Closure Duration and Pitch as Phonetic Cues to Korean Stop Identity in AP-medial Position: Perception Test

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ABSTRACT

The present study investigated some perceptual phonetic attributes of two Korean stop types, aspirated and lax, in medial position of an accentual phrase. The intonational pattern across syllables (Jun, 1993) is argued to depend on the type of stop (aspirated vs. lax) only in the initial position of an accentual phrase. In Kang & Dilley (2007), we showed that significant differences between aspirated and lax stops in medial position of an accentual phrase exist in closure duration, voice-onset time, and fundamental frequency (F0) values for post-stop vowels. In the present perception experiment, we investigated whether these phonetic attributes contribute to the perception of these two types of stops: The closure durations and/or F0's of post-stop vowels on accentual-phrase medial words were altered and twenty native Korean speakers then judged these words as beginning with an aspirated or lax stop. Both closure duration and F0 significantly affected judgments of stop identity. These results indicate that a wider range of acoustic cues that distinguish aspirated and lax Korean stops in production also plays a role in perception. To account for these results we suggest some phonetic and phonological models of consonant-tone interactions for Korean.

Keywords: Korean stop type, medial position of an accentual phrase, perception, F0, closure duration

1. Introduction

Korean is notable in having three manners of articulation, namely, lax, aspirated, and tense (or fortis) in addition to three places of articulation for stops. Thus, nine voiceless stops occur word-initially, word-medially and word-finally (Table 1). <Tables 2 and 3> show Korean stops in several different prosodic positions. These tables are from Kang & Dilley (2007).

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Table 1. Stops in Korean

	Bilabial	Dental	Velar
Lax	p	t	k
Tense	P	T	K
Aspirated	p^h	t^h	k^h

Table 2. Example lexical items with stops in word-initial position

	Bilabial	Dental	Velar
Lax	pul 'fire'	tam 'fence'	kaŋ 'river'
Tense	Pul 'horn'	Tam 'sweat'	Kori 'tail'
Aspirated	p^hul 'grass'	t^ham 'greed'	k^hal 'knife'

Table 3. Example lexical items with stops in word-medial position

	Bilabial	Dental	Velar
Lax	apəci 'father'	kita 'to crawl'	aki 'baby'
Tense	oPa 'brother'	kwiTurami 'cricket'	aKita 'be precious'
Aspirated	ap^hita 'be sick'	Kat^huri 'hen pheasant'	sok^huri 'bamboo basket'

These Korean stops are shown to be distinguished from one another by three phonetic variables. First, voice-onset time (VOT) is generally longest for aspirated stops, longer for lax stops and shortest for tense stops. (cf. Lisker & Abramson, 1964; C.-W. Kim, 1965, 1970; Han & Weitzman, 1970). However, VOT ranges for different manners of articulation often overlap (Lisker & Abramson, 1964; Kim, 1965, 1970; Silva, 1992).

Another factor that distinguishes Korean stops is F0. It has been shown that F0 levels of vowels after aspirated and tense stops are higher than those of vowels following lax stops (Han and Weitzman, 1970; Hardcastle, 1973; Jun, 1993). It is known that in general voiceless consonants raise the F0 of vowels in post-consonantal position (Lehiste & Peterson, 1961; Liberman, 1963; Ladefoged, 1964; Hombert, 1978). However, several researchers have shown that segmental effects in the vicinity of the stop release cannot solely explain differences in F0 observed among different stop types across the post-stop vowel (Kohler, 1993).

Third, closure duration differences have been shown to exist in productions of aspirated, tense, and lax stops. Aspirated stops have the longest closure duration, while tense stops have the shortest closure duration (Silva, 1992; Han, 1996).

Phonetic attributes of Korean stops we mentioned above are shown to vary depending on their positions within prosodic constituents (cf. Jun, 1993, 1995; Cho & Keating, 2001). Prosodic structure in Korean is generally held to consist of several hierarchical levels (Jun, 1993; Pierrehumbert, 1980; Beckman & Pierrehumbert, 1986). These are the intonational phrase (IP),

an accentual phrase (AP), or a prosodic word (PW) from the largest to the smallest constituent. Voice-onset time (VOT) is shown to depend on whether stops are positioned at the onset of an intonational phrase (IP), an accentual phrase (AP), or a prosodic word (PW) (Jun, 1993, 1995; Cho & Keating 2001). Moreover, in AP-initial position, F0 differences are stronger perceptual cues to stop contrasts than VOT differences (Kim, Beddor & Horrocks, 2002).

