The production and perception of coronal fricatives in Seoul Korean

The case for a fourth laryngeal category

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This article presents new data on the contrast between the two voiceless coronal fricatives of Korean, variously described as a lenis/fortis or aspirated/fortis contrast. In utterance-initial position, the fricatives were found to differ in centroid frequency; duration of frication, aspiration, and the following vowel; and several aspects of the following vowel onset, including intensity profile, spectral tilt, and F_1 onset. The between-fricative differences varied across vowel contexts, however, and spectral differences in the vowel onset especially were more pronounced for /a/ than for /i, ɯ, u/. This disparity led to the hypothesis that cues in the following vowel onset would exert a weaker influence on perception for high vowels than for low vowels. Perception data provided general support for this hypothesis, indicating that while vowel onset cues had the largest impact on perception for both high- and low-vowel stimuli, this influence was weaker for high vowels. Perception was also strongly influenced by aspiration duration, with modest contributions from frication duration and f_0 onset. Taken together, these findings suggest that the 'non-fortis' fricative is best characterized not in terms of the lenis or aspirated categories for stops, but in terms of a unique representation that is both lenis and aspirated.

Keywords: fricatives, laryngeal contrast, vowel onset, aspiration, duration, perceptual cues

1. Introduction

The three-way laryngeal contrast in Korean has attracted a great deal of attention in the phonetics literature due to its typological rarity. While most languages contrasting more than two laryngeal categories (e.g., Thai, Burmese, Hindi) make use of at least one voiced setting, Korean's three stop types are all voiceless in

Korean Linguistics 15:1 (2013), **7–49**. DOI 10.1075/kl.15.1.02cha
ISSN 0257–3784 / E-ISSN 2212–9731

word-initial position (Ladefoged & Maddieson 1996). Many studies have sought to identify markers of this unusual contrast, finding differences in a number of articulatory, acoustic, and aerodynamic dimensions (for a broad overview, see Cho et al. 2002). Despite some conflicting results, complicated by relatively rapid sound change in the language (Silva 2006a,b, Wright 2007, Kang & Guion 2008), most research on Korean has differentiated the three series of plosives and affricates in terms of a LENIS category (also called "lax", "weak", or "plain"), a FORTIS category (also called "tense", "strong", "forced", or "laryngealized"), and an ASPIRATED category, which is heavily aspirated in initial position (cf. Martin 1951, Han 1996, Avery & Idsardi 2001, and Ahn & Iverson 2004 for alternative analyses of the fortis obstruents as geminate, as well as Kim & Duanmu 2004 for an alternative analysis of the lenis obstruents as voiced).

In Korean there is also a rare laryngeal contrast between two voiceless denti-alveolar fricatives — two kinds of 's'. Compared to the analysis of the three-way stop contrast, the analysis of the two-way fricative distinction has been the subject of much more disagreement among phoneticians and phonologists. While one fricative has been identified relatively uncontroversially with the fortis stops on the basis of similar phonetic properties and phonological patterning, the second fricative has evaded straightforward identification with one of the Korean stop types, as it bears similarities to both the lenis stops and the aspirated stops. Consequently, this "non-fortis" fricative has been analyzed in various ways — as aspirated by some (e.g., Kagaya 1974, Park 1999, Yoon 2002), as lenis by others (e.g., Iverson 1983, Cho et al. 2002), and as both aspirated and lenis by others still (e.g., Kang 2000).

This paper provides new phonetic evidence in favor of a hybrid analysis of the non-fortis fricative along the lines of Kang (2000). Section 2 provides a comprehensive overview of the literature on the phonetics and phonology of Korean fricatives, summarizing how the facts are split with respect to the phonological classification of the non-fortis fricative. Sections 3–4 present the results of two experiments examining the production and perception of these fricatives by native speakers of Seoul Korean. Finally, Section 5 discusses the implications of these results for the phonological analysis of the Korean fricative contrast.

2. Background

2.1 Korean fricatives in the Korean laryngeal system

Research on Korean fricatives has generally attempted to analyze the fricatives in terms of the laryngeal categories for the plosives and affricates, which have been extensively described in phonetic studies of Korean. Previous work on the three Korean stop types has found that they differ from each other along glottal, subglottal, and supraglottal dimensions, including linguopalatal contact, glottal configuration, laryngeal and supralaryngeal articulatory tension, subglottal and intraoral pressure, and articulator velocity (Cho & Keating 2001, Kim 1970, Kagaya 1974, Kim et al. 2005, Kim, Maeda, & Honda 2010, Kim 1965, Hardcastle 1973, Hirose et al. 1974, Dart 1987, Brunner et al. 2003). The two distinguishing acoustic properties most often discussed with respect to the Korean stop types are voice onset time (VOT) and fundamental frequency (f_0) in the following vowel, typically measured at vowel onset (e.g., Lisker & Abramson 1964, Han & Weitzman 1970, Hardcastle 1973, Han 1996, Ahn 1999, Lee & Jung 2000, Cho et al. 2002, Choi 2002, Kim 2004). In addition, several other vocalic properties have been shown to distinguish the three laryngeal categories to some degree, such as first formant (F_1) trajectory, intensity buildup, and voice quality (Park 2002b, Han & Weitzman 1970, Abberton 1972, Han 1998, Cho et al. 2002, Kim & Duanmu 2004). In fact, the vowel following a Korean stop carries so much information about its laryngeal type that perception of the contrast has been shown to be quite good on the basis of vocalic information alone (Cho 1996, Kim et al. 2002). Finally, the stop types also differ in terms of durations — both the duration of closure and of adjacent vowels — which is most evident in examinations of the stops in intervocalic position (e.g., Oh & Johnson 1997, Park 2002a, Brunner et al. 2003). These acoustic differences are summarized in Table 1.

Given these characteristics of the Korean stops, studies of the Korean fricatives have approached the issue of their classification by comparing their properties to those of the stops. Phonological facts are consistent with the classification of one fricative as fortis (hereafter, /s_F/), but are unclear regarding the classification of the non-fortis fricative (hereafter, /s_{NF}/). Unlike the lenis stops, /s_{NF}/ rarely undergoes a degree of voicing resembling Intervocalic Lenis Stop Voicing (Silva 1992, Jun 1993), although it does undergo some vocal fold slackening in intervocalic environments (Iverson 1983). Kim, Maeda, Honda, and Hans (2010), for example,

Table 1. Acoustic differences among Korean stop types in utterance-initial position.

Property	FORTIS	LENIS	ASPIRATED
VOT	short	long	very long
f_0 onset	high	low	very high
F_1 onset	low	high	high
Voice quality	pressed	very breathy	breathy
Intensity buildup	very quick	slow	quick
Following vowel duration	long	long	short

observed that — similar to the fortis and aspirated stops — both /s_F/ and /s_{NF}/ usually (80% of the time on average) remain voiceless, regardless of position (cf. Cho et al. 2002, who found /s_{NF}/ remaining voiceless 54% of the time intervocalically). Nevertheless, /s_{NF}/ patterns with the lenis stops in undergoing Post-Obstruent Tensing (Cho & Inkelas 1994, Kim 2001, 2003) as well as semantically intensive tensing (Kim-Renaud 1974).

Articulatory and aerodynamic facts are similarly ambiguous regarding /s_{NF}/. Several differences with respect to /s_F/ have been identified, but while /s_F/ generally resembles the fortis stops, the properties of /s_{NF}/ are mixed, alternately resembling the lenis stops and the aspirated stops. For example, /s_{NF}/ has significantly less linguopalatal contact than /s_F/ (Kim 2001), a difference resembling that between the lenis and fortis stops. In terms of airflow, too, /s_{NF}/ patterns more closely with the lenis stops than the aspirated stops; moreover, it shows lower airflow resistance than /s_F/, consistent with linguopalatal contact differences (Kim, Maeda, Honda, & Hans 2010). However, /s_{NF}/ is associated with a significantly wider glottal width than /s_F/ (Kagaya 1974, Iverson 1983, Jun et al. 1998), a width greater than that of the lenis stops and often described in the literature as resembling that of the aspirated stops.

