, with stronger pronunciations in stronger positions**.** Positions of lexical and phrasal prosodic prominence seem strong due to their suprasegmental properties (e.g. greater loudness in the case of stress, pitch excursions in the case of accent), and in these positions segment qualities can also vary. The notion of a strong position is then generalized to other positions in which the same variants are observed. For example, Donegan & Stampe (1979) observe

that traditional segmental fortitions are most likely in 'strong' positions, in which they include prosodically prominent positions and syllable-initial position. Similarly, Vaissière (1988) related certain prominent, domain-initial, and domain-final positions, in which velum position patterned similarly, as "[+strong]".

What exactly does strengthening mean? Our strengthening is articulatory, meaning that the articulations themselves are stronger, or more extreme. For consonants in strong positions, for example, the primary oral constriction is more extreme, meaning that the primary articulator moves farther from a neutral position into a more extreme position which reduces the size of any mouth opening[1]. Also, any glottal opening is more extreme, giving more aspiration. Such strengthening (often called fortition in the historical linguistics literature) can be seen as the opposite of weakening (or lenition), by which, for example, a more reduced primary consonant articulation results in a greater mouth opening, or a more reduced glottal opening results in greater voicing. (However, other views are possible; for example, Donegan & Stampe (1979) define fortition as perceptual enhancement, and lenition as articulatory reduction.) In historical sound changes (e.g. Hock, 1991, 1992), 'initial strengthening' as a specific process refers to something that happens to initial sonorants, in languages which also weaken medial obstruents; that is, it is a generalization to sonorants of the pattern of strong initial obstruents vs. weak medial obstruents. In our phonetic work the term is used even more generally, to refer to increased articulatory opening or constriction in any articulation of any segment type.

[1] Possibly the articulations are more forceful, with greater muscular contraction – see Fougeron (1999, 2001) for discussion.

Many previous studies have been concerned with the articulation of prominent vowels, including the direction of displacement for prominent high vowels, and differences between prominence and other strengthenings (e.g. Beckman et al.,1992; Cho, 2002; de Jong, 1995; Edwards et al., 1991; Erickson, 2002; Fletcher & Vatikiotis-Bateson, 1994; Harrington et al., 2000). Other studies (reviewed in Epstein, 2002, 2003) have been concerned with the phonation qualities associated with prominence. Strengthenings at the beginnings of prosodic domains and in prominent syllables are complemented by domain-final lengthenings, the well-known phenomenon where segments at the ends of domains have longer durations (e.g. Wightman et al., 1992). See Shattuck-Hufnagel & Turk (1996) and Fougeron (1999) for reviews of the articulation of prominence and final lengthening, which will not be discussed in any detail in this chapter.

The total effect, then, is that at the end of one domain there is a slowing down, then at the beginning of the next domain a strong attack, with another strong moment associated with any prominence. Such phonetic effects are also seen in synchronic phonological patterns. At the word level, languages may license or distribute inherently stronger segment types in stronger positions, e.g. a preference for initial obstruents, especially stops, as opposed to non-initial sonorants or continuants (e.g. Bell & Hooper, 1978; Martinet, 1955)[2]. Overall, then, there is a tendency for

[2] See Zhang (2004:167-68) for a phonological effect of domain-final lengthening, namely on the distribution or licensing of contour tones in languages.

prosodic domains, such as words, in a given language to have a phonological and/or phonetic shape conditioned by the prosodic structure of the language[3].

BASIC DOMAIN-INITIAL EFFECTS

In my work (with various collaborators) I have been most interested in domain-initial articulatory strengthening, that is, strengthening associated with the beginnings of prosodic domains. I have put forward a specific claim about how this strengthening works through the whole of prosodic structure: that it is cumulative, in the sense that the higher in the prosodic tree an initial position is, the stronger that position and the segment in it. The empirical support for this claim is somewhat mixed, as I will make clear below, but there is an interesting range of data that seem to work this way.

The prosodic positions we compare are generally edges of domains. A domain-initial segment (or syllable) is at the beginning of some prosodic domain. A domain-final segment (or syllable) is at the end of some prosodic domain. Because prosodic domains are hierarchically organized, a given segment (or syllable) is usually initial or final in multiple (nested) domains. To see how this works for domain-initial syllables, look at the six syllables shown in the partial tree in Figure XXX.1. The first is initial in all the domains shown. We generally refer to the *highest* domain in which some segment or syllable is initial, so in this case the syllable is IP-initial. The second and third syllables are word-initial, but IP- and ip-medial. The other syllables

3 This is not to say that synchronic phonological patterns or sound changes across languages uniformly illustrate initial strengthening. It seems clear that in some languages, at least at the word level, the stem, root, or some other part of a word is more important than the beginning. A striking example is provided by Australian languages, as described by Butcher (this volume) and Tabain, Breen, & Butcher (2004).

are not initial in any domains. The last syllable of the six is final in the ip and in all lower domains.