The F0 characteristics of stop-initial syllables in Korean are held to depend on their position within the AP. Jun (1993) argues that an AP consists of a sequence of four tones, $[T_1H_2..L_{n-1}H_n]$. The first tone, T_1, is associated with the first syllable in the AP. If the initial word in an AP begins with a tense or aspirated consonant, the first syllable will have a high tone. If the initial word begins with a lax stop or other segment, the first syllable will have a low tone. The F0 in positions other than AP-initial position is assumed not to be affected by the type of stop consonant. The second tone H is assumed to be assigned to the second syllable in the phrase. The third tone, Low, is assigned to the penultimate syllable in the phrase. The fourth tone, which is High, is assigned to the final syllable in the phrase. Any medial syllables that occur between the High tone on the second syllable and the Low tone on the penultimate syllable are expected to show phonetic interpolation between the High and the Low.

Kang & Dilley (2007) have conducted a production study on the acoustic properties of different types of stops in AP-medial position and reported several noteworthy results. One finding was that aspirated stops showed longer closure durations and VOT's compared to lax stops, as expected. Another finding concerned three sorts of F0 differences that are not predicted under existing phonological accounts of Korean phonetics and phonology. First, analysis of materials consisting of an AP with 4 syllables revealed that AP-medial syllables that were assigned a phrasal H tone had a higher F0 if they began with an aspirated stop than if they began with a lax stop. Second, analysis of materials consisting of an AP with 5-6 syllables revealed that the F0 levels of stop-initial syllables occurring between syllables assigned phrasal H and L tones were affected by whether the stops were aspirated or lax. Third, a histogram revealed partial separation of lax vs. aspirated stops when ratios of F0 measurement points were plotted, suggesting that F0 might be productively used as a phonetic cue in distinguishing these stops. Finally, the fact that relations among F0 values show more consistency across talkers when expressed as a ratio than as a simple frequency difference in Hz is consistent with the view that the relevant phonetic F0 cue to linguistic and semantic distinctions is a ratio of frequencies (Dilley, 2005). These three sorts of differences were obtained even though measurement points occurred later than onset F0's associated with segmental perturbations (Silverman, 1986; Whalen, Abramson, Lisker & Mody, 1990), suggesting that these differences in the F0's of aspirated and lax stops arose from the intonational component of Korean prosodic structure. These facts cannot be accounted for by current Korean prosodic theory.

In this paper, we investigated the extent to which listeners use differences in F0 and closure

duration in order to perceptually distinguish between aspirated and lax stops in AP-medial position. Kang & Dilley (2007) have shown that talkers produce F0 and closure duration differences consistently in distinguishing between Korean stops. Thus, if talkers use these differences consistently in perceptually distinguishing between Korean stops, it will highlight the need for revisions to Korean phonological theory.

2. Experiment

Kang & Dilley (2007) demonstrated that speakers utilize distinct F0 levels on syllables beginning with aspirated vs. lax stops, even in AP-medial position. However, the extent to which these F0 differences are used in perception of the aspirated vs. lax stop distinction is not clear. The present Experiment was therefore conducted to address this issue.

2.1 Methods

Stimuli. Two series of stimuli were constructed for the perception test. The first series, termed the Original-Lax series, was based on a single token of the utterance *kyəŋa tanari-lil*, while the second series, termed the Original-Aspirated series, was based on a single token of the utterance *kyəŋu t^{h}anari-lil*. Both tokens were produced by one of the speakers (JL) who participated in the production test reported in Kang & Dilley (2007). This speaker, like all speakers who participated in the production study, was naïve to the purposes of the experiment. Both tokens showed little to no segment-related F0 perturbation at the point of transition from the stop consonant to the following vowel.[1)]