Acoustically /s_{NF}/ is just as ambiguous. Following from its wide glottal opening, /s_{NF}/ tends to be heavily aspirated like the aspirated stops (Moon 1997, Kang 2000, Cho et al. 2002). In fact, Yoon (1999) observed in a set of acoustic data that before mid and low vowels, aspiration duration provided the only consistent difference between /s_F/ and /s_{NF}/. Aspiration duration distinguishes /s_F/ and /s_{NF}/ in both initial and medial positions (Kim, Maeda, Honda, & Hans 2010), although aspiration differences have been found to be reduced or absent in high vowel environments (Kang et al. 2009). Furthermore, the linguopalatal contact differences that were noted above to suggest a lenis classification of /s_{NF}/ are reflected in spectral differences such as in center of gravity (i.e., centroid frequency), which is significantly higher for /s_F/ than /s_{NF}/ (Cho et al. 2002, Hwang 2004a,b, Kang et al. 2009, Holliday 2010).

As with the stop contrast, many of the acoustic cues to the fricative contrast have been shown to occur in the following vowel, but these cues often vary substantially across vowel environments and do not give clear indication of the most appropriate classification of /s_{NF}/. The f_0 onset associated with /s_{NF}/ is so close to the elevated f_0 onset associated with /s_F/ that consistent differences between the two have repeatedly failed to be found in Seoul Korean (e.g., Cho et al. 2002, Kang et al. 2009). This similarity in f_0 parallels the similarity in f_0 between the aspirated and fortis stops. In a low vowel, F_1 starts off significantly higher following /s_{NF}/ than /s_F/ due to the aspiration associated with /s_{NF}/, and in initial position, this high F_1 onset resembles that of both the lenis and aspirated stops (Park 2002b). In addition, the voice quality of the following vowel, as indicated by spectral properties such as the difference in amplitude between the first and second harmonics ($H_1 - H_2$) and between the first harmonic and second formant ($H_1 - A_2$), is breathier following /s_{NF}/ than /s_F/ (Cho et al. 2002). However, as with F_1, the difference in voice quality bears similarity both to the difference between lenis and fortis stops and to the difference between aspirated and fortis stops. Moreover, differences in spectral tilt measures are substantially smaller for high vowels than low vowels (Park 1999).

Durational characteristics have played a particularly large part in descriptions of the fricative contrast and are also divided with respect to the classification of /s_{NF}/. While constriction (i.e., closure) duration has generally been discussed with respect to the stop contrast in word-medial position (as differences in voiceless closure duration are not audible in absolute utterance-initial position), constriction (i.e., frication) duration has figured into the description of the fricative contrast in both initial and medial positions. In initial position, the frication duration of /s_{NF}/ is shorter than that of /s_F/ (Cho et al. 2002), a difference that recalls the closure duration difference between the lenis and fortis stops (cf. Kang 2000, Park 2002a). Intervocalically, moreover, the duration of /s_{NF}/ is shortened like the lenis stops (Kang 2000, Cho et al. 2002). Although the durational difference between the two fricatives varies across prosodic positions (Yoon 2005), it has been shown to have perceptual consequences in a number of domains: loanword adaptation of foreign fricatives, especially from English (Kim 1999, Kim & Curtis 2001, Lee 2006, Iverson & Lee 2006); second language acquisition of Korean fricatives by English-speaking learners (Cheon 2005, 2006); and discrimination of Korean and English fricatives by naïve English speakers (Cheon & Anderson 2008).

Durational differences between the fricatives extend to adjacent vowels, though the differences vary depending on position. For medial fricatives, a preceding vowel is significantly longer before /s_{NF}/ than /s_F/, and this difference has a measurable effect on perceptual judgments of VCV duration continua (Kang & Yoon 2005). Following vowel duration, too, is longer for medial /s_{NF}/ as compared to medial /s_F/ (Kang 2000). In the case of initial fricatives, however, following vowel duration is shorter for /s_{NF}/ than /s_F/ (Park 2002a). Regardless, it has only a marginal effect on perception compared to preceding vowel duration (Kang & Yoon 2005). These differences, along with the other main acoustic differences between the fricatives, are summarized in Table 2.

Like studies on production of the Korean fricatives, studies on perception of this contrast have been equivocal about the analysis of /s_{NF}/. In one identification experiment, Yoon (1999) synthesized monosyllabic stimuli with onset /s_{NF}/ followed by /a/ and found that when the aspiration interval of the fricative was shortened, perception shifted from /s_{NF}/ to /s_F/ for most listeners at around 37 ms of

Table 2. Acoustic differences between Korean fricatives in utterance-initial position.

Property	$/s_F/$	F	L	A	$/s_{NF}/$	F	L	A
Centroid frequency	high				low			
Constriction duration	long	✓		✓	short		✓	
Aspiration duration	short	✓			long		✓	✓
f_0 onset	high	✓		✓	high	✓		✓
F_1 onset	low	✓			high		✓	✓
Voice quality	pressed	✓			breathy		✓	✓
Intensity buildup	quick	✓		✓	slow		✓	
Following vowel duration	long	✓	✓		short			✓

[a] For each property, the fricative categories are compared to the stop categories (*f[ortis]*, *l[enis]*, and *a[spirated]*), with a check mark indicating a resemblance (cf. Table 1).

aspiration. In another identification experiment, Yoon (1999, 2002) took natural utterances of words beginning with $/s_{NF}/$ and generated stimuli by incrementally reducing the aspiration interval in 10-ms steps. Here, too, he found that perception shifted from $/s_{NF}/$ to $/s_F/$, but only for some listeners. Park (1999) conducted a similar identification experiment, but generated a 15-step continuum by incrementally cutting out 10-ms portions of a natural $/s_{NF}/$ token, starting from 50 ms into the following vowel and going backward. Listeners in this experiment were found to begin giving more $/s_F/$ responses after the entire 50-ms vowel onset was removed, then showed a categorical switch to $/s_F/$ at around the middle of the continuum (where all of the vowel onset and all but 20 ms of the aspiration interval were absent), a result suggesting that both a substantial degree of aspiration and the cues in the following vowel onset are important to the percept of $/s_{NF}/$.

Separate findings reported by Park (1999), however, suggested that the following vowel plays the primary role in perception of the fricative contrast. Data from perception of cross-spliced stimuli showed responses following the original onset fricative affiliation of the vowel (/a/) regardless of the laryngeal category of the stimulus fricative or the presence/absence of aspiration: $/s_F/$ cross-spliced with a vowel that originally followed $/s_{NF}/$ was perceived as $/s_{NF}/$ even with no aspiration present, while $/s_{NF}/$ cross-spliced with a vowel that originally followed $/s_F/$ was perceived as $/s_F/$ even with aspiration present. Thus, these findings were interpreted as indicating that the cues of the following vowel onset are more important than aspiration in perception of the fricatives.

In a recent perception study using naturally produced stimuli that included the vowel contexts /i, ɛ, a, o, u/, Holliday (2010) found that, in addition to aspiration duration, the centroid of the frication noise had a considerable influence on identification of the fricatives for both native listeners and English-speaking second language listeners. In fact, for native listeners centroid generally ranked second overall behind aspiration duration in terms of its effect on perception. Effects of spectral tilt and intensity were more modest, while the effect of f_0 was weak for most native listeners.

In sum, phonological and phonetic properties of the two Korean sibilants support a fortis identification of /s_F/, but are ambivalent about /s_{NF}/. The latter fricative displays phonological characteristics of both lenis and aspirated stops, and its articulatory, acoustic, and aerodynamic features are similarly divided between resembling the lenis stops and resembling the aspirated stops. Perceptual findings have been ambiguous as well, indicating significant (though limited) effects of both aspiration and f_0 in perception of the fricatives. Thus, the classification of /s_{NF}/ in the context of the Korean laryngeal system has remained controversial, with many researchers (e.g., Iverson & Lee 2006, Kang et al. 2009, Holliday 2010) now opting to refer to it in opposition to /s_F/ as non-fortis.

