Acoustic and aerodynamic correlates to Korean stops and fricatives

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This study examines acoustic and aerodynamic characteristics of Korean consonants in two dialects, Seoul and Cheju, with the focus on the well-known three-way distinction among voiceless stops (i.e., lenis, fortis, aspirated) and the two-way distinction between **s** and **s***. While such a typologically unusually voicing contrast among voiceless stops has long drawn the attention of many phoneticians and phonologists, there is no single work documented in the literature that provides us with a coherent and comprehensive body of data representing a large number of speakers. By examining a variety of acoustic and aerodynamic parameters simultaneously from a large body of data (from a total of 12 speakers from two dialects), we aim to contribute a comprehensive study to the literature that could serve as a basis for future studies bearing on issues related to Korean obstruents. Among other findings there are three crucial points worth noting. Firstly, lenis, fortis, and aspirated stops are systematically differentiated from each other by the voice quality of the following vowel. Secondly, these stops are also differentiated by aerodynamic mechanisms. The aspirated and fortis stops are similar in supralaryngeal articulation, but employ a different relation between intraoral pressure and flow. Thirdly, our study suggests that the fricative **s** is better categorized as 'lenis' than as 'aspirated' in terms of its phonetic realization. This paper can also be viewed as documenting an endangered language, the Cheju dialect, as number of its speakers has gradually decreased over time.

1. Introduction

In most of the world's languages, when stops have a three way contrast, they are categorized in terms of voicing and aspiration: 'voiced', 'voiceless unaspirated' and 'aspirated' (e.g., Lisker & Abramson, 1964; Klatt, 1975; Ladefoged & Maddieson, 1996). Korean stops, however, are typologically unusual in that they have a three-way contrast, but they are all *voiceless*. They also use the same airstream mechanism, i.e. pulmonic egressive. The three different categories are often called lenis, fortis and aspirated, and all these occur at three places of articulation: bilabial, denti-alveolar, and velar. The lenis stops have been described as lax, breathy, and slightly aspirated, the fortis stops as tense, laryngealized, and unaspirated, and the aspirated stops as being strongly aspirated.

Along with the stops, Korean has a three-way contrast in affricates but only a two-way contrast in denti-alveolar fricatives, which we will call plain **s** vs. fortis **s***, so as to avoid any unnecessary confusion brought about by the terminology *lenis* vs. *aspirated*. Table 1 shows all the Korean obstruents. In this table, **s** is categorized as lenis for the sake of simplicity. The diacritic '*' is used to mark fortis obstruents. Table 2 gives minimal triplets (or, in the case of the denti-alveolar fricatives, a minimal pair) for the obstruents in Table 1.

Table 1. Obstruents in Korean: lenis, fortis, and/or aspirated distinctions

lenis series	p	t	tʃ	k	s
fortis series	p*	t*	tʃ*	k*	s*
aspirated series	p^h	t^h	$tʃ^h$	k^h	

Table 2. Minimal contrasts for Korean obstruents in word-initial position

Lenis		Fortis		Aspirated	
paŋ	'room'	p*aŋ	'bread'	p^haŋ	'bang'
tal	'moon'	t*al	'daughter'	t^hal	'mask'
tʃata	'to sleep'	tʃ*ata	'to squeeze'	$tʃ^h$ata	'to kick'
kæta	'to fold up'	k*æta	'to break'	k^hæta	'to dig up'
sata	'to buy'	s*ata	'to wrap'	—	—

As reviewed in the next section, several studies have examined a number of acoustic/aerodynamic parameters that might differentiate the three-way contrast in stops. Nevertheless, as far as we know, there is no single work documented in the literature that addresses all these parameters with a relatively large subject pool. The nearest is Dart's (1987) study which had data from ten speakers, but was limited to aerodynamic data for the lenis and fortis stops, excluding the aspirated stop. To understand the phonetic properties underlying the three-way contrastive stops in Korean, we need to collect a body of data from a number of speakers and examine a variety of phonetic parameters at the same time in much the same way. Without such controls, we cannot be assured about the generalizability of the data. It may be possible that any observed differences can be simply due to the procedures used to obtain data or due to characteristics specific to the small number of speakers recorded. In the present study, we collect both acoustic and aerodynamic data from twelve speakers in two dialects, Seoul and

Cheju, of Korean, and examine a variety of phonetic parameters at the same time. It is hoped that the present study will serve as a comprehensive reference for future research related to Korean obstruents. In addition to providing extensive data, we have several specific goals in mind. Firstly, we will examine not only the acoustic properties of the consonant itself (e.g., VOT, burst energy, and closure/frication duration) but also properties of the following vowel such as voice quality and fundamental frequency. In particular, we will investigate how and to what degree the three-way contrast of stops can be differentiated by the voice quality of the following vowel.

Secondly, we will examine the aerodynamic properties of stops in terms of airflow and air pressure. There are only a few studies available that have examined airflow and air pressure of Korean stops (e.g., Dart, 1987; Silverman & Jun, 1994). As far as we know, the current study is the first one to examine the aerodynamic properties of all three stop categories in Korean.

Thirdly, we will investigate the acoustic properties of the two contrasting fricatives, **s** and **s***. Unlike stops, the phonetic properties of the fricatives have not been well studied, and the categorization of the plain **s** has been controversial. It is sometimes categorized as lenis and sometimes as aspirated (cf. Kagaya, 1974; Iverson, 1983; Jun, 1999; Park, 1999). By examining the acoustic properties of fricatives using the same methods as for stops, we will determine what acoustic parameters differentiate **s** and **s***, and what category the plain **s** belongs to or is better classified as. The present study is the first one directly comparing the acoustic properties of stops with those of fricatives. Based on this comparison, we will provide phonetic evidence that the plain **s** belongs to a lenis-like category.

Finally, this study provides a cross-dialectal comparison across two very different dialects, Seoul and Cheju Korean. Seoul Korean is the standard dialect of Korean spoken in Seoul, and Cheju Korean is spoken on Cheju Island, Cheju Province of Korea, located in the south of the Korean Peninsula, and west of Japan. Cheju is the most conservative dialect in Korean in that it still preserves a Middle Korean vowel, the back-mid-unrounded vowel. This vowel was merged with the back-mid-rounded vowel in all other dialects of Korean around the late 1800s. Cheju shares the same morphosyntactic system as other dialects of Korean, and has been traditionally considered as simply a dialect of Korean. On the other hand, due to its significant number of different lexical items, especially suffixes and verbal endings, Cheju is not mutually intelligible with the rest of Korean, and might be considered to be a separate language. In this paper, however, we will assume that Cheju is simply a dialect of Korean sound since, as mentioned earlier, the Cheju sound system is the same as that of standard Korean except for the back-mid-unrounded vowel. Our own previous work has shown that the Seoul and Cheju dialects maintain the same consonantal phonological systems (Cho, Jun & Ladefoged, 2000; Cho, Jun, Jung, & Ladefoged, 2000). The current paper will allow us to examine how the phonetic properties of the consonants differ or are similar in these two extreme Korean dialects (Cheju as the most conservative and Seoul as the most dynamic in language change). Another merit in examining the Cheju dialect lies in documenting an endangered language. Due to the high level of education on Cheju island and the influence of mass media, these days it is not easy to find a pure native speaker of Cheju. Presently, it is spoken only by people over 60, and found more commonly in the inland, rural areas. Thus, we believe that documentation of the phonetic properties of Cheju obstruents in comparison with those of standard Korean has its own merit.

1.1 *Previous investigations of Korean obstruents*

Before introducing the experiment, we will review previous findings on acoustic and articulatory properties of Korean obstruents.

1.1.1 *Stops*

Researchers have proposed different ways of distinguishing Korean stops in word or phase-initial positions. The mean VOT distinguishes the three-way distinction, but the VOT ranges overlaps (Kim, 1965, 1970; Han & Weitzman, 1970; Hardcastle, 1973; Hirose, Lee & Ushijima, 1974; M. Kim, 1994; Y. Kim, 1995; J. Han, 1996; Cho, 1996). Han & Weitzman (1970) noted that, in addition to the VOT differences, different acoustic features can be observed in the onset phase of voicing following the stop release. They reported that f0 and the intensity characteristics of vowel onset also contribute to the manner distinction. In general, f0 after aspirated or fortis stops is relatively higher than after lenis stops (cf. Hardcastle, 1973; Kagaya, 1974; M. Kim, 1994; Cho, 1996). These studies indicate that f0 contrasts serve as a supplementary cue to distinguish lenis stops from fortis and aspirated stops, but not necessarily to distinguish aspirated from fortis stops, a finding that was later supported by a perception test (J. Han, 1996). Furthermore, Jun (1993, 1996a) found that the f0 difference is not simply due to the phonetic perturbation of the preceding consonant as has been noticed in other languages (Lehiste & Peterson, 1961; Lieberman, 1963; Ladefoged, 1964; Hombert, 1978; Hombert, Ohala & William, 1979, *inter alia*,), but is phonologically encoded in the intonation system in most dialects of Korean (including the Seoul dialect), so that a phrase-initial syllable beginning with a fortis or an aspirated stop is realized with a high (H) tone.

Han & Weitzman (1970) also reported that the harmonic components are weak for lenis stops, intermediate for aspirated stops, and strong for fortis stops. They further argued that these observations are indicative of a difference in the intensity build-up following the voice onset associated with each stop: relatively more time is needed for glottal intensity to build up following a lenis stop or an aspirated stop than that following a fortis stop.

The duration of the stop closure has been considered as another acoustically distinctive feature associated with Korean stops — in general, the stop closure is shortest for lenis stops, intermediate for aspirated stops, and longest for fortis stops (Silva 1992; M. Kim 1994; J. Han 1996). But an electropalatographic (EPG) study by Cho & Keating (1999, to appear) showed that there is no significant difference between aspirated and fortis stop closure durations, all else being equal. Cho & Keating (1999, to appear) also examined linguopalatal contact (the contact between the tongue and the roof of the mouth) for different stops using EPG and found that lenis stops have less linguopalatal contact than aspirated or fortis ones (see also Cho (1998)). The longer duration and the greater linguopalatal contact associated with both the aspirated and the fortis stops indicate that they are articulatorily 'strong' stops, compared to the lenis stop.

The nature of the aspirated and the fortis stops has also been examined with reference to laryngeal and supralaryngeal articulatory tension. One of the earlier studies, C. Kim (1965), characterized the stops in terms of two features: 'tension' of the articulation, which served to distinguish aspirated and fortis stops from lenis stops; and 'aspiration', which served to distinguish aspirated stops from fortis stops (and lenis stops). Some of the supportive findings for 'tension' associated with fortis and aspirated stops were a faster rate of vocal fold vibration after release, greater amplitude of pressure, longer duration of increased pressure, faster pressure build-up, greater linguopalatal contact, greater lip muscle activity (for bilabial stops). In line with C. Kim, Hardcastle (1973:271) suggested on the basis of results of VOT, frequency of glottal cycle at vowel onset and air-flow rate that "a feature 'tensity', defined in terms of isometric muscular tension in the vocal cords and pharynx, can usefully be employed to explain some of these properties".

Articulatory aspects of Korean stops have become better understood by examination of glottal configuration. C. Kim (1970), using cineradiographic evidence, reported that the glottal opening is larger for aspirated stops, intermediate for lenis stops, and narrower for fortis stops, arguing that the degree of aspiration is proportionally correlated with the degree of glottal opening at the time of release of the oral closure. Kagaya (1974), in a fiberscopic study, found that fortis stops have approximated vocal folds well before the articulatory release, while the glottis is quite open for the lenis stop at the time of the release, but not as large as for the aspirated stop. Kagaya suggested that both the fortis and aspirated stops are characterized by some intrinsic laryngeal gestures. In his view, fortis stops can be characterized by (1) a completely adducted state of the vocal folds before the articulatory release, (2) stiffening of the vocal folds, (3) abrupt closure of the vibrating vocal folds near the voice onset, (4) increasing subglottal pressure, and (5) lowering of the glottis immediately before the release. Aspirated stops are associated with positive abduction of the vocal folds and heightened subglottal pressure. On the other hand, none of these positive laryngeal gestures are observed for lenis stops. More recently, Jun, Beckman, & Lee (1998), in their fiberscopic study of vowel devoicing, found a similar result in terms of the timing and size of the glottal opening for the three stop types.

The glottal state in these stops has also been examined by the Electromyography (EMG), which allows us to investigate the activities of the intrinsic laryngeal muscles. Hirose et al. (1974) reported that fortis stops are characterized by a sharp increase in thyroarytenoid activity before the stop release, which presumably resulted in increased tension of the vocal folds and constriction of the glottis during or immediately after the stop closure. In aspirated stops, all activity of the adductor muscles of the larynx is suppressed immediately after the articulatory release. A steep increase in activity of the adductor muscles always followed this suppression, presumably due to the movement into the position for voicing. In lenis stops, the suppression of adductor muscle activity is not significantly involved as compared with aspirated stops, and there is no transient increase in thyroarytenoid activity before the articulatory closure. These results suggest that a simple dimension of adduction-abduction of the vocal folds is not sufficient in characterizing Korean stops, as implied in the studies of C. Kim (1970) and Kagaya (1974).

