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Articulatory and acoustic studies on domain-initial strengthening in Korean

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This study examines the effect of prosodic position on segmental properties of Korean consonants /n, t, t^h, t*/ along the articulatory parameters peak linguopalatal contact and stop seal duration, and several acoustic parameters. These parameters were compared in initial position in different domains of the Korean prosodic hierarchy. The first result is that consonants initial in higher prosodic domains are articulatorily stronger than those in lower domains, in the sense of having more linguopalatal contact. Second, there is a strong correlation between linguopalatal contact and duration (both articulatory and acoustic), suggesting that "strengthening" and "lengthening" is a single effect in Korean. We interpret this relation as one of undershoot: in weaker positions, consonants are shorter and undershoot contact targets. The different consonant manners of Korean can be characterized as varying in both duration and contact in this way. Third, there is another, less consistent, kind of lengthening and strengthening specific to Korean, namely that tense and aspirated consonant oral articulations can be longer and stronger word-medially than word-initially. Fourth, the acoustic properties VOT, total voiceless interval, %voicing during closure, nasal energy minimum, and to a lesser extent stop burst energy and voicing into closure, were found to vary with prosodic position and, in some cases, to correlate with linguopalatal contact. They could thus potentially provide cues to listeners about prosodic structure.

1. Introduction

Recent work has established that many segmental properties may be affected by suprasegmental, or prosodic, structure. (By *prosody* we mean all aspects of the higher-level (suprasegmental) organization of speech; see Shattuck-Hufnagel & Turk, 1996.) One line of research has concerned the articulation of segments, especially consonants, at the beginnings of prosodic domains. We and our colleagues have found in previous work that consonants at beginnings of phrases are more constricted than consonants in the middles of phrases, and furthermore, consonants at the beginnings of larger phrases are more constricted than consonants at the beginnings of smaller phrases, or of words. Such

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a pattern has been interpreted as a kind of strengthening of a consonant's oral articulation according to the strength of its prosodic position — the stronger the position, the stronger the articulation — and referred to as *domain-initial strengthening.* Domain-initial strengthening has been found now for four languages, as described by Keating, Cho, Fougeron & Hsu (1999, to appear): English (see also Fougeron & Keating, 1997), French (see also Fougeron & Keating, 1996; Fougeron, 1998, 2001), Taiwanese (see also Hsu & Jun, 1998; Hayashi, Hsu, & Keating, 1999), and Korean.

Korean is an especially interesting case for a number of reasons. First, it is already well known as a language in which both phonological and/or phonetic processes are sensitive to prosodic domains. Jun (1993) has shown not only that several phonological rules of Korean apply only in particular prosodic domains, but also that the Voice Onset Time (VOT) of Korean aspirated /$\mathrm{p^h}$/depends on the position of /$\mathrm{p^h}$/ in prosodic structure. In her study, VOT was systematically longer at the beginning of a word than medially in a word, and longer still at the beginning of a small phrase, the Korean Accentual Phrase (AP). Thus, while Korean aspirated stops are always aspirated, the degree of aspiration varies prosodically. Jun suggested that this phonetic variation reflects a strength hierarchy of prosodic positions. Furthermore, the Korean rule of "Lenis Stop Intervocalic Voicing", by which lenis stops /p t k/ are voiced to [b d g], is a well-known prosodically-conditioned segmental lenition; its effects are so strong that they are audible without any instrumental analysis. Jun (1993, 1998*a*) found that this voicing is generally constrained by the consonant's position in a phrasal domain, in that consonants voice when they are inside an accentual phrase. Most recently, Jun and colleagues (Jun, Beckman & Lee, 1998) confirmed that both aspirated and lenis Korean stops exhibit prosodically-conditioned differences in the degree of glottal opening. Thus, it is already clear that the laryngeal properties of Korean stops are closely tied to prosodic structure, and therefore it might be expected that such patterning would be more general in the language.

Second, and probably related, Korean is prosodically interesting and possibly unusual: according to Jun, it has no lexical stress, no prominence lent by phrasal tones, and no final lengthening at the end of Accentual Phrases (Jun, 1995*a*). There is also no discernibly greater amplitude at the end of the Korean AP (Jun, 1995*b*, 1998*b*); thus Korean is different from French, in which an AP-final accented syllable is realized with greater amplitude (Martin, 1982). In sum, it can be hypothesized that Korean reinforces the beginning of the phrase, but French the end. If this is so, we might expect not only initial lengthening rather than final lengthening, but also greater domain-initial articulatory strengthening in Korean. Indeed, our earlier work on initial strengthening (Keating *et al.*, 1999, to appear) has already shown that Korean had the strongest and most consistent initial strengthening compared to English, French, and Taiwanese.

Third, this earlier result makes Korean an excellent case to examine for the acoustic consequences of articulatory strengthening. Therefore, in this paper we extend our earlier work to examine various acoustic dimensions for Korean stops of different manners. If there are clear acoustic correlates of initial strengthening, then it is possible that listeners use those correlates as cues in prosodic parsing. This study includes no perceptual testing, but it can establish whether such testing would be worthwhile, at least for Korean.

Fourth, in our earlier work we also found that among the four languages, Korean showed the strongest relation between articulatory strength and duration. Therefore, in this paper we extend our earlier work to explore this spatio-temporal relationship. Following Fougeron & Keating (1997), we hypothesize that articulatory strengthening may be due to longer durations in stronger positions. Longer durations could result in less articulatory undershoot, so that the articulatory targets of consonants would be more closely approximated, while shorter durations would result in undershoot of those targets, in the sense of Lindblom (1963) and Moon & Lindblom (1994). In other words, initial consonants with longer durations would have more time to achieve more extreme articulations. For example, Soler & Romero (1999) account for Spanish stop lenition by relating duration and constriction degree. In this paper, we further explore this possibility by measuring stop seal duration and testing its correlation with constriction degree as measured by linguopalatal contact.

Fifth, Korean appears to present a possible counter-example to the general pattern of word-initial strengthening. This counter-example comes from the behavior of the Korean tense (fortis) stops. In Korean, it has been reported that word-medial tense stops lengthen (e.g., Silva, 1992; Han, 1996). We have already mentioned that word-medial position appears to be a weak position for Korean lenis and aspirated stops (which show more voicing and less aspiration, respectively), but it seems to be a strong position for tense stops. Therefore, in this paper we look especially at this position, and we include in our study all three manners of oral stops in Korean.

The goal of this study, then, is to provide an extended case-study of domain-initial strengthening by examining the effect of prosodic position on segmental properties of Korean consonants /n, t, t^h, t*/ along several articulatory and acoustic parameters, including timing. In particular, we look at more stop manners of articulation than in our earlier work, with attention to their inherent properties as well as their prosodically-conditioned behavior, and we look at more parameters than in our earlier work, with special attention to temporal parameters. This greater scope of study will allow us to consider the nature of initial strengthening in Korean. Two issues here are whether strengthening has a basis in timing; and whether it has acoustic correlates that could potentially be informative to a listener.

Studying prosodic effects on articulation requires an independent scale of prosodic position and strength. A well-known scale of this kind is the *prosodic hierarchy*. The hypothesis of a prosodic hierarchy is that speech utterances are hierarchically organized, with higher (or larger) units being decomposed into lower (or smaller) constituents. These prosodic constituents, or domains, can be in part derived from syntactic constituents (Selkirk, 1984, 1986; Nespor & Vogel, 1986) and can be identified on the basis of segmental phonological rule application (e.g., Nespor & Vogel, 1986; Jun, 1993) and/or intonation (e.g., Beckman & Pierrehumbert, 1986; Jun, 1993). Crucial for our purposes is the idea that adjacent higher constituents show greater disjuncture than adjacent lower constituents, as coded, for example, by the Break Indices of ToBI transcription systems (e.g., Silverman, Beckman, Pitrelli, Ostendorf, Wightman, Price, Pierrehumbert & Hirschberg, 1992).

In this work, we use the model of Korean prosodic structure of Jun (1993) and Beckman & Jun (1996), which departs from earlier work concerned with syntactic bases for prosody (e.g., Cho, 1990; Silva, 1992; Kang, 1992) in that phrase levels are defined by intonational correlates (cf. de Jong, 1989; Lee, 1989). For Korean, Jun (1993, 1998*a*) has shown that the prosodic hierarchy must include at least two phrasal prosodic domains (accentual phrase, intonational phrase) as well as the prosodic word plus any intra-word domains. We also add a possible higher prosodic constituent, the *utterance*. This model is shown in Fig. 1, which gives a sample structure showing the hierarchical organization of the prosodic domains.

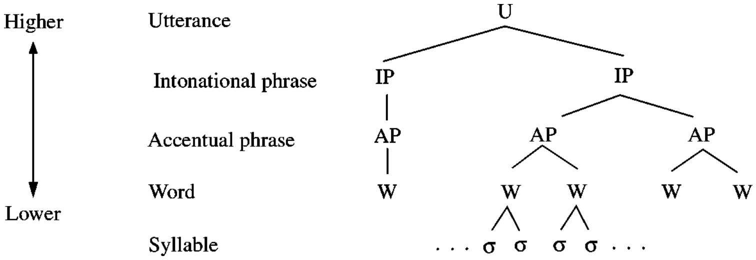


Figure 1. Prosodic structure of Korean (adapted from Jun (1993) and Beckman & Jun (1996) with utterance level added in this study).

As seen in the figure, *Syllables* (S) are grouped into *Words* (W); Words are grouped into *Accentual Phrases* (AP); *Accentual Phrases* are grouped into *intonational phrases* (IP). In Seoul Korean, an accentual phrase is usually marked by a (LH)LH tonal pattern; an intonational phrase, by a final tonal pattern along with a substantial final lengthening. The highest level *Utterance* (U, usually punctuated by a period), into which intonational phrases are grouped, is said by Nespor & Vogel (1986) to be distinguished from IP by a pause, and by a more marked final intonation. We tested for this domain U in Korean by observing if a substantial pause, triggered by an orthographic period, causes any articulatory and/or acoustic differences compared to IP. Following the Strict Layer Hypothesis (Selkirk, 1986), it is assumed that the beginning and end of each higher domain is also the beginning and end of lower domains.

Nonetheless, we do not assume that the effects of prosody on articulation are strictly categorical, even though prosodic constituents and break indices are treated as categories. Indeed, in our previous work we have never found uniformity across speakers of a language as to how many or which prosodic constituents show initial strengthening. In this study, we consider whether the data on final vowel lengthening and initial consonant strengthening appear to fall into strictly separate categories, or are more continuously distributed.

2. Method

2.1. *Electropalatography* (*EPG*)

In our articulatory experiment, we examine variation in the oral articulation of consonants. The articulatory measure for consonants was linguopalatal contact, i.e., contact between the tongue (especially tongue blade and front) and the hard palate. The amount of linguopalatal contact indicates the degree of overall oral constriction: the more linguopalatal contact, the greater oral constriction with a greater articulatory magnitude. Linguopalatal contact was measured by electropalatography (EPG) using the Kay Elemetrics Palatometer model 6300. The Kay Palatometer uses custom-fabricated pseudo-palates made of a thin acrylic, held in place by wrapping around the upper teeth. A pseudo-palate has 96 electrodes, as shown in Fig. 2, covering the entire hard palate, the entire inside surfaces of the upper molars, and part of the inside surfaces of the upper front teeth. In order to capture more denti-alveolar contact, a custom configuration of electrodes was designed in which two electrodes were located lower on the upper front teeth; these are shaded in the figure. When an electrode is contacted by the tongue,

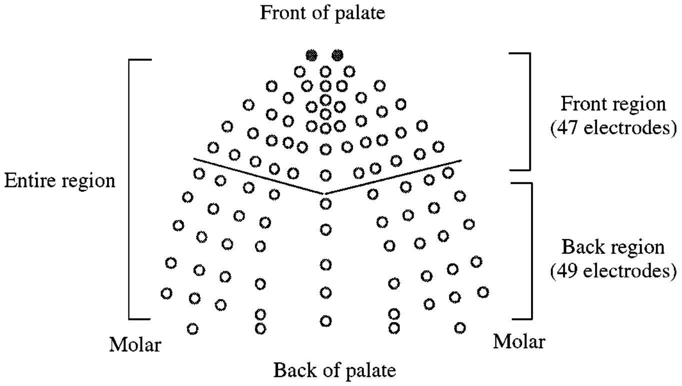


Figure 2. Placement of 96 electrodes with three analysis regions. The two shaded electrodes are located lower on the upper front teeth in order to capture more denti-alveolar contact.

a circuit is completed and the contact is recorded by the Palatometer. Each sweep of the 96 electrodes takes 1.7 ms, and the sampling interval is 10 ms.