2.2 Research questions and predictions

In light of the widespread disagreement about the phonological classification of /s_{NF}/, the present study reexamined aspects of its production and perception in initial position by native speakers of Seoul Korean. As discussed above, phonetic studies have shown significant variation of between-fricative distinctions in different vowel contexts, yet with few exceptions (e.g., Park 1999), previous research has examined the fricative contrast in a limited set of vowel environments, most often in the context of the low vowel /a/. Consequently, the present study had three main objectives. The first objective was to broaden findings on the phonetic properties of /s_F/ and /s_{NF}/ by conducting a thorough investigation of their acoustic realization across a variety of vowel environments. The second objective was to gain a more complete picture of the relative contribution of consonantal and vocalic cues to perception of the fricative contrast by examining identification patterns in diverse vowel contexts. The final objective was to evaluate these new production and perception data in service of an empirically grounded analysis of /s_{NF}/.

Thus, the production experiment reported in Section 3 comprised a comprehensive set of analyses intended to confirm and expand upon disparate prior findings with one group of Korean speakers. In each case, there were two research questions. First, is the previously reported acoustic (non-)distinction between fricatives reliable? Second, how does the previously reported acoustic (non-)distinction vary across vowel environments? It was generally predicted that prior findings would be replicated, but that acoustic differences between the fricatives would vary significantly across vowel environments. In particular, many of the differences in a low vowel context, especially those found in the vowel onset, were predicted to be reduced or absent in high vowel contexts, in accordance with patterns documented by Park (1999) and Kang et al. (2009).

Following from the expected results of the production experiment, the perception experiment reported in Section 4 tested the hypothesis that vowel-dependent variation in acoustic differences found in the vowel onset would result in cues to the fricative contrast associated with the following vowel onset exerting a weaker influence on perception for high vowels than for low vowels. Would this be the case? It was predicted that, consistent with the findings of Park (1999), there would be close correspondence of responses with the cues of a low vowel onset, but significantly more departure of responses from the cues of a high vowel onset, thus allowing for a greater influence of other cues in a high vowel context.

The unique contributions of this study to the current state of knowledge on Korean fricatives are threefold. First, it reports on between-fricative differences in intensity buildup, F_1 onset, and following vowel duration in still unexamined high vowel contexts. Second, the study provides entirely new acoustic data on the fricatives in the context of the high back unrounded vowel /ɯ/, which is the best high vowel context to compare to the well-studied low vowel context /a/ because it does not exert the heavy coarticulation effects on the fricative that front and rounded vowels do (i.e., palatalization, rounding). Finally, it refines previous perceptual findings by systematically distinguishing between vowel contexts in terms of the cues used in identification. In this way, the study is able to approach the analysis of /s_{NF}/ in a more broadly informed manner.

3. Production of Korean fricatives

The production experiment investigated eight acoustic properties in native production of utterance-initial Korean fricatives — specifically, centroid frequency, frication duration, aspiration duration, vowel duration, and four properties of the vowel onset (intensity, spectral tilt, F_1, f_0). These properties were chosen because they had been shown previously to distinguish Korean obstruent categories, and they comprised a wide range of acoustic measures that could distinguish the fricatives, irrespective of their phonological analysis. Measurements were taken with respect to the low and high vowels of Korean (/a, i, ɯ, u/) in order to examine the coarticulatory effects of vowel height, backness, and rounding on acoustic differences between fricatives.

3.1 Methods

3.1.1 *Participants*

Thirteen native speakers of Korean participated in the production experiment, with two excluded from the analysis due to failure to follow directions or production of highly unnatural-sounding speech. Thus, in the end the final group comprised eleven native speakers of Korean (seven male; mean age 28.5 yr, SD 9.8). All participants spoke Seoul Korean, having grown up in Seoul or one of its satellite cities, and they were paid for their participation. None reported any history of hearing, speech, or language disorders.

3.1.2 *Speech material*

A list of Korean (C)V monosyllables was constructed varying the presence vs. absence of a coronal onset consonant, its continuancy (plosive, affricate, or fricative), its laryngeal type (lenis, fortis, or aspirated), and the vowel context (/a, i, ɯ, u/). This resulted in a set of 40 stimulus items, of which eight were critical items containing the fricatives of interest: 사 /s_{NF}a/ 'buy', 싸 /s_Fa/ 'cheap', 시 /s_{NF}i/ 'poem', 씨 /s_Fi/ 'seed', 스 /s_{NF}ɯ/ (nonsense syllable), 쓰 /s_Fɯ/ 'bitter', 수 /s_{NF}u/ 'number', 쑤 /s_Fu/ 'make (porridge)'.

3.1.3 *Procedure*

The production experiment was conducted in a sound-attenuated booth at the University of California, Berkeley (three participants) or at Seoul National University (all other participants). Speech was recorded at 22.05 kHz with 16-bit resolution using an AKG C420 head-mounted condenser microphone connected to a Sony Vaio PCG-TR5L laptop computer through an M-Audio USB pre-amp. Participants were told that the purpose of the experiment was to examine Korean pronunciation, and informed consent was obtained. Instructions and clarifications, both spoken and written, were provided in Korean.

Stimuli were presented and responses recorded in DMDX (Forster 2008). In order to prevent the production of stimuli with list intonation, participants were told to produce each item in the sentence __라고 하세요 [__ɾago has$_{NF}$ejo] 'Please say __'. Each item was presented on screen in Korean orthography for 1.5 sec, after which a picture of a green traffic light appeared to cue the participant to begin speaking. Following a short warm-up period of four filler items, stimuli were presented in eight blocks, randomized within each block, such that eight tokens were collected of each item. The experiment lasted approximately 25–30 minutes in all, including a short break in the middle.

3.1.4 *Acoustic analysis*

Acoustic measurements were taken in Praat (Boersma & Weenink 2008) on a Fourier spectrogram with a Gaussian window shape and a window length of 5 ms, dynamic range of 50 dB, and pre-emphasis of 6 dB/oct.

The frication interval was measured from the onset of high-frequency noise to the onset of a distributed spectrum characteristic of aspiration, a point marked off using the Praat script in Yoon (2009). This script worked by analyzing spectral balance across a given frequency and took two parameters: a dividing value separating the frequency range into upper and lower bands and a threshold value for the intensity difference between the two bands. The values of these parameters were found by analyzing a few spectra for a given vowel context by hand and adjusting the parameters until there was close correspondence (i.e., < 5 ms) between the boundaries laid down by hand and by the script. The aspiration interval was then measured from the onset of the distributed spectrum identified by the script to the onset of vowel periodicity. Centroid frequency was measured over an average spectrum of the middle 50 ms of the frication interval, to which a low-frequency stopband filter was applied going from 0 to the F_2 region (estimated as ⅗ of the participant's average F_3 for the vowel /a/). This filter was applied to get a better measure of front cavity resonances varying with place of articulation (Li et al. 2007).

Other acoustic properties were measured during the vowel interval, which was marked off from the beginning of the first glottal period to the beginning of the sharp decrease in amplitude coinciding with [ɾ]. Intensity was measured in three different ways. Intensity onset was measured over a three-period interval at the onset of the vowel; intensity buildup was measured as the average of differences between consecutive intensity measures taken every 5 ms during the first 30 ms of the vowel; and mean intensity was measured over the whole vowel interval. Spectral tilt was measured over a spectrum of the first three glottal periods in terms of the amplitude difference between the first and second harmonics ($H_1 - H_2$), and between the first and second harmonics corrected for the effects of different vocal tract configurations ($H_1{}^* - H_2{}^*$). This correction accounted for the disparate spectral influences of F_1 and F_2 across different vowels (Iseli & Alwan 2004; Iseli et al. 2007). Measurements of f_0 onset were taken by converting the average wavelength of the first three regular glottal periods to a frequency value. Finally, F_1 onset was measured over this three-period interval using linear predictive coding (LPC) analysis.