Dart (1987) investigated the different aerodynamic properties of fortis and lenis stops in Korean. She measured intraoral air pressure and oral flow associated with the fortis and lenis stops in prevocalic position. One of the main results in her study is that the production of fortis stops is characterized by “a higher intraoral pressure before release, yet a lower oral flow after release,” which is counterintuitive since in general higher intraoral pressure is associated with greater oral flow. Dart’s aerodynamic modeling accounted for the pressure-flow relations by modeling fortis stops with tightly adducted vocal folds before the articulatory release and greater vocal tract wall tension.

As it became clear that the different types of stops are associated with different glottal configurations in the production of not only the stops themselves but also the onset of the following vowel, researchers began to raise the question of whether the voice quality of the vowel is influenced by the preceding consonant. They hypothesized that the voice quality of the vowel is similar to a breathy voice after the lenis stop and to a laryngealized or ‘pressed’ voice after the fortis stop. A laryngographic study by Abberton (1972) showed that the onset of vowels after fortis stops has some of the characteristics of creaky voice with a long closed phase and a slow opening phase. N. Han (1998) reported that vowels after lenis stops have a breathy voice as indicated by positive H1-H2 values (the difference in amplitude between the first and the second harmonics). On the other hand, vowels after fortis stops do not always have negative H1-H2 values, which, if present, would have indicated a laryngealized or pressed voice quality.

1.1.2 *Fricatives*

Korean has two denti-alveolar fricatives. As in the stops, there is no voicing contrast. But unlike stops, there is only a two-way contrast between **s** and **s***. As mentioned earlier, **s*** is a tense or fortis fricative, but the categorization of **s** has been controversial. In Korean orthography, the plain **s** is regarded as lenis and behaves that way in phonological processes. But its behavior in phonetic processes and its phonetic realizations are generally believed to be similar to stops in the aspirated category. For example, **s** becomes tense after a lenis stop (e.g., /pak**s**a/ → [pak**s***a] 'Ph.D') as does the lenis stop (e.g., /pak**t**a/ → [pak**t***a] 'to pin down'). It is also similar to the aspirated stops in that it is not likely to become voiced between voiced segments, and it generally triggers a high tone in the beginning of an Accentual Phrase (Jun 1993). Fiberscopic data in Kagaya (1974) and Jun, Beckman, & Lee (1998) showed that **s** has a glottal opening configuration similar to aspirated stops, and Jun et al. further showed that **s** has a larger glottal opening than **s***. More recently, Yoon (1998) and Park (1999) showed that **s** has some degree of aspiration as in aspirated stops, and Park (1999) claimed, based on the energy difference between the first and second harmonics at vowel onset, that the plain **s** should be categorized in the aspirated category because the vowel onset after plain **s** is breathier than after fortis **s***. However, the relative breathiness associated with **s** cannot be a direct metric for whether **s** has the characteristics of an aspirated segment or not, since the lenis segment, as noted earlier, can also be associated with breathy voicing in the following vowel onset.

2. **Methods**

2.1 *Data acquisition and speakers*

2.1.1 *Speakers*

The Cheju data are based on recordings of eight male speakers of Cheju, aged 55 to 75. The Seoul data were collected from four Seoul speakers in Los Angeles, California in their late fifties and early sixties. Two of them were visiting America for a year or two, and two others moved to America 10-13 years ago, but they cannot speak English. All the speakers were literate.

2.1.2 *Data acquisition procedures*

Each of the speakers was recorded using a close-talking, noise-canceling Shure microphone and a Sony DAT recorder. For Cheju data, the recordings were made in the home of one of the speakers, or in a quiet part of the village community center. For the Seoul data, two speakers (visiting scholars) were recorded in the UCLA phonetics lab, and the other two speakers were recorded in their home or office.

For the Cheju speakers, each word was written on an index card in Korean orthography reflecting the sounds of Cheju as closely as possible. To help the speakers produce each word more naturally, a word triggering the context was written next to the target word on the index card. For example, a word for ‘baby’ was written for the target word ‘to give a birth’; a word for ‘ground’ was written for the target word ‘to dig’. Speakers produced each word twice after being prompted by one of the authors, S-A. Jun, or by a Cheju-native linguist (see Acknowledgements). The word list was rehearsed with each speaker before the recording was made. Data collection procedures were similar for Seoul speakers except that each word was written in the standard orthography found in a textbook.

For the aerodynamic data, oral airflow and pressure were recorded using the Macquirer X16 system. Speakers held a face mask against the lower part of the face, below the nose, capturing all the oral airflow. They also held a tube (internal diameter 2 mm) between their lips to record the pressure of the air in the mouth. A microphone within the face mask recorded the audio signal. Speakers found little difficulty in producing the required phrases in these conditions, and the audio signal indicated that the utterances sounded reasonably natural. Only bilabial stops, as shown in Table 5, can be investigated in this way. (The speakers were too elderly and unaccustomed to phonetic experimentation to ask them to pass a tube through the nose so that pressures behind dental and velar closures could be recorded.) (See Ladefoged (1997) for detailed procedure.) Recorded materials were digitized at a sampling rate of 22,050 Hz and analyzed using the Kay Elemetrics’s Computerized Speech Lab (CSL). The flow and pressure signals were sampled at a rate of 2 kHz and the audio signal was sampled at 10 kHz. They were analyzed using Scicon's Macquirer.

2.2 *Speech material*

For the acoustic study, all nine stops of Korean were examined. Each stop was placed in the initial position of a word in isolation, and was followed by the open vowel **a.** Table 3 shows the word list in a phonemic transcription. Note that for the Cheju lenis **t**, two different words were used because some speakers were more familiar with one than the other.

The fricatives **s**, **s*** were recorded in word-initial and medial positions, in the words shown in Table 4. Here we will simply note that the approximant **l** in word initial position (i.e., /latio/ ‘radio’) was included to provide a baseline when comparing the voice qualities of vowels conditioned by the type of preceding consonant (see Sec. 3.4). Each word in Tables 3 and 4 was read six times by each Seoul speaker, and twice by each Cheju speaker.

For the aerodynamic study, a corpus with only bilabial stops in word-initial position was included in the current study as shown in Table 5. The items in Table 5 were read nine times each by each Seoul speaker, and four times each by each Cheju speaker (except for one speaker in the rural area who did not participate).

Table 3. Stops recorded for acoustic measurements

	Seoul		Cheju	
pʰ	**pʰata**	'to dig'	**pʰamtʃə**	'to dig'
p*	**p*ata**	'to grind'	**p*amtʃə**	'to squeeze oil'
p	**pata**	'sea'	**pataŋ**	'sea'
tʰ	**tʰata**	'to ride'	**tʰamtʃə**	'to get (shy)'
t*	**t*ata**	'to pick'	**t*api**	'ground'
t	**talta**	'to be sweet'	**talkwatʃəmtʃə**	'to heat iron'
			tɐlanamtʃə	'to run away'
kʰ	**kʰatɨ**	'card'	**kʰamtʃə**	'to get burned'
k*	**k*ata**	'to peel'	**k*amtʃə**	'to peel'
k	**kata**	'to go'	**kamtʃə**	'to go'

Table 4. Fricatives recorded for acoustic measurements

(word-initial)

	Seoul		Cheju	
s	**sata**	'to buy'	**salamtʃə**	'to live'
s*	**s*ata**	'to wrap'	**s*amtʃə**	'to wrap'

(word-medial)

	Seoul		Cheju	
s	**nasata**	'(this) is a bolt'	**asakatʃə**	'to take away'
s*	**pas*ak**	'completely (dried)'	**pʰas*ak**	'breaking noise'

Table 5. Word list for aerodynamic study

	Seoul		Cheju	
p^h	**p^he**	'card'	**p^he**	'card'
p	**pe**	'ship'	**pe**	'ship'
p*	**p*e**	a stem of 'to draw'	**p*e**	'bone'

2.3 *Measurements*

In this section, we will describe the measurement criteria employed to investigate the acoustic and aerodynamic properties of stops and fricatives. For stops, we will examine VOT, burst energy, fundamental frequency (f0), amplitude difference between the first harmonic and the second harmonic (H1-H2), amplitude difference between the first harmonic and the second formant (H1-F2), intraoral pressure and airflow data. For fricatives, we will examine the duration, centroid of fricative noise, RMS energy, f0, amplitude difference between the first harmonic (H1) and the second harmonic (H2), and amplitude difference between the first harmonic (H1) and the second formant (F2), with particular reference to the contrasting nature of **s** and **s***.

2.3.1 *Measurements for stops*

• *Voice onset time:* VOTs for all stops were taken from the point of the stop release to the voice onset of the second formant in the following vowel, as seen in spectrograms. Thus for the lenis stops, any breathy voicing with only low-frequency harmonics was included in the VOT.

• *Relative burst energy:* The acoustic energy at the burst and in the middle of the following vowel were measured from an acoustic energy profile, using a 10 ms window. To normalize the energy difference across speakers, the percentage value of the burst energy relative to the energy at the midpoint of the vowel was employed. Greater burst energy for a stop can be expected in two cases—when a consonant (i.e., /t/) has a relatively smaller amount of linguopalatal contact, resulting in a fast release, as opposed to a larger contact area (cf. Stevens, Keyser, & Kawasaki, 1986), and when the air flow is greater at the release (which is presumably due to a greater air pressure behind the constriction immediately before the release).

• *Fundamental frequency (f0):* f0 was measured at the onset and the midpoint of the vowel, using the pitch track along with the first harmonic values from an FFT with a 25 ms window as supplementary checks. From the f0 differences, we would infer some physical information about the vocal folds (e.g., tension or stiffness) associated with different consonant types.

• *H1-H2 and H1-F2:* Energy values (dB) for the first (H1) and second (H2) harmonics, and the peak harmonic forming the second formant (F2) were taken at the onset and midpoint of the vowel, using FFT spectra with a 25 ms window. In addition, harmonic values were also measured at the corresponding points of the vowel after the liquid **l**, which was used as control data representing modal voicing. To avoid the influence of the first formant energy on the amplitude of H1 and H2, low vowels are used for the target words.

The difference in amplitude between H1 and H2 has been frequently used to distinguish between breathy and modal voicings (e.g., Bickely, 1982; Ladefoged, 1983; Huffman, 1987; Klatt & Klatt, 1990; Blankenship, 1997). Breathy voicing is produced with a relatively larger open quotient with the vocal folds remaining closed for a shorter time (e.g., open for 80-100% of the cycle for breathy phonation, vs. 65-70% for modal phonation (Childers & Lee, 1991)). As a result, the spectrum is dominated by the energy at the fundamental frequency, resulting in the amplitude of H1 being markedly higher than that of other harmonics. On the other hand, laryngealized vowels with creaky voicing (or ‘pressed voicing’ in Stevens’ (1999) term) would have the opposite result, as they are produced with a smaller open quotient with the vocal folds remaining closed for a longer time. Thus, a greater H1-H2 would indicate breathiness of the vowel and a smaller or negative H1-H2, would indicate 'pressed' voicing quality.

• *H1-F2:* The spectral slope, as obtained from H1-F2, was measured at the onset and the midpoint of the vowel. This is an indicator of the abruptness of vocal fold closure. A gradual adduction of the vocal folds excites mainly the lower resonances of the vocal tract and, as a result, the sound wave is nearly sinusoidal with most energy near f0. The resulting spectrum has a steep downward slope from which a greater H1-F2 is expected. We expect that any breathy voicing should be associated with a gradual adduction with a greater H1-F2. On the other hand, when there is an abrupt adduction with the vocal folds coming together all at once, which is one of the characteristics of pressed or creaky voicing, the abruptness of the closure excites a wider range of frequencies. As a result, the sound wave has a spectrum with energy spread across a higher range of frequencies. Schematized spectra for different types of voicing are shown in Figure 1, based on Stevens (1999:86, 90).

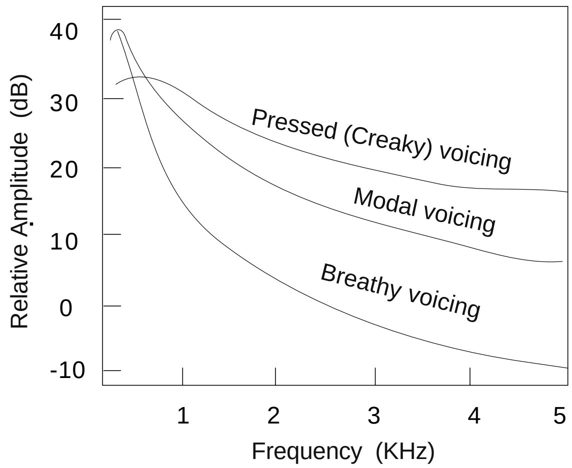

Figure 1. Schematized spectra for different phonation types, based on Stevens (1999:86, 90).

• *Oral pressure and flow:* The maximum flow after the release of the closure and the peak oral pressure during the closure were measured, as indicated by the arrows (a) and (b) in Figure 2, respectively. Oral pressure and flow provide information about the degree of glottal constriction (cf. Ladefoged, Maddieson & Jackson, 1987). As we have noted, Dart (1987) using these measures found indications of differences in phonation type in the vowel onsets after the fortis and lenis Korean stops.