2.2. *Test sentences and procedure*

The test consonants are the four anterior coronal stops /n, t, t^h, t*/ (where /t*/ represents the fortis, or tense, stop, for which there is no official IPA transcription). Each test consonant was placed in a fixed segmental context within a set of sentences. Example sentences for /n/ are shown in Table I. The sets of sentences were constructed to vary in their likely phrasing, so that the prosodic context of the test consonants would vary. When subjects produced these sentences with the expected phrasings, then the test consonant was initial in a prosodic domain that varied systematically from high (utterance) to low (syllable). Table I characterizes the prosodic position of the test consonants as the highest prosodic domain in which the consonant is initial. Thus, "Ui" means that the highest domain in which this consonant is initial, is the utterance (U). The number of syllables preceding each test consonant was also controlled, in order to factor out the possibility of articulatory declination (Krakow, Bell-Berti & Wang, 1994) which may induce differences in articulatory magnitude (though this was not seen in the study by Fougeron & Keating (1997) of English).

As it was difficult or impossible to construct meaningful sentences with the same segmental context and syllable count for all prosodic conditions, the sentences for each test consonant were constructed in two subsets. Those shown in (a) in Table I provide matched comparisons at and above word-initial position; those in (b) provide a comparison at and below word-initial position.

Two male and one female Seoul Korean speakers (ages 33–37) participated in the experiment. Speakers NHL and JYY (students at UCLA) had been in America for 2 and 1 years, respectively, at the time of recording and speaker THC (one of the authors) for 3 years. Each test sentence was repeated 20 times. The audio and EPG signals, with 12.8 kHz and 100 Hz sampling rates, respectively, were recorded directly into the computer through Kay Elemetric's Computerized Speech Lab (CSL) and Palatometer. In total, 960 sentences (4 levels × 4 consonants × 3 speakers × 20 repetitions) were analyzed for the

TABLE I. Test sentences for the target consonant /n/ (see Appendix A for /t, tʰ, t*/)

(a) Higher levels above Word for /n/ in /a#_a/ (# = a prosodic boundary)	
U-initial (Ui)	igosɨn patakka. [U namdʒuga jəgisə sanda.] This place seashore NAMJOO here lives 'This place is the seashore. NAMJOO lives here'.
IP-initial (IPi)	igosɨn patakka, [IP namdʒue kohjaŋida.] This place seashore NAMJOO's hometown 'This place is the seashore, which is NAMJOO's hometown'.
AP-initial (APi)	igosɨn patakka [AP namtʃ*oge] itt*a This place seashore south_Loc be 'This place is located to the south of the seashore'.
Word-initial (Wi)	igosɨn [AP patakka (W namdʒaga)] sanɨn goʃida This place seashore man-Nom live-REL place-Dec 'This place is where the seashore man lives'.
(b) Word and syllable levels for /n/ in /o#_ɛ/ (# = a prosodic boundary)	
Word-initial (Wi)	kɨjədʒanɨn [AP maɾɨmmo (W nɛgiɾɨl)] tʃɛanhɛtt*a the woman-Top. parallelogram betting-acc. suggested 'The woman suggested betting with the parallelogram (on something)'.
Syllable-initial (IPi)	kɨjədʒanɨn [AP jəɾɨm (W mo(S nɛgiɾɨl)] tʃɛanhɛtt*a the woman-Top. summer harvest-acc. suggested 'The woman suggested the fall harvest'.

higher level comparisons (U, IP, AP, W) and 480 sentences (2 levels × 4 consonants × 3 speakers × 20 repetitions) were analyzed for the lower level comparisons (word, syllable).

Subjects were told in part how to phrase each sentence for some prosodic boundaries. They were asked to pause after a period (which marked an Utterance boundary) but not to pause after a comma (which was used to induce an IP boundary). No instructions other than this were given to the speakers. For the AP and Word boundaries, subjects in general made the intended intonational contours with an appropriate break without being told to do so. Each uttered sentence was checked during the recording session by the first author who is a trained K-ToBI (Beckman & Jun, 1996) transcriber. In the rare instances when subjects produced something other than the contours we intended, they were asked to repeat the token a few times, until there were enough repetitions to provide enough "correct" renditions. This indirect procedure was necessary because, although subjects were not given explicit instructions on how to produce the utterances, it was crucial to the experiment that each token have the particular desired contour. The criteria used for prosodic coding (i.e., for coding the type of prosodic boundaries after which the target consonants occur) are summarized in Table II.

2.3. *Measurement*

For analysis of linguopalatal contact, three different regions on the palate were defined as shown in Fig. 2. The entire region covers all 96 electrodes; the front region, which is a region of primary coronal consonant contact, includes the front 47 electrodes from the front teeth to the alveolo-palatal area; and the back region, which is a region of vowel contact, includes the back 49 electrodes covering mainly the mid-palatal area. Analyses

TABLE II. Criteria used for prosodic coding, based on K-ToBI (Beckman & Jun, 1996)

U	Period mark used for triggering a pause as well as IP boundary Boundary tone (L%) Preceded by a pause (greater than break index number 3 in K-ToBI)
IP	Comma used for triggering IP boundary Boundary tone (usually H% but sometimes HL% or L%) Considerable final lengthening with break index number 3
AP	Adverbial phrase used for triggering AP boundary (LH)LH or (HH)LH phrasal tones Break index number 2
W	Second word of two successive words which are grouped into AP No tonal specification, but in general, W-initial syllables are associated with AP-internal phrasal L Virtually no perceived break (break index number 1)
σ	Second syllable of the second word of two successive words which are grouped into AP No tonal specification

are primarily based on contact patterns in the entire region, unless otherwise specified. Linguopalatal contacts in the front and back regions will be compared to those in the entire region to see which part of the tongue and palate contributes more to the overall variations.

2.3.1. *Linguopalatal contact*

EPG data were analyzed by computing the percent of the electrodes in a region contacted in each data frame (see Byrd, Flemming, Mueller & Tan (1995) for detailed method). For the entire region of 96 electrodes, one contacted electrode is thus approximately equal to one percentage point. For each consonant, peak linguopalatal contact was measured in the single frame that shows the most extreme contact for that segment. Fig. 3 shows data for sample tokens of /n/ by Speaker NHL with variations in the amount of peak linguopalatal contact as a function of prosodic position. As seen in the figure, the peak contact measure captures variations in the amount of linguopalatal contact of domain-initial consonants at different prosodic levels. (A similar measure was made in Fougeron & Keating, 1997.) It does not, however, capture other aspects of the variation, such as the shift in place of articulation seen here: the nominal place moves back in lower prosodic positions as the front, dental, contact is lost.

2.3.2. *Seal duration*

The duration between the first and the last frames in which the oral cavity was completely sealed, called the seal duration, was measured. This measure was not made in the English study by Fougeron & Keating (1997) but was included in the French study by Fougeron (1998, 2001).

2.3.3. *Skewness of Articulatory Movement*

Overall contact trajectories (Barry, 1991) as a function of time within each token were treated as distributions, and the skewness of each trajectory's shape was measured.

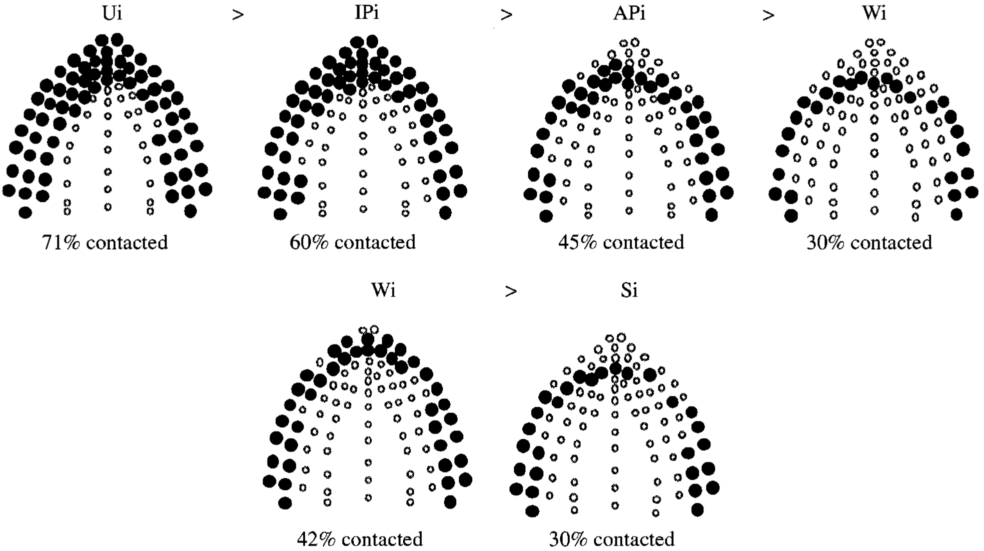


Figure 3. Sample tokens of linguopalatal contacts for /n/ by Speaker NHL, from two experiments. Wi *vs.* Si comparisons were made separately from the other comparisons due to the difficulties of controlling for segmental context. For this lower level comparison, contact in Wi is greater and more fronted than that in Wi for higher level comparisons, because the following vowel is front.

A movement trajectory is said to be skewed if the highest point of the trajectory does not correspond to the center of the distribution, thus causing one of the "tails" in the distribution to be longer than the other. The trajectory's shape is 'skewed to the right' or 'positively skewed' with a longer right 'tail' and 'skewed to the left' or 'negatively skewed' with a longer left 'tail'. Byrd *et al.* (1995) suggest that the degree of asymmetry between the onset and offset of articulatory movement can be measured by the skewness of the linguopalatal contact profile. A positive skew indicates that the consonant closing gesture occurs more quickly than its opening or releasing gesture, for the portion of the gesture during which linguopalatal contact occurs. On the other hand, a negative skew indicates that the consonant closing gesture occurs more slowly than its opening or releasing gesture. Fougeron & Keating (1997, p. 3737) discuss the possibility that higher movement velocity would result in a "greater impact of the tongue against the palate at closure" which may in turn result in a greater linguopalatal contact. If this is true, we would expect relatively greater positive skewness for a consonant with greater linguopalatal contact. So, the measurement of skewness examines whether any variation in the amount of linguopalatal contact can be partly attributable to different speeds of closing, relative to releasing.

To get the contact profile from which the skewness was calculated, an approximation of that part of the articulatory movement which involves linguopalatal contact was identified for each consonant: from the first frame where the tongue, in beginning to contact the hard palate area progressively forward, reaches 20% contact, to the last frame where the tongue is moving away from the consonant contact, but contact remains above 20%. The 20% threshold was used because for some cases, especially lower domains, it was difficult to locate an exact onset or offset of the part of the movement involving contact. Thus, the approximated articulatory movement whose skewness was

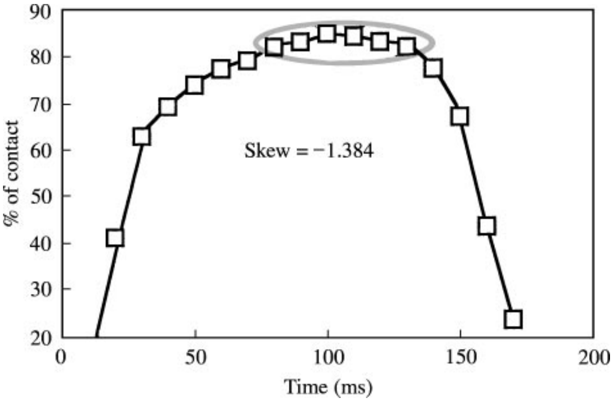


Figure 4. Sample contact profile with a negative skewness for /t*/ in U-initial position. Note that the circled maximum contact area is formed to the right of the midpoint along the time dimension.

calculated, is within the interval between the onset of the consonant closing gesture and the offset of the consonant opening gesture (neither of which can be seen in their entirety in EPG data). The trimmed data were submitted to descriptive statistics in StatView 5.0 (SAS, 1998) which generated skewness values. Fig. 4 shows a sample contact profile with a negative skewness (skew = − 1.384). This particular sample profile suggests that the closing movement towards the maximum linguopalatal contact is slower than the releasing movement. The skewness was measured for three stops /t, t^h, t*/ for the higher levels, Ui to Wi.