The set of major annotations is exemplified in Figure 1 for a waveform and spectrogram of a male participant's production of 사 /s_{NF}a/ 'buy'. As described above, the annotations delimited four main intervals: a frication interval, an aspiration interval, a vowel interval, and an interval of the first three regular glottal periods in the vowel. All tokens of critical items were annotated in this way, except

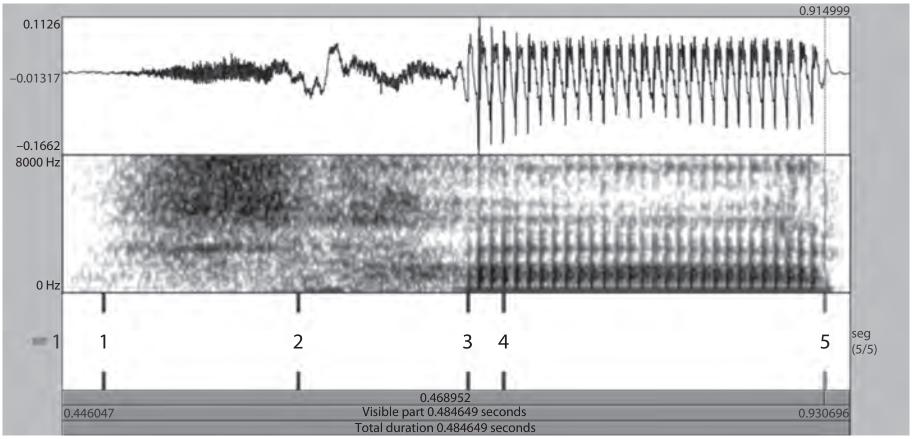

Figure 1. Waveform and spectrogram of 사 /s_{NF}a/ 'buy', annotated with landmarks used in acoustic analysis: 1 = start of frication; 2 = start of aspiration; 3 = start of vowel; 4 = end of first three regular glottal periods; 5 = end of vowel.

when they contained an anomalous pronunciation (e.g., because of a cough) or when the item spoken was not the correct item. These latter tokens were few in number (4.4% of all tokens of critical items) and were discarded.

3.1.5 *Statistical analysis*

In order to determine whether the measured acoustic properties differed significantly between fricative categories and whether any differences varied across vowel environments, each acoustic measure was analyzed as a dependent variable in a repeated-measures analysis of variance (ANOVA) using R (R Development Core Team 2010). In every case, there were two within-subjects factors: fricative category (FricCat; two levels: /s_F/ or /s_{NF}/) and vowel environment (VEnv; four levels: /a, i, ɯ, u/).

3.2 Results

FricCat had a statistically significant (at $\alpha = 0.05$) main effect on all acoustic measures except f_0 onset and mean intensity, while VEnv had a main effect on all except intensity buildup and $H_1 - H_2$ (Table 3). Notably, with respect to both the measures that differed reliably between the two fricatives and those that did not, there was variability in the interaction of FricCat and VEnv — that is, whether the effect of fricative category on the measured variable differed across vowel environments. Whereas there was no significant interaction in the case of centroid frequency, vowel duration, and f_0 onset, a significant interaction was obtained in the case of every other acoustic measure.

Table 3. Results of repeated-measures ANOVAs in the production study.

	FACTOR		INTERACTION
	FricCat	**VEnv**	**FricCat x VEnv**
Dependent variable	$F_{(1,10)}$	$F_{(3,30)}$	$F_{(3,30)}$
Centroid frequency	29.18 ***	29.03 ***	0.27 *n.s.*
Frication duration	57.03 ***	31.03 ***	22.56 ***
Aspiration duration	69.01 ***	11.06 ***	21.61 ***
Vowel duration	38.53 ***	19.18 ***	0.79 *n.s.*
Intensity onset	17.66 **	15.95 ***	20.80 ***
Intensity buildup	6.99 *	0.58 *n.s.*	5.86 **
Mean intensity	4.05 *n.s.*	12.86 ***	4.94 **
$H_1 - H_2$	89.84 ***	0.99 *n.s.*	9.63 ***
$H_1^* - H_2^*$	34.26 ***	5.42 **	9.89 ***
F_1 onset	67.66 ***	459.22 ***	77.78 ***
f_0 onset	0.08 *n.s.*	45.97 ***	1.72 *n.s.*

[a] *n.s.* = $p > 0.05$; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

The main effect of VEnv on the acoustic measures examined was generally attributable either to inherent vowel properties or to coarticulatory influence. The effect on $H_1^* - H_2^*$ was due to lower values for the back vowels, while the effects on vowel duration, intensity, f_0, and F_1 were accounted for by well-described phonetic differences between high and low vowels (e.g., Peterson & Lehiste 1960, Lehiste 1970, Lisker 1974, Beckman 1986, Whalen & Levitt 1995, Ladefoged 2005). On the other hand, the effect on centroid frequency was due to the allophonic palatalization and rounding of the fricatives before /i/ and /u/, respectively, which resulted in lower centroid frequencies preceding these vowels relative to /a/ and /ɯ/. The effects on frication duration and aspiration duration were also consistent with an explanation in terms of coarticulation. The vowel with the most open vocal tract configuration, /a/, was associated with the shortest period of consonantal constriction (i.e., frication duration) and the longest period of consonantal openness (i.e., aspiration duration); conversely, the vowel with the most constricted vocal tract configuration, /i/, was associated with the longest period of constriction and the shortest period of openness. This inverse pattern of covariance between frication and aspiration by vowel environment was consistent with a general negative correlation between frication duration and aspiration duration [$r = -0.57$; $p < 0.001$]: fricatives produced with long frication tended to have short aspiration (i.e., /s_F/), while fricatives produced with short frication tended to have long aspiration (i.e., /s_{NF}/). Aspiration duration was not significantly correlated with vowel duration,

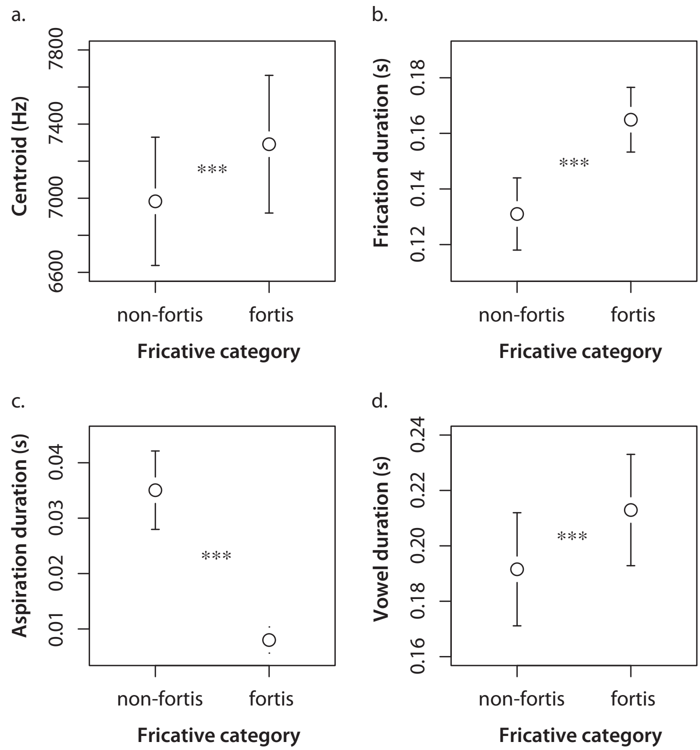

Figure 2. Mean acoustic measures, by fricative category: (a) centroid frequency; (b) frication duration; (c) aspiration duration; (d) following vowel duration.

but frication duration was [$r = 0.53$; $p < 0.001$]: long frication duration tended to co-occur with long vowel duration (/s_F/), while short frication duration tended to co-occur with short vowel duration (/s_{NF}/).

The effects of FricCat on centroid frequency, frication duration, aspiration duration, and following vowel duration are shown in Figure 2, which plots the mean values of these acoustic measures for each fricative category.[1] Compared to /s_F/, /s_{NF}/ was found to be approximately 300 Hz lower in centroid, 30 ms shorter in frication, and 30 ms longer in aspiration on average. The contrast between the fricatives was also found to differentiate the following vowel, which was on average about 20 ms longer after /s_F/ than /s_{NF}/. All of these between-fricative differences were consistent with previously reported results and statistically significant in post-hoc comparisons via paired one-tailed *t*-tests [ts(43) > 6.00; ps < 0.001]. Frication duration and aspiration duration, moreover, showed a significant interaction

1. In Figure 2 and all subsequent figures, error bars represent 95% confidence intervals of means over participants, and significant differences are marked with stars (*, **, *** = $p < 0.05$, 0.01, 0.001).