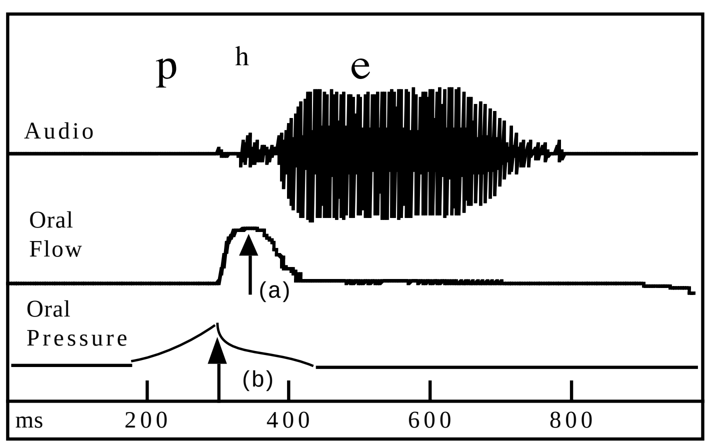

Figure 2. Waveforms of audio, oral airflow and oral pressure. The points marked by arrows indicate peak oral flow (a) and oral pressure (b).

2.3.2 *Measurements for fricatives*

• *Fricative duration:* Duration measurements were made from the spectrograms of each token for **s** and **s*** both in word-initial and word-medial positions. For **s**, we also measured the duration of both frication and aspiration, separately and combined.

• *Centroid of the fricative noise:* The centroid is the center of gravity of a defined part of the spectrum, each frequency being weighted according to its amplitude (cf. Forrest, Weismer, Milenkovic & Dougall, 1988; Zsiga, 1993). Centroid values were taken from FFT spectra in the frequency range from 500 Hz to 10,000 Hz, using a 25 ms window centered around the midpoint of the fricative portion. For denti-alveolar fricatives, **s** and **s***, a higher centroid is expected as the source is filtered by the front cavity resonance, resulting in a spectrum peak in the vicinity of F4 or F5 (Stevens 1999). We were particularly interested in determining whether there was a difference in the centroid frequency of **s** and **s***, which would indicate the difference in the size of the front cavity—the higher, the smaller.

• *H1-H2 and H1-F2:* As measured for stops, H1-H2 and H1-F2 were measured at the onset and the midpoint of the vowels that follow **s** and **s***.

• *Fundamental frequency (f0):* As measured for stops, f0 was taken at the onset and the midpoint of the following vowel.

3. Results and discussion for stops

3.1 *VOT*

Results of three-way ANOVA ([stop category] by [place of articulation] by [dialect]) show main effects of all three factors on VOT ($F(2, 341) = 750.79$, $p < .0001$ for [stop category]; $F(2, 341) = 34.66$, $p < .0001$ for [place of articulation]; $F(1, 341) = 62.41$, $p < .0001$ for [dialect]). The results are summarized in Figure 3. First, pairwise Fisher's PLSD post hoc comparison showed that VOT is shortest for the fortis stop, intermediate for the lenis stop, and longer for the aspirated stop ($p < .0001$ for each comparison), which is true for both Seoul and Cheju Koreans, as seen in Figure 3a. Second, there is a dialectal difference in VOT—i.e., VOT for Seoul Korean is in general longer than that for Cheju Korean.

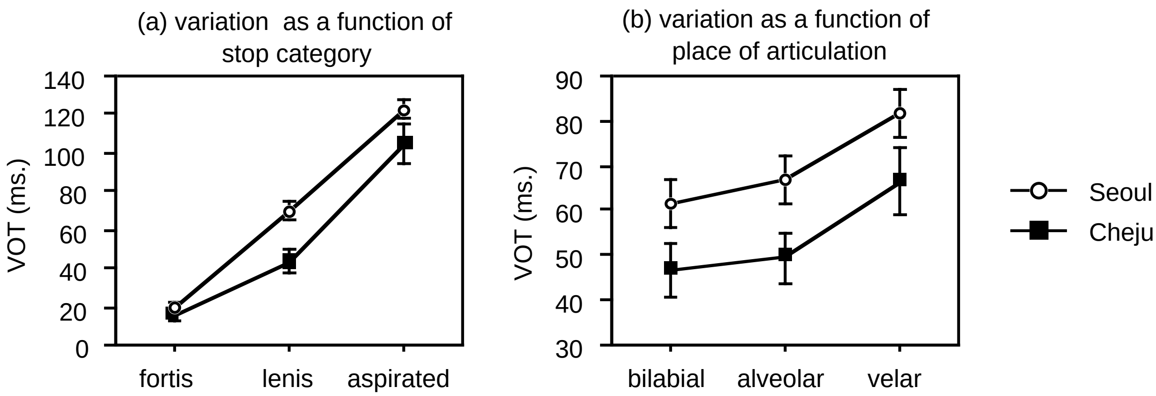

Figure 3. Variation of VOT: (a) as a junction of stop category and (b) as a function of place of articulation. Error bars indicate standard errors.

It is interesting to compare this dialectal difference with diacronic differences observed in the literature (e.g., Silva, 1992; N. Han, 1998). For example, reviewing the literature about Korean VOTs over the past 50 years or so, N. Han obseved that VOT for the aspirated and the lenis stop have increased over time. We have reported some evidence elsewhere (Cho, Jun, Jung & Ladefoged, 2000) that Cheju speakers are in general conservative in terms of preserving vowel sounds. It is then conceivable that the overall shorter VOT in Cheju is due to the conservatism of the Cheju people who are isolated from mainland Korea.

There is also a significant interaction between [stop category] and [dialect] ($F(2, 341) = 9.771$, $p < .0001$). This interaction is accounted for primarily by the fact that VOT for the Cheju lenis stop is substantially shorter (average 43 ms) than that for Seoul lenis stop (average 67 ms). As seen in Figure 3a, the three stop categories for Seoul Korean are evenly separated by about 55 ms. in VOT, whereas in Cheju the difference in the mean VOT between the fortis and the lenis stops is smaller (29 ms) than that for the lenis and the aspirated stops (61 ms). The distribution of VOT across different stop categories is further illustrated in histograms in Figure 4. The first point to be made from the figure is that for both Seoul and Cheju Korean, there is some overlap in VOT among stops. Such overlap suggests that VOT is not the only or perhaps the most significant perceptual cue for differentiating stops in Korean (cf. Han & Weitzman, 1970; Hardcastle, 1973; Cho, 1995, 1996, *inter alia*). The dialectal difference can also be seen in that there is more overlapping among stops in Cheju Korean than in Seoul Korean. This dialectal difference leads us to infer that Seoul Korean may rely more on VOT than Cheju Korean, an inference that is confirmed by analysis of the VOT data for the speakers individually. All of the Seoul speakers made a highly significant distinction between each of the three stop types, fortis, lenis and aspirated ($p<.0001$), but two of the Cheju speakers did not have a significant distinction in VOT between fortis and lenis stops, and two others had only weakly significant distinctions ($p = .04$ and $.0109$) between these stops. It appears that the Cheju speakers rely on other acoustic cues to distinguish these sounds. This is, of course, subject to confirmation by perceptual experiments.

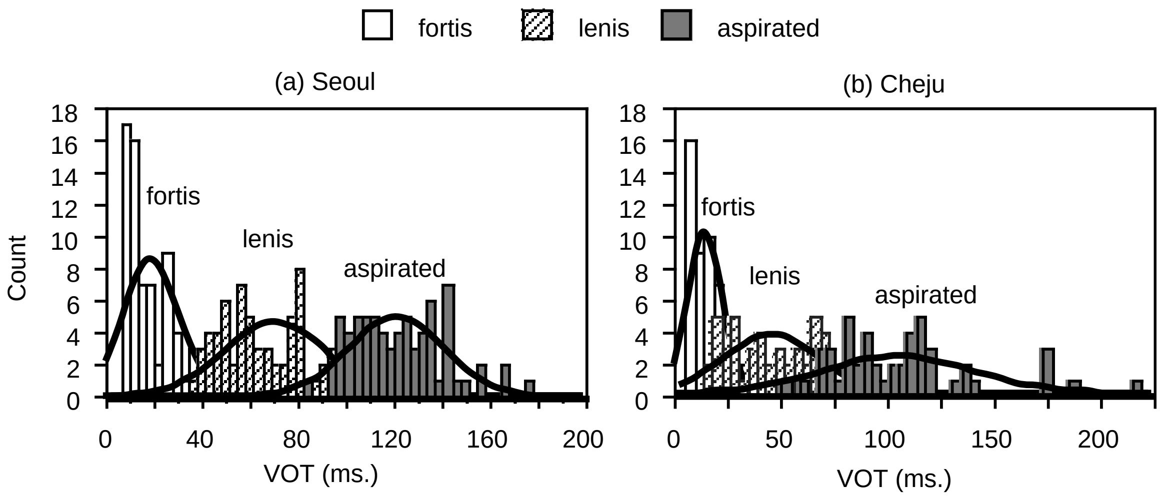

Figure 4. Distribution of VOT in three stop categories: (a) Seoul and (b) Cheju.

Finally, let us consider the effect of place of articulation. VOT of the velar stop is significantly longer than that of either the bilabial or the denti-alveolar stops ($p < .0001$), as seen in Figure 3b. There is no significant difference between the bilabial and the denti-alveolar VOTs. This pattern remains true for both Seoul and Cheju Korean with no interaction between [place of articulation] and [dialect]. This is in general in agreement with the tendencies noted in other languages (Cho & Ladefoged, 1999).

3.2 *Relative Burst Energy*

Results of two-way ANOVAs ([stop category] by [dialect]) show that there is a significant effect of [stop category] on the relative burst energy ($F(2, 341) = 16.13$, $p < .0001$) but no effect of [dialect]. Fisher's PLSD pairwise post hoc comparisons reveal that the aspirated stop has significantly greater burst energy than the other two types of stops ($p < .0001$) while there is no difference between the fortis and the lenis stops, though there is a trend for the lenis stop to have a greater burst energy than the fortis stop, as shown in Figure 5. Although there is no main effect of [dialect] on the relative burst energy, there is a significant interaction between [stop category] and [dialect] ($F(2, 341) = 5.06$, $p = .0068$). This interaction comes primarily from the fact that the effect observed is greater for Cheju Korean ($F(2,141) = 10.35$) than for Seoul

Korean (F(2, 212) = 3.26), which is illustrated in Figure 5 by a greater range of variation for Cheju Korean as a function of [stop category].

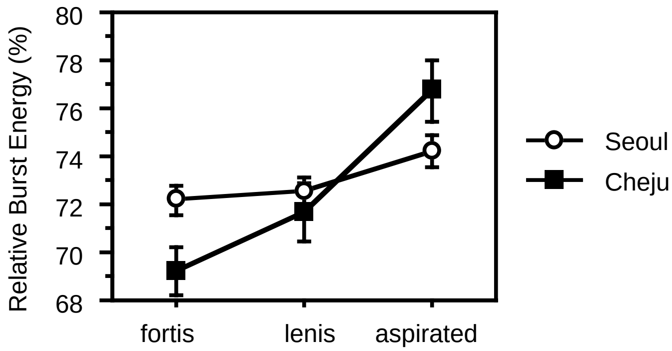

Figure 5. The relative burst energy (%) for different stop categories.

There may be several explanations of a greater burst energy—i.e., (a) a smaller linguopalatal contact (Stevens et al., 1986) (and, therefore, a greater speed of movement), (b) a greater intraoral airflow at the release, or (c) higher intraoral air pressure. Cho & Keating (1999, to appear) found that both fortis and aspirated Korean stops have greater linguopalatal contact than the lenis stops while there is no difference between the fortis and aspirated stops. If the greater contact induces slower release, which is in turn associated with lesser burst energy, then both fortis and aspirated stops should have lesser burst energy than lenis stops, all else being equal. Our data, however, show that aspirated stops have stronger burst energy than lenis stops. This indicates that the amount of the contact itself is not the primary source for the greater burst energy.

Now let us consider aerodynamic factors. Dart (1987) found that the lenis stop has a greater airflow at the release than does the fortis one, though the fortis stop has a greater air pressure before the release. (A similar result was found in our own aerodynamic study. See below.) If the airflow is the primary factor, then we would expect a greater burst energy for the lenis stop; if the source of the burst energy comes mainly from the air pressure, we expect a greater burst energy for the fortis stop. However, our data show that there is no significant difference between the lenis and the fortis stop. It is then conceivable that the different stops have difference primary sources of the burst energy—i.e., the greater air pressure for the fortis stop and the greater airflow for the lenis stop would result in no difference in burst energy between them. Furthermore, the aspirated stop which is expected to be produced with a greater oral pressure and a greater airflow in fact shows the greatest burst energy, reflecting both aerodynamic factors. This is in fact consistent with the aerodynamic results reported below, showing that the aspirated stop is produced with the greatest airflow and as high air pressure as the fortis stop at the release.

This aerodynamic explanation of the burst energy is supported by the observation that there is a significant effect of [place of articulation] ($F(2, 356) = 8.02$, $p = .0004$) when data are pooled across dialects. The burst energy for the velar stop is significantly greater than that for both the bilabial and denti-alveolar stops ($p < .001$, Fisher's PLSD post hoc comparisons) between which there is no difference. The velar stop, which is usually produced with a relatively greater linguopalatal contact, might be expected to have smaller burst energy. This would be the case if the amount of linguopalatal contact and its consequent slow speed of the release movement is the primary factor responsible for the burst energy difference. But the cavity behind the constriction of the velar closure is relatively smaller than those of other stops, and, as a result, will have relatively greater air pressure buildup before the release. The greater air pressure would give higher airflow volume velocity, which appears to be responsible for the greater burst energy for the velar stop. However, we should not ignore the possibility that the difference may be due to the shape of the constriction just after the release.