Experimentally, we measure something we take to be related to segment strength, for example linguo-palate contact as a measure of oral constriction. At UCLA we have primarily used electropalatography (EPG) to infer the strength of segment articulation. With the Kay Elemetrics EPG system, a speaker wears a custom-made false palate embedded with 96 contact electrodes. When the tongue touches any electrodes, a circuit is completed, current flows, and the contact is thereby registered. Figure XXX.2 shows the electrode layout, which concentrates electrodes around the inner tooth surfaces and thus registers variation in tongue height. A computer samples the contact over the entire palate every 10 msec, and each frame of data shows which electrodes were contacted at that time. Figure XXX.3 shows a sample frame of contact. Our general method is to construct speech materials that put a test consonant into different prosodic positions, and then take the simplest measure of strength, namely the maximum amount of contact between tongue and palate found during that consonant in each condition. This measure ignores where on the palate, and when during the consonant, this peak contact occurs, but those aspects can be measured as follow-ups. For stop consonants, we also generally measure the duration of the stop seal, that is, the amount of time (in number of data frames) that the vocal tract is completely sealed off by the stop occlusion.

- Figure XXX.2 about here -

- Figure XXX.3 about here –

Our first study, Fougeron & Keating (1997), looked at English /n/ and /o/ in initial and final positions in several domains. Three American speakers read reiterant versions of sentences, using the reiterant syllable /no/ to replace every syllable of the sentences. The sentences were arithmetic expressions in which the use of parentheses was crucial to the meanings of the expressions. One speaker produced a larger set of sentences in which different numerals occurred in the sentences, but the other two speakers produced only sentences with the numeral "89". This numeral was chosen because its lexical stress is generally on the last syllable, and thus should not be a factor in the articulation of the initial syllable. The prosodic phrasing of the utterances was coded post-hoc, using ToBI constituents[4], and the prosodic position of each reiterant syllable was determined from these phrasings. The domains coded were the Utterance, the IP, the ip (or PP for Phonological Phrase, for typographical clarity), the Word, and the Syllable.

- Figure XXX.4 about here -

The percent contact was calculated for each frame of data; Figure XXX.4 shows such data in a contact profile for a sample utterance. This figure illustrates that not only the consonants but also the vowels vary in contact across the utterance. The

[4] ToBI transcription uses the acoustic signal, particularly fundamental frequency and durations, to determine the phrasing of a spoken utterance. This phrasing is thus potentially different from a prosodic parse assigned by a theory of prosodic phonology, e.g. Nespor & Vogel (1986). In effect, ToBI transcription gives up a concern with predicting the different factors that could influence phrasing, in favor of a more veridical account of surface phonological form, after any restructurings. (Prosodic theories must allow for restructuring, or its non-derivational equivalent, since most sentences have multiple possible prosodic phrasings.) For a review of the correspondences between these two types of representation, see Shattuck-Hufnagel & Turk (1996). For a proposal about how they might be related in production planning, see Keating & Shattuck-Hufnagel (2002). For discussion of transcription practice for boundaries, see de Pijper & Sanderman (1994).

measured contacts for each segment are the values of the consonant peaks and vowel valleys as seen here. The temporal pattern can also be seen in this figure, though the duration measures that we took did not come from this kind of record. Articulatory seal duration (the duration of the frames in which a complete stop occlusion can be inferred) was not measured or reported in Fougeron & Keating (1997) but was measured subsequently and reported in Keating, Cho, Fougeron, & Hsu (2003). Figure XXX.5 shows the results for both measures (peak contact on the left, seal duration on the right). This figure, like Figure XXX.6 later, shows the mean peak contact for all /n/s initial in each prosodic domain, laid out like a prosodic hierarchy, with the highest domains at the top of the figure. If the prosodic positions have a cumulative effect on a measure, then the dark bars at the top will be longest and the light bars at the bottom will be shortest. And overall, this is what the figure shows, though not completely consistently.

- Figure XXX.5 about here -

The original hypothesis motivating this study did not involve domain-initial strengthening; we expected to see some kind of final or progressive weakening (declination), as discussed in detail in Fougeron & Keating (1997). Yet many explicit tests for declination failed to provide any evidence for it. What we found instead in our data for /n/ was fairly cumulative domain-initial strengthening: each speaker made three or four pairwise cumulative distinctions between /n/s in domain-initial positions. However, no speaker made all possible distinctions, and there was no pairwise distinction that was made by all three speakers. There was also a trend towards strengthening (meaning less contact) of the vowels in initial /no/ syllables;

and strengthening of /n/ in domain-final syllables was occasionally found. Domain-final vowel strengthening was observed, but it was not as strongly cumulative, in that phrase-final /o/s at different levels were not distinguished by amount of opening. Also, acoustic duration of /o/ did not vary much according to domain. In contrast, acoustic and articulatory durations of /n/ were more consistently cumulative than linguopalatal contact; nonetheless, correlations between /n/ durations and contact were minimal to modest.