2.3.4. *Acoustic parameters*

Several standard acoustic measures were made from the audio signal:

- *V1 and V2 duration.* The durations of the vowel before a boundary (V1) and the vowel after a boundary (V2) were measured. Note that V1 is always word-final (in an open syllable) and therefore likely to show any preboundary lengthening. This measure was included in Fougeron & Keating (1997).
- *Closure duration.* Acoustic closure duration for all test consonants was taken from spectrograms. For oral stops this measure included both voiced and voiceless portions of closure, from the offset of $F2$ in V1 to the beginning of the stop burst. For /n/ this measure was nasal duration, taken from the onset to the offset of nasal energy displayed in the spectrogram.
- *Voicing during stop closure.* Voicing residue interval during stop closure, indicated by the voicing bar (glottal pulsing) at the bottom of the spectrogram, was taken from the offset of $F2$ in V1 to the onset of the completely voiceless closure. Then, the percent of this interval relative to the entire closure duration was calculated, for /t, t^h, t*/, for the higher levels IPi to Wi (not for Ui because these were postpausal). The presence of voicing at the beginning of the closure of a voiceless stop indicates that the vocal cords have not yet completely abducted; to some extent it also reflects vocal tract tension, since closure voicing is more likely with less vocal tract tension.

- *Voice onset time.* VOTs for /t, t^h, t*/ were taken from the point of the stop release to the voice onset of the following vowel, as seen in spectrograms in $F2$ and above. Thus, for the lenis stops, any breathy voicing with only low-frequency harmonics was included in the VOT.
- *Total voiceless interval.* The interval from the onset of the voiceless portion of closure to the voice onset (i.e., voiceless closure plus VOT) was calculated for just the aspirated stop /t^h/. This measure reflects the total time of glottal opening during the stop.
- *RMS burst energy.* The acoustic energy at the burst was measured from an FFT spectrum giving the RMS value over all frequencies. A 10 ms (124 point) window was centered over the release of the stops /t, t^h/; for the tense stop /t*/ which has a very short VOT, a shorter window (5 ms, 64 point) was used in order to prevent the window from including the following vocalic energy. The burst energy for word-initial lenis stop /t/ could not be measured in a comparable fashion, due to the presence of voicing throughout the consonant; therefore only tokens from higher levels were measured.
- *Nasal energy minimum.* The energy during nasal consonants was measured as the lowest point (valley) of the RMS acoustic energy profile. The minimum value was measured because a nasal consonant has less energy than surrounding vowels. (Peak energy is always found at the edges of a nasal, next to the surrounding vowels; thus, it does not constitute an independent measure for the consonant and there is no reason to measure it.) This measure reflects (in part) the size of the velopharyngeal opening during the consonants. Following Fougeron (1998) and the references cited there, we assume that the velum is likely to be less open in stronger prosodic positions, resulting in less radiated acoustic energy. However, a problem arises with this measure for utterance-initial nasals, which are adjacent to a pause. After a silent pause, the energy rises from zero at the beginning of the nasal, to its maximum value associated with the following vowel. In such a case, the minimum is always the smallest value that can be measured above zero. Thus, there is no independent energy measure to be made for nasals in this position, and therefore no energy measure is reported for utterance-initial nasals.

2.4. *Statistical analysis*

The coded data were submitted to statistical analyses using StatView 5.0 (SAS, 1998). ANOVA was used with data from the corpora comparing word-initial and higher prosodic positions. Analysis of studies with few subjects, as is the case here, is problematic: the individual subject should be treated as the experimental unit, but an analysis with only three such units has too little power. Common practice is instead to analyze the data for each subject separately, using trial (repetition) as the experimental unit, but such an analysis overestimates any significance and has recently been warned against by Max & Onghena (1999). Caught between the rock of too little power and the hard place of overestimating significance levels (Type I, or alpha, error), we rely on a compromise approach: factorial analyses in which speaker, consonant, and prosodic position are the factors, but the datapoints are averages of the 20 repetitions. Averaging the repetitions keeps the degrees of freedom of the denominator of the F-ratio somewhat low, and thus reduces somewhat the overestimation of the significance levels common to all studies with few subjects. We further compensate for this overestimation by setting the alpha level for significance at $p \leq 0.01$.

Post-hoc comparisons within factors are especially important in this study. To avoid inflating the alpha error in these *post-hoc* tests, they use the Bonferroni/Dunn model (Hays, 1994, p. 451), but at the lowered alpha level of 3% (equivalent to $p < 0.005$ when there are four groups to compare within a factor, but $p < 0.01$ when there are three groups to compare within a factor). When speaker differences are of interest here, they will be examined qualitatively, based on graphs of the data.

For lower level comparisons between word- and syllable-initial positions, which will be made separately from higher level comparisons above the word level, simple *t*-tests with an alpha level of 5% are used.

We will also run regressions to examine correlations among various articulatory and acoustic measures — e.g., among articulatory measures, and between articulatory and acoustic measures if an acoustic measure shows a strong domain-initial strengthening effect. Since many measures show effects of prosodic position, we need to know how many of them are independent; this is important for understanding the nature of strengthening. That is, a strong relationship between two effects would suggest that they arise from a single mechanism.

3. Results

Section 3.1 presents results for articulatory parameters; Section 3.2 for acoustic parameters. In each case, results are first presented for the corpus comparing prosodic positions above the word, and second for the smaller corpus comparing prosodic positions within the word. Section 3.3 presents results on relations between articulatory and acoustic parameters.

3.1. *Variation in articulatory parameters*

3.1.1. *Peak linguopalatal contact*

We first examine the extent to which peak linguopalatal contact over the entire pseudopalate varies with the hierarchically-nested prosodic positions, specifically to test the hypothesis that a higher-domain-initial consonant is produced with a greater linguopalatal contact compared to a lower-domain-initial one. First, for comparisons above the word, two-way ANOVA (Prosodic Position by Consonant) showed that peak linguopalatal contact varies significantly depending on the prosodic position ($F(3, 32) = 14.874$, $p < 0.0001$). Bonferroni/Dunn pairwise comparison confirmed that all domains are differentiated from one another by peak contact (at a significance level of 0.005, equivalent to 3% alpha level) in decreasing order Ui, IPi, APi, and Wi, as shown in Fig. 5(a).

There is also a main effect of consonant on peak linguopalatal contact ($F(3, 32) = 8.097$, $p = 0.0004$). Bonferroni/Dunn pairwise comparison showed a pattern of $\mathrm{t}^* > \mathrm{t}^{\mathrm{h}} > \mathrm{t} > \mathrm{n}$, all being significantly distinguished from one another at the level of $p < 0.005$. Figure 6(a)–(d) show peak contact for each consonant with (a) for the pooled data across speakers, and (b)–(d) for each speaker. The first point to be made from Fig. 6 is that variation in linguopalatal contact as a function of prosodic position is similar

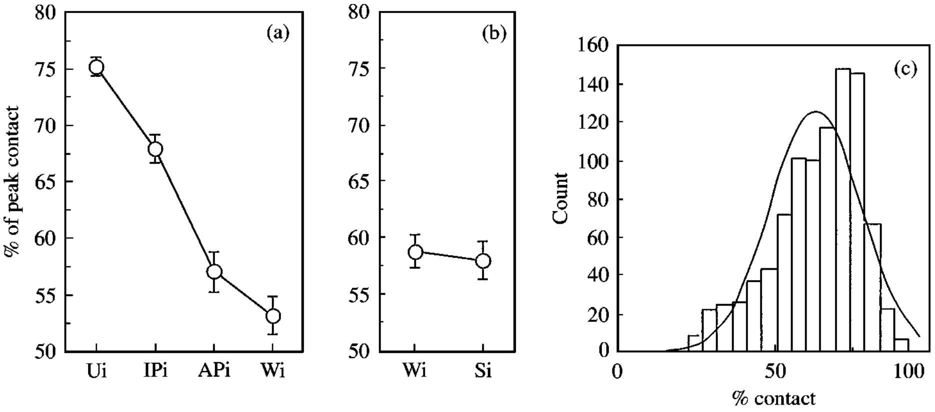


Figure 5. Peak contact across speakers and consonants over the entire palate. (a) higher levels from Ui through Wi; (b) lower levels Wi and Si, and (c) histogram of postboundary linguopalatal contact. Error bars show 97% confidence intervals. Each datapoint is the mean of 240 values.

across speakers. (Results of detailed statistical comparisons for linguopalatal contact for each speaker's consonants are given in Appendix B.) Secondly, it can be seen that for all speakers /t/ and /n/ tend to have a wider range of variation than /t^h/ and /t*/, such that the consonants look more similar in higher prosodic positions and more different in lower prosodic positions. However, there is no significant Prosodic Position by Consonant interaction ($F(9, 32) = 0.784$, $p = 0.6328$).

Is the effect of prosodic position due to variation in the front part of the consonant articulation, the back part, or both? The effect is due to both, but more to the front part, as seen in Fig. 7 ($F(3, 32) = 51.143$, $p < 0.0001$ for front region; $F(3, 32) = 5.801$, $p = 0.0028$ for back region). The degree of variation in the front region (roughly, tongue blade contact) is similar to that over the entire palate, while the back region (roughly, tongue body contact) shows less variation. This difference suggests that it is the primary oral articulation in the front region that contributes more to the variations of peak linguopalatal contact as a function of prosodic position, more than overall tongue height.

We also qualitatively examined EPG displays (and the locations of the electrodes on the individual speaker's pseudo-palates) to see how the primary oral articulation varied with prosodic position. It was noted above that Fig. 3 shows a shift in place, a backing of the rear-most contact as the stop moves from higher to lower domains. This difference is consistent for all three speakers for /n/. When this consonant has more contact, its place is denti-alveolar, but when it has less contact, its place is palato-alveolar. (By "a shift in place", we mean that tokens from different prosodic positions have different places of articulation; there is no shift in the location of the constriction, either forward or backward, within any single token that we examined.) There is a similar, but less dramatic, effect for /t/: when /t/ has less contact, its place is alveolar, with no contact in the dental area. However, there is no equivalent place shift for /t^h/ and /t*/.

Fig. 5(c) shows a histogram of the %contact data in Fig. 5(a). It can be seen that no obvious categories present themselves in this figure. From this figure, it seems clear that

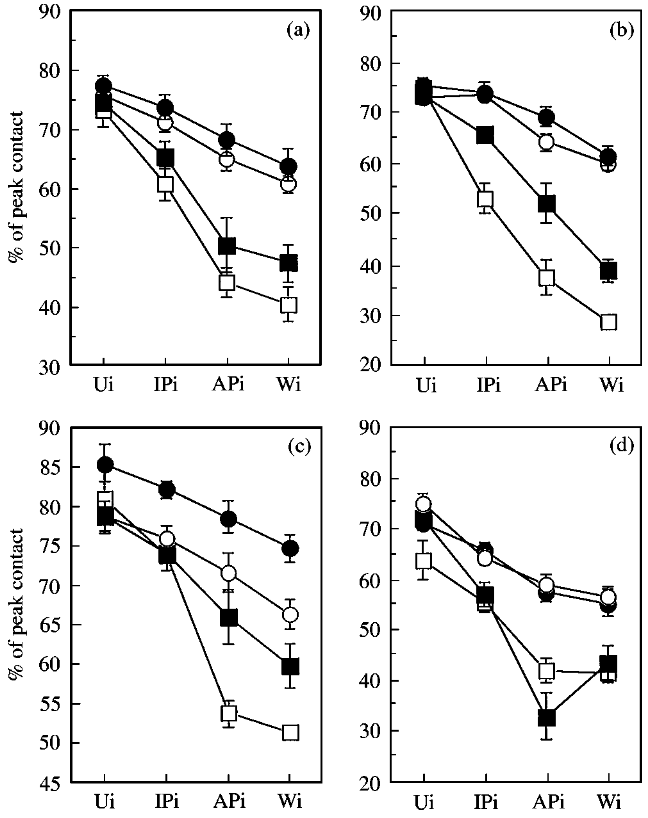


Figure 6. Peak contact for each consonant over the entire pseudo-palate area. (a) contact across speakers (each datapoint the mean of 60 values); (b) contact for speaker NHL (each datapoint the mean of 20 values); (c) contact for speaker THC (each datapoint the mean of 20 values); and (d) contact for speaker JYY (each datapoint the mean of 20 values). Error bars show 97% confidence intervals. —●—/t*/; —○—/t^h/; —■—/t/; —□—/n/.

%contact varies gradiently. We will later compare this distribution with that for preboundary vowel lengthening.