3.3 *f0 differences*

A three-way ANOVA ([stop category] by [position-in-vowel] (onset vs. midpoint) by [dialect]) shows that f0 is significantly influenced by [stop category] ($F(2, 672) = 78.36$, $p < .0001$) and [dialect] ($F(1, 672) = 96.99$, $p < .0001$), but not by [position-in-vowel]. There is also a significant [stop category] by [dialect] interaction ($F(2, 672) = 5.18$, $p = .0058$). Fisher's PLSD pairwise post hoc comparisons show that f0 for the lenis stop is lower than the other two stops at $p < .0001$ and Cheju speakers have in general higher f0 than Seoul speakers at $p < .0001$, as can be seen in Figure 6. The [stop category] by [dialect] interaction comes from the fact that each stop category is associated with significantly distinctive f0 in the onset of the following vowel at least at the $p < .01$ level for Cheju, while Seoul Korean makes a distinction only between the lenis and the other two stops. However, this generalization of dialect differences should be taken with caution because three out of eight Cheju speakers showed no difference in f0 between the fortis and aspirated stops like all four Seoul speakers.

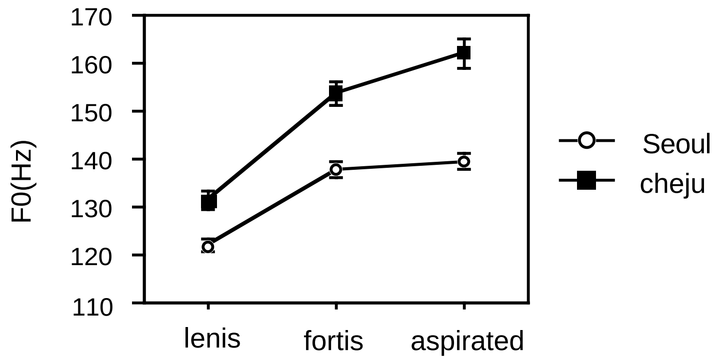

Figure 6. f0 differences in the following vowels. Data are pooled across position-in-vowel (see text). Error bars refer to standard errors.

3.4 *H1-H2 and H1-F2*

A three-way ANOVA ([stop category] by [position-in-vowel] by [dialect]) indicates main effects of all three factors on H1-H2 ($F(2, 670) = 121.392$, $p < .0001$ for [stop category]; $F(1, 670) = 33.38$, $p < .0001$ for [position-in-vowel]; $F(1, 670) = 12.21$, $p = .0005$ for [dialect]). In addition, there are significant interactions of (a) [stop category] by [position-in-vowel] ($F(2, 670) = 21.06$, $p<.0001$), (b) [stop category] by [dialect] ($F(2, 670) = 5.74$, $p = .0034$), and (c) [stop category] by [position-in-vowel] by [dialect] interactions ($F(2, 670) = 4.52$, $p < .05$).

Pairwise *post hoc* comparisons show that stops differ significantly from each other at $p < .0001$, which is true for both dialects—H1-H2 is greatest (positive) for lenis stops, intermediate for aspirated stops, and smallest (negative) for fortis stops, as shown in Figure 7. This suggests that the onset of the vowel (the first 30 ms period) has more breathy voicing immediately after the lenis stop, and more pressed (or laryngealized) voicing after the fortis stop. The voice quality of the vowel after the aspirated stop is close to the modal voice: its H1-H2 value is about the same as the control (modal) value taken from the onset of the vowel after **l** which has no known effect on the phonation type of the following vowel. This is consistent with Kagaya's (1974) observation that aspirated stops are produced with the suppression of all activities of the adductor muscles of the larynx immediately after the articulatory release, while lenis stops do not show such robust suppression of adductor muscle activity. This appears to contribute to the fact that aspirated stops are not associated with breathy voice even though they have the largest glottal opening during the closure. What is especially interesting about the overall finding is that both the fortis and the lenis stops appear to be associated with non-modal phonation, and that this difference is significantly maintained into the midpoint of the vowel consistently across dialects, though the difference becomes smaller at the midpoint.

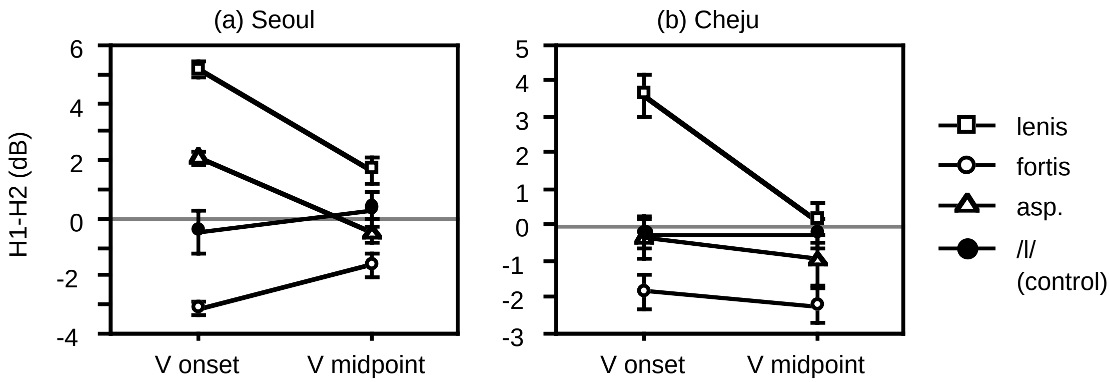

Figure 7. Difference between the amplitudes (dB) of the first harmonic (H1) and the second harmonic (H2) for different stop categories and /l/. Error bars indicate standard errors.

Now let us consider the dialect/speaker difference. It is especially worth examining speakers separately since paralinguistic difference in voice quality among speakers may have caused the results described in the preceding paragraph. Figure 8 shows the H1-H2 difference for each speaker separately. A rather obvious point is that the absolute values of H1-H2 vary with speakers, showing an overall speaker variation in voice quality. Nonetheless what is consistent across speakers is that the lenis stop is associated with a larger H1-H2, and the fortis stop, with a smaller H1-H2. This leads us to generalize with confidence that the voice quality is linguistically controlled by speakers in order to differentiate at least the lenis and the fortis stops. However, what is inconsistent across speakers or perhaps across dialects is whether or not H1-H2 values for the aspirated stop fall in between these for the lenis and the fortis stops. All four Seoul speakers make a three-way distinction among stops at least at the level of $p < .01$, showing a pattern of fortis < aspirated < lenis in H1-H2. Note that this is inconsistent with the findings of H. Ahn (1999), who examined differences in the voice quality of the vowels as a function of the preceding stop category. He found that both raw and normalized H1-H2 values for the fortis stop were smaller than those for the lenis stop, whereas those for aspirated stops were greater, giving an order of fortis < lenis < aspirated. We do not know why there is a difference between Ahn's and our findings. While the difference could be due to the relatively younger age group of Ahn's speakers (on average 36.5 years old), it may also be possible that the procedural difference may have caused the inconsistency between the two studies.

In Cheju Korean, H1-H2 of the aspirated stop is close to that of the lenis stop for some speakers (e.g., C1, C3, C7), or to that of the fortis stop for some others (e.g., C4, C6). The other three speakers (C2, C5 and C8) make a clear three-way distinction as do Seoul speakers. This suggests that the voice quality associated with the aspirated stop does not matter too much, perhaps because the other phonetic cues (e.g., huge aspiration) may be enough to differentiate the aspirated stop from the other two stop categories, or perhaps because the language simply chose not to rely on H1-H2 for identifying aspirated stops.

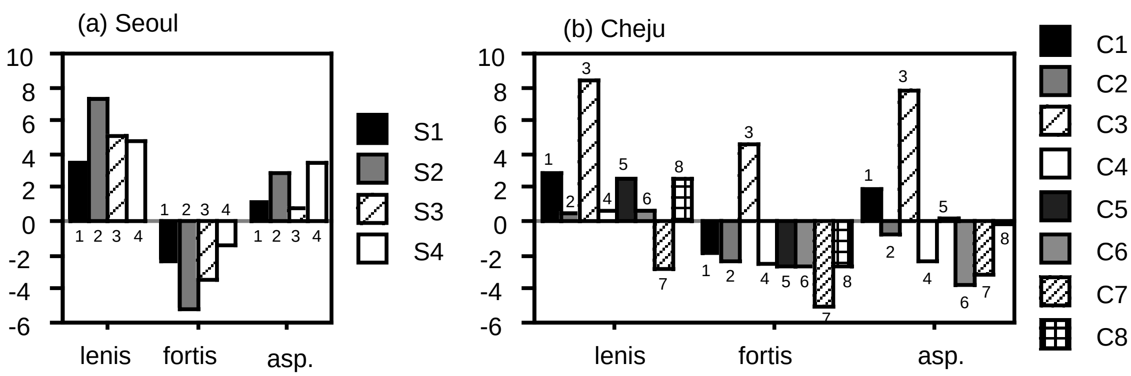

Figure 8. Difference between the amplitudes (dB) of the first harmonic (H1) and the second harmonic (H2) separated by each speaker. The numbers in the figures identify the different speakers.

We now turn to the spectral slope (H1-F2), a hypothesized indicator of the abruptness of vocal fold closure. A three-way ANOVA indicates significant effects of all three factors on H1-F2 ($F(2, 670) = 96.12$, $p < .0001$ for [stop category]; $F(1, 670) = 17.56$, $p < .0001$ for [position-in-vowel]; $F(1, 670) = 25.57$, $p <.0001$ for [dialect]). There are also significant interactions of [stop category] by [position-in-vowel] ($F(2, 670) = 3.16$, $p < .05$), [stop category] by [dialect] ($F(2, 670) = 5.94$, $p = .0028$), and [position-in-vowel] by [dialect] ($F(1, 670) = 10.13$, $p = .0015$).

Posthoc comparisons show that the fortis stop has the smallest (negative) H1-F2 while the lenis and aspirated stops have positive H1-F2s, as shown in Figure 9. This direction is consistently true cross-dialectally for both the onset and the midpoint. This indicates that the closing phase of the vocal folds during the voicing is more abrupt for the fortis stop than for the other stops, even in the middle of the following vowel. The vowel is produced with the folds coming together more rapidly after the fortis stop, providing more energy in the second or higher formant region, presumably because they are under greater tension. As was the case for H1-H2, difference in H1-F2 between the lenis and the aspirated stops was not consistently observed across dialects/speakers. Three out of the four Seoul speakers show a significantly greater H1-F2 for lenis than for aspirated stops (at least at the level of $p < .01$) while only one Cheju speaker shows a significant difference in the same direction. There is also another noteworthy dialectal difference in H1-F2. For the vowel onset, both lenis and aspirated stops for Seoul Korean have greater H1-F2 than the /l/, the control case. By contrast, H1-F2 for Cheju lenis and aspirated stops is smaller than, or equal to, that of the /l/. Considering all things together, it is conceivable that Cheju speakers in general use the relative abruptness to differentiate the fortis stop from the lenis and aspirated stops but not between the latter two, whereas Seoul speakers use the relative abruptness to help differentiate all three stop categories during the abduction/adduction phases.

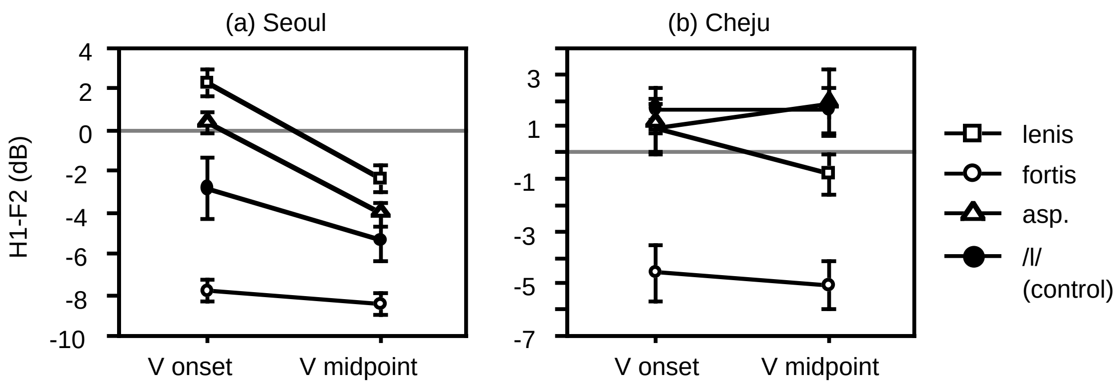

Figure 9. Difference between the amplitudes (dB) of the first harmonic (H1) and the second formant (F2). Error bars indicate standard errors.

To sum up, what emerges from H1-H2 and H1-F2 data is that the stops can be further differentiated at least in part by the voice quality of the following vowel. Despite some dialectal and speaker differences, the common result is that vowels after the fortis stop are relatively pressed with companying abruptness of the adduction gesture but vowels after the lenis stop are breathy with a relatively less abrupt adduction gesture.