We then followed up with a study of domain-initial strengthening in three other languages which differ in their prosodic properties: French, Korean, and Taiwanese (Keating et al., 2003). None have lexical stress – French and Korean have phrasal tone patterns, Taiwanese has lexical tones. In this study we used real-word utterances rather than reiterant speech, with test words beginning with the consonants /n/ or /t/, but similar prosodic domains as in the English study[5]. Overall, each language showed cumulative initial strengthening – as in English, contact and duration are generally greater in higher prosodic positions. In fact, the surprising result was how similar the results were for the three languages, despite their prosodic differences. The pattern was most consistent for Korean, which we had predicted could show the most articulatory strengthening, as its domain beginnings are generally thought to be prosodically strong. Figure XXX.6 shows the results for Korean /n/; /t/ is similar. Here the smaller phrase is the Accentual Phrase (AP). This figure combines results for 2 different corpora, one for Word and above, the other for

[5] Two points deserve mention in this connection. First, there is no reason that the prosodic domains should be exactly comparable across the languages; the small phrases in particular seem to vary across languages. Second, the speakers of the different languages differed in their use of pauses;

Word and below. Because the vowel contexts for the /n/s in the 2 corpora are different, the amount of contact for the 2 Word-initial /n/s is different. Indeed, it can be seen that the difference in contact between two prosodic domains is about the same size as the difference between two vowel contexts; it is furthermore about the same size as the difference between two consonant manners, such as /n/ vs. /t/ (/n/ having less contact).

- Figure XXX.6 about here -

A further result concerned the relation of duration to linguopalatal contact in the different languages: while all the languages had fairly consistent cumulative initial lengthening, only in Korean was strengthening (contact) strongly related to that lengthening. In our English data, the correlations of contact with duration were low to modest ($r^2 < .3$); in French there was a stronger relation ($r^2 > .6$); but in Korean the correlations were very high ($r^2 < .9$). This strong relation suggests a sort of undershoot mechanism. Strengthening in Korean seems to be related to how much time is available for the articulation: in Cho & Keating (2001) we showed that up to about 80 msec, the amount of contact is a function of the duration, with the peak contact coming at the end of the consonant and shorter consonants undershooting their target; but above about 80 msec, there is no additional contact. Thus it seems that in Korean, there is little if any independent effect of strengthening apart from lengthening. However, to the extent that the other languages are not like this, they in

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the French speakers sometimes paused at IP boundaries, while the Korean and Taiwanese speakers were instructed not to do so.

turn provide evidence that initial strengthening is a separate effect from lengthening – two effects, but both sensitive to prosodic position.

Other researchers have contributed to our knowledge about initial strengthening in a variety of languages, including Byrd et al. (2000), Gordon (1999), Lavoie (2001), and Tabain (2003b). Most studies that have included several prosodic domains have found an overall tendency, but not a perfect pattern, of cumulative domain-inital strengthening. For example, in an EPG study of Japanese (Onaka, 2003; Onaka et al., 2004), two speakers showed some effects of prosodic position on contact for /n/, but only one of the speakers showed effects for /t/. The effects on consonant duration (domain-initial lengthening), and on the pre-boundary vowel's openness, were perhaps more striking in this study.

A major exception is found in EMA studies in which displacement is the spatial measure. Thus Byrd et al. (2000) found that in Tamil /m/ and /n/ lengthen but show only small differences in spatial displacement; and Tabain (2003b) likewise found no effect of prosodic position on the peak displacement of French domain-initial consonants / b d g f s ʃ /. And, Byrd & Saltzman (1998) found a very different result for English than we did: comparing lip movements at the boundaries of what were probably three different prosodic domains, they found that displacement to the postboundary consonant was highly correlated with duration[6]. It seems from these studies that displacement does not depend on prosodic position in the way that peak

[6] This result might seem to suggest that English is in fact like Korean, with a relation between strengthening and lengthening, contrary to our own result. However, our correlations are with peak contact, not displacement.

linguopalatal contact does. Even in Fougeron & Keating (1997), we found that the closest EPG measure to true articulator displacement, namely change (difference) in contact, is not strongly related to peak contact. Peak linguopalatal contact is probably more closely related to constriction degree, and thus to the magnitude of the articulation, than is displacement of an EMA coil.

FURTHER RESULTS

Further observations can be made about domain-initial strengthening on the basis of additional analyses in Fougeron & Keating, as well as later studies at UCLA: on English, Cho (2002), Keating, Wright & Zhang (1999); on Korean, Cho & Jun (2000), Cho & Keating (2001), and Kim (2001); and on French, Fougeron (1998, 2001).

First, some segments vary more than others; indeed some segment types show no initial strengthening. For example, Fougeron (1998, 2001) looked at EPG contact for French /n t k l s i/, and found that prosodic position had less effect on contact for /s/ and /i/ than for the other segments. For the sibilant fricative /s/, Fougeron measured several aspects of the fricative constriction, not just overall contact. By all measures, it varied very little across prosodic positions, presumably because the production of sibilance constrains the articulation. That fricative /s/ is highly constrained in its articulation is no surprise, and the same has been shown at the word level for English, e.g. Byrd (1996) and Keating et al. (1999). However, Kim (2001) did find differences in the two Korean sibilants, /s/ and /s*/, specifically in the contact in the mid-palate and the fricative channel region, across three prosodic positions, with /s/ seemingly showing more of an effect than /s*/. This result shows that sibilants in at least one language are free to vary, but no reason is offered for why Korean might

be different in this respect. Perhaps it is another reflection of the strong relation in Korean between duration and articulatory contact; clear prosodically-determined duration differences are seen for /s/ but not /s*/. As another example, Cho & Keating (2001) compared the four Korean coronal stops /n/, /t/, /t^h/, /t*/, and while all showed an effect of prosodic position on contact, the range of variation differed across the consonants, such that the prosodic effect was larger for some than for others.