Now let us compare contact for lower levels Wi and Si. Figure 5(b) shows Wi and Si with very similar amounts of linguopalatal contact — only slightly more for Wi than for Si — and not surprisingly the two-way ANOVA (Prosodic Position by Consonant) shows no main effect of Prosodic Position on linguopalatal contact ($F(1, 16) = 0.029$, $p = 0.866$). Figure 8(a) shows contact separately for each of the four consonants, and there is a main effect of consonant ($F(1, 16) = 7.118$, $p = 0.003$), with ($t^* = t^h$) > ($t = n$) at the level of $p < 0.005$ (Bonferroni/Dunn pairwise comparison). As with the above-word comparisons, no Prosodic Position by Consonant interaction was found ($F(3, 16) = 0.286$, $p = 0.8347$). However, as with the above-word comparisons, some patterning can be seen in Fig. 8, especially for the individual subject data in Fig. 8(b)–(d). Results of t-tests show that all three speakers distinguish Wi and Si for /n/ at $p < 0.05$, with the linguopalatal contact being greater word-initially than syllable-initially (= word-medially), in each region. On the other hand, the reverse pattern (i.e., Wi < Si) for /t^h/ and /t*/ was found to be significant for two speakers (NHL and JYY for /t^h/; THC

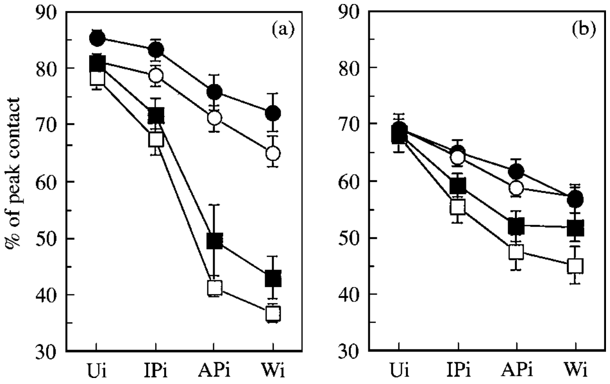


Figure 7. Contact over the front pseudo-palate region (a) *vs.* contact over the back pseudo-palate region (b). Error bars show 97% confidence intervals. —●—/t*/; —○—/t^{h}/; —■— /t/; —□— /n/.

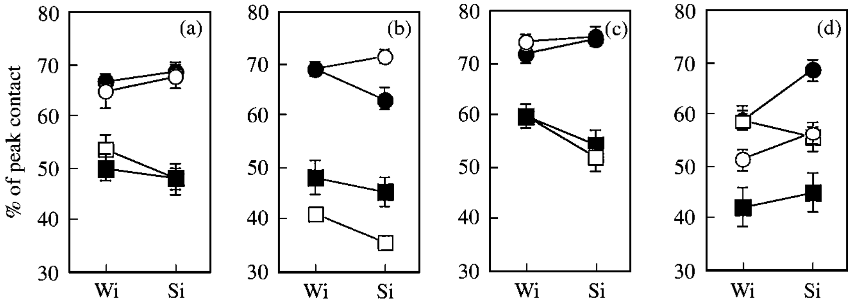


Figure 8. Contact difference between Wi and Si. (a) contact with the pooled data across speakers (each datapoint the mean of 60 values); (b) contact for NHL (each datapoint the mean of 20 values); (c) contact for THC (each datapoint the mean of 20 values); and (d) contact for JYY (each datapoint the mean of 20 values). Error bars show 97% confidence intervals. —●—/t*/; —○—/t^{h}/; —■—/t/; —□—/n/.

and JYY for /t*/). Thus, peak linguopalatal contact for these two consonants does pattern somewhat differently word-internally than in other prosodic positions. Detailed results of *t*-tests are given in Appendix B. Nonetheless, the most striking result here is the lack of consistency across the speakers, especially when compared with the above-word conditions.

In sum, the data show that, overall, all consonants are produced with greater peak linguopalatal contact in higher domain-initial positions, especially for higher level comparisons from Ui to Wi, with just small interspeaker and interconsonantal differences. For lower level comparisons, all speakers make distinctions between Wi and Si for /n/, but not always for other consonants.

3.1.2. *Stop seal duration*

The variations in stop seal duration across prosodic position and consonants are presented in Fig. 9(a) and (b), which show patterns similar to those found for peak linguopalatal contact. For the above-word comparisons, there are again main effects of Prosodic Position ($F(3, 32) = 49.469$, $p < 0.0001$) and Consonant ($F(3, 32) = 12.028$,

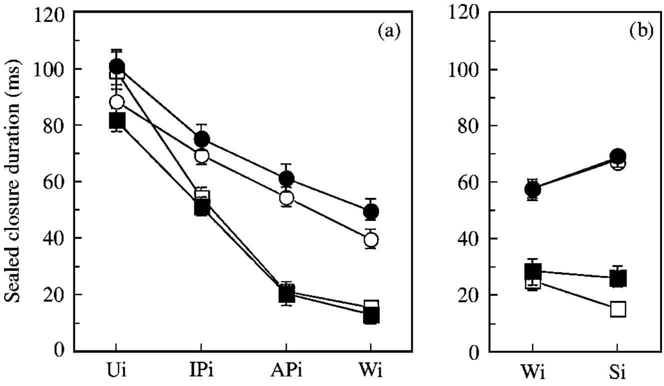


Figure 9. Seal duration as a function of prosodic position and consonant type. Data pooled across speakers (each datapoint the mean of 60 values). Error bars show 97% confidence intervals. (a) higher levels; (b) Wi *vs.* Si. —●—/t*/; —○— /t^h/; —■—/t/; —□—/n/.

$p < 0.0001$) on stop seal duration, but no interaction between the two factors ($F(9, 32) = 1.241, p = 0.3061$). The common result obtained from Bonferroni/Dunn *post-hoc* comparisons is that each consonant shows a pattern of Ui > IPi > APi > Wi at the significance level of $p < 0.005$, except for the comparison between APi and Wi for /n/, which shows a trend at $p = 0.036$. (Detailed statistical results for each consonant separated by speaker appear in Appendix B.) For the consonant effect, all consonants are significantly differentiated by seal duration, showing a pattern of t* > t^h > t > n, as in the case of linguopalatal contact.

For the word-level comparisons, the results are again similar to those for peak linguopalatal contact: no main effect of Prosodic Position ($F(1, 16) = 0.379, p = 0.5466$); a main effect of Consonant ($F(3, 16) = 32.523$, $p < 0.0001$); no Position by Consonant interaction ($F(3, 16) = 1.624, p = 0.2233$). Nonetheless, there are again patterns apparent in the figure: /t/ and /n/ look longer when Wi than when Si (W-medial), while /t^h/ and /t*/ look the reverse. Again, speakers differ, and again *t*-tests bear out what is seen in the figure. While all speakers showed a significantly distinct pattern of Si > Wi for /t^h/, only two speakers (THC and JYY) show this pattern for /t*/. For /t, n/, two speakers (NHL and THC) show a significantly distinct, reverse, pattern of Wi > Si. (Detailed statistical results of *t*-tests are given in Appendix B.)

3.1.3. *Skewness of contact profile*

Recall that skewness here is a measure of the shape of the contact profile when at least 20% of the electrodes are contacted. In general, the skewness value is smaller in higher domain-initial positions, as shown in Figs 10 and 11. Most prosodic positions show negative skewness. As Byrd *et al.* (1995) suggested, this direction of skewness can show that the consonant closing is made relatively slowly — here, in higher domain-initial positions compared to lower ones — and/or that the peak of the contact is formed relatively later in higher domains.

3.1.4. *Correlations among articulatory parameters*

Peak linguopalatal contact, stop seal duration, and profile skewness all show a progressive pattern of variation with prosodic position. Here we determine if any of these

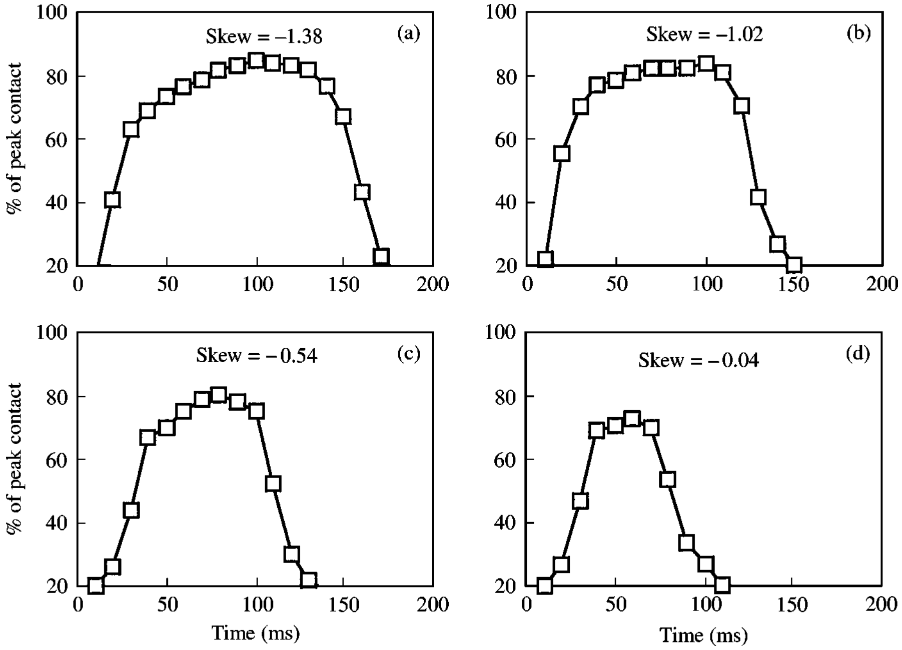


Figure 10. Representative articulatory trajectories, with skewness varying as a function of prosodic position. Tokens are from /t*/ produced by speaker THC. (a) Ui; (b) IPi; (c) APi; (d) Wi.

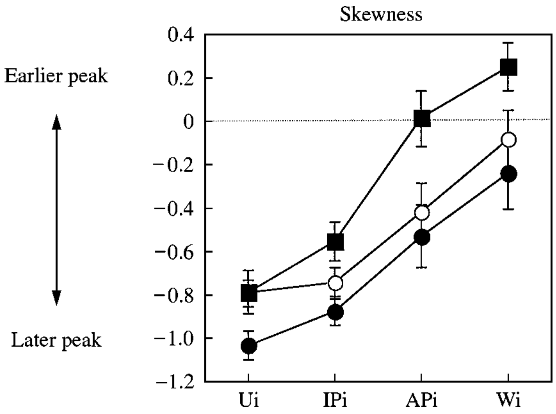
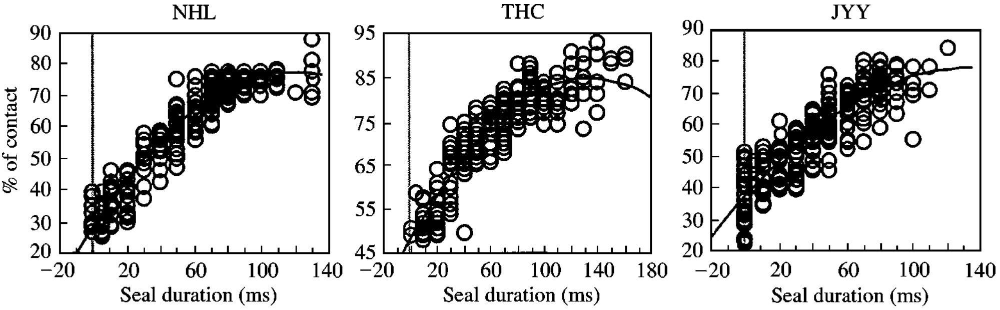


Figure 11. Skewness of linguopalatal contact profile with data pooled across speakers (each datapoint the mean of 60 values). Error bars show 97% confidence intervals. —●— /t*/; —○— /t^{h}/; —■— /t/.

measures are more directly related. We first examine correlations between linguopalatal contact and seal duration. Fig. 12 shows regression plots with linguopalatal contact against seal duration. Though the linear relation between these two variables is strong for all three speakers, it can be seen in the graphs that the relation is not in fact linear, but instead asymptotes at the largest values of contact. Therefore, some nonlinear regression function should fit the data better; in Fig. 12, we show polynomial fits, which



$Y = 27.303 + 0.832 * X - 0.003 * X^{\wedge}2$; $R^{\wedge}2 = 0.907$

$Y = 47.411 + 0.555 * X - 0.002 * X^{\wedge}2$; $R^{\wedge}2 = 0.848$

$Y = 36.37 + 0.605 * X - 0.002 * X^{\wedge}2$; $R^{\wedge}2 = 0.767$

Figure 12. Polynomial regression plots with linguopalatal contact against seal duration. Note that y- and x-axis are scaled for each subject's data. Data are pooled across consonants.

give slightly stronger relations than linear regression ($R^2 = 0.91$ for speaker NHL; 0.85 for speaker THC; and 0.77 for speaker JYY). A strikingly high proportion of the variance is accounted for by this single variable for all three subjects. (Other functions, e.g., an exponential, would presumably improve the fits even more, but given that these high R^2 values suffice to make the points that there is a strong relation in the data, and an asymptote at greater durations, we did not pursue this further.)

There are also other reliable linear relationships — i.e., between the linguopalatal contact and the skewness ($R^2 = 0.52$–0.62) and between the skewness and the seal duration ($R^2 = 0.66$–0.81) — suggesting that the more the peak contact, the later it comes, and the longer the duration, the later the peak comes.