3.5 *Aerodynamics*

3.5.1 *Intraoral air pressure (Po)*

Let us first examine intraoral air pressure. A two-way ANOVA ([stop category] by [dialect]) suggests that intraoral air pressure is significantly influenced by [stop category] ($F(2, 215)=8.74$, $p < .001$) and [dialect] ($F(1, 215) = 9.63$, $p <.001$). As shown in Figure 10a, the peak oral pressure during the closure is smaller for the lenis stop than for the fortis and aspirated stops, while there is no difference between the latter two. The dialectal difference is due in large part to overall greater air pressure for Seoul Korean. Though not every speaker showed the same pattern, there is no significant [stop category] by [dialect] interaction. Three out of twelve speakers (two Seoul and one Cheju speakers) showed no difference in Po between the fortis and the lenis stop.

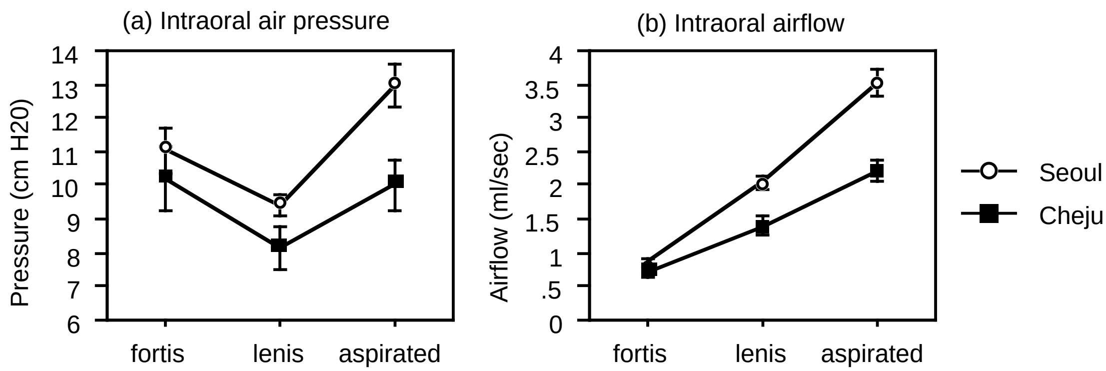

Figure 10. (a) Oral pressure (cm H_20) and (b) airflow (ml/sec). Error bars indicate standard errors.

The oral pressure during a stop closure is dependent on four factors. First the subglottal pressure which is its ultimate source; second the glottal impedance, which results in the oral pressure being less than the subglottal pressure; third the tension of the walls of the vocal tract, which, if allowed to expand, will result in a lowering of the oral pressure; and fourth the duration of the stop closure, which, in the case of initial stops when the subglottal pressure is still increasing, would result in stops with a long closure having a higher oral pressure. From the oral pressure data alone it is difficult to assess which of these factors is most responsible for the higher pressure in the aspirated and fortis stops in comparison with the lenis stops.

Dart's model suggested that the first factor, an increase in the subglottal pressure due to an increase in respiratory effort, was the most likely cause of the higher pressure in fortis stops. We should also note that the second factor, the glottal impedance, might make the fortis stops have a lower oral pressure than the aspirated stops, as the fortis stop is produced with constricted or approximated vocal folds well before the release (Kim, 1970; Kagaya, 1974; Jun et al., 1998). This factor may induce a trend toward relatively lower Po for the fortis stop as compared to the aspirated stop, as shown in Figure 10, especially for Seoul Korean. But insofar as the fortis stops have oral pressures that are similar to those in aspirated stops, it seems that the fortis stops may have an even higher subglottal pressure than the aspirated stops.

The third factor, the tension of the walls of the vocal tract, may also account for the higher Po for the fortis stop, which is arguably produced with a relatively more tense vocal tract wall (Kagaya, 1974; Dart, 1987). C. Kim (1965) suggested that aspirated stops might also be associated with a greater articulatory tension than the lenis stop, making this factor account for their relativley high pressure as well. Finally, Cho & Keating (1999, to appear) showed that both aspirated and fortis stops stops have greater closure duration than lenis stops (as measured by electropalatography) utterance-initially. This factor might also account for some of the increased pressure in utterance-initial stops.

3.5.2 *Airflow (Uo)*

We now turn to intraoral airflow (Uo). There are significant effects of [stop category] ($F(2, 215) = 114.32$, $p < .0001$) and [dialect] ($F(1, 215) = 38.95$, $p < .0001$) on Uo. Fisher's PLSD pairwise post hoc comparisons showed that the fortis stop is produced with substantially less Uo than the lenis stop, consistent with Dart (1987). It also showed that the lenis stop is produced with significantly smaller Uo than the aspirated stop, as shown in Figure 10. This is true for all 12 speakers across dialects. The effect of [dialect] comes mainly from the fact that Seoul speakers produce stops with greater Uo regardless of [stop category].

The fact that the fortis stop has greater oral pressure and possibly greater subglottal pressure, but little flow seems counterintuitive as all else being equal the higher Po, the greater Uo, as noted by Dart (1987). This seemingly unbalanced high Po and low Uo pattern in fact falls out from a combination of several physiological/aerodynamic factors such as the glottal impedance (which depends largely on the glottal area, Ag), the vocal tract wall tension, and a possible increase in the subglottal pressure which are crucial aerodynamic parameters in modeling the fortis stop in Dart (1987). As discussed earlier, the greater tension on the vocal tract wall and the heightened Ps associated with the fortis stop would have the effect of heightening Po. However, the stiffened vocal tract wall can also result in a decrease in the volume velocity of airflow since the reduction in the elasticity of the walls would also reduce the amount of elastic recoil of the walls, which would in turn cut down the initial flow volume velocity at release. In addition, a smaller glottal area (and therefore increased glottal resistance) would result in a decrease of transglottal airflow (Ug) and therefore a decrease of Uo. Contrastively, however, the aspirated stop which has as high Po as the fortis is produced with a far greater Uo, crucially because of a large glottal area at the oral release. This suggests that the effect of the vocal tract wall tension assumed by C. Kim (1965) is presumably too small, if existant, to override the effect of the glottal opening.

4. Results and discussion for fricatives, s and s*

4.1 *Spectrographic observation*

Some acoustic characteristics for **s** and **s*** can be qualitatively observed in the spectrograms. Spectrograms of word-initial **s** and **s*** are given in Figure 11. Both **s** and **s*** have two components, frication and aspiration, like a complex, aspirated segment. This complex nature of the plain **s** was observed in most of the tokens examined across dialects. This suggests that the plain **s** is phonetically aspirated, agreeing with the previous studies (e.g., Kagaya, 1974; Jun, 1993; H. Park, 1999). However, it does not always behave like the aspirated stops in that it does not retain a period of aspiration word-medially. The plain **s** is unaspirated when it occurs word-medially, as shown in Figure 12a. In these circumstances it has intervocalic weakening, like the lenis stops. Furthermore, although it is commonly assumed that **s** in general does not become voiced intervocalically (which is generally used as evidence that **s** does not belong to the lenis category), we in fact observed about 46% of tokens for **s** being fully voiced in this position. Two examples of the fully voiced **s** between vowels are given in Figure 13.

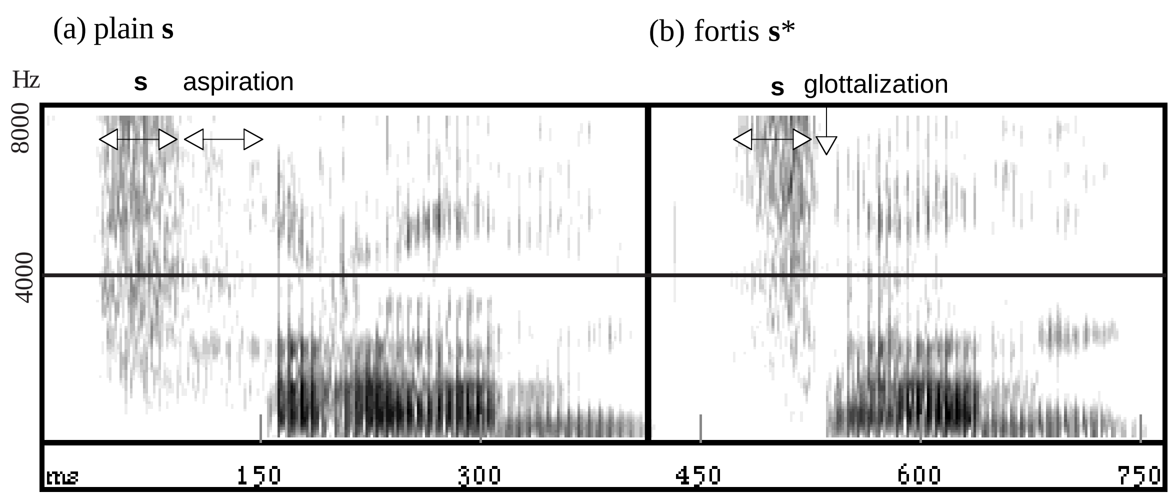

Figure 11. Spectrograms of **s** and **s*** in word-initial positions (speaker S6).

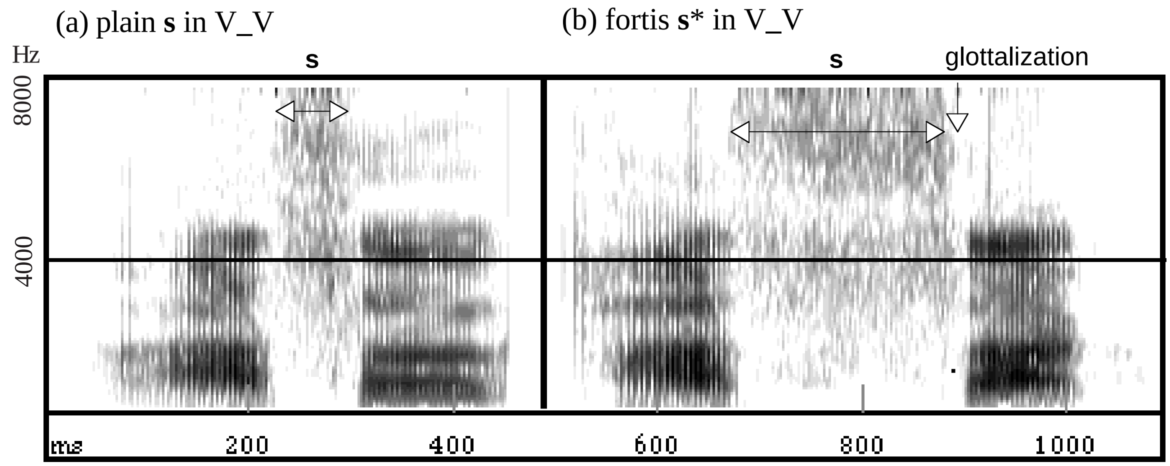

Figure 12. Spectrograms for **s** and **s*** word-medially between vowels.

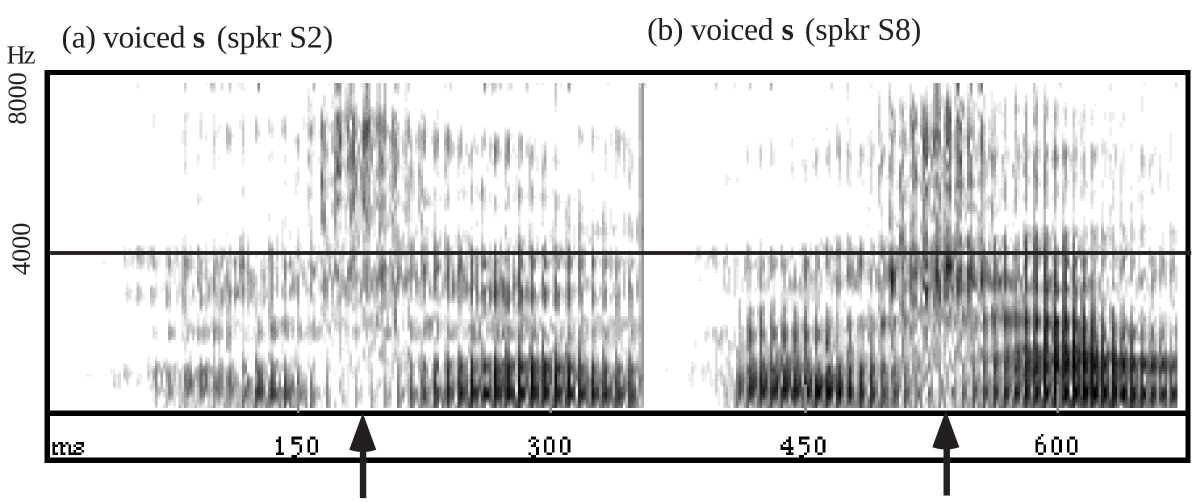

Figure 13. Spectrograms for fully voiced intervocalic **s**.

A noteworthy point regarding intervocalic voicing of **s** is that voicing occurs in a gradient fashion. Figure 14 shows the percentage of occurrence as a function of the percentage of voicing during the intervocalic **s**. As can be seen in the figure, there is no clear-cut difference between voiced and voiceless for **s** in the distribution of the percentage of voicing, but rather, voicing for **s** occurs over a wide range varying in degree. This gradient nature of intervocalic voicing for **s** is consistent with Jun's (1995) finding that lenis stop voicing in Korean occurs gradiently (see also J. Han, 2000).