Second, domain-initial strengthening appears to be a very local effect largely limited to the first segment after a boundary, and is thus unlike final lengthening, which extends over a larger span. For example, in the French study (Fougeron, 1998) domain-initial strengthening was limited to only the /k/ in a /kl/ cluster, and to a vowel only when there is no preceding initial consonant (/i/ in /#ip/ but not /a/ in /#na/). This very local effect is perhaps consistent with the fact that in French, final lengthening is more limited in extent than in English (Fletcher, 1991). Similarly, in our Korean study (Cho & Keating, 2001) we found no consistent domain-initial vowel lengthening in initial CVs. In English the evidence seems more mixed, but in two studies vowels in #CV varied only somewhat with prosodic domain (Cho, 2002, in press; Fougeron & Keating, 1997).

Third, it is noteworthy that strengthening does not result in discrete phonetic categories, corresponding to the domains of the prosodic hierarchy, even though descriptions of prosody are couched in terms of these discrete domains. In Cho & Keating (2001) we compared pooled measures of acoustic domain-final lengthening and EPG domain-initial contact, as seen here in Figure XXX.7. In statistical comparisons, both sets of measures support a four-way prosodic distinction.

However, only the data for final duration clearly fall into discrete categories, and only two of those; in contrast, the data for initial contact belong to a single large unimodal distribution. That is, it cannot be claimed that there are four (or however many) categories of phonetic strength, each of which gets some additional increment of constriction; the effect appears instead to be continuous.

- Figure XXX.7 about here -

Finally, it is worth stressing that in Fougeron & Keating (1997) we were careful to distinguish initial strengthening from final weakening and declination. While these terms might sound as if they are different names for the same thing (e.g. some sort of downtrend), they in fact describe different outcomes when a large enough span of speech is considered. Fougeron & Keating called the effect initial strengthening because of explicit tests[7] that favored that interpretation. (To be sure, initial strengthening cannot be distinguished from everywhere-but-initial-weakening, but that is the only sense in which strengthening and weakening are two sides of the same coin here.) Simple comparisons of two positions cannot decide this point. For example, a comparison of initial vs. final positions by itself cannot distinguish these three possibilities, and much of the literature compares only two positions in this way. In such two-way comparisons the terms initial strengthening, final weakening, and declination all come to the same thing, and no importance can be placed on the choice of descriptive term.

[7] Because our test utterances contained many syllables we were able to compare initial vs. medial vs. final syllables in the various domains. For example, final weakening would have meant that the final syllable consonants had less contact, and declination would have meant a decrease in contact across consonants in the domain.

Fougeron & Keating did not look at domain-final consonants, since all our test syllables were CVs. Given the historical linguistics literature, it is plausible that domain-final consonants should show some weakening. In Keating et al. (1999) we made a very limited comparison of domain-initial and domain-final consonants – four coronals / t d n l /; in the test corpus, word-initial consonants occurred utterance-initially vs. utterance-medially, while word-final consonants occurred utterance-medially vs. utterance-finally. The maximum EPG contact depended on position in both the word and the utterance. Overall, as expected, word-initial consonants had more contact than word-final, and also as expected, word-initial consonants had more contact when they were also at the beginning of an utterance. However, utterance-final consonants had more contact than other word-final consonants. That is, there appears to be no cumulative domain-final weakening of consonants; instead we see some strengthening at the end of the largest domain. The role of domain-final lengthening in this apparent strengthening deserves further study.

ACOUSTIC AND OPTICAL CORRELATES

The kinds of articulatory variation discussed above give rise to two kinds of potentially perceivable variation: acoustic and optical[8]. Two influential phonetic studies of initial strengthening, Pierrehumbert & Talkin (1992) and Dilley et al. (1996), were in fact acoustic, not articulatory, studies. Pierrehumbert & Talkin showed that in phrase-initial position, /h/Vs are more consonant-like by an RMS

[8] The term “optical”, as opposed to “visual”, is perhaps surprising, but it is parallel to “acoustic” in the sound domain. That is, acoustic:auditory::optical:visual -- optical and acoustic properties of signals lead to auditory and visual percepts. Characterization of the stimuli used in visual perception experiments involves optical phonetics.

measure (lower RMS indicating less glottal excitation); and aspirated stops are more aspirated, suggesting greater magnitude of their glottal spreading gestures. Another interesting example of prosodically-conditioned acoustic variation involving the glottis is Hsu & Jun's (1998) study of Taiwanese VOT. Taiwanese has voiced (often prenasalized), voiceless unaspirated, and voiceless aspirated stops. Hsu & Jun found that when /k^h/ and /b/ are initial in higher domains, the /k^h/ is more aspirated and the /b/ is more voiced. Thus the phonetic voicing categories are acoustically more distinct in stronger positions. Other acoustic studies of initial strengthening include Cho & Keating (2001) and Tabain (2003a).

The optical correlates of prosody have been studied very little to date, mainly the correlates of prominence, but since many articulations involve the face, at least some aspects of phrasing should also be visible. Certainly durational differences should be apparent, even if subtler articulatory differences are difficult to see. A study with colleagues at the House Ear Institute in Los Angeles (Auer et al., 2004) tested the visual perceptibility of prosodic boundaries. Talkers read minimal pairs of sentences differing in the presence/absence of boundaries, while movements of reflective markers on their faces, including on the chin, were tracked by the Qualysis infrared system. Some sentences contrasted in presence/absence of a word boundary (e.g. *He was noted for getting the right number* vs. *He just hated forgetting the right number*), while others contrasted in presence/absence of a phrase boundary (e.g. *When you sing, his songs are better* vs. *When you sing his songs, they're better*). The duration of the movement of the marker on the chin was measured, and was found to be longer around a boundary. Acoustic durations were also longer across a boundary. Perceivers then saw sentence fragments and had to

decide which sentence (with or without boundary) the fragment had come from. Perceivers were generally good at doing this.