Each utterance was produced as a single AP ($L_1H_1 \cdots L_2H_2$), so that the initial two tones, L_1 and H_1, were realized on *kyəŋ-* and *-a/-u*, while L_2 and H_2 were realized on *-ri* and *-lil*, respectively. In addition, the syllables between *-a/-u* and *-ri* showed monotonically falling F0s between the locally high value for H_1 and the low value for L_2. Moreover, each token had a VOT which was intermediate between canonical lax and canonical aspirated stops for this speaker.[2)]

Our expectation was that varying the F0 level of the first part of utterances relative to the second part or vice versa would affect the rate at which listeners heard lax vs. aspirated /t/. F0 levels for the first or second half of utterances for the two stimulus series were selected

1) In particular, the F0 did not drop steeply after the stop release for the aspirated token, nor did the F0 rise right after the release of the lax token. These characteristics have been implicated in distinguishing voiced and voiceless obstruents (Lehiste & Peterson, 1961; Hombert, 1978; Silverman, 1986).

2) In particular, the VOT's for the lax and aspirated tokens were 27 ms and 44 ms; the mean VOT's for lax and aspirated tokens for this speaker were 15 ms and 58 ms, respectively.

through a process by which the first author, who is a native Korean speaker, determined a minimal degree of F0 change to the first or second half of the utterance which seemed to elicit a change in stop identity from aspirated to lax or vice versa. A second, larger degree of F0 change was then determined based on this value which corresponded to a value which was equal on a log scale to the amount of F0 change between the unmodified and modified F0 values. In all cases, local F0 shape cues in the vicinity of the aspirated vs. lax stop consonant were held constant, in order to rule out the possibility that any effects of the F0 manipulations on stop identification could be attributed to phonetic, segment-related F0 perturbations. Two pilot experiments were then conducted to determine whether the F0 changes in stimuli would be interpreted by naïve listeners as a change in stop identity. None of the subjects participating in either of the pilot studies participated in the full perception experiment.

Based on these procedures, five levels of F0 were introduced for each stimulus series, as follows. First, the relative F0 levels in the Original-Lax series were either (1) unaltered, (2) varied by lowering the F0 of the first half of the utterance (*kyəŋa*) by a relatively smaller or larger amount (7.6% vs. 14.6%), or (2) varied by raising the F0 of the last half of the utterance (*tanari-lil*) by a relatively smaller or larger amount (4.5% vs. 9.2%). Similarly, the relative F0 levels in the Original-Aspirated series were either (1) unaltered, (2) varied by raising the F0 of the first half of the utterance (*kyəŋu*) by a relatively small or larger amount (16.2% vs. 35%), (3) varied by lowering the F0 of the second half of the utterance (*t^{h}anari-lil*) by a relatively small or larger amount (11% vs. 20.8%). In the case of both the Original-Lax and the Original-Aspirated series, stimuli involving a smaller amount of F0 change had F0 values which were halfway between those of unaltered stimuli and those of stimuli involving a larger change on a logarithmic scale. Stimuli for both series are shown in <Figure 1>. F0 manipulations were carried out using Praat software (Boersma & Weenink, 2002) and resynthesized using an implementation of a PSOLA algorithm (Moulines & Charpentier, 1990). Again, local F0 shape cues in the vicinity of the aspirated vs. lax stop consonant were held constant.

Moreover, closure duration was manipulated in both series. For the Original-Lax series, closure duration was either (1) held constant or (2) lengthened by 14 ms (from 53 ms to 67 ms). For the Original-Aspirated series, closure duration was either (1) held constant or (2) shortened by 31 ms (from 77 ms to 46 ms). All splices were made at zero crossings. These 5 F0 levels x 2 closure durations led to 10 stimuli in the Original Lax series and 10 stimuli in the Original Aspirated series, for a total of 20 stimuli.

Participants. Twenty Seoul-dialect speaking Hanyang University students participated in the experiment. Subjects were either given course credit or were paid a nominal sum. None reported any hearing problem.