3.2. *Acoustic parameters*

3.2.1. *Acoustic consonant duration*

Fig. 13(a) shows the acoustic closure duration for the oral stops and the nasal duration for /n/. (Recall that acoustic closure duration could not be measured for oral stops in utterance-initial position due to the substantial silent pause.) Two-way ANOVA yields a main effect of Prosodic Position ($F(2, 23) = 16.294$, $p < 0.0001$), and *post-hoc* comparisons show a significantly distinct pattern of IPi > APi > Wi at the level of $p < 0.01$. There is also a main effect of Consonant ($F(3, 23) = 9.607$, $p = 0.0003$), showing a significantly distinct pattern of t* > t^h > (t = n) at the level of $p < 0.005$. However, there is no Prosodic Position by Consonant interaction ($F(6, 23) = 0.257$, $p = 0.514$).

These data can be compared to the measurements of articulatory seal duration, shown above in Fig. 9 (Section 3.1.2). The measured acoustic duration was generally longer than the measured seal duration. There are at least three reasons for this difference. First, there were quite a few tokens with no visible seal in the EPG record—i.e., 0 ms seal duration — which nonetheless showed a closure interval in the acoustic signal — i.e., a closure duration greater than 0 ms. For these tokens, either the closure was shorter than 10 ms (and was not sampled by the EPG recording), or the constriction was longer but whatever air exited the vocal tract did not produce any appreciable acoustic noise. Second, since seal duration was counted as the number of EPG frames showing the seal,

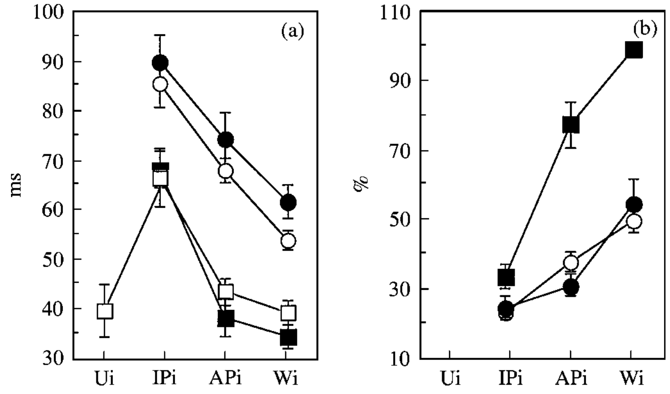


Figure 13. (a) Variation in acoustic duration (ms) for /n, t, t^h, t*/ and (b) variation in %voicing during the acoustic closure duration for /t, t^h, t*/. Error bars show 97% confidence intervals (each datapoint the mean of 60 values). —●— /t*/; —○— /t^h/; —■— /t/; —□— /n/.

any time between the last such frame and the actual release was excluded. Third, for the nasal in postpausal position, the articulatory seal can be formed well before the acoustic source is initiated. Thus, the acoustic duration of the U-initial nasals is the shortest even though their articulatory seal duration is longest, a result consistent with Fougeron &Keating (1997) as well.

For comparisons between Wi and Si (figures not provided), syllable-initial stops are significantly longer than word-initial ones for /t^h, t*/, but the opposite is true for /n/ at the level of $p < 0.001$, as was found in the case of seal duration. Closure duration for /t/ was not measured in these positions due to the difficulty caused by its frequent pronunciation as an approximant, with no acoustic discontinuity, in which case closure duration is 0 ms.

3.2.2. *Voicing and %voicing during acoustic closure*

There is no main effect of either Prosodic Position ($F(2, 18) = 2.457$, $p = 0.1139$) or Consonant ($F(2, 18) = 0.598$, $p = 0.5606$) on the voicing measure, and no interaction between the two factors ($F(4, 18) = 0.203$, $p = 0.9333$). That is, the absolute amount of voicing into closure does not differ among the three oral stops and the three prosodic positions. The mean values show a tendency to a three-way distinction among prosodic positions (IPi < APi < Wi), but this tendency is not statistically reliable.

As for %voicing, there is a main effect of Prosodic Position ($F(2, 18) = 20.560$, $p < 0.0001$) when we consider closure voicing as a percentage of the entire stop closure duration, as shown in Fig. 13(b). For this parameter, there is a significantly distinct pattern of IPi < APi < Wi. This is not surprising, since if total closure is longer while closure voicing shortens or remains constant in higher prosodic positions, %voicing decreases. There is also a main effect of consonant ($F(2, 18) = 22.643$, $p < 0.0001$). As can be seen in Fig. 13(b), %voicing is greater for /t/ than /t^h, t*/. The Prosodic Position by Consonant interaction is not significant ($F(4, 18) = 2.800$, $p = 0.0572$), but as can be seen in Fig. 14(b), there is a trend towards greater variation for /t/ than /t^h, t*/.

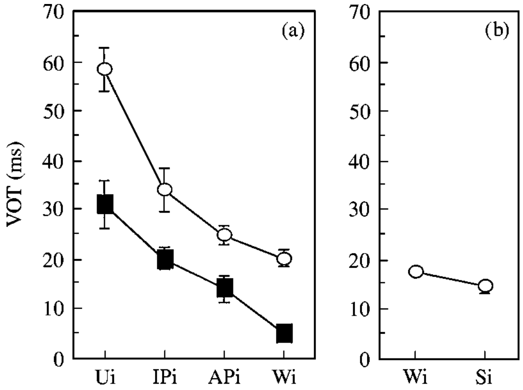


Figure 14. Variations in VOT. (a) higher levels and (b) lower levels. Error bars refer to 97% confidence intervals (each datapoint the mean of 40 values). —○—/tʰ/; —■—/t/.

3.2.3. *VOT*

VOT for /t, tʰ/ is longer when the stop occurs in a higher domain-initial position, as shown in Fig. 14(a). VOT is not shown for the tense stop /t*/, as systematic differences were not found (VOT is always quite short and there is little variation). Two-way ANOVA performed on data including only /t, tʰ/ shows that there is a main effect of Prosodic Position ($F(3,16) = 10.319$, $p = 0.0005$) and Consonant ($F(1,16) = 15.104$, $p = 0.0013$), but no interaction between the two factors ($F(3,16) = 0.660$, $p = 0.5888$). Pairwise *post-hoc* comparisons (Bonferroni/Dunn) confirm that there is a four-way distinction among prosodic positions (Ui > IPi > APi > Wi) at the level of $p < 0.005$.

In the comparison between Wi and Si /tʰ/, Wi has a longer VOT than Si ($t = 5.201$, $p < 0.0001$), as shown in Fig. 14(b). This is so despite the tendencies seen earlier for this stop to be longer and have more linguopalatal contact when Si. (Note that VOTs for /t/ for Wi and Si were not plotted due to the intervocalic voicing throughout the closure in most of the tokens, which makes measured VOT zero.)

3.2.4. *Total voiceless interval*

Fig. 15 shows the acoustic total voiceless interval, which combines voiceless closure duration and VOT, thus indexing the duration of glottal opening. Only the aspirated stop /tʰ/ was examined since only it is consistently produced with a fair amount of glottal opening during the closure. As noted above, the voiceless closure duration for Ui could not be measured because it could not be distinguished from any silent pause. However, a rough gauge of this comparison can be observed when voiceless closure duration is replaced by seal duration. Either way, there is a main effect of Prosodic Position ($F(3,8) = 129.983$, $p < 0.0001$ for total voiceless interval; $F(3,9) = 80.160$, $p < 0.0001$ for seal duration plus VOT). Pairwise *post-hoc* comparisons show that all levels are distinguished from one another at the level of $p < 0.0001$. Thus, it appears that this measure of the duration of glottal opening for /tʰ/ more consistently distinguishes the prosodic domains than does either VOT or closure duration alone.

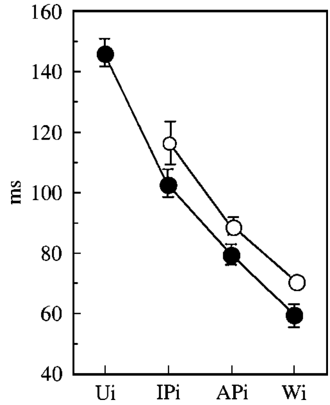


Figure 15. Total voiceless interval and seal duration plus VOT (ms) for /t^h/. Error bars refer to 97% confidence intervals (each datapoint the mean of 60 values). —○— total voiceless interval; —●—seal duration + VOT.

3.2.5. *RMS burst energy and nasal energy minimum*

The RMS burst energy measure was not made for the word-initial lenis stop /t/ due to the presence of voicing throughout the consonant. Two-way ANOVA of /t^h, t*/ shows no main effect of Prosodic Position ($F(3, 16) = 0.571$, $p = 0.6422$) and no Prosodic Position by Consonant interaction ($F(3, 16) = 0.046$, $p = 0.9865$). However, there is a clear trend visible in Fig. 16(a) for RMS burst energy to be smaller for Ui and IPi than for APi and Wi for /t^h, t*/, though no systematic pattern is found for /t/. Fig. 16(a) also shows a consistently greater RMS energy for /t^h/ than for /t*/ at all levels, which is shown to be reliable by the main effect of Consonant ($F(1, 16) = 7.946$, $p = 0.01$).

Now let us consider the nasal energy minimum. This measure reflects the minimum nasal airflow during a nasal consonant. Recall that nasal energy for Ui, which follows a pause, was not measured because the minimum energy is always just above 0. In general, nasal energy minimum is lower in higher domain-initial positions, as shown in Fig. 16(b). Bonferroni/Dunn *post-hoc* comparisons confirm that IPi is significantly lower than APi and Wi at the level of $p < 0.0001$. For the lower levels Wi *vs.* Si (figures not shown), nasal energy for Wi is significantly lower than for Si ($p < 0.001$).

3.2.6. *Duration of V in domain-initial CV* (*V*2)

This is a measure of postboundary vowel lengthening (note, however, that the segment immediately after the boundary is the initial C; V2 follows that C). There is no main effect of Prosodic Position ($F(3, 32) = 2.291$, $p = 0.097$) nor an interaction of Prosodic Position by Consonant ($F(9, 32) = 1.261$, $p = 0.2953$), but there was a significant main effect of Consonant ($F(3, 32) = 3.429$, $p = 0.286$). Fig. 17 shows V2 duration separated by consonant. The direction of variation differs across consonant contexts.[1] The clearest pattern is associated with V2 after /t*/ — V2 is generally longer in a higher domain.

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[1] The lack of any overall consistent pattern in the initial vowels suggests that Korean vowels are subject to durational variation to a lesser degree than vowels in some other languages. This appears to be compatible with results of Jun & Lee (1998), who found that in Korean, vowels are not lengthened in another prosodically prominent position (i.e., under focus).

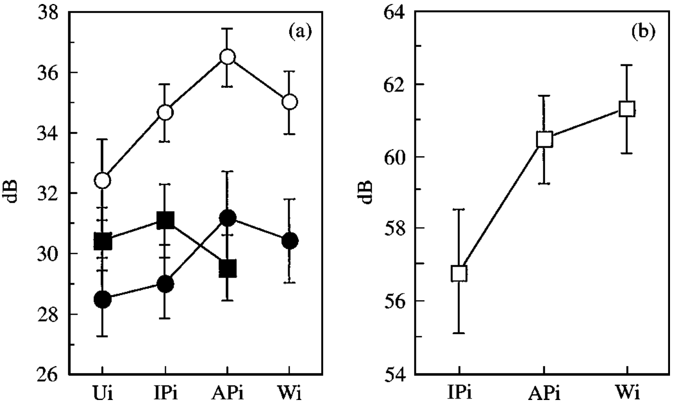

Figure 16. (a) RMS burst energy for oral stops and (b) nasal energy minimum for /n/. Error bars refer to 97% confidence intervals (each datapoint the mean of 60 values). Note that RMS burst energy for Wi /t/ was not included due to voicing throughout the closure, and that nasal energy minimum for Ui /n/ was not included due to the preceding silent pause. —○— /t^h/; —■— /t/; —●— /t*/.