IMPLICATIONS OF STRENGTHENING

Whether the acoustic correlates of prosody, of the sort discussed in the preceding section, are used in auditory perception has only recently begun to be determined. When segmental contrasts are enhanced, listeners' perception of segments might be improved[9]. And, when the acoustic correlates indicate a prosodic boundary, listeners' prosodic parsing might be improved. Cho et al. (2004) review the literature so far and offer some evidence that listeners use segmental correlates in perceiving prosodic boundaries. In this section I speculate on two possible functional implications of domain-initial strengthening, if it turns out to be useful to perceivers in these ways.

First, the information about phrase boundaries that might be conveyed by segment strength could also be seen as information about the local coherence vs. disjuncture in connected speech. A strengthened segment indicates a break and the start of a new domain, while domain-internal spans of segments are not interrupted by strengthening. We do not know whether speakers manipulate strength on purpose for the sake of listeners, but on this view, if they do, they may do so to indicate the degree of break/cohesion between words in connected speech. This suggests to me the possibility that while stronger segments may consume more calories of a

[9] It must be noted that the hypothesis that strengthening serves an enhancing function for listeners is controversial. Various views on the nature and possible function of segmental enhancement in domain-initial positions can be found in, for example, Pierrehumbert & Talkin (1992), Fougeron & Keating (1997), Hsu & Jun (1998), Fougeron (1998, 1999, 2001), and Cho & McQueen (in press).

speaker's articulatory energy than do weaker ones, weaker segments do not reflect laziness or inattention on the part of the speaker. Rather, we should think of the speaker's energy as constantly directed to control of the modulation of articulation, because all levels of strength carry information. To be sure, there is a general tendency in speaking towards ease of articulation, which is resisted in strong positions; and as a result, segmental cues may be weaker in weak positions. (See several chapters in Hayes et al., 2004 for examples.) But then this reduction in segmental information is itself information for listeners – information about juncture.

Second, if strengthening increases information about segment identity, it does so in just those positions where such information is most important. Psycholinguists (e.g. Levelt et al., 1999) have noted the special status of word-initial position in speech errors, at least in English; word-initial segments

- are more vulnerable to speech errors
- are exchanged in speech errors
- show stronger similarity effects in speech errors (Frisch, 2000)

And these word-initial segments are produced with articulatory strengthening. Is this a paradox? Phonetically, word-initial position is said to be "strong", yet much of the psycholinguistic evidence concerns errors. If these segments are strong, why do they seem so vulnerable? A possible resolution to this quandary can be found in the contributions of Dell (2000) and Frisch (2000) to the *Laboratory Phonology V* volume, in which they suggest that speech errors arise in word- (or in most such experiments, utterance-) initial position due to lack of a constraining prior context. Because other words are possible, other word candidates are activated and

compete with the correct word, resulting in selection errors. Furthermore, word-initial position is a position of competition between many competitors, in the sense that words generally can begin with a greater variety of segments than they end with, such that there are more (different) segments in strong competition word-initially than elsewhere. That is, word-initial segments are more vulnerable to errors because there are more possibilities when context does not provide strong constraints.

This explanation seems comparable to a suggestion by Fougeron & Keating (1997) concerning phonetic strengthening. They noted that, from the perspective of the listener, initial segments are probably on average less determined by prior context, and that therefore the acoustic signal must bear a greater load in the recovery of the message in those positions. Anything that improves the perception of initial segments would compensate for their lack of predictability. Initial strengthening could thus help the listener by enhancing segmental properties in positions of uncertainty. Thus the resolution of the paradox would be that initial segments are contextually weak, that is, relatively unconstrained by their prior context. Because of this contextual weakness they are more vulnerable to competition from other lexical entries in the process of speech production, and more vulnerable to mis-hearing in speech perception; yet for the same reason they stand to benefit more from strengthening. On this view, we would expect to find a relation between predictability (on some independent measure) and degree of strengthening, with greater predictability associated with less strengthening.

Finally, as shown earlier, phonetic strengthening occurs in higher prosodic domains. The larger the phrasal domain, the more likely is the initial position to be unconstrained by context (for example, the first segment of a sentence is probably far less predictable than the first segment of most words within a sentence[10]). If contextual uncertainty is indeed the connection between the psycholinguistic phenomena and phonetic strengthening, then we would also predict that speech errors and mis-hearings should be more frequent in initial positions of higher phrasal domains. As Keating & Shattuck-Hufnagel (2002) review, errors across phonological words are far more common than errors within words, so this prediction is plausible.