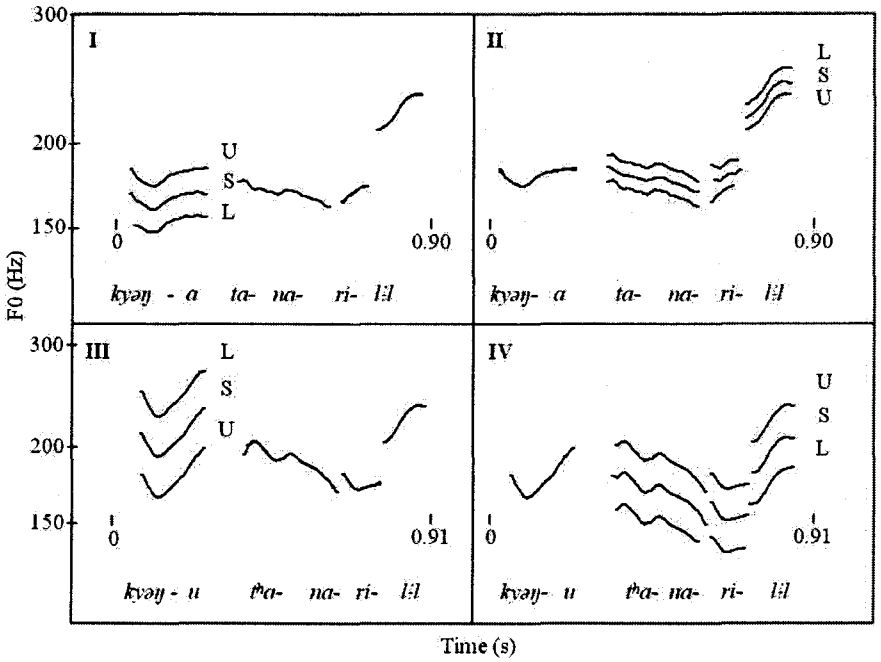

Figure 1. Stimuli used in the perception experiment. Original-Lax stimuli with their first or second portions altered are shown in panels I and II, respectively, while Original-Aspirated stimuli with their first or second portions altered are shown in panels III and IV. Each panel illustrates relatively small (S) or large (L) F0 alterations, along with the unaltered (U) F0 curve for comparison. All stimuli are depicted with the original closure duration.

Procedure. Original-Lax and Original-Aspirated stimuli were randomized and then presented in five separate blocks. Stimuli were presented over high quality headphones in a quiet office. Four phrases were displayed on a computer monitor, corresponding to the two possible context words (*kyəŋa* vs. *kyəŋu*) combined with the two stop types (aspirated vs. lax), giving *kyəŋu tʰanari-l:l*, *kyəŋu tanari-l:l*, *kyəŋa tʰanari-l:l* and *kyəŋa tanari-l:l*. A number from 1-4 was shown next to each phrase. Participants were told to use a mouse to select the answer on the computer screen corresponding to what they heard. Their responses were recorded on a PC. All subjects were first given four practice trials with feedback to ensure they could perform the task. Since each of the 20 stimuli was presented five times over the course of the experiment, each participant made a total of 100 judgments. The entire experiment lasted less than 20 minutes.

Analysis. For each stimulus, we determined the percentage of stimulus presentations for which participants reported hearing an aspirated stop. Because identification of *kyəŋa* vs. *kyəŋu*

was not relevant to the distinction of what the type of stop was, we collapsed responses which indicated a lax stop preceded by either *kyəŋa* or *kyəŋu*, as well as responses which indicated an aspirated stop preceded by either *kyəŋa* or *kyəŋu*.[3)]

2.2. Results

Separate ANOVAs were conducted on the Original-Lax and Original-Aspirated stimuli with three main factors: Closure Duration (Unaltered vs. Lengthened for the Original-Lax stimuli or Unaltered vs. Shortened for Original-Aspirated stimuli), F0 Difference (Unaltered, Small, or Large), and Position, i.e., whether the F0 of the first part (*kyəŋV*) or the second part (*tanari-lil* /*t*^{h}*anari-lil*) of the utterance was altered. <Figure 2> shows results for the Original-Lax series. For this series, there was a main effect of Closure Duration ($p < .0001$, $F = 206.44$, $df = 19$) and F0 Difference ($p < .0001$, $F = 88.48$, $df = 19$), but no main effect of Position ($p > .05$, $F = 0.196$, $df = 19$). There was, however, a significant interaction of F0 Difference and Closure Duration ($p < .0001$, $F = 76.87$, $df = 19$), as well as of F0 Difference and Position ($p < .0001$, $F = 18.78$, $df = 19$), but no other significant interactions.