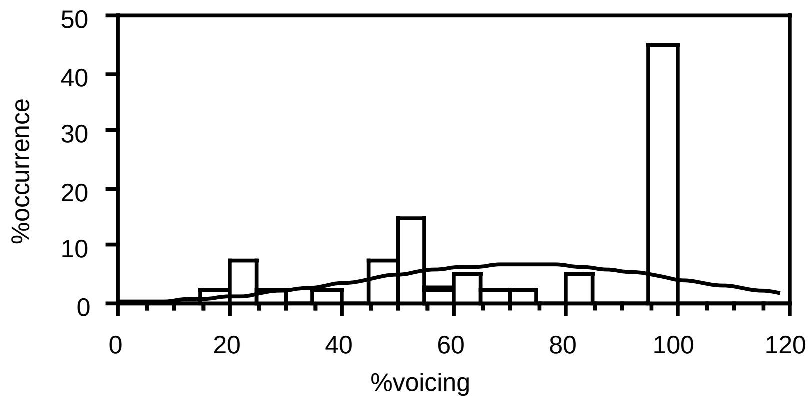

Figure 14. %-voicing during the intervocalic **s**.

The fortis **s*** also has two components. As shown in Figures 11b and 12b, it has a frication portion similar to that of the plain **s**, followed by a vertical gap immediately before the vowel onset. The gap appears to be an indication of the glottalization for **s***. Figure 15 shows examples of glottalization spanning over the first several cycles of the following vowel. There are a total of 12 out of 24 tokens (50%) for Seoul Korean and 9 out of 16 tokens (56%) for Cheju Korean showing a clear gap in the word-initial position. A similar gap is found but less frequently for word-medial tokens in 4 out of 24 tokens (16%) for Seoul Korean and in 8 out of 16 tokens (50%) for Cheju Korean.

Such a glottalization gap was not generally observed when we examined fortis stops. In fortis stops the vocal folds close just before the oral release and start vibrating immediately for the following vowel, as implied by a short VOT. However, as noted by Jun et al. (1998), for the Korean fortis fricative (as well as the plain one) the glottis must remain open to a certain degree in order to permit sufficient air flow for the frication noise. Consequently it seems that it is only in the last part of **s*** that the glottal characteristics of a fortis consonant are present.

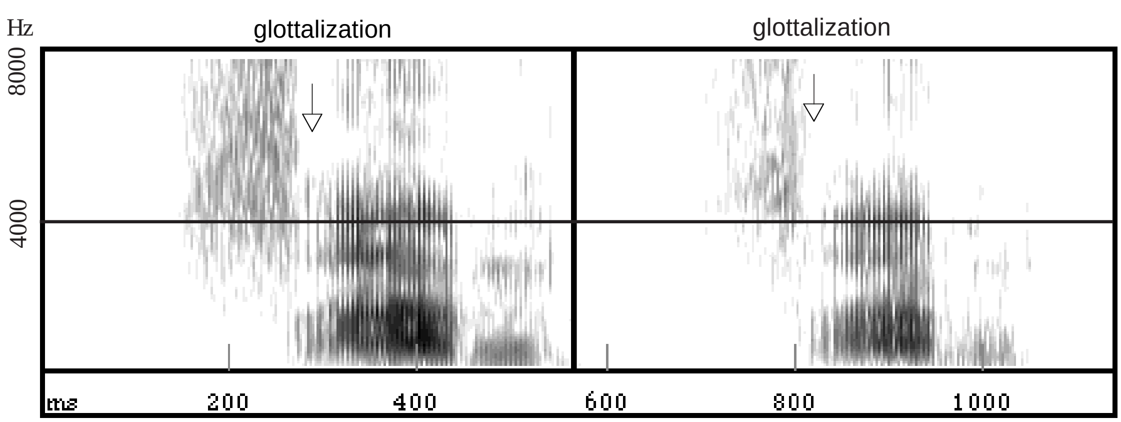

Figure 15. Spectrographic evidence of glottalization for **s*** in word-initial positions in **s*amtʃə**, produced twice by speaker C4.

4.2 *Fricative duration*

In word-initial position, the duration of the plain **s** (frication plus aspiration) is significantly longer than that of the fortis **s*** (F(1,76) = 31.81, p = <. 0001), as shown in Figure 16. This is the opposite of the difference in closure duration between the lenis and the fortis stops; that is, the closure of the fortis stop is longer than that of the lenis stop in the word initial position (Cho & Keating, 1999, to appear). However, if we exclude the aspiration period associated with the plain **s**, **s*** becomes significantly longer than **s** for Seoul Korean (t(46) = 5.99, p <.0001) which is consistent with Yoon's (1998) finding. But there is no such difference in Cheju Korean. When the data were separated by the speaker, **s*** is significantly longer than **s** (excluding aspiration) for all four Seoul speakers, but only two out of eight Cheju speakers (C4, C6) show a significant duration difference between the two fricatives. In contrast to the increase in duration for the word-medial fortis **s***, there is a significant decrease in duration for the plain **s** (F(1, 76) = 10.76, p = .0016, from a two-way ANOVA ([position-in-word] by [dialect])). There is no interaction between factors. The decrease appears to be primarily due to the absence of the aspiration and partial or full voicing intervocalically.

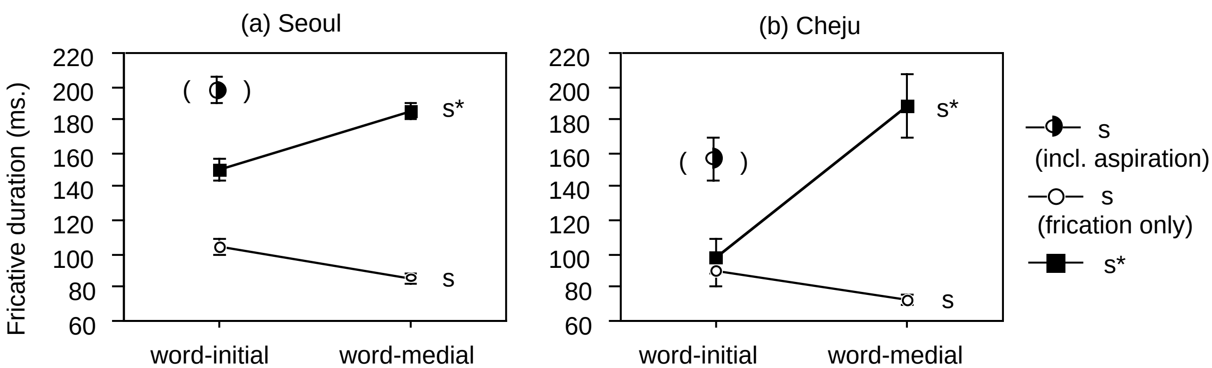

Figure 16. Duration of the plain **s** and the fortis **s*** in word-initial and word-medial positions. For the word-initial plain **s**, the durations with and without aspiration are shown. The duration including both frication and aspiration is given in parenthesis. Error bars indicates standard errors.

The duration difference between **s** and **s*** is even larger in word-medial position (F(1, 76) = 157.39, p< .0001), as also shown in Figure 16. There is no effect of either [dialect] or the [dialect] by [fricative category] interaction. The word-medial, intervocalic **s*** is about 120% and 200% as long as the word-initial one for Seoul and Cheju Koreans, respectively, showing the geminate nature of the fortis segment, which is phonetically realized with a longer duration intervocalically (see Cho & Keating, 1999, for the closure duration difference between word-initial and word-medial fortis stops in Korean).

4.3 *Centroid Frequency*

There is a small but significant difference in centroid frequency between **s** and **s***. A two-way ANOVA ([fricative category] by [dialect]) shows significant effects of both [fricative category] ($F(1, 76) = 5.59$, $p < .05$) and [dialect] ($F(1, 76) = 46.09$, $p < .0001$). As can be seen in Figure 17, **s*** has a higher centroid frequency than **s** for both dialects. When the data were separated by the speaker, however, half (four) of the Cheju speakers did not make such a distinction, but all others (four Cheju and all Seoul speakers) made the distinction at least at the level of $p < .01$. We infer that, at least for those who show this difference, **s*** is produced with a relatively smaller front cavity, which presumably results in a higher centroid frequency. It is conceivable that the channel between the palate and the tongue necessary for the frication noise of **s*** is formed over a wider range than that for **s**, resulting in a smaller front cavity in front of the linguopalatal constriction. Another dialect difference comes from the fact that Seoul speakers in general produce **s** and **s*** with a higher centroid frequency than Cheju speakers. One possible explanation for such dialectal difference may be that the fricatives **s** and **s*** are denti-alveolar for Seoul speakers but alveolar for Cheju. Of course, a cross-dialect articulatory study is needed to verify this possibility.

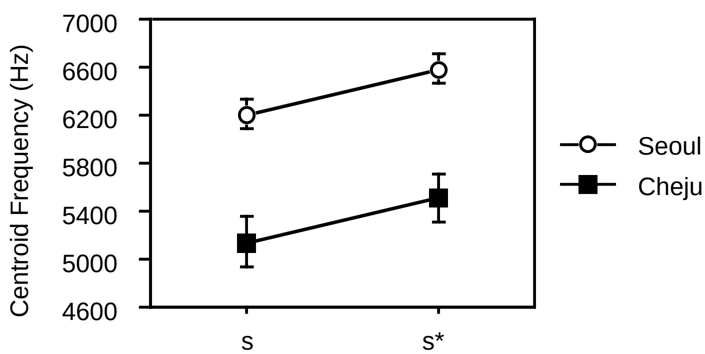

Figure 17. Centroid frequencies for **s** and **s*** in word-initial positions.

4.4 *Fundamental Frequency (f0)*

A three-way ANOVA ([fricative category] by [position-in-vowel] (onset/mid) by [dialect]) showed that there are significant effects of [fricative category] ($F(1, 145) = 6.11$, $p < .05$) and [dialect] ($F(1, 145) = 14.016$, $p = .0003$) on f0, but no effect of [position-in-vowel]. There is no interaction among factors, either. Figure 18 illustrates effects of fricative category and dialect. Posthoc comparison by Fisher's PLSD shows that f0 is generally higher for **s*** than for **s**. However, the dialectal difference appears to be due primarily to the fact that the f0 of the Cheju

s* is significantly higher than that of the Cheju **s**, whereas there is no such difference for Seoul Korean. When the data were separated by speaker, seven Cheju and two Seoul speakers showed a significantly higher f0 for **s*** than **s**. This suggests that the dialectal difference observed may be in fact derived from speaker variation.

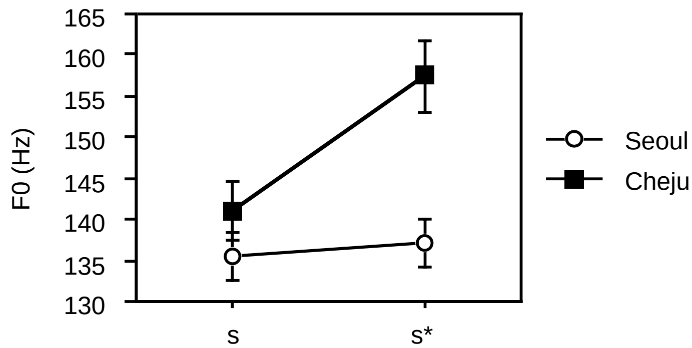

Figure 18. f0 difference between **s** and **s*** in the following vowel. Error bars indicate standard errors. Data were pooled across the factor, [position-in-vowel] (onset vs. midpoint) because it has no effect.

It is also interesting to compare differences in f0 between the fricatives and stops. On the one hand, in the Seoul dialect, f0 for the plain **s** is similar to that for the aspirated stops, whereas in Cheju, f0 for **s** is similar to that for the lenis stop—no significant difference was found between the plain **s** and the lenis stop. On the other hand, f0 for the fortis **s*** is similar to that for the fortis stop in both dialects. (We will discuss this further in the general discussion section.)

4.5 *H1-H2 and H1-F2*

A three-way ANOVA ([fricative category] by [position-in-vowel] by [dialect]) indicated that [fricative category] and [position-in-vowel] have significant effects on H1-H2 ($F(1, 145) = 43.04$, $p < .0001$ for [fricative category]; $F(1, 145) = 6.28$, $p <.05$ for [position-in-vowel]). There is a significant interaction between [position-in-vowel] and [fricative category] ($F(1, 145) = 25.62$, $p < .0001$), but no effects of dialect or other interactions were found. Posthoc comparisons showed that H1-H2 is significantly higher for **s** (positive) than for **s*** (negative), which is true for both dialects and across all speakers except one Cheju speaker (C6). Figure 19 illustrates the difference. The difference, however, becomes non-significant at the midpoint of the vowel, which is the major source of the significant interaction between [fricative category] and [position-in-vowel].

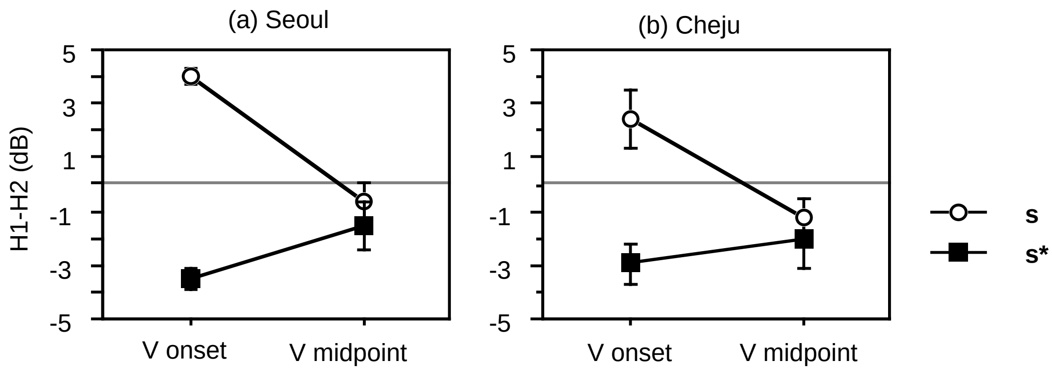

Figure 19. Difference in dB between the first and the second harmonic (H1-H2) at the onset and midpoint of the following vowel. Error bars indicate standard errors.