CONCLUSION

This review of findings about domain-initial articulatory strengthening counters the view, espoused by Levelt et al. (1999), that segmental and prosodic planning for speech production can proceed separately. Since phonetic encoding of segments is highly sensitive to prosodic structure, prosody needs to be computed first, not last as in Levelt's model. Returning to the example phrase in Figure XXX.1 ("that new propaganda"), consider the effects of prosodic position on the feature values indicated. The word "that" is in the strongest position, initial in the highest domain, so the initial continuant consonant is likely to be strengthened to a stop articulation[11].

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[10] We do not know of any evidence about segment predictability by prosodic position. If large domains were more likely to begin with *th-* function words, then our assumption would be wrong.

[11] Although not generally noted in the literature (though see Pierrehumbert & Talkin 1992 for one mention), stopping of non-sibilant fricatives, both labiodental and dental, seems to be common in at least American English. In the case of the dentals, the interdental articulation means that these stops do not sound like alveolars. By hypothesis, the stopped variants are in prosodically strong positions.

The word “propaganda” is in a strong position because of its prominence, which will affect the stressed syllable “gan”. The /p/ at the beginning of the word should be somewhat stronger than the /p/ in the second syllable, and thus should have a closer oral consonant constriction, while its glottal abduction should be larger. Phonetic plans for those, and all other, aspects of the utterance must refer to prosody.

How might such prosody-dependent phonetic encoding of features be modeled? One possibility would be Byrd et al. (2000)’s $\underline{\pi}$-gestures, gestures associated with prosodic boundaries, by which the prosody could modulate precompiled syllable scores. Another possibility is a window-style model, in which prosody could modulate articulatory targets. Window models (Keating 1990, 1996) posit ranges, rather than fixed points, as the targets of articulatory movements. Guenther (1995) first suggested that such target ranges could be sensitive to prosody, expanding or contracting over the course of an utterance; Cho (2002, 2004) in contrast proposes that prosody specifies a subrange within the window. Either way, at an edge or a prominence, target ranges would shift towards extreme values. While such proposals remain to be worked out, they have the potential advantage of extending readily to other kinds of variability, on other timescales, that are not accounted for by fixed windows, or by Byrd et al.’s gestures. In addition to shifts that are local to a prosodic position, target ranges could shift at the word level, as a function of lexical difficulty due to competition, and more globally, as a function of discourse factors.

In sum, when a speaker plans for the phonetic aspects of speech production, prosodic structure organizes the treatment of possibly every feature in every segment, and the interactions of segments. One aspect of this dependence is the

relation between the strength of a prosodic position, and the phonetic strength of a segment in that position. A theory of phonetic encoding that incorporates this basic fact is a major challenge, but an important one.

ACKNOWLEDGEMENTS

This research was supported by an NSF Linguistics grant to P. Keating (#95-11118), an NSF dissertation improvement grant to P. Keating and T. Cho (#BCS-0001716), and an NSF KDI grant to L. Bernstein *et al.* (#99-96088). Collaborations with all my co-authors on the various papers cited here, the contributions of the former students cited, and helpful comments on the manuscript by the editors and reviewers, are gratefully acknowledged.

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Figure XXX.1. Sample partial prosodic tree for a phrase, “that new propaganda”. Phrasal accent and lexical stress are indicated ad-hoc on the appropriate branches in the tree. Only three segments and selected feature values are shown.

Figure XXX.2. Sample pseudo-palate used with Kay Elemetrics Palatometer, showing arrangement of 96 contact electrodes. The front of the mouth is at the top of the picture.

Figure XXX.3. Sample frame showing peak linguopalatal contact for a Korean word-initial /n/. The orientation is the same as in Figure XXX.2. Each circle is an electrode on the palate; filled circles have been contacted by the tongue (here, 42% contacted).

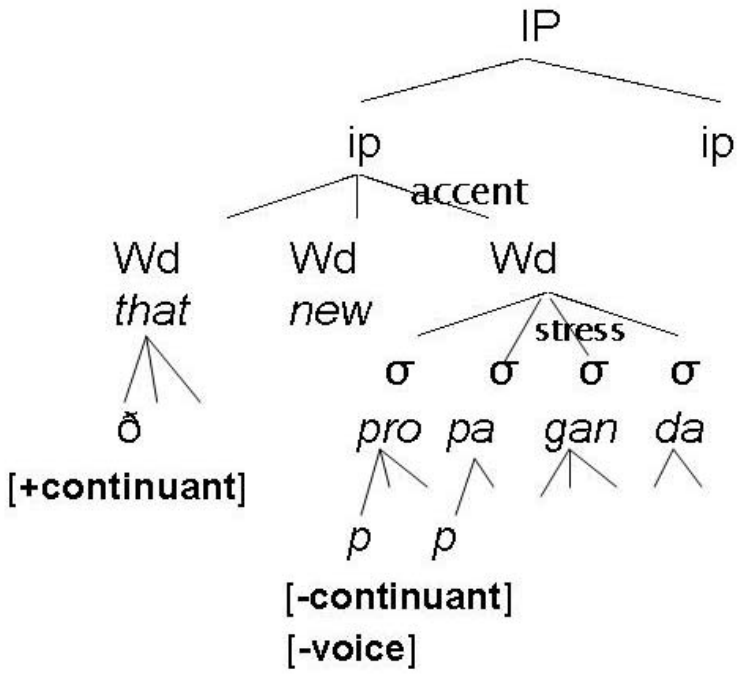
Figure XXX.4. Sample trace of percent contact over time for a reiterant utterance. The reiterant utterance is modeled on the arithmetic expression shown at the top of the figure; the 15 reiterant syllables are indicated above the trace. High values of contact occur for /n/ while low values of contact occur for /o/.