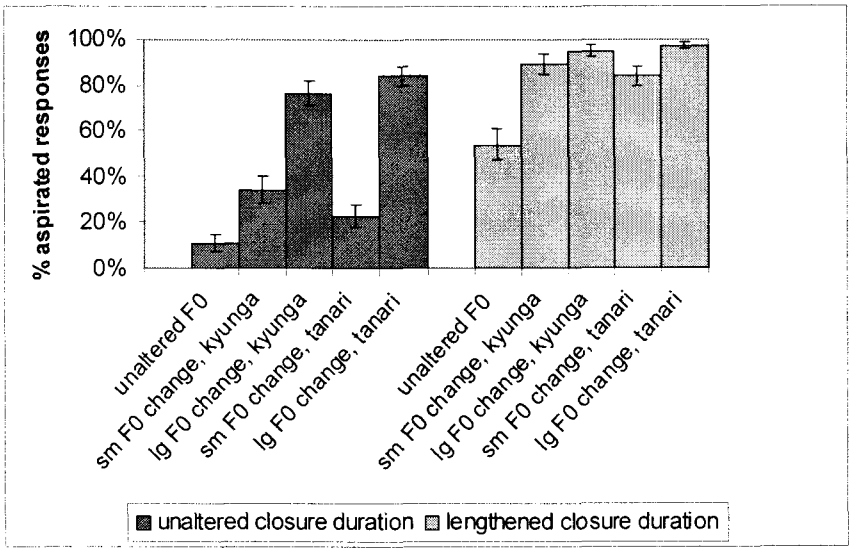

Figure 2. Percentage of "aspirated" responses to Original-Lax stimuli with unaltered or lengthened closure duration. Stimuli had one of three degrees of F0 change (unaltered, small, or large) applied to the first (*kyəŋa*) or second (*tanari*) portion of the utterance.

3) Across all subject responses, there were only 15 times out of 2000 presentations in which a subject misclassified a stimulus that started with *kyəŋa* as *kyəŋu* or vice versa. These were likely errors associated with the added complexity of having four response choices, rather than two.

<Figure 3> shows results for the Original-Aspirated series. For this series, there were main effects of Closure Duration ($p < .0001$, $F = 384.99$, $df = 19$), F0 Difference ($p < .0001$, $F = 62.24$, $df = 19$), and Position ($p < .0001$, $F = 85.25$, $df = 19$). Moreover, there was an interaction of F0 Difference and Position ($p < .0001$, $F = 19.29$, $df = 19$), as well as a three-way interaction ($p < .0001$, $F = 25.92$, $df = 19$), but no other significant interactions.

To estimate the relative effectiveness of manipulations to the Original-Lax and Original-Aspirated stimuli, we conducted a separate ANOVA with main factors of Stimulus (Original-Lax vs. Original Aspirated) and Closure Duration. There was a main effect of Stimulus Series ($p< .0001$, $F = 165.76$, $df = 19$) and of Closure Duration ($p < .003$, $F = 11.4$, $df = 19$). Moreover, there was a significant interaction between the two factors ($p < .0001$, $F = 53.97$, $df = 19$).