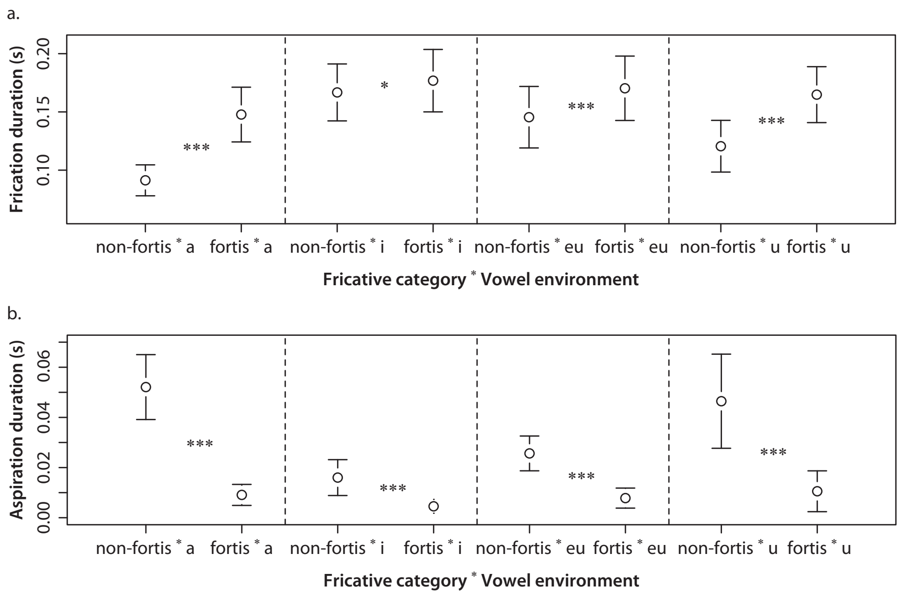

Figure 3. Mean frication duration (a) and aspiration duration (b), by fricative category and vowel environment (from left to right: /a/, /i/, /ɯ/, /u/).

between FricCat and VEnv (Table 3): both measures varied across vowels more for /s_{NF}/ than /s_F/, as shown in Figure 3.

Post-hoc comparisons via paired one-tailed *t*-tests by vowel context showed that while the between-fricative difference in frication duration was significantly greater than zero in all vowel environments [$p < 0.05$], it was greater preceding /a/ than preceding /i, ɯ, u/. For the /i/ context in particular, there was a difference of only 10 ms, more than 40 ms less than the difference in the /a/ context (Figure 3a). The difference in aspiration duration was also significantly greater than zero in all vowel environments [$p < 0.001$], and again the magnitude of the difference varied substantially, being 7–32 ms greater before /a/ than before /i, ɯ, u/ (Figure 3b).

In short, /s_{NF}/ was characterized by lower centroid frequency during frication, shorter frication duration, longer aspiration duration, and shorter following vowel duration than /s_F/ for all vowel environments. However, the differences in frication duration and aspiration duration were more pronounced preceding /a/ than /u/, /ɯ/, and especially /i/.

There were also effects of FricCat on the intensity characteristics of the following vowel (Figure 4). Compared to the vowel following /s_F/, the vowel following /s_{NF}/ was found to start approximately 1 dB higher in intensity, to increase in intensity 40 dB/s more slowly, and to be 0.4 dB lower in overall mean intensity on average. Like frication and aspiration differences, intensity differences varied across vowel contexts. Post-hoc comparisons via paired *t*-tests showed that while the difference in intensity onset — at a magnitude of approximately 2.2 dB — was significant for all vowel contexts [$p < 0.01$], the general pattern of higher intensity onset following /s_{NF}/ did not occur for /a/, which showed the reverse pattern (Figure 5a). The difference in intensity buildup was significant for /i/, /ɯ/, and /u/ [$p < 0.05$], but not for /a/ [$p > 0.1$]; moreover, it was about twice as large for /ɯ/ than for /i/ or /u/ (Figure 5b). Mean intensity showed a complementary pattern, whereby /s_F/ and /s_{NF}/ differed significantly for /a/ [$p < 0.001$], but not for /i/, /ɯ/, or /u/ [$p > 0.1$]: /a/ following /s_{NF}/ had, on average, a mean intensity approximately 1.4 dB lower than /a/ following /s_F/ (Figure 5c). In sum, the vowel following /s_{NF}/ was characterized by a different intensity profile than the vowel following /s_F/, but the distinction differed between high and low vowels. The low vowel /a/ had a lower intensity onset and lower overall mean intensity following /s_{NF}/ than /s_F/. In contrast, the high vowels /i, ɯ, u/ had a higher intensity onset and slower intensity buildup following /s_{NF}/ than /s_F/ such that they did not differ in overall mean intensity between the two fricatives.

Finally, FricCat had effects on the spectral tilt and F_1, but not f_0, of the following vowel onset (Figure 6). $H_1 - H_2$ and $H_1^* - H_2^*$ were, respectively, 3.0 dB and

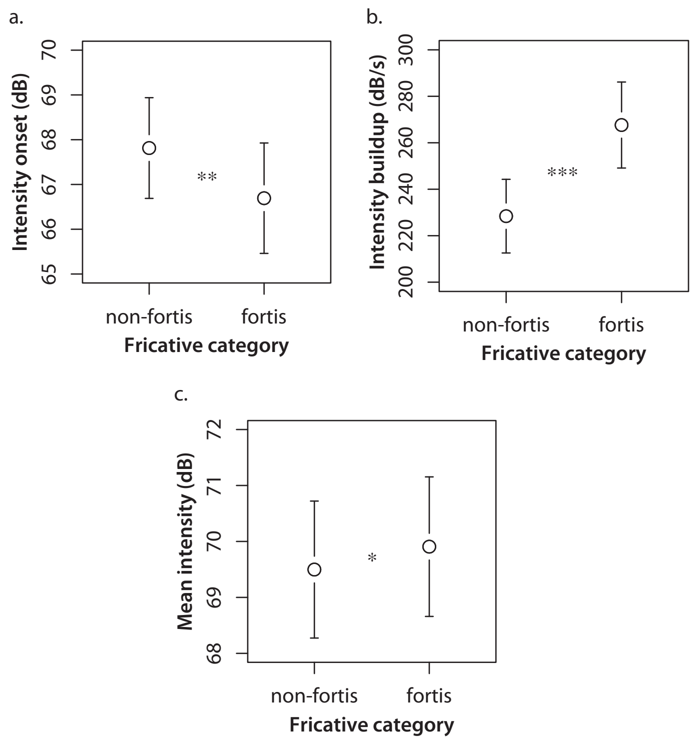

Figure 4. Mean intensity measures, by fricative category: (a) intensity onset; (b) intensity buildup; (c) overall mean intensity.

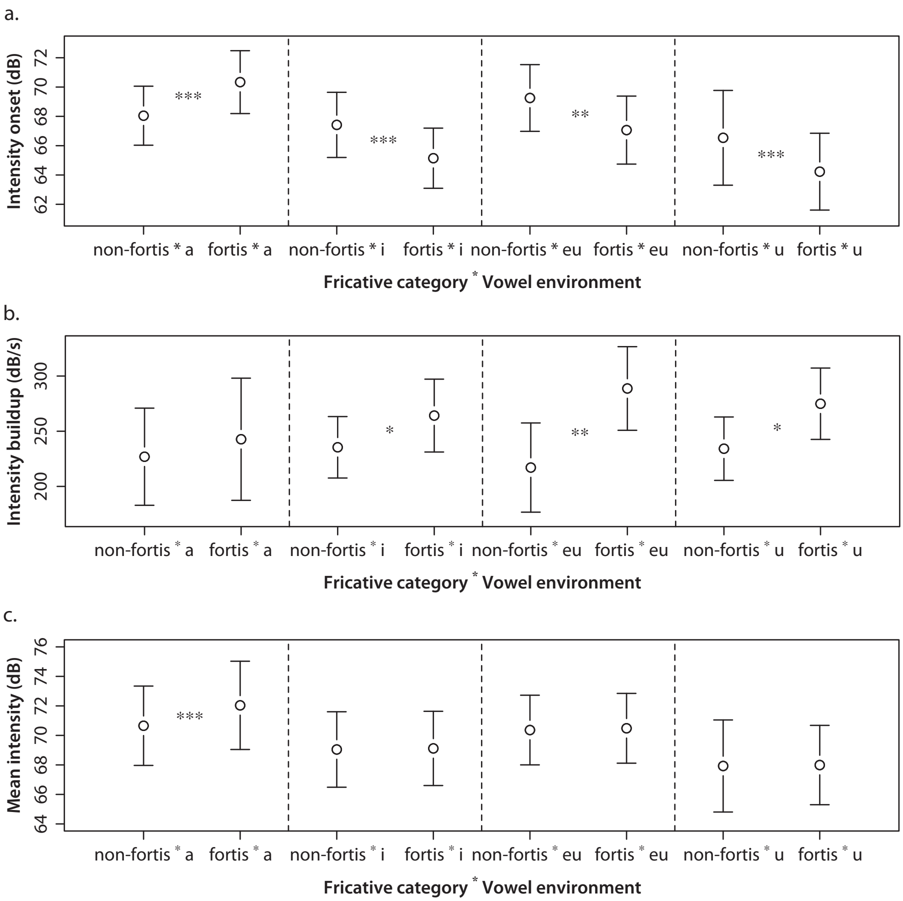

Figure 5. Mean intensity onset (a), intensity buildup (b), and overall mean intensity (c), by fricative category and vowel environment (from left to right: /a/, /i/, /ɯ/, /u/).