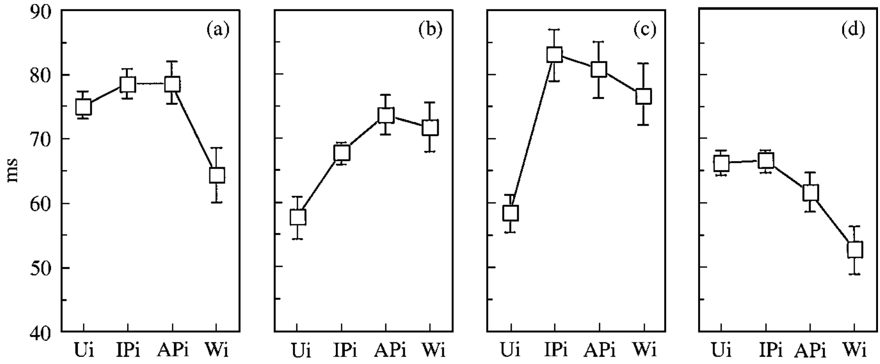

Figure 17. Vowel duration in domain-initial CV. Error bars refer to 97% confidence intervals (each datapoint the mean of 60 values). (a) /n_/; (b) /t_/; (c) /t^h_/; (d) /t*_/.

3.2.7. *Duration of vowel in domain-final position* ($V1$)

Results for V1 are rather different than for V2. V1 duration is a measure of domain-final lengthening. (Pause duration is another such measure, which is not included here.) There is a main effect of Prosodic Position ($F(3, 32) = 169.993$, $p < 0.0001$), but neither a (following) Consonant effect ($F(3, 32) = 1.545$) nor an interaction between the two factors ($F(9, 32) = 0.562$). As can be seen in Fig. 18(a), the common result from pairwise Bonferroni/Dunn *post-hoc* comparisons is that across (following) consonants the domain-final vowel is longest for either U-final or IP-final, intermediate for AP-final and shortest for W-final. There is a great and significant difference between U-final/IP-final and AP-final/W-final; and a relatively small but significant difference between AP-final and W-final. In general, the higher the prosodic position, the longer the domain-final vowel.

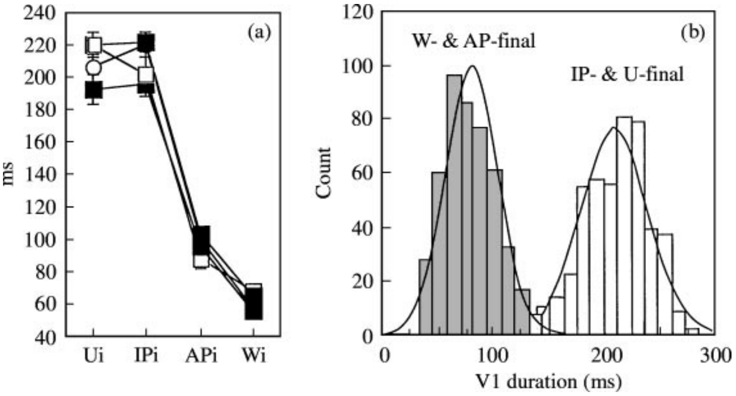

Figure 18. (a) Domain-final (preboundary) vowel (V1) duration and (b) distribution of V1 duration measurements.

The difference between AP-final and word-final vowels, though statistically significant, is subtle. The histogram in Fig. 18(b) shows that vowel durations divide into two quite distinct distributions, such that IP-final vowels are categorically longer than AP-final vowels — this is the difference also revealed in Jun (1993, 1995*a*) — while AP-final vowels are only gradiently longer than word-final ones — a difference not found by Jun.

In the lower-level comparisons between W- and S-final (W-medial) vowels, there is no main effect of either Prosodic Position ($F(1,16) = 0.073$, $p = 0.7904$) or Consonant ($F(3,16) = 2.095$, $p = 0.1411$), nor is there prosodic position by consonant interaction ($F(3,16) = 0.656$, $p = 0.5906$). Detailed observations across consonants and speakers confirm that the W-internal differences are not at all consistent in the way the higher level ones are.

3.3. *Relations between articulatory and acoustic measures*

In this section, we examine correlations between linguopalatal contact and the acoustic measures that were shown to be significantly influenced by prosodic position. Strong relationships between such measures would suggest acoustic correlates of the articulatory variation.

Firstly, there is a significant and very strong relationship between linguopalatal contact and acoustic closure duration ($R^2 = 0.744$ for speaker NHL; $R^2 = 0.632$ for speaker THC; $R^2 = 0.602$ for speaker JYY). This is not surprising, since we have already seen a strong correlation between linguopalatal contact and articulatory seal duration, and articulatory durations are of course closely related to acoustic durations.

Secondly, following Fourgeron & Keating (1997), we examine the correlation between linguopalatal contact and preboundary V1 duration. There is a significant linear relationship between these variables ($R^2 = 0.299$ for speaker NHL; $R^2 = 0.367$ for speaker THC; $R^2 = 0.443$ for speaker JYY). When the data are considered separately for each consonant, regression values increase considerably, putting R^2 values in a range between 0.51 and 0.89. That is, quite a great portion (up to 89%) of the variance in linguopalatal contact can be predicted by preceding vowel durations.

TABLE III. A summary of multiple regressions of %contact with two independents, preceding vowel (V1) duration and seal duration. Parenthesized values are from simple polynomial regressions with a single independent, seal duration. Cells are shaded when multiple regression values are greater than simple polynomial regression values

	Speaker NHL		Speaker THC		Speaker JYY	
	R	R^2	R	R^2	R	R^2
/n/	0.964	0.929	0.965	0.930	0.913	0.833
	(0.970	0.942)	(0.916	0.840)	(0.881	0.776)
/t/	0.956	0.914	0.900	0.809	0.907	0.822
	(0.961	0.923)	(0.961	0.923)	(0.917	0.840)
/tʰ/	0.915	0.837	0.682	0.674	0.928	0.862
	(0.829	0.687)	(0.829	0.687)	(0.920	0.846)
/t*/	0.902	0.814	0.808	0.644	0.940	0.883
	(0.855	0.718)	(0.853	0.728)	(0.945	0.893)

Now that we know that consonant durations (especially articulatory seal durations) and preceding vowel durations account for much of the variance in consonant contact, we further ask whether the dependent variable, %contact, can be better explained by these two independent variables together. As seen in Table III (the first row of each consonant section), a series of multiple linear regressions reveals that the %contact for a consonant is quite well predicted from these two independent variables together. For speakers NHL and JYY, these two variables account for almost all the variance in consonant contact. However, multiple regression values are not always greater than those of simple polynomial regressions with seal duration as an independent variable (the second row of each consonant section). As marked by shading in Table III, only five out of 12 comparisons show that preceding vowel duration and seal duration together account for the %contact variance better than does seal duration alone, and just as often the reverse is true. This suggests that preceding vowel duration and seal duration are independent correlates of %contact to only a slight extent.

Finally, there is a significant positive linear relationship between linguopalatal contact and VOT for /t/ and /tʰ/ ($R^2 = 0.375$ for speaker NHL; $R^2 = 0.381$ for speaker THC; $R^2 = 0.584$ for speaker JYY). R^2 values suggest that linguopalatal contact accounts for about 37–58% of the variance in VOT.

4. Discussion

4.1. *Domain-initial strengthening as cumulative*

The articulatory and acoustic parameters examined in the current study strongly support the hypothesis that there is domain-initial strengthening in Korean, and that it is cumulative. Recall that in our corpus, a syllable-initial consonant was word-medial; a word-initial consonant, AP-medial; an AP-initial consonant, IP-medial; and finally an

IP-initial consonant, U-medial. Almost all domain-initial strengthening found in a higher position was greater than any strengthening found in a lower position. This progressively increasing trend was also found in domain-initial lengthening of seal duration, VOT, and total voiceless interval. Similarly, a progressively decreasing trend was found in nasal energy and RMS burst energy, though the latter was not so consistently cumulative. The exception to this overall cumulative pattern is discussed in Section 4.5 on word-medial consonants.

When we say that strengthening is cumulative, we do not necessarily mean that each higher prosodic position adds its quantum of strength to the consonant. Indeed, the histogram of linguopalatal contact data in Fig. 5(c) shows a continuous distribution of values from the four prosodic positions. Though this figure combines data from all speakers and consonants, it is markedly different from the distribution of preboundary vowel duration in Fig. 18(b), where one break between categories is apparent. Thus, initial strengthening could well be a gradient effect of prosodic position.

4.2. *Nature of articulatory strengthening*

Fougeron & Keating (1997) presented several possible mechanisms for domain-initial strengthening. We will discuss two of these in light of the present study.

First, the present study reinforces our earlier finding that in Korean, linguopalatal contact is strongly related to consonant duration. We found that more than 80% of the contact is accounted for by the articulatory (seal) duration ($R^2 = 0.91$ for speaker NHL; 0.85 for speaker THC; and 0.77 for speaker JYY). Overall, the longer the consonant seal, the greater the linguopalatal contact. However, as seen in Fig. 12, contact asymptotes: for durations above 80 ms, peak contact remains similar (and large). This relation suggests that about 80 ms is enough time to reach a contact target, and there is some articulatory undershoot for durations shorter than this. Thus, the results of the present study support the hypothesis that in Korean, articulatory strengthening is due to longer segment durations in stronger positions.

The articulatory undershoot hypothesis is further supported by the skewness of the articulatory trajectories, which varies as a function of prosodic position (see Figs 10 and 11). As seen in Section 3.1.4, there is a fairly strong inverse linear relationship between the linguopalatal contact and the skewness, and between the skewness and the seal duration. As seen in Fig. 10, the articulatory trajectories are asymmetrical, being skewed further to the left with longer durations in higher positions. This suggests that the most extreme articulation occurs toward the end of the articulatory trajectory. On the other hand, the articulatory trajectories in lower positions (i.e., APi and Wi) show less linguopalatal contact. This is presumably because the time taken for the articulation does not allow the articulator to reach its extreme target value, and this results in less skewness.

The skewness pattern in these Korean data is consistent with the findings by Byrd (1994) for English coronal consonants. Byrd compared consonants in word- (and syllable-) initial position *vs.* word- (and syllable-) final position. She found that consonants had more positive skew in final position than in initial position. Since her word/syllable-initial position, which is prosodically stronger than her word/syllable-final position, has less positive skew, our result can be seen as extending this pattern to higher-level strong positions, which have more negative skew.

Thus, it appears that in Korean coronal consonants, the longer the duration, the later and larger the peak contact. Korean is unusual among the languages studied to date in having such a close relation between lengthening and strengthening. Byrd, Kaun, Narayanan & Saltzman (2000) found lengthening, but essentially no strengthening, of Tamil /m/; Fougeron & Keating (1997) found a weak correlation in English; Fougeron (1998) found moderate correlations in French, but weaker than reported here. Thus, there is no *necessary* connection between lengthening and strengthening cross-linguistically, and therefore we would not claim that every case of articulatory strengthening is temporally-based. Nonetheless, this appears to be the case for Korean.

Second, Fougeron and Keating also suggested that initial strengthening may be attributable to greater impact of the tongue against the hard palate in consonant formation. This greater impact would arise from higher articulator velocity, which would in turn result from a greater distance to be covered by the articulator (velocity proportional to displacement). The distance would be greater because final lengthening of a (nonhigh) vowel before the prosodic boundary would result in a more open vowel. In Section 3.2.7 it was seen that in our data preboundary lengthening is fairly cumulative, making this hypothesized mechanism a plausible one here. Unfortunately, it cannot be tested directly: we do not have contact data, V-to-C displacement data, or movement velocity data for the preboundary vowels in this study (because, unlike in Fougeron and Keating's study, all our vowels are open vowels, with little or no contact). Nonetheless, the results on skewness are suggestive. As shown in Section 3.1.3, the skewness differences indicate that peak contact is reached later in the movement at the end of the stop closure in higher prosodic positions. That is, the differences in peak contact across prosodic positions occur at the end of the closing movements. As can be seen in Fig. 10 (top), the late peaks come well after the initial quick increase in contact. Presumably, any differences in closing velocity related to the preceding vowel would be strongest in this initial quick closing, and have spent their course by the very end of the closure, when peak contact occurs. However, no firm conclusion can be drawn without the relevant direct measurements, ideally from articulatory movement data.

In sum, based on the evidence available so far, it appears that in Korean, initial strengthening arises from effects of prosodic position on segment durations.

4.3. *Final vowel lengthening*

We found that domain-final lengthening of a vowel was progressively greater as its prosodic position moves up in the prosodic hierarchy (see Fig. 18). Furthermore, we found that the vowel durations form two groups, U- and IP-final vowels *vs.* AP- and W-final vowels. We suggest that the small size of the difference between AP- *vs.* W-final vowels, compared to the large size of the difference between AP- *vs.* IP-final vowels, accounts for the difference between our results and those of earlier studies in which no significant AP-final lengthening was found (Jun 1993, 1995*a*). An alternative account of our result which must be addressed, is that it is due to the different segmental context associated with our AP-final vowel. All AP-final vowels in our study are preceded by voiced [g] while W-final vowels are preceded by voiceless (geminate) tense [k*], except in the /n/ corpus. If vowels are longer after [g] than after [k*], then the present result could be due to this confound. However, Cho (1996) showed that, in fact, vowels tend to be longer after voiceless tense stops than after voiced plain stops. If the vowel duration were determined by the preceding consonant type, then the results would be the opposite of what we found. Thus, the segmental context in our corpus even reinforces the strength of our result. Furthermore, the same AP-final lengthening was found for /n/, for which the segmental context is exactly the same across the test sentences. Therefore, the present study suggests that final lengthening in Korean may not be limited to IP- or utterance-final positions but extends to AP-final position, as in French (Hirst & Di Cristo, 1984; Pasdeloup, 1990; Fougeron & Jun, 1998). This is also in agreement with Oh (1998), who found a small but significant duration difference between AP- and W-final vowels.