Figure XXX.5. Mean results for three speakers of English: peak contact on the left, seal duration on the right, for /n/s initial in five prosodic domains (Utterance-initial Ui, Intonational Phrase-initial IPi, Phonological Phrase-initial PPi, Word-initial Wi, Syllable-initial Si). From Keating et al. (2003).

Figure XXX.6. Mean results for three speakers of Korean: peak contact on the left, seal duration on the right, for /n/s initial in five prosodic domains (Utterance-initial Ui,

Intonational Phrase-initial IPi, Accentual Phrase-initial APi, Word-initial Wi, Syllable-initial Si). The dashed horizontal line divides one set of comparisons, of levels above the Word, from another comparison, Word vs. Syllable, as explained in the text. From Keating et al. (2003).

Figure XXX.7. Histograms of all measurements of (a) domain-final vowel duration and (b) domain-initial consonant contact, pooled across consonants and speakers. From Cho & Keating (2001).


IP
ip
ip
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that
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stress
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σ
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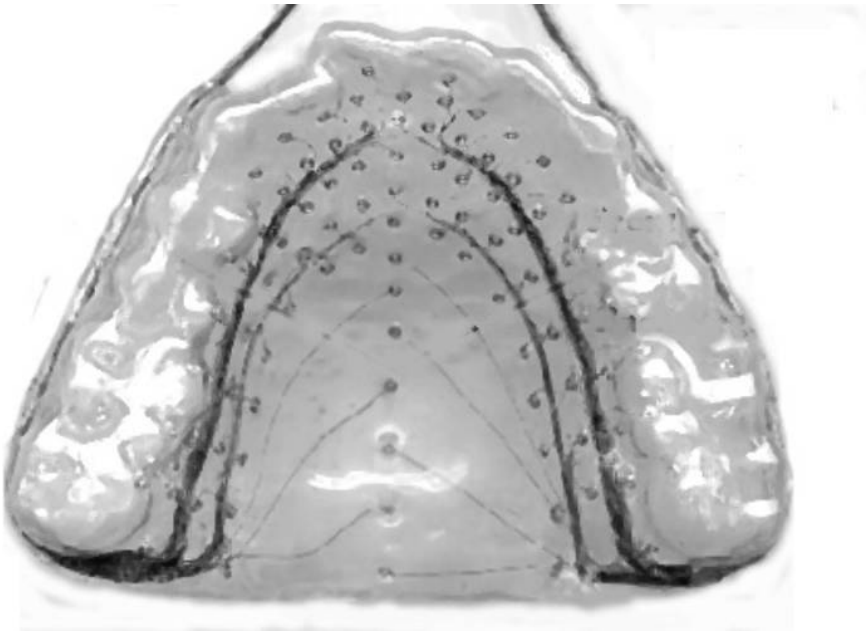
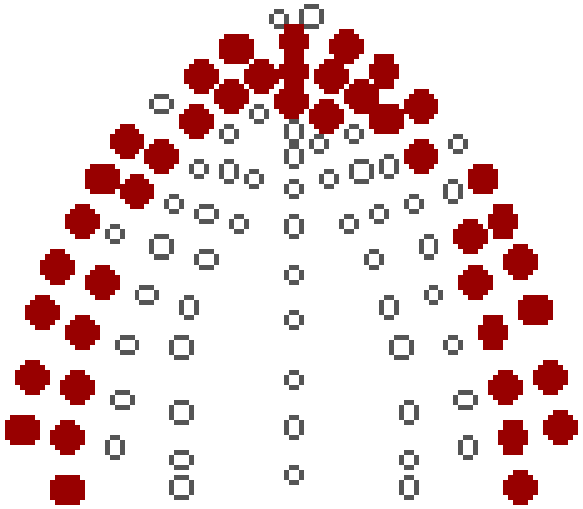
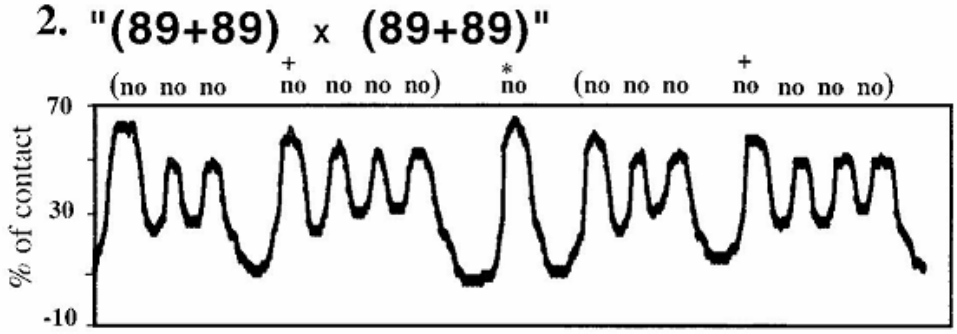
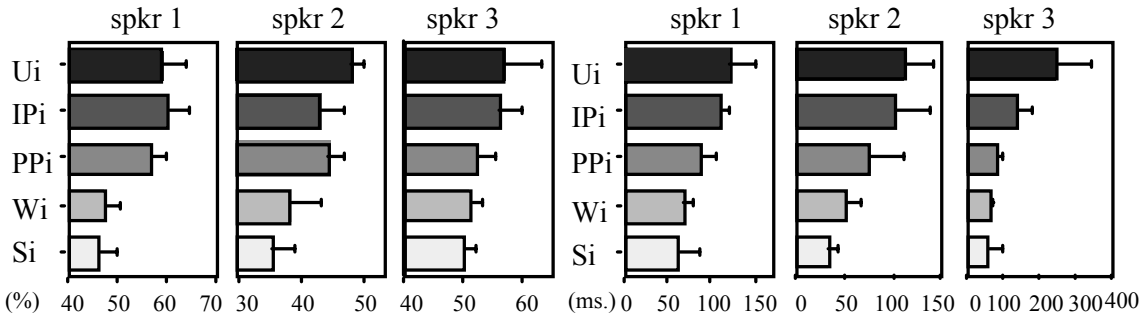
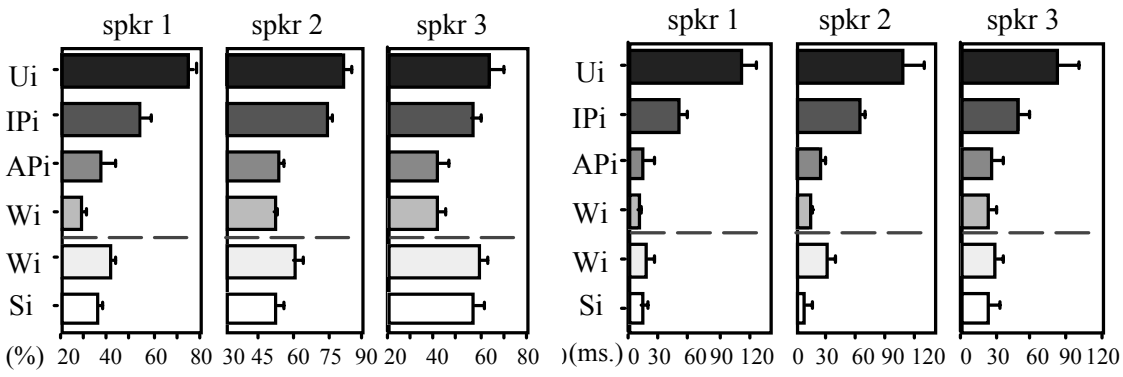
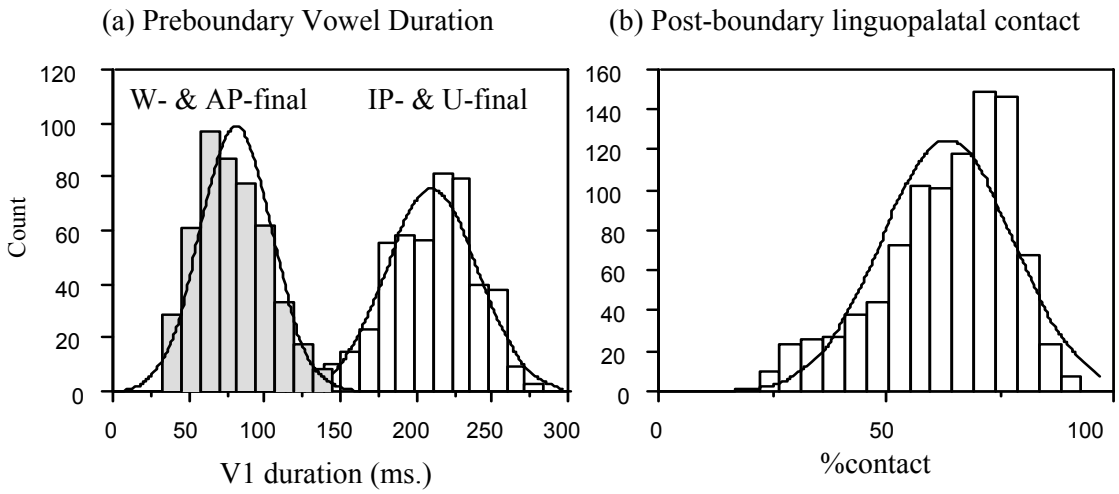





2. "(89+89) x (89+89)"
(no no no + no no no no) * no (no no no + no no no no)
70
30
-10
% of contact


spkr 1
spkr 2
spkr 3
spkr 1
spkr 2
spkr 3
Ui
IPi
PPi
Wi
Si
(%) 40 50 60 70 30 40 50 40 50 60
(ms.) 0 50 100 150 0 50 100 150 0 100 200 300 400


spkr 1
spkr 2
spkr 3
Ui
IPi
APi
Wi
Wi
Si
(%) 20 40 60 80 30 45 60 75 90 20 40 60 80
spkr 1
spkr 2
spkr 3
Ui
IPi
APi
Wi
Wi
Si
(ms.) 0 30 60 90 120 0 30 60 90 120 0 30 60 90 120


(a) Preboundary Vowel Duration
(b) Post-boundary linguopalatal contact
W- & AP-final
IP- & U-final
Count
V1 duration (ms.)
%contact
0
20
40
60
80
100
120
140
160
0
50
100
150
200
250
300