1.6 dB greater on average following /s_{NF}/ than /s_F/, but as with the other acoustic distinctions, these differences varied significantly across vowels. Post-hoc comparisons showed that the spectral tilt differences were significant [$p < 0.05$] in all cases except $H_1^* - H_2^*$ for /u/. However, the magnitude of $H_1 - H_2$ and $H_1^* - H_2^*$ differences varied across vowels: both were largest for /a/, 2–3 dB larger than those for /ɯ/, which were in turn larger than those for /i/ and /u/ (Figures 7a–b).

With regard to frequency components, F_1 was found to start approximately 60 Hz higher on average following /s_{NF}/ than /s_F/, but this difference was attributable entirely to the large F_1 onset difference in the /a/ context. Post-hoc comparisons showed that F_1 onset differences were significant for /a/, /i/, and /ɯ/ [$p < 0.05$], but not for /u/ [$p > 0.1$]. However, of the significant by-vowel differences, only the 250-Hz difference for /a/ was consistent with the overall pattern; the small differences

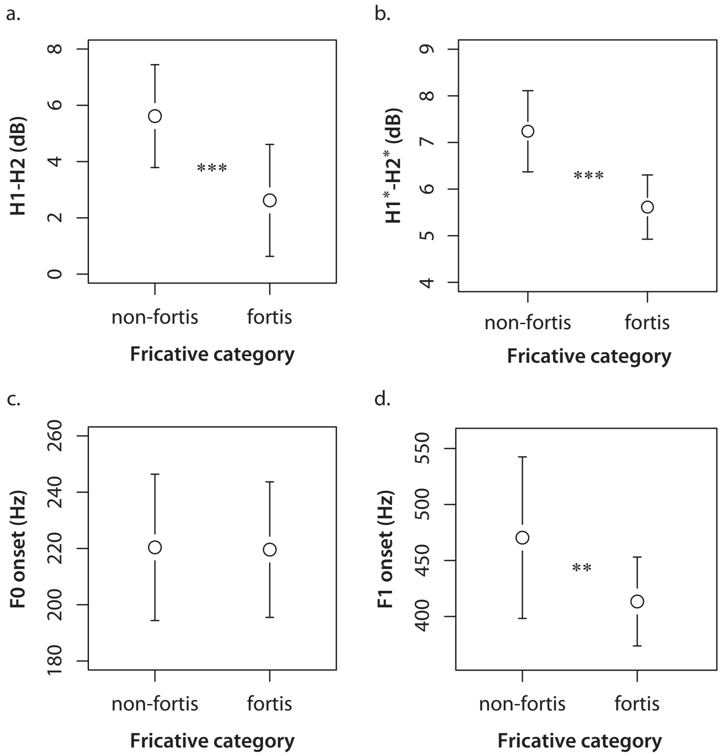

Figure 6. Mean vowel onset measures, by fricative category: (a) $H_1 - H_2$; (b) $H_1{}^* - H_2{}^*$; (c) f_0 onset; (d) F_1 onset.

for /i/ and /ɯ/ (on the order of 10 Hz) were in the opposite direction (Figure 7c). In contrast to F_1 onset, no significant difference between /s_F/ and /s_{NF}/ was found in f_0 onset — overall (Figure 6c) or in any vowel environment. This result was in line with previous phonetic examinations of Seoul Korean, which have repeatedly failed to find a reliable difference between the fricatives in f_0 onset.

In short, there were significant differences between /s_F/ and /s_{NF}/ in spectral tilt and F_1 of the following vowel onset. The vowel onset was consistently breathier following /s_{NF}/ than /s_F/, although this difference was attenuated in high vowels relative to low vowels. Moreover, F_1 started off substantially higher following /s_{NF}/ than /s_F/, but only when the vowel was /a/.

3.3 Discussion

Consistent with previous findings, the present results indicate that there are multiple cues to the Korean fricative contrast. In initial position, /s_F/ and /s_{NF}/ differ in centroid frequency, frication duration, aspiration duration, and following vowel

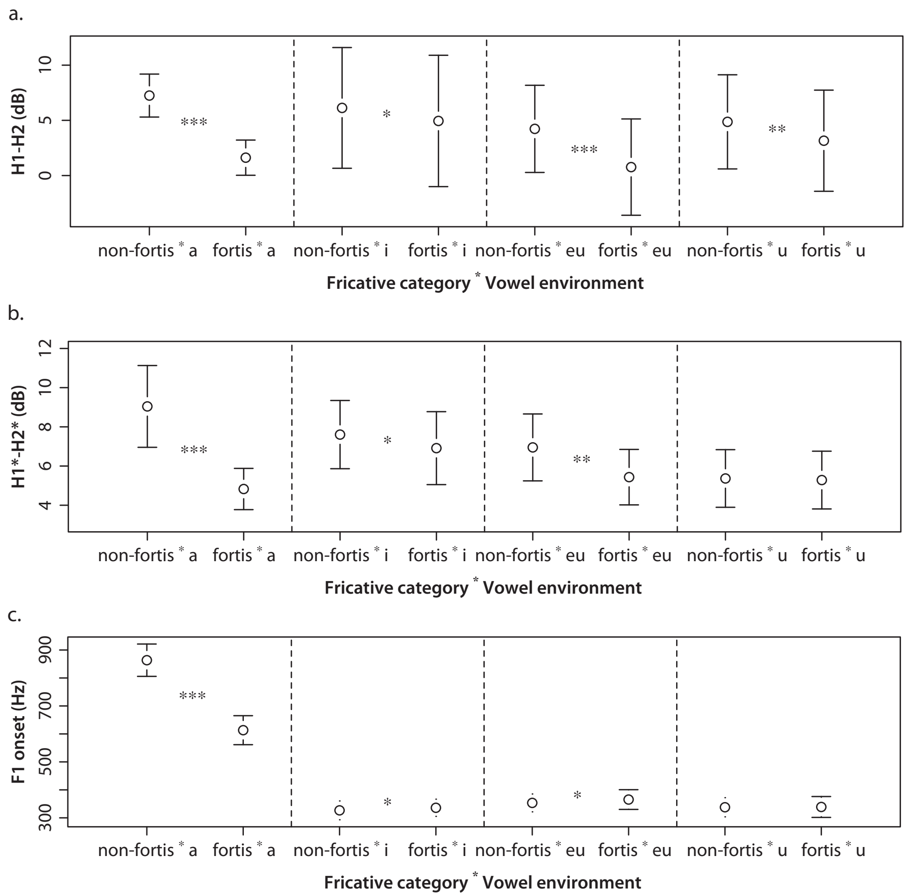

Figure 7. Mean $H_1 - H_2$ (a), $H_1{}^* - H_2{}^*$ (b), and F_1 onset (c), by fricative category and vowel environment (from left to right: /a/, /i/, /ɯ/, /u/).

duration, and the following vowel is further distinct between the two fricatives in intensity profile, spectral tilt, and F_1 onset.[2] While many of these properties are 'vo-

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2. An anonymous reviewer was concerned that the measurement of between-fricative differences in F_1 onset across a variety of vowel contexts was not meaningful, since variation in F_1 onset differences across vowels could simply be an artifact of more or less room for variability in different frequency ranges. This argument is not convincing because it fails to provide a principled explanation for why there should be a "floor effect" on F_1 variation in the low frequency range (i.e., for high vowels). The view adopted in this study is that F_1 onset differences between fricatives are smaller in the case of high vowels than low vowels due to the greater similarity in tongue posture between a coronal consonant and a high vowel than between a coronal consonant and a low vowel, which results in the maximum F_1 perturbation of the CV transition being smaller when V is high as opposed to low and, therefore, a lengthened VOT (via aspiration) creating less of a between-fricative disparity in this transition for high vowels.

calic' in that they are associated with the periodic following vowel interval, some may be considered truly 'consonantal' in being associated with the non-periodic fricative interval. This constitutes a potentially important difference between the Korean fricative and stop contrasts in absolute utterance-initial position, indeed between initial voiceless fricative and stop contrasts in general: more cues internal to the consonant can be exploited in perception of initial fricatives compared to initial stops, as the silence of post-pausal voiceless stop closure does not provide any useful acoustic information.