The systematic H1-H2 difference between **s** and **s*** indicates that at least at the beginning of the vowel, the open qoutient is relatively larger for **s,** resulting in breathy phonation, but relatively smaller for **s***, resulting in pressed phonation. This difference is consistent with that between the lenis and fortis stops as was shown in Figure 7.

Now let us consider H1-F2, from which we can infer the relative abruptness of the vocal folds closing gesture for voicing cycles. A three-way ANOVA ([fricative category] by [position-in-vowel] by [dialect]) indicates that H1-F2 is significantly influenced by [fricative category] ($F(1, 145) = 49.76$, $p < .0001$) and [position-in-vowel] ($F(1, 145) = 12.55$, $p < .001$), but not by [dialect]. There is a significant [fricative category] by [position-in-vowel] interaction ($F(1, 145) = 3.951$, $p < .05$), but no other interactions were found to be significant. A crucial point here is that, in parallel with the H1-H2 difference, H1-F2 is significantly greater for **s** than for **s***, as confirmed by posthoc comparisions. This is true for both dialects and across speakers except two Cheju speakers (C2, C6). (Recall that the speaker C6 did not make a distinction in H1-H2, either.) Figure 20 illustrates the difference. As shown in the figure, this difference is maintained through the midpoint of the vowel significantly in both dialects. Put differently, vowels after the fortis **s*** are generally produced with more abrupt vocal fold closure, as opposed to vowels after the plain **s,** as is the case with vowels after fortis stops, and such abruptness continues into the middle of the vowel. However, whether H1-F2 values for **s** are closer to those for the aspirated stop or to those for the lenis stop appears to depend on dialect. In the Seoul dialect, there is a tendency towards H1-F2 values for **s** being closer to those for the lenis stop than those for the aspirated stop: the mean H1-F2 for the plain **s** (4.9 dB) is closer to that for the lenis stop (2.5 dB) than that for the aspirated stop (0.3 dB). But no such distinction can be found in the Cheju dialect due to the lack of difference in H1-F2 between the lenis and aspirated stops themselves as seen in Figure 9.

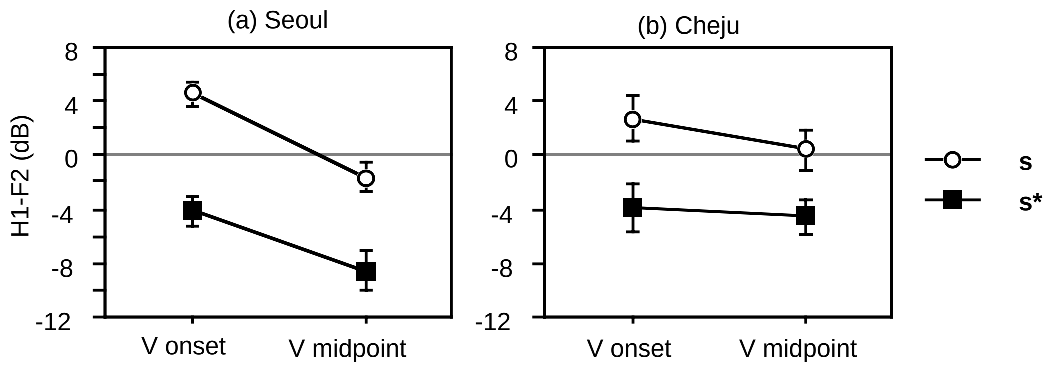

Figure 20. Difference in dB between the first and the second formant (H1-F2) at the onset and midpoint of the following vowel.

5. Summary and general discussion

In the current study, we have observed several acoustic/aerodynamic parameters in accounting for the three-way contrast in stops and the two-way contrast in fricatives. Among many other findings, there are several crucial points worth recapitulating. Firstly, stops are systematically differentiated by the voice quality of the following vowel. Secondly, stops are also differentiated by aerodynamic mechanisms. The aspirated and fortis stops are similar in supralaryngeal articulation, but employ a different relation between intraoral pressure and flow. Thirdly, our study suggests that the fricative **s** has acoustic features that are associated with both lenis and aspirated categories. Finally, although Cheju and Seoul Korean are not mutually intelligible, acoustic and aerodynamic properties of Cheju consonants are very similar in many respects to those of the standard Korean dialect. In what follows, we will first summarize potential dialectal differences between Seoul and Cheju Korean. Then we will discuss two issues that we believe are worthing addressing in conjuction with the data provided by the current study: (a) the role of the following vowel in differentiating the three-way distinction of stops and (b) the phonetic/phonogical nature of **s**.

5.1 *Dialectal difference and similarity*

In general, most parameters (e.g., VOT, Relative Burst Energy, f0, H1-H2 and H1-F2, intraoral air pressure and airflow for stops; centroid frequency, f0, H1-H2 and H1-F2 for fricatives) show similar systematic patterns across dialects. Below are similarities which we ascribe to phonetic properties common across dialects.

(stops)

a. VOT is long for the aspirated stop, intermediate for the lenis stop, and short for the fortis stop.

b. f0 for the lenis stop is always lower than that for the fortis and the aspirated stop.

c. H1-H2 and H1-F2 are both highest for the lenis stop and lowest for the fortis stop, showing that the vowel following the lenis stop is breathier and has a less abrupt adduction phase of the voicing cycle while the vowel following the fortis stop is more pressed and more abrupt in the adduction phase of the voicing cycle.

d. The order of intraoral air pressure (Po) is aspirated ≥ fortis > lenis while the order of the intraoral airflow (Uo) is aspirated > lenis > fortis.

(fricative **s**, **s***)

e. Centorid frequency of the fortis **s*** is higher than that of **s**, suggesting that the front cavity is relatively smaller in front of the constriction for **s*** than **s**.

f. H1-H2 and H1-F2 are both higher for the vowel following **s** than for one following **s***.

Although Cheju is said to be unintelligible to the rest of Korean speakers, we found that the phonetic properties of obstruents in both dialects are surprisingly similar. We infer that the unintelligibility of Cheju comes in larger part from other components of grammar such as morphosyntactic and/or lexical differences. (See also Cho, Jun, Jung, & Ladefoged (2000) for dialect differences in the vowel system). However, two- and three-factor ANOVAs indicated significant effects of dialect and stop category by dialect interactions for some cases. In what follows we would like to sum up some potentially significant dialectal differences focusing on main dialectal effects found in the ANOVAs.

(stops)

a. Cheju speakers have in general shorter VOTs than Seoul speakers.

b. Cheju speakers have a higher f0 associated with stops than Seoul speakers; Cheju speakers make a three-way distinction in f0 (i.e., aspirated > fortis > lenis) at the onset of the vowel while Seoul speakers make a two-way distinction (i.e, aspirated = fortis > lenis).

c. While there is no salient difference in H1-H2 between the dialects, Cheju speakers make a two-way distinction in H1-F2 but Seoul speakers make a three-way distinction (lenis > aspirated > fortis).

d. Cheju speakers generally produce stops with lower air pressure and smaller airflow than Seoul speakers; the greater airflow in Seoul speakers is consistent with the relatively longer VOTs found for Seoul speakers.

(fricatives **s**, **s***)

e. Frication duration of the fortis **s*** is longer for Cheju than for Seoul Korean.

f. f0 is generally higher for the vowel following **s*** than following **s** only in Cheju.

g. Centroid frequency is substantially lower for Cheju fricatives than for Seoul fricatives, suggesting that Cheju speakers form a relatively larger front cavity in front of the constriction, compared to Seoul speakers.

It should be emphasized here, however, that we also found substantial speaker variation associated with the above-mentioned parameters in such a way that suggests that the observed dialectal differences may be ascribable to speaker variation. Thus, the generalizability of the observed dialect differences is subject to further research.

5.2 *Vowel correlates of the three-way contrast in stops in both dialects*

Some of the acoustic correlates (e.g., f0 difference, H1-H2, H1-F2) of the three-way contrast of stops examined in the current study are realized on the following vowels. This is not new or surprising in principle. Quite a few studies have suggested that the onset of the following vowels differ in f0 (e.g., Han & Weitzman, 1970; Hardcastle, 1973; Cho, 1996; N. Han, 1996) and intensity buildup (e.g., Han & Weitzman, 1970), which indicates an importance of the vowel in characterizing the three-way contrast in Korean stops. In the current study, however, we found that such differences are in fact not confined to the onset of the following vowel but spread into the middle of the following vowel.

Jun (1996b) claims that the substantial difference in f0 between the lenis and other stops cannot be understood simply in terms of the phonetic pitch perturbation caused by the voicing of the preceding consonant (i.e., microprosody) as found in many other languages (Hombert, 1978; Hombert et al., 1979). First, the f0 difference between the groups shown in Figure 6 is substantially greater than that found in other languages (e.g., Kohler, 1982; Kingston & Diehl, 1994), and the f0 difference is still present at the midpoint of the syllable. Furthermore, all three stops are voiceless unlike other languages where f0 differences are associated with the voiced vs. voiceless distinctions. Jun claims that this segmentally triggered f0 distinction in Seoul Korean is phonologized in the intonation system of Seoul Korean as described by Jun (1993, 1996a, 1998). In this intonation system, the Accentual Phrase is realized in two distinct tonal patterns, LHLH and HHLH, where the phrase-initial tone (L vs. H) is determined by the type of the consonant occurring in the onset of the phrase initial syllable. When there is a fortis or aspirated obstruent in the onset, the Accentual Phrase starts with H, and otherwise (i.e., when there is a lenis obstruent, a sonorant consonant, or a vowel), it starts with L. This phonologization of microprosody is confirmed by our data from Seoul, and seems to occur in Cheju as well, though we do not yet know the details of the intonation system of Cheju.

We now turn to H1-H2 and H1-F2, indicative of phonation types. One of the crucial findings in the current study is that voice quality of the following vowel changes systematically as a function of preceding stop categories, and that such difference is maintained in the middle of the vowel, though it becomes smaller. Languages like Mazatec, Chong, and Mpi where vowels have either three-way or three-way phonological contrast in phonation types (i.e., modal, breathy, and pressed) do not in fact show acoustic differences for the entire time course of the vowel (Blankenship 1997). For example, Silverman, Blankenship, Kirk, & Ladefoged (1995) reported that in Mazatec, a difference in breathiness is maintained only for 43% of the vowel duration, leaving modal phonation to the rest of the vowel. Korean is a case where phonation differences in the vowels do not occur contrastively, but rather phonetically due to consonant context. Nonetheless, our data show quite robust differences even in the middle of the vowel, suggesting that the voice quality of the vowel plays an important role in differentiating the three-way contrast.

The importance of vowel correlates in the three-way contrast in stops is illuminated by a perception experiment reported in Cho (1995, 1996). In the experiment, subjects heard only vowels and chose one from 3 provided categories (lenis, fortis, and aspirated) for the preceding stop. Cho found that although different hearers respond to the stimuli somewhat differently, the overall accuracy rate was 67%. (The chance level was 33% with a forced choice out of three categories.) Interestingly, as shown in Figure 21, hearers perceived lenis stops and fortis stops with a greater accuracy rate (71~83% and 65~86%, respectively) than aspirated stops (42~57%), from which one could infer that hearers without access to VOT differences are cued by the non-modal phonation types (i.e., the breathy and the pressed phonations for the lenis and fortis stops, respectively). Furthermore, posthoc comparisions among correctly perceived and misperceived tokens showed that aspirated consonants were more often misperceived as fortis consonants (52%) than as lenis ones (10%), and fortis consonants were more often perceived as aspirated consonants (26%) than as lenis consonants (12%). Jun (1996b) interprets this pattern of error as a reflection of f0 differences in that both fortis and aspirated stops have a higher f0 in the following vowel, and therefore are interchangeably misperceived as each other. Although futher systematic perception tests are required to know exactly which acoustic/perceptual cues embedded in vowels are utilized by hearers, it seems safe at the moment to conclude that the acoustic and perceptual information of the preceding consonants spreads into the following vowels to a large extent, and thus helps listeners identify preceding stop categories.

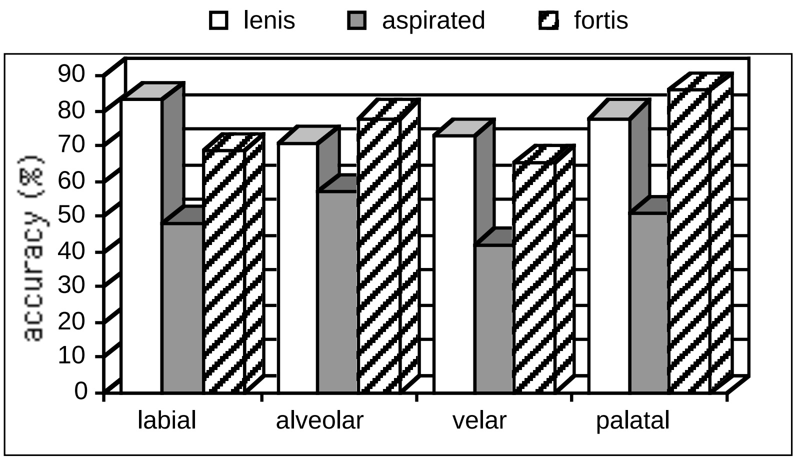

Figure 21. Accuracy rates in a perception test of each place of articulation from the sound of the following vowel (redrawn from Cho, 1996:73).