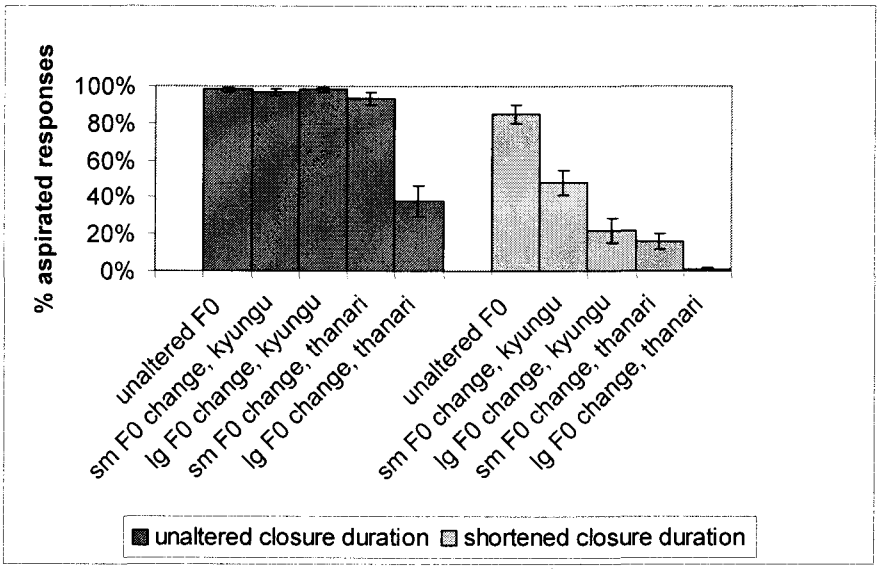

Figure 3. Percentage of "aspirated" responses to Original-Aspirated stimuli with unaltered or shortened closure duration. Stimuli had one of three degrees of F0 change (unaltered, small, or large) applied to the first (*kyəŋu*) or second (*t^{h}anari*) portion of the utterance.

2.3 Discussion

Contrary to the predictions of phonological theory, the results from this perception experiment suggest that even in AP-medial position, F0 is a strong and effective cue to the distinction between lax and aspirated stops. For both stimulus series, altering the F0 of stimuli resulted in significant changes in stop consonant identification. These results cannot be explained by differences in segment-related perturbations to F0 shape on individual syllables, since F0 shape was held constant within each stimulus series. This experiment therefore

establishes the relevance of F0 changes in AP-medial position like those demonstrated in the production study (Kang & Dilley, 2007) to the perception of aspirated vs. lax stops, as well as their significance for phonological theories of segment-tone interactions.

The interactions between F0 and closure duration across the two stimulus series indicate that a given degree of F0 change was differentially effective at eliciting a change in stimulus percept when paired with a given change in closure duration. This could be due in part to the fact that "large" and "small" F0 changes for the two series corresponded to different absolute amounts of F0 change, leading to differential effects on perception. Moreover, the stimuli in each of the two series contained different amounts of aspiration noise. This could potentially explain the fact that F0 changes had little effect on rate of reporting aspirated stops in the Original-Aspirated series when the original closure duration was maintained. This appears to be consistent with previous results that for stop consonants with certain VOT ranges, an F0 change across a post-stop vowel does not yield a change in stop consonant percept (Abramson & Lisker, 1985; Whalen, Abramson, Lisker & Mody, 1990).

3. General Discussion

This study investigated some perceptual correlates of the distinction between aspirated and lax stops in Korean occurring in a particular prosodic position, namely, medial in an accentual phrase (AP). In particular, Kang & Dilley (2007) showed that speakers produce F0 and closure duration differences on vowels following aspirated and lax stops in AP-medial position. The present experiment showed that listeners use pitch and closure duration differences to perceptually distinguish between aspirated and lax stops in AP-medial position. These results add to a growing body of work demonstrating the effects of F0 on perception of segmental contrasts for a prosodic context which has previously received little attention (cf. Kim, Beddor & Horrock, 2002). In the following paragraphs, we focus on the F0 differences between aspirated and lax stops and the implications of these findings for phonological theory.

First, the observed F0 differences in production (Kang & Dilley, 2007) and their effects on perception are not predicted by current theories of Korean phonology and phonetics. In particular, given an AP defined by a string of tones $T_1H_2L_3H_4$, phonological theory does not predict significant F0 differences between aspirated and lax stops in AP-medial position. Kang & Dilley (2007) have shown that such differences are observed in production and the present experiment show that they are significant for perception. Later we will address the issue of how these results might be accounted for within phonological theory.

In addition to demonstrating the importance of F0 for aspirated vs. lax stops in perception, the present paper is the first to demonstrate a role for closure duration in the perception of