The question to ask, then, is: how are these additional consonantal cues used in conjunction with vocalic cues to distinguish between the Korean fricatives? As discussed in Section 2, vocalic cues do so much of the work in perception of the stop contrast that it is reasonable to predict that they exert more influence than consonantal cues in perception of the fricative contrast, and some evidence has suggested that in a low vowel context vocalic cues are indeed dominant. However, a recurring finding in the production experiment was that vowel context had a significant effect on whether and how a given acoustic dimension distinguished the fricatives. To be specific, differences in frication duration, aspiration duration, intensity profile, spectral tilt, and F_1 onset varied across vowel environments in magnitude or direction, and in general the differences were found to be smaller for the high vowels /i, ɯ, u/ than the low vowel /a/. This implies that the dominance of vocalic cues in perception of the fricative contrast will be weakened in high vowel contexts, where they will be less effective in distinguishing the two fricatives, and that, as a result, consonantal cues will play a larger role in these contexts than in a low vowel context. This hypothesis was tested in a multidimensional perception experiment.

4. Perception of Korean fricatives

The goals of the perception experiment were twofold: to confirm that cues found to differentiate the Korean fricatives in production are in fact utilized in perception, and to examine how the relative influence of cues varies across vowel environments. In particular, the perception experiment described below tested the hypothesis that consonantal cues would be dominated by vocalic cues in a low vowel environment, but not in a high vowel environment, where vocalic cues to the fricative contrast are attenuated. Thus, the experiment compared the perceptual impact of consonantal cues (frication quality, frication duration, aspiration duration) to that of vocalic cues (intensity profile, spectral tilt, F_1 onset) across the vowel contexts examined in the production study.

4.1 Methods

4.1.1 *Participants*

Thirty-one native speakers of Korean participated in the perception study, with one excluded from the analysis due to a complicated residential history inconsistent with the focus of the study. The final group thus comprised 30 native speakers of Korean (17 male; mean age 22.6 yr, SD 3.2). All participants had grown up in Seoul and spoke Seoul Korean, and they were paid for their participation. None reported any history of hearing, speech, or language disorders, and none had participated in the production experiment.

4.1.2 *Stimuli*

Six parameters were included in the design of the experimental stimuli (Table 4), representing the consonantal cues to the Korean fricative contrast (frication quality, frication duration, aspiration duration), the cohort of vocalic cues (vowel affiliation), and the variation in vowel environment that was examined in the production study (vowel quality). Also included was f_0 onset, since some evidence (e.g., Holliday 2010) has suggested that it has an effect on perception of the fricatives despite not reliably distinguishing them in production. Following vowel duration, however, was not included, as it has been shown to have only a marginal effect on perception (e.g., Kang & Yoon 2005).

As discussed in Section 2, many, but not all, of the stimulus parameters have been shown in previous work to have an effect on perception of the fricative contrast — namely, centroid frequency (higher centroid = /s_F/), aspiration duration (longer aspiration = /s_{NF}/), and vowel affiliation (fortis-affiliated vowel = /s_F/; non-fortis-affiliated vowel = /s_{NF}/). Given the results of the production experiment, it is reasonable to expect frication duration to have an effect as well (longer frication = /s_F/). Furthermore, given the variation of acoustic distinctions across vowels, one might also expect vowel quality to have an effect, since the differences between /s_F/ and /s_{NF}/ are generally larger with low vowels than with high vowels.

Table 4. Stimulus parameters in the perception experiment.

Parameter	Levels
Frication quality (FricQual)	non-fortis / fortis
Frication duration (FricDur)	short / mid / long
Aspiration duration (AspDur)	short / mid / long
Vowel affiliation (VAff)	non-fortis / fortis
Vowel quality (VQual)	a / i / ɯ / u
f_0 onset (F0Ons)	low / mid / high

Because /s_F/ is less distinct from /s_{NF}/ when the following vowel is one of /i, ɯ, u/ than when it is /a/, it is possible that hearing /s_F/ in a high vowel context will generally decrease the probability of it being identified as fortis compared to the probability of fortis identification in a low vowel context. In this way, there could arise a bias against fortis identification with high vowels. However, in the case of /ɯ/ specifically, such a bias is likely to be overpowered by a "Ganong effect" (Ganong 1980) biasing perception away from the non-word /s_{NF}ɯ/ and toward the real word /s_Fɯ/ 'bitter'.

The stimuli were created using eight base tokens from a female participant ("Jane") in the production experiment. These tokens came from a second completion of the production experiment in which Jane pronounced the items in isolation rather than in a sentence. The items were re-recorded in isolation in order to avoid having to excise them from running speech (as they were to be played to listeners in isolation), thereby allowing the perception stimuli to sound as natural as possible, and acoustic analysis of the isolated word productions showed the same general patterns of acoustic distinctions evident in sentence-embedded productions. The base tokens comprised all possible combinations of the frication quality[3] (FricQual) and vowel quality (VQual) parameters (i.e., a token of /s_{NF}/ and a token of /s_F/ for each vowel quality) and were selected on the basis of maximal difference in centroid frequency and minimal difference in following vowel duration. These base tokens were manipulated in three ways to vary frication duration (FricDur), aspiration duration (AspDur), vowel affiliation (VAff), and f_0 onset (F0Ons). First, manual splicing was done both to insert aspiration noise into a token of /s_F/ (from a central portion of the aspiration interval in the corresponding token of /s_{NF}/) and to cross fricatives and vowels of different categories (/s_F/ with non-fortis-affiliated vowel, /s_{NF}/ with fortis-affiliated vowel). Second, Praat's duration manipulation function was used to adjust the length of frication and aspiration. Finally, Praat's pitch manipulation function was used to adjust f_0 onset (by moving the whole contour). Vowel duration was not manipulated, but was similar between /s_F/ and /s_{NF}/. Vowel durations following /s_F/ and /s_{NF}/ in the base tokens were, respectively (in ms), 241 and 239 for /a/; 295 and 325 for /i/; 348 and 345 for /ɯ/; and 286 and 260 for /u/. Thus, vowel duration was not likely to serve as a useful cue to listeners.