4.4. *Acoustic cues and their correlation with articulatory strengthening*

The domain-initial articulatory strengthening revealed in linguopalatal contact will be linguistically more significant if it has acoustic or auditory consequences that could be accessible to a listener. In the present study, we found that values along the acoustic parameters tested do vary as a function of prosodic position. That is, domain-initial positions are signalled to a significant extent by a number of acoustic correlates such as stop closure duration, VOT, total voiceless interval, %voicing, vowel duration, RMS burst energy, nasal duration, and nasal energy minimum. However, not every cue is potentially attributable to the strengthening in linguopalatal articulation. For example, the variation in %voicing and total voiceless interval is surely attributable to articulatory events at the glottis, while nasal energy and duration should be closely linked with the articulatory events at the velum. In what follows, we will summarize the acoustic results according to their relations to articulatory events.

4.4.1. *Acoustic correlates of the linguopalatal articulatory strengthening*

First, acoustic closure durations (which are roughly equivalent to seal durations for oral stops) are cumulatively longer in higher prosodic positions. This is similar to results in Silva (1992) and Oh (1998). As shown in Fig. 12, there is a significant and strong linear relationship between the linguopalatal contact and the seal duration. As discussed earlier, this durational difference can be related to articulatory undershoot, and thus seems to account for the articulatory strengthening. Since lengthening and strengthening are so strongly related in Korean, the variation in duration could be a significant perceptual cue for the articulatory strengthening.

Second, RMS burst energy tends to be smaller in oral stops in higher domain-initial positions for some cases. This result, however, must be taken to be only suggestive because of the inconsistent patterns across speakers and consonants. Although there is some effect of prosodic position on burst energy, the effect is not as strong as other acoustic and articulatory parameters. In fact, there is only a modest negative correlation between maximum linguopalatal contact and RMS burst energy ($R^2 = 0.134$ with data pooled across speakers and consonants). However, the correlation varies with consonant types and is notable for /t*/ ($R^2 = 0.434$). Thus, the results indicate that burst energy could be a weak acoustic cue for articulatory strengthening. For /t*/, this significant inverse relationship accords with a prediction made by Stevens, Keyser & Kawasaki (1986), that greater contact should result in a longer release duration, and thus with less peak burst energy. In any case, there is no support for the converse hypothesis, that the release of a strengthened articulation is faster and results in a louder burst.

Third, we found that stops /t^h/ have longer VOTs in higher domain-initial positions (see Fig. 14), and that there is a significant linear relationship between linguopalatal contact and VOT (see Section 3.3). As discussed further below, the longer VOT is probably due primarily to the glottal opening gesture that is strengthened domain-initially compared to domain-medially. However, it is also possible that the differences in linguopalatal contact result in aerodynamic differences at the release, which also partially affect VOT.[2]

4.4.2. *Acoustic correlates of other articulatory events*

The first acoustic measure showing a dependence on prosodic position is VOT of /t, t^h/. Clearly, the most important source of variation in VOT for these consonants will be variation in glottal opening gestures. If the glottis opens more, and takes longer to do so, the VOT — the time between the oral release and the onset of voicing after glottal adduction — is likely to be longer as well. In the present study, VOT of these stops was found to be longer in higher prosodic positions. This is not surprising, since Pierrehumbert & Talkin (1992) and Keating *et al.* (1999) have found effects of prosodic position on VOT. Furthermore, in a transillumination study, Cooper (1991) found that English voiceless aspirated stops in word-initial position have a larger glottal opening gesture compared to word-medial position; and the fiberscopic study by Jun *et al.* (1998*a*, *b*) of glottal configurations of Korean obstruents found larger glottal apertures in AP-initial position than in AP-medial position. Thus, it is reasonable to infer that the VOT differences we found arise from prosodic conditioning of glottal aperture. This is consistent with the result that the tense stop /t*/ shows no VOT variation, as it involves no glottal abduction gesture that could increase when strengthened.

However, VOT depends not only on the glottal opening, but also on the timing of the oral release relative to that glottal opening. A better acoustic correlate of the glottal opening *per se* is the total voiceless interval. In the present study, this measure for the aspirated stop /t^h/ is cumulatively longer in higher domain-initial positions, marking all distinctions from IPi through Wi. This suggests that the finding by Jun *et al.* about prosodic conditioning of glottal aperture in Korean holds for higher prosodic positions as well.

A third, and related, measure is the interval that is voiced during the stop closure, which shows some tendency to be shorter in higher domain-initial positions (e.g., IPi) and longer in lower domain-initial positions (e.g., Wi). It is possible that glottal abduction occurs earlier in the higher positions, resulting in a longer voiceless interval, and to some extent a shorter voiced interval. It is also likely that the glottal abduction is formed

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[2] The reasoning is as follows: if the oral pressure behind the constriction increases proportionally with longer duration — possible if the vocal tract walls remain fairly lax — but the speed of oral opening is constant, then the resulting greater oral pressure will take relatively longer to vent after release and allow an adequate transglottal pressure for the initiation of vocal fold vibration (Cho & Ladefoged, 1999). That is, some proportion of the VOT effect could be a consequence of the oral articulation effect, over the above any glottal effect. A problem with this explanation for our data, however, is that if oral pressure were higher but the release constant, burst energy would be expected to be greater, which it is not. Alternatively, a longer VOT can be associated with a larger contact area, if speed of release is inversely proportional to contact. Cho & Ladefoged (1999) following Stevens (1999), explain that a slower release could be attributable to a Bernoulli effect over the large contact area pulling the articulators back together after release. If the articulators come apart more slowly, a longer time will be needed before an appropriate transglottal pressure is achieved. The reliable linear relationship between linguopalatal contact and VOT appears to support this latter possibility, and the hypothesis of slower releases in higher prosodic positions receives support from studies of English (Byrd, 1994; Byrd & Saltzman, 1998). Thus, it is indeed plausible that there is an effect of prosodic position on VOT via its effect on consonants' oral articulation, in addition to the effect discussed below.

more quickly: Jun *et al.* (1998*a*, *b*) found greater magnitude of the glottal opening gesture in AP-initial position. The velocity of the movement may be proportional to its magnitude, and higher velocity of glottal opening would result in earlier devoicing.[3]

A fourth measure is the nasal energy minimum for nasal /n/, which tends to be lower in higher domain-initial positions (Fig. 16(b)). Most likely the velum is higher (resulting in less nasal energy) for a higher domain-initial /n/. Our data are like those of Fougeron (1998, 2001) for French; Fougeron has furthermore proposed that such variation in nasal energy is caused by differences in muscular tension — that by hypothesis, in higher prosodic positions, the levator palatini is more tensed and the velum is higher, regardless of whether the consonant is oral or nasal. She compares this hypothesis favorably with an alternative, that consonants in strong prosodic positions are generally produced with less sonority (e.g., less energy in lower harmonic components).

4.4.3. *Closure voicing and the Korean voicing rule*

We saw above (Fig. 13(b)) that %voicing during acoustic closure is smaller for stops in higher domain-initial positions. The proportion of closure which is voiced bears on whether a stop will be heard as voiced or voiceless. Thus, this measure allows us to look at the prosodic conditioning of the intervocalic voicing of the lenis stop /t/. Jun (1993, 1995*a*) claimed that the rule of Korean intervocalic voicing applies to lenis stops anywhere inside an AP, but not AP-initially. She also showed that when consonant duration was regressed against the duration of the following vowel, there was no distinct separation between fully voiced, partially voiced, and voiceless plain stops. She argued that this result showed that voicing is a gradient, phonetic rule. Docherty (1995) took exception to Jun's assumption that any amount of overlap means there are not separate categories, noting that real distributions often show overlap across categories. Our data allow us to revisit this issue, since we have data on the voicing of lenis stop /t/ in a range of prosodic positions.

Figure 19 shows the distribution of %voicing during closure in each domain-initial position in which it could be determined (these are the same data as in Fig. 13(b)). In general, it can be seen that almost all the AP-medial (Wi) stops have 100% closure voicing (right panel), while the IPi stops never do (left panel). Instead, the IPi stops generally have less than 60% closure voicing. Thus, the stops in these two prosodic positions are well distinguished as "fully voiced" *vs.* "partially voiced", and with just these cases, the rule could be considered categorical. In contrast, however, the APi stops vary continuously from one extreme to the other, though with a clear peak in the distribution at 100% voicing (representing the shorter APi stops). This continuous distribution indicates that voicing is not simply "optional" for APi stops (else there would be a bimodal distribution); there must be some additional factor besides phrasal position alone that determines how much voicing APi stops show. Jun says as much when she states that the lenis stop voicing rule is a "by-product of some other effect of

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[3] It is interesting to compare the effect of phrasal position, as in the present study, and stress accent on closure voicing. Keating (1984) showed that in English and Swedish, stress on a following vowel *increased* the closure voicing of (syllable-initial) stop consonants, corresponding to predictions from an aerodynamic model of consonant production. The explanation was that the greater respiratory effort associated with stress caused subglottal pressure to increase more than it caused oral pressure to increase, thus favoring voicing. This difference between (English/Swedish) stress and (Korean) phrasal position suggests that domain-initial strengthening is not the same as stress, at least not in the sense of increased respiratory effort.

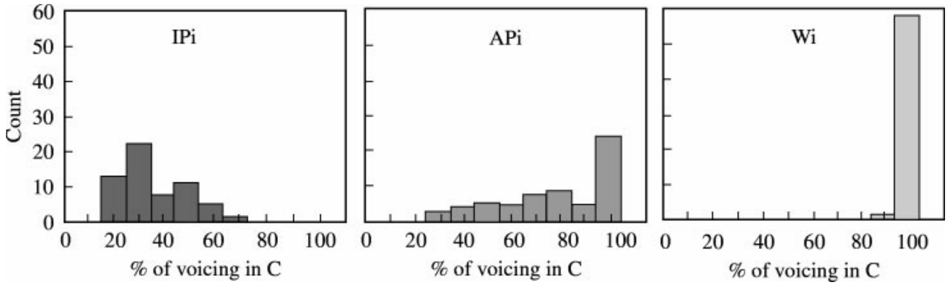

Figure 19. Distribution of %voicing measurements in different prosodic positions.

prosodic position on the gestural amplitude and overlapping, thus producing a continuum of voicing (1995*a*, p. 250)". Our data show that this effect is strongest in AP-initial position. Until that additional factor is understood, the grammatical status of Korean intervocalic voicing remains open.

4.5. *Competition between word-initial strengthening and word-medial gemination*

Recall that in Korean, word-medial tense stops are said to be lengthened (geminated), and perhaps articulated more forcefully, compared to word-initial tense stops. Under some accounts, tense stops are underlyingly geminates of two plain stops (e.g., Martin, 1982; Yu, 1989; Jun, 1994; Han, 1996) but are obligatorily degeminated word-initially (Han, 1996). Similarly, Oh & Johnson (1997), based on results on acoustic duration of word-medial stops, suggested that the extra length of geminate consonants is present only word-medially. In addition, Jun (1994) has proposed that aspirated stops are also longer word-medially, and therefore both the aspirated and the tense stops are phonological geminates (in his account, bimoraic) medially. Setting aside any theoretical issues about the phonological basis of gemination, what emerges from previous studies, and from our own, is that there is some sort of word-medial lengthening and strengthening effect for the tense stop, and perhaps the aspirated as well. In terms of linguopalatal contact, we saw (in Fig. 8) that two speakers had more contact for word-medial than word-initial /t^h/, and two speakers had more contact for word-medial than word-initial /t*/. In terms of seal duration, we saw that all three speakers had longer word-medial than word-initial /t^h/, and two speakers had longer word-medial than word-initial /t*/.

On the other hand, variation in VOT for /t^h/ follows the more general trend in strengthening (W-initial greater than W-medial). Thus, the behavior of stops in these domains is somewhat inconsistent. Word-medial oral lengthening and strengthening of /t^h/ and /t*/ often seem to override any general tendency to word-initial strengthening of consonants. It seems that medial strengthening of /t*/ and possibly /t^h/ is a more specific process that competes with the more general process of initial strengthening in Korean. It may be that in their competition, the two processes partially cancel each other out, so that the overall positional difference is small, or even nil, depending on the speaker.