5.3 *Phonetic/phonological nature of plain **s***

We found some phonetic properties that may contribute to distinguishing the contrasting segments **s** and **s*** in Korean. The phonetic nature of **s*** as fortis is rather straightforward: it is produced with (1) frication and frequent glottalization immediately before the vowel, (2) relatively higher centroid frequency, (3) higher f0 in the vowel onset, (4) pressed voicing (negative H1-H2) at the vowel onset, and (5) abrupt vocal fold closure during the following vowel (negative H1-F2).

The phonetic and phonological nature of the plain **s** is quite complex and ambiguous. It is produced with frication, aspiration, and f0 at the vowel onset that are relatively high as compared to a lenis stop. This might make one believe that it is an aspirated **s** appropriately transcribed as [s^h]. However, we also found several reasons why the plain **s** might be categorized as a lenis segment. First, its counterpart lenis stop is also produced with a fair amount of aspiration. Second, the onset of the vowel after **s** has a similar breathy voice quality to vowels after the lenis stop. Third, f0 in the vowel onset after **s,** though higher compared to f0 after a lenis stop, is lower than that after an aspirated stop. Fourth, interestingly enough, the plain **s** loses its aspiration word-medially as does the lenis stop. Finally, though it has been generally assumed that **s** does not become voiced (cf. Iverson, 1983), we have observed that about 48% of tokens were fully voiced intervocalically, which undermines the contention that **s** behaves like an aspirated stop in that it fails to undergo intervocalic voicing. Considering all these observations, it seems that **s** has more in common with the lenis category than the aspirated one in terms of its phonetic nature. This is in harmony with its phonological behavior as a lenis category as in the Post-Obstruent Tensing rule in Korean.

5.4 *Concluding comment*

In the current study, we have observed several acoustic/aerodynamic parameters in accounting for the three-way contrast in stops and the two-way contrast in fricatives. Some of the results (e.g., VOT, f0 at the onset of the vowel, Po and Uo) replicate what has been previously found, while others (e.g., VOT as a function of place of articulation, stop burst energy, f0 and voice quality of the following vowel, Po and Uo for the aspirated stops, centroid frequency for fricatives) contribute new data to the literature about Korean obstruents. The Korean consonant system is, as far as we know, unique among the world's languages. It is worthy of intense study in any investigation of the limits of human speech capabilities. We hope that the present study will serve as a comprehensive reference for future research bearing on issues about not only Korean obstruents but also related issues addressing phonation types and voicing contrasts in other languages.

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References

Ahn, H. 1999. *Post-Release Phonatory Processes in English and Korean: Acoustic Correlates and Implications for Korean Phonology.* Ph.D. dissertation. University of Texas, Austin.

Abberton, E. 1972. Some laryngographic data for Korean stops. *Journal of International Phonetic Association*, **2**, 67-78.

Bickely, C. 1982. Acoustic analysis and perception of breathy vowels. *Speech Communication Group Working Papers I.* Research Laboratory of Electronics, MIT, pp. 73-83.

Blankenship, B. 1997. *The time course of brethiness and laryngealization in vowels.* Ph.D. dissertation. UCLA.

Childers, D.G. & C.K. Lee. 1991. Vowel quality factors: analysis, syntheses, and perception. *Journal of the Acoustical Society of America*, **90**(5), 2394-2410.

Cho, T. 1995. Korean stops and affricates: Acoustic and perceptual characteristics of the following vowel. *Journal of the Acoustical Society of America,* **98** (5), 2891. [Abstract].

Cho, T. 1996. *Vowel Correlates to Consonant Phonation: An Acoustic-Perceptual Study of Korean Obstruents.* M.A. Thesis. University of Texas at Arlington.

Cho, T. 1998. Domain-initial strengthening in the prosodic hierarchy: An EPG study. *Proceedings of 11th International Conference on Korean Linguistics (ICKL 11),* July 6-9, 1998. University of Hawaii at Manoa.

Cho, T., S.-A. Jun & P. Ladefoged. 2000. An acoustic and aerodynamic study of consonants in Cheju. *Speech Sciences,* **7**, 109-142. (The Journal of the Korean Association of Speech Sciences.) (Also in *UCLA Working Papers in Phonetics,* **98**, 54-80.)

Cho, T., S.-A. Jun, S. Jung & P. Ladefoged. 2000. The vowels of Cheju. *UCLA Working Papers in Phonetics,* **98**, 81-94.

Cho, T. & P. Keating. 1999. Articulatory and acoustic studies of domain-initial strengthening in Korean. *UCLA Working Papers in Phonetics,* **97**, 100-138.

Cho, T. & P. Ladefoged. 1999. Variations and universals in VOT: evidence from 18 languages. *Journal of Phonetics*, **27**(2), 207-229.

Dart, S. 1987. An aerodynamic study of Korean stop consonants: Measurements and modeling. *Journal of the Acoustical Society of America*, **81**(1), 138-147

Forrest, K., G. Weismer, P. Milenkovic & R. Dougall. 1988. Statistical Analysis of Word-Initial Voiceless Obstruents: Preliminary Data. *Journal of the Acoustical Society of America,* **84**(1), 115-123.

Han, J.-I. 2000 Intervocalic stop voicing revisited. *Speech Sciences*, **7**, 203-216. (The Journal of the Korean Association of Speech Sciences.)

Han, J.-I. 1996. *The Phonetics and Phonology of "Tense" and "Plain" Consonants in Korean.* Ph.D. dissertation. Cornell University.

Han, N. 1998. *A comparative Acoustic study of Korean by native Korean children and Korean-American children.* M.A. thesis. UCLA.

Han, M.S. & R.S. Weitzman. 1970. Acoustic features of Korean /P,T,K/, /p,t,k/ and /p^h,t^h,k^h/. *Phonetica,* **22**, 112-28.

Hardcastle, W.J. 1973. Some observations on the Tense-Lax Distinction in Initial Stops in Korean. *Journal of Phonetics,* **1**, 263-271.

Hirose, H., C.Y. Lee & T. Ushijima. 1974. Laryngeal control in Korean stop production. *Journal of Phonetics*, **2**, 145-152.

Hombert, J.-M. 1978. Consonant types, vowel quality, and tone. In *Tone: A linguistic survey*. (V. Fromkin, ed.), pp. 77-111. NY: Academic Press.

Hombert, J.-M., J. Ohala and E. William. 1979. Phonetic explanations for the development of tones. *Language*, **55**, 37-58

Huffman, M. 1987. Measures of phonation type in Hmong. *Journal of the Acoustical Society of America*, **81**, 495-504.

Iverson, G. 1983. Korean *s*. *Journal of Phonetics*, **11**, 191-200.

Jun, S.-A. 1993. *The phonetics and phonology of Korean prosody*. Ph.D. dissertation. Ohio State University.

Jun, S.-A. 1995. Asymmetrical prosodic effects on the laryngeal gesture in Korean. *Phonology and phonetic evidence: Papers in Laboratory Phonology IV*. (B. Connell & A. Arvaniti, eds.), pp. 235-253. Cambridge, UK: Cambridge University Press.

Jun, S.-A. 1996a. *The Phonetics and Phonology of Korean Prosody: Intonational Phonology and Prosodic Structure*. Garland Press. New York.

Jun, S.-A. 1996b. Influence of microprosody on macroprosody: A case of phrase initial strengthening. *UCLA Working Papers in Phonetics*, **92**, 97-116.

Jun, S.-A. 1998. The Accentual Phrase in the Korean prosodic hierarchy. *Phonology*, **15**(2), 189-226.

Jun, S.-A. 1999. Microprosody of English, French, and Korean: Phonologization of microprosody in Korean. Unpublished manuscript. UCLA.

Jun, S.-A., M. Beckman & H. Lee. 1998. Fiberscopic evidence for the influence on vowel devoicing of the glottal configurations for Korean obstruents. *UCLA Working Papers in Phonetics,* **96**, 43-68.

Kagaya, R. 1974. A fiberscopic and acoustic study of the Korean stops, affricates and fricatives. *Journal of Phonetics*, **2**, 161-80.

Kim, W.-J. 1963. *Kuk-eo Mo-eum-che-kye-eui Shin-ko-chal* (*Re-analysis of Korean Vowel System*). Chin-tan-hak-po 24. Il-cho-kak, Seoul Korea.

Kim, H.-K. 1980. An acoustic study of the Cheju dialect in Korean. *Eon-eo (Language*), **5**(1), 25-61. (The Journal of Linguistics Society of Korea.)

Kim, C.-W. 1965. On the autonomy of the tensity feature in stop classification. *Word*, **21**, 339-359.

Kim, C.-W. 1970. A theory of aspiration. *Phonetica*, **21**, 107-116.

Kim, M.-R. C. 1994. *Acoustic Characteristics of Korean Stops and Perception of English Stop Consonants.* Ph.D. dissertation. University of Wisconsin, Madison.

Kim, Y. 1995. *Acoustic Characteristics of Korean Coronal.* M.A. thesis. University of Texas at Arlington

Kingston, J. & R. Diehl. 1994. Phonetic knowledge. *Language*, **70**(3), 419-54.

Klatt, D. 1975. Voice onset time, frication, and aspiration in word-initial consonant clusters. *Journal of Speech and Hearing Research*, **18**, 686-706.

Klatt, D. & L. Klatt. 1990. Analysis, synthesis, and perception of voice quality variations among female and male talkers. *Journal of the Acoustical Society of America* , **87**, 820-857.

Kohler, K. J. 1982. F0 in the production of lenis and fortis plosives. *Phonetica*, **39**(4-5), 199-218.

Ladefoged, P. 1964. *A Phonetic Study of West African Languages.* Cambridge: Cambridge University Press.

Ladefoged, P. 1983. The linguistic use of different phonation types. In *Vocal Fold Physiology: Contemporary Research and Clinical Issues*, (D. Bless & J. Abbs eds.), pp. 351-360. San Diego: College Hill Press.

Ladefoged. P. 1997. Instrumental techniques for linguistic phonetic fieldwork. In *The Handbook of Phonetic Sciences.* (W. Hardcastle. and J. Laver, eds.), pp. 137-166. Oxford: Blackwell Publishers.

Ladefoged, P., I. Maddieson & M. Jackson. 1987. Investigating phonation types in different languages. In *Vocal Physiology: Voice Production, Mechanisms and Functions*, (O. Fujimura, ed.), pp. 297-317. New York: Raven.

Ladefoged, P. & I. Maddieson. 1996. *The Sounds of the World's Languages*. Oxford: Blackwell Publishers.

Lehiste, I. & G.E. Peterson. 1961. Some basic considerations in the analysis of intonation. *Journal of the Acoustical Society of America*, **33**, 419-425.

Lieberman, P. 1963. Some acoustic measures of the fundamental periodicity of normal and pathologic larynges. *Journal of the Acoustical Society of America*, **35**, 344-353.

Lisker, L. & A. S. Abramson. 1964. Cross-language study of voicing in initial stops: Acoustical measurements. *Word*, **20**, 384-422.

Park, H.S. 1999. The phonetic nature of the phonological contrast between the lenis and fortis fricatives in Korean. In *Proceedings of the 14th International Congress of Phonetic Science (ICPhS 99)*, vol. 1, 424-427.

Pierrehumbert, J. & D. Talkin. 1992. Lenition of /h/ and glottal stop. In *Papers in Laboratory Phonology II: Gesture, Segment, Prosody*. (G. Docherty & D. R. Ladd, eds.), pp. 90-117. Cambridge, UK: Cambridge University Press.

Silva, D. J. 1992. *The Phonetics and Phonology of Stop Lenition in Korean.* Ph.D. dissertation. Cornell University.

Silverman, D., B. Blankenship, P. Kirk, & P. Ladefoged. 1995. *Anthropological Linguistics*, **37**(1), 70-88.

Silverman, D. & J. Jun. 1994. Aerodynamic evidence for articulatory overlap in Korean. *Phonetica*, **51**, 210-220.

Stevens, K. N. 1999. *Acoustic Phonetics*. Cambridge: MIT Press.

Stevens, K. N., S. J. Keyser & H. Kawasaki. 1986. Toward a phonetic and phonological theory of redundant features. In *Invariance and Variability in Speech Processes*. (J.S. Perkell & D.H. Klatt, eds.), pp. 426-463. New Jersey: Lawrence Erlbaum Associates.

Yang, B. 1996. A comparative study of American English and Korean vowels produced by male and female speakers. *Journal of Phonetics*, **24**, 245-261.

Yoon, K. 1998. *An acoustic analysis of Korean aspirated and tense alveolar fricatives using Multi-Speech.* M.A. thesis. University of Kansas.

Zsiga, E. 1993. *Features, Gestures, and the Temporal Aspects of Phonological Organization.* Ph.D. dissertation. Yale University.