these two stop types. These findings are significant for at least two reasons. First, these results are consistent with the notion of a common perceptual basis across languages for phonological distinctions involving length contrasts (Port & Dalby, 1982; Han, 1996; Kim & Curtis, 2002; Kang & Yoon, 2005, etc.). Second, these results support the claim of some linguists (Silva, 1992; J.-H. Jun, 1994; Kang, 2004) who have claimed that aspirated stops should be represented as geminated. Moreover, these results support the proposal of Kang (2004) that stop closure duration serves as the phonetic basis of a productive morpho-phonological process in Korean involving a change from a lax to an aspirated stop. For example, concatenating a morpheme ending in aspirated /h/ (e.g., /coh/) to one beginning with a lax stop (e.g., /ta/) results in perception of an aspirated stop: [cot^{h}a] 'happy'. Similarly, if a morpheme ending in a lax stop (e.g., /cap/) is concatenated with a morpheme beginning an /h/, an aspirated stop again occurs, as in /cap-hi-ta/ [cap^{h}ita]: 'be held.' She argues that the long closure duration derived by the addition of the segment /h/ is the phonetic basis that prevents stops from being lenited intervocalically. Previously, Han (1996) found that lengthening closure duration for a tense stop results in the perception of a lax stop, while Kang & Kang (2006) replicated this finding using greater controls and a large number of tokens, and show that lengthening the closure duration transforms most of lax stops to tense. On the basis of this Kang & Kang (2006) conducted another perception test, showing that closure duration plays a role in a process known as post-stop tensification, whereby lax stops are transformed into tense stops when they occur after another stop through morpheme concatenation. Given observations that lax stops have variable degrees of aspiration, these results support the contention that closure duration constitutes part of the phonetic basis of both types of phonological process in Korean.

There are two limitations on the present results. First, these studies investigated only a single contrast, namely, the distinction between aspirated and lax alveolar consonants. This provided a convenient starting point for investigation of a previously unexplored issue, and generalization from these results to other places of articulation (labial, velar) will need to be made carefully. Second, only the contrast between aspirated and lax stops was examined; tense stops were not examined. Future work will be needed to determine if these findings generalize to other stop types.

How can these results be incorporated into phonological theory? The issue of how to accommodate phonetic variability has recently received much attention in phonology. Two general approaches to this issue have been taken. Under one view, variability is represented in the lexicon directly; this approach is known as exemplar theory (cf. Semon, 1923; Hintzman, 1986; Skousen, 1989; Goldinger, 1996; Bybee, 2001). According to this view, listeners represent individual instances or "exemplars" of token items (e.g., words) in the lexicon. Under this view, exemplars give rise to emergent probability distributions which form the basis of linguistic categories. Under an alternative view, the lexicon specifies phonetic cues as either primary to a

given linguistic distinction, or else as secondary or subordinate "enhancement" cues (Stevens & Keyser, 1989; Kingston & Diehl, 1994; Silverman, 1986). In support of this latter view, there are many examples cross-linguistically of cases in which phonetic attributes show redundancy with one another in cueing phonological distinctions. For example, the distinction between canonical voiced and voiceless consonants rests in part on a VOT length distinction, where this durational difference is usually redundant with a vowel length distinction. In particular, vowels preceding voiced stops are longer than those preceding voiceless stops (e.g., Klatt, 1976). These cues normally are thought to "enhance" one another and thereby making the contrast more perceptually salient to a listener. For example, when /t/ or /d/ is realized as a flap, the durational difference between these underlyingly distinct stops is neutralized; nevertheless, there is a significant difference in the durations of vowels preceding underlying /d/ and /t/ (Fox & Terbeek, 1977; Zue & Laferriere, 1979; Patterson & Connine, 2001). Similarly, the duration of the vowel which precedes stops in German which have been devoiced depends on the voicing status of the underlying segment (Port & O'Dell, 1985). It appears that closure duration and F0 may exhibit a similar redundancy relationship in Korean. This may partly account for the perceptual salience of the aspirated vs. lax distinction in the face of variability in the realization of these two phonetic cues. Our results are consistent with both possibilities, and future work will be needed to distinguish between them.

Moreover, we see two distinct implications of these results for phonological theories of intonation. First, it is necessary to modify phonological theory so as to account for the fact that the F0 was often higher in the case of aspirated consonants in AP-medial position, compared with lax consonants. According to standard Korean intonational phonology (cf. Jun, 1993), interactions between segmental identity and intonation occur only in initial position in an AP (notated here as the tone sequence $T_1H_2L_3H_4$). In particular, it is assumed (1) that a H tone replaces T_1 when an aspirated or tense stop is in AP-initial position, (2) that a L tone replaces T_1 when a lax stop is in AP-initial position, and (3) that segmental identity does not affect intonation elsewhere in an AP. Our results are clearly in contradiction with (3). How can the effects of segment type on intonational F0 levels in AP-medial position be accommodated?