Medial strengthening, if that is what it is, is somewhat surprising, as this position in Korean is not marked tonally or by any other prominence, and it is at the edge of only a very small prosodic domain, the syllable. However, medial lengthening is not so surprising, considering the phonological distribution of geminate consonants in languages, which are more common in word-medial, intervocalic position (Ladefoged & Maddieson, 1996). That is, if this effect is gemination rather than the kind of articulatory strengthening we have been considering, then it would not be expected to associate with prominent positions in general.

Is the medial lengthening that is observed in our data consistent with these two consonants being "geminated"? Although medial lengthening is the general pattern in our sample, the amount of lengthening is by no means a doubling, but is less than 20%. This is somewhat surprising since in Han (1996), word-medial /t*/ was found to be nearly twice as long as word-initial /t*/. However, in Han's study, the comparison probably involved more than simply word-medial *vs.* word-initial. The carrier sentence for the word-medial test consonants was "This is called ____" in which the test word, a nonsense word, is likely to be produced emphatically, forming an AP by itself. On the other hand, the word-initial test consonants were located in real words and placed in an unemphatic position. Thus, there may be another difference between her test words for word-initial and -medial consonants, namely the medial ones could be focused and the initial ones nonfocused. Jun & Lee (1998) found that Korean focused words, specifically, the consonants, were significantly longer than corresponding neutral words for three out of four speakers. So if Han's test words differ in both consonantal position and focus, her durational difference is likely to be greater than ours. In our sample, the comparison is a minimal one.

4.6. *Inherent articulatory properties of stops*

In Section 3.1.1 (Fig. 6), we observed that the test consonants varied in their extent of linguopalatal contact, in the decreasing order of /t*, t^h, t, n/. It appears that tense and aspirated stops can be grouped into a "strong" consonant type having greater linguopalatal contact, while nasal and plain stops can be grouped into a "weak" consonant type with lesser linguopalatal contact. As can be seen qualitatively in Fig. 6, the two stronger consonants maintain their large contact area at the beginning of all prosodic domains, and therefore we see smaller effects of prosodic position, while the two weaker consonants are overall more variable, and thus we see larger effects of prosodic position, with their contact ranging from large in higher prosodic positions to small in lower prosodic positions. Most notably in the figure, the weaker consonants /t/ and /n/ show particularly large differences in contact between AP- and IP-initial positions compared to the stronger consonants /t*/ and /t^h/. The lesser contact in these lower prosodic positions has been previously noticed for /t/ as an oral lenition (cf. Shin, 1997); here we see that /n/ exhibits this same lenition.

The consonant types differ in both peak contact and articulatory seal duration (compare Figs 6 and 9). As discussed in Section 4.2, differences in seal duration provide a good account of differences in peak contact, assuming target undershoot in shorter consonants. It is therefore possible that the inherent strength differences among consonant types arise from their differences in inherent duration. The only inherent differences in linguopalatal contact among the consonant types would be those seen in U-initial position in Fig. 9, and the differences in other prosodic positions would be temporally driven.

As a result of this possibly greater prosodic effect on /t/ and /n/, the differences in overall amounts of contact between the four consonants can be seen more clearly in the lower prosodic positions, where the stronger consonants remain strong while the weaker consonants show more weakening. In contrast, in higher prosodic positions where all the consonants are at their strongest, the differences between /t, n/ and /t*, t^h/ are less striking.

5. Conclusion

We have shown that Korean consonants /t, t^h, t*, n/ vary in their linguopalatal contact as a function of their position in a prosodic hierarchy. Consonants initial in higher phrasal prosodic domains are strengthened relative to consonants in lower domains. These results for Korean are particularly clear: not only do all four consonants studied here show this pattern, but there is more consistency across speakers than in previous studies of English, French and Taiwanese consonant articulation (Keating *et al.*, 1999). All three Korean speakers distinguish at least three prosodic levels by consonant contact. Segments on either side of prosodic domain boundaries are also lengthened, consistent with results from other languages. Thus, Korean does seem to reinforce the beginnings of prosodic domains with both lengthening and strengthening. Although this study, with only three subjects, cannot prove that Korean as a whole is always more consistent in this respect than other languages, the results are clear enough to be suggestive.

A second clear result of this study is the strong correlation of linguopalatal contact with duration (both articulatory and acoustic). This relation was much less strong in the previous studies of other languages. Thus in Korean, unlike in these other languages, it seems likely that differences in articulatory contact directly result from, or directly give rise to, differences in duration. That is, in Korean "lengthening" and "strengthening" appear to be a single effect, whereas in the other languages they appear to be somewhat more independent effects. We have interpreted our data as suggesting that oral strengthening results from lengthening: up to about 80 ms in duration, consonants show articulatory undershoot proportional to their durations; beyond this duration no undershoot is seen. This undershoot mechanism might even account for differences across the four types of stop consonants in Korean, since these vary in duration as well as in linguopalatal articulation.

At the same time, this study shows that Korean probably has two different strengthening effects. One is the more general effect seen in other languages as well, namely that consonants are stronger in higher prosodic positions, with respect to oral, nasal, and glottal articulations. The second is an effect specific to Korean, namely that tense and aspirated consonants can be stronger word-medially than word-initially. This holds only for the length and strength of their oral articulations; the glottal opening gesture for aspirated stops appears to follow the more general pattern of initial strengthening. We have proposed that the more general and more specific effects compete within the word domain, with somewhat variable results across speakers.

A final result of this study is that certain consonant acoustic dimensions also vary with prosodic position, especially the temporal dimensions stop closure duration, VOT, total voiceless interval. Even RMS burst energy, which is the dimension most clearly associated with the oral articulation, is somewhat correlated with linguopalatal contact. We also found preboundary vowel lengthening across prosodic positions, showing that Korean has final lengthening like other languages. Any or all of these acoustic dimensions may help listeners to hear the prosodic phrasing intended by the speaker; this remains to be established by perceptual testing.

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Appendix A

Test sentences for /t, tʰ, t*/

(a) Higher levels above word for /t/ in /a#_a/ (# = a prosodic boundary)
U-initial igosɨn patakka. [U tambiga jəgisə nɛɾinda]
(Ui) this place seashore ‘sweet-rain’ here is-falling
‘This place is the seashore. Sweet-rain falls down here’.

IP-initial igosɨn patakka, [IP tambiga nɛɾinɨn goʃida]
(IPi) this place seashore, ‘sweet-rain’ falls-Rel place
‘This place is the seashore, where the ‘sweet-rain’ falls down’.

AP-initial idɨɾɨn moduga [AP tambiɾɨl] tʃoahanda
(APi) these people all sweet-rain likes
‘These people all like ‘Sweet-rain’.’

Word-initial idɨɾɨn [AP patakka (W tambiɾɨl)] tʃoahanda
(Wi) these people seashore sweet-rain likes
‘These people like ‘seashore sweet-rain’.’

(b) Word and syllable levels for /t/ in /a#_a/ (# = a prosodic boundary)
Word-initial idɨɾɨn [AP kogjesa (W taɾiɾ̄l)] tʃabat*a
(Wi) these people acrobat legs held
‘These people held the legs of the acrobat’.

Syllable-initial idɨɾɨn [AP kogje (W sa(S taɾiɾɨl)] tʃabat*a
(Si) these people circus ladder held
‘These people held the circus ladder’.

(c) Higher levels above word for /tʰ/ in /a#_a/ (# = a prosodic boundary)
U-initial igosɨn patakka. [U tʰadʒani igosɨl tʃoahanda]
(Ui) this place seashore. Tarzan here like
‘This place is the seashore. Tarzan likes it’.

IP-initial igosɨn patakka, [IP tʰadʒanɨy kohjaŋida]
(IPi) this place seashore. Tarzan’s hometown
‘This place is the seashore, Tarzan’s home town’.

AP-initial idɨɾɨn moduga [AP tʰadʒanɨl] tʃoahanda
(APi) these people all Tarzan likes
‘These people all like Tarzan’.

Word-initial idɨɾɨn [AP patakka (W tʰadʒanɨl)] tʃoahanda
(Wi) These people seashore Tarzan likes
‘These people like the seashore-Tarzan’.

(d) Word and syllable levels for /tʰ/ in /a#_a/ (# = a prosodic boundary)
Word-initial idɨɾɨn [AP pakhasa (W tʰaŋsogɨl)] tɨljəda pwat*a
(Wi) these people sergeant Park’s bath tub looked in
‘These people looked in Sergeant Park’s bath tub’.

Syllable-initial idɨɾɨn [AP pakha (W sa(s tʰaŋsogɨl))] tɨljəda pwat*a
(Si) these people mint candy looked in
‘These people looked in the mint candy’.

Appendix A (Continued)

(e) Higher levels above word for /t*/ in /a#_a/ (# = a prosodic boundary)	
U-initial	igosɨn patakka. [U t*akpuɾiga jəgisə sanda]
(Ui)	this place seashore. T*akpuli (nickname) here lives
	'This place is the seashore. T*akpuli lives here'.
IP-initial	igosɨn patakka, [IP t*akpuɾiɨy kohjaŋida.]
(IPi)	this place seashore. T*akpuli's hometown
	'This place is the seashore, T*akpuli's hometown'.
AP-initial	idɨɾɨn moduga [AP t*akpuɾiɾɨl tʃoahanda]
(APi)	these people all T*akpuli-Acc. likes
	'These people all like T*akpuli'.
Word-initial	idɨɾɨn [AP patakka (W t*akpuriɾɨl)] tʃoahanda
(Wi)	these people seashore T*akpuli likes
	'These people like the seashore-T*akpuli'.
(f) Word and syllable levels for /t*/ in /ɛ #_a/ (# = a prosodic boundary)	
Word-initial	kɨjədʒanɨn [AP tʃoŋibɛ (W t*aɾagagiɾɨl)] tʃoahanda
(Wi)	the woman-Top. sail boat running-after-Acc likes
	'The woman likes running after the paper boat'.
Syllable-Initial	kɨjədʒanɨn [AP hjəndɛ (W bɛ(s t*aɾagiɾɨl)] tʃoahanda
	the woman-Nom. modern 'a kind of dance' like
(Si)	'The woman likes the modern 'pet*alaki''.

Appendix B

Results of statistical comparisons for linguopalatal contact, seal duration from ANOVAs performed separately for each speaker in which repetitions are the experimental unit, in accord with typical practice in the literature. These tests are not reported in the text of the paper. Bonferroni/Dunn pairwise comparison of percent of linguopalatal contact for higher levels and *t*-tests for lower levels. " > " (or " < ") refers to $p < 0.005$ for higher-levels. (Bonferroni/Dunn test with 3% significant alpha level) and $p < 0.05$ for lower levels (*t*-test) and " = " refers to no significance.

	Maximum contact	Seal duration
(a) Higher level comparisons		
Spkr NHL		
/n/	Ui > IPi > APi > Wi	Ui > IPi > APi = Wi
/t/	Ui > IPi > APi > Wi	Ui > IPi > APi > Wi
/t^h/	Ui = IPi > APi > Wi	Ui > IPi > APi > Wi
/t*/	Ui = IPi > APi > Wi	Ui > IPi = APi > Wi
Spkr THC		
/n/	Ui > IPi > APi = Wi	Ui > IPi > APi = Wi
/t/	Ui > IPi > APi > Wi	Ui > IPi > APi = Wi
/t^h/	Ui = IPi > APi > Wi	Ui > IPi > APi > Wi
/t*/	Ui = IPi > APi > Wi	Ui > IPi > APi > Wi

Appendix B (Continued)

Spkr JYY		
/n/	Ui > IPi > APi = Wi	Ui > IPi > APi = Wi
/t/	Ui > IPi > APi < Wi	Ui > IPi > APi = Wi
/tʰ/	Ui > IPi > APi = Wi	Ui > IPi = APi > Wi
/t*/	Ui > IPi > APi = Wi	Ui > IPi > APi = Wi
(b) Lower level comparisons		
Spkr NHL		
/n/	Wi > Si	Wi > Si
/t/	Wi = Si	Wi = Si
/tʰ/	Wi < Si	Wi < Si
/t*/	Wi > Si	Wi < Si
Spkr THC		
/n/	Wi > Si	Wi > Si
/t/	Wi > Si	Wi > Si
/tʰ/	Wi = Si	Wi < Si
/t*/	Wi < Si	Wi < Si
Spkr JYY		
/n/	Wi > Si	Wi = Si
/t/	Wi = Si	Wi < Si
/tʰ/	Wi < Si	Wi < Si
/t*/	Wi < Si	Wi < Si