Our account of the fact that syllables in AP-medial position beginning with aspirated stops have higher F0 than those beginning with lax stops rests on two propositions. First, we propose to extend the work of Jun (1993, 1998) regarding segmental-intonational interactions by suggesting that a H tone is always assigned to a syllable bearing an aspirated consonant, regardless of its position in an AP. Thus, according to this account, the intonational structure is determined both by the segmental level tone structure as well as by the phrasal level tone structure (i.e., the assignment of $T_1H_2L_3H_4$ to the entire AP).[4] We assume that at the segmental

4) Given that the present study did not address the F0 characteristics of tense stops in AP-medial position, we tentatively propose that a H tone is assigned to these stops as well

level, syllables beginning with aspirated and tense stops are assigned a high tonal target, while syllables beginning with a lax stop are assigned no tonal target, regardless of position. Then following Jun's proposal, tones at the suprasegmental level are assigned to syllables based on their positions within the prosodic structure. In particular, tones T_1, H_2, L_3, and H_4 are assigned to particular syllables based on position within an AP; a H tone replaces T1 when an aspirated or tense stop is in AP-initial position and a L tone replaces T_1 when a lax stop is in AP-initial position. Second, we propose that the effect of a segmental H is to induce "upstep" to the syllable by increasing its local pitch range. Such pitch range effects can be modeled in a variety of different ways (e.g., Pierrehumbert & Beckman, 1988; Dilley, 2005).

A second implication for phonological theory concerns the fact that the relevant phonetic F0 cue to stop distinctions was the F0 of syllables relative to other syllables, rather than the absolute F0 of a syllable. This was demonstrated by the finding that raising or lowering the first part of the utterance affected perceived stop consonant identity, even when the F0 contour of the second part of the utterance, which contained the stop consonant, was held fixed. This is not predicted under some interpretations of the phonetics-phonology relation for F0. In particular, the absolute F0 level within a speaker's pitch range is emphasized as the phonologically relevant phonetic factor to distinctions among intonational categories in seminal work in intonational phonetics and phonology (Goldsmith, 1976; Pierrehumbert, 1980; Pierrehumbert & Beckman, 1988; Dilley & Brown, forthcoming). In contrast, the relative F0 levels of syllables are seen as phonetic variation which do not contribute directly to the phonological representation.[5] This claim is inconsistent with the present results, which demonstrate that the relative F0 levels of syllables affect the perceived phonological identity of segments. These results can be accommodated within the framework of Dilley (2005, forthcoming), who proposes that the phonetic cues to the phonological distinction between H and L in intonation languages are the relative pitch (i.e. F0) relations among tones with respect to one another in sequence. Given the present findings, we therefore interpret these results as

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and leave this issue for future work

5) As shown in Dilley (2005), previously articulated theories of the relationship between phonology and phonetics for tone-F0 relations assume multiple unconstrained parameters (cf. Pierrehumbert 1980, Liberman and Pierrehumbert 1984, and Pierrehumbert and Beckman 1988). As a result, they do not make testable predictions about the relationship between (phonological) tonal sequences and (phonetic) F0 contours. However, it is possible to nevertheless test these theories on the basis of two assumptions. (1) All these proposals assume that the height of F0 within the speaker's pitch range is the primary phonetic correlate, and that relative height relations among tones are secondary (Pierrehumbert, 1980, Liberman and Pierrehumbert, 1984) or nonexistent (Pierrehumbert and Beckman, 1988). (2) Most versions of these proposals implicitly assume that the parameters mediating the phonetics-phonology relation are constrained so that e.g. H has a higher F0 than that of adjacent L. When these assumptions are made, these proposals become testable.

support for Dilley's proposal.

In summary, the present study demonstrated that speakers use pitch to differentiate between aspirated and lax stops in AP-medial position, and that listeners use these cues in perceiving this stop contrast in this prosodic position. These results are not predicted under current intonational phonological theories. Moreover, the present study is the first to demonstrate an effect of closure duration on the distinction between aspirated and lax stops. These findings have implications for the understanding of morphological processes in Korean.

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