Most stimulus parameters had two or three levels, the values of which were based on the range of variation in Jane's isolated word productions. Following from the production experiment, VQual had four levels: the low vowel /a/ and the

3. The frication quality parameter refers to the overall spectral quality of the frication, since, strictly speaking, the levels involve alternation of the whole spectrum, not just the centroid frequency.

high vowels /i, ɯ, u/ (which were all included to maximize the generalizability of any low-high vowel differences). FricQual had two levels: non-fortis (the frication of one of the lowest-centroid /s_{NF}/ productions in a given vowel context) and fortis (the frication of one of the highest-centroid /s_F/ productions in a given vowel context), with the specific centroids of these levels differing across vowel qualities. In the /a/, /i/, /ɯ/, and /u/ contexts, the centroids of the 'non-fortis' level of the FricQual parameter were, respectively, 6936, 5473, 5950, and 6754 Hz, and of the 'fortis' level, 9102, 6051, 9061, and 8612 Hz. FricDur had three levels based on a range of 96–247 ms found in Jane's speech: 100 ms (the short end of frication), 240 ms (the long end of frication), and 170 ms (midway between the short and long ends). AspDur also had three levels based on a range of 0–101 ms found in Jane's speech: 0 ms (the short end of aspiration), 100 ms (the long end of aspiration), and 50 ms (midway between the short and long ends). VAff had two levels: non-fortis (a vowel that originally followed /s_{NF}/) and fortis (a vowel that originally followed /s_F/). Finally, F0Ons had three levels: low (the low end of f_0 for a given vowel quality), high (the high end of f_0 for a given vowel quality), and mid (midway between the low and high ends), with the specific values of the levels differing across vowel qualities. In the /a/, /i/, /ɯ/, and /u/ contexts, the values of the 'low' level of the F0Ons parameter were, respectively, 240, 260, 270, and 250 Hz, and of the 'high' level, 320, 340, 350, and 330 Hz. The total stimulus set thus contained 432 stimuli (2 levels of FricQual x 3 levels of FricDur x 3 levels of AspDur x 2 levels of VAff x 4 levels of VQual x 3 levels of F0Ons).

4.1.3 *Procedure*

The perception experiment was conducted in a quiet room at Seoul National University. Participants were told that the purpose of the experiment was to examine Korean listening skills, and informed consent was obtained. The task was two-alternative forced-choice identification, and instructions were provided in Korean. Participants were informed that during the experiment they would hear one of eight items (/s_{NF}a/, /s_Fa/, /s_{NF}i/, /s_Fi/, /s_{NF}ɯ/, /s_Fɯ/, /s_{NF}u/, /s_Fu/) and were to identify the initial consonant as either /s_F/ or /s_{NF}/ by pressing the appropriate key on the keyboard.

Stimuli were presented via DMDX (Forster 2008) on a Sony Vaio PCG-TR5L laptop computer over Direct Sound EX-29 headphones. Following a short familiarization phase of four items, the stimuli were played in random order once each. After each stimulus was played, a prompt appeared on screen reminding the participant of what the response buttons were: '1' for /s_{NF}/, '9' for /s_F/. Participants had to press either '1' or '9' to move on to the next item. The experiment lasted approximately 25–30 minutes in all, including a short break at the midway point.

4.1.4 *Statistical modeling*

In order to examine how the stimulus variations influenced perception, participants' responses were coded as fortis identifications and modeled using logistic regression in R (R Development Core Team 2010). As an initial step, all parameters and interactions were entered into a stepwise logistic regression to see which variables improved the performance of a model having only within-participant predictors (i.e., fixed effects). Once these variables were identified, they were used to build a mixed-effects logistic regression model (Johnson 2008: 259–264) accounting for between-participant variation in perceptual biases and strategies. The model was built in an incremental fashion so as to minimize the number of predictor variables and thereby guard against overfitting the model to the data, and at each stage the robustness of the model was measured via cross-validation (Johnson 2008: 238–240): the same type of model was built 100 times based upon a random subset of 85% of the data and then tested against the remaining 15% of the data. At each stage the random effect in the model was Participant, while the fixed effects comprised one or more of the stimulus parameters (Table 4) and their interactions.

4.2 Results

The results of the stepwise logistic regression showed that five of the stimulus parameters improved the predictive power of a model with only fixed effects. In descending order of deviance accounted for, they were VAff (2756.93), VQual (1159.15), AspDur (962.39), F0Ons (178.20), and FricDur (106.37). FricQual did not emerge as a significant predictor. In addition, seven of the 30 possible two-way interactions improved the model: VAff x VQual (966.37), VQual x AspDur (120.63), VAff x AspDur (71.00), VAff x F0Ons (55.52), VQual x F0Ons (26.52), AspDur x FricDur (18.75), and AspDur x F0Ons (8.31). Two of the 120 possible three-way interactions improved the model further: VAff x VQual x AspDur (37.86) and VAff x VQual x F0Ons (15.86).

Mixed-effects models fit to the response data with one fixed effect indicated that of the five parameters found to be significant predictor variables, VAff had the strongest effect on perception. The 95% confidence interval for the percentage of responses correctly predicted by a model with only VAff as a fixed effect was 72.9–76.6%. In contrast, the corresponding figures for models with only VQual, AspDur, F0Ons, or FricDur as a fixed effect were, respectively, 63.6–67.7%, 63.1–66.9%, 59.8–64.0%, and 59.4–63.5%. In other words, the type of fricative that a stimulus vowel was originally affiliated with (i.e., the cohort of vocalic cues associated with that fricative) was the most informative predictor of responses to that stimulus in the perception experiment. Nevertheless, inclusion of the other parameters significantly improved upon a model that had only VAff as a fixed effect. When VQual, AspDur, F0Ons, and FricDur were added as fixed effects, the percentage of correct predictions made by the model increased by approximately 6%, from 74.8 to 80.9% [$t(193) = 47.76$; $p < 0.001$]. Thus, the effects of these parameters on perception were significant, though much smaller than the effect of VAff.

Inclusion of many, but not all, of the two-way interactions further improved the model's performance. The percentage of correct predictions continued to increase significantly with the addition of the interactions VAff x VQual, VQual x AspDur, VAff x AspDur, VAff x F0Ons, and VQual x F0Ons. The addition of these interaction terms to the model improved its performance from 80.9% to 83.7% [$t(198) = 24.98$; $p < 0.001$]. Adding the interactions AspDur x FricDur and AspDur x F0Ons — singly or in combination — did not further improve the model [$t(198) = 0.02$; *n.s.*]. However, adding the three-way interactions VAff x VQual x AspDur and VAff x VQual x F0Ons slightly improved the model's performance to 84.0% [$t(198) = 2.02$; $p < 0.05$]. Thus, the final mixed-effects model (summarized in Table 5) was able to correctly predict the response data with a probability approximately 34% higher than chance.

The intercept — comprising stimuli with a short FricDur, short AspDur, nonfortis VAff, low VQual, and low F0Ons — was associated with a probability of fortis

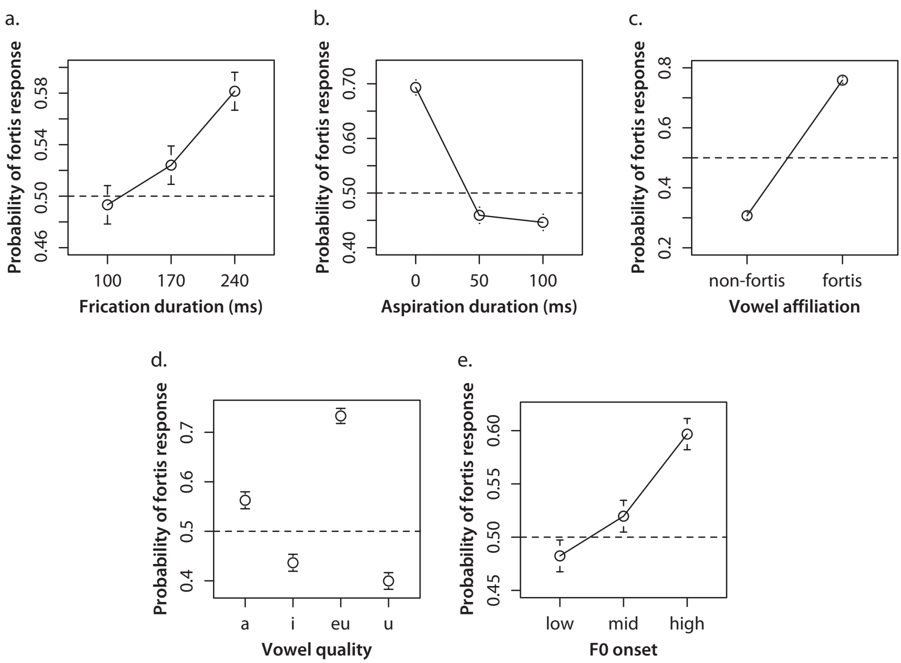

Figure 8. Probability of perception as fortis, by stimulus parameter: (a) FricDur; (b) AspDur; (c) VAff; (d) VQual ('eu' = /ɯ/); (e) F0Ons. Dotted lines mark chance (50%).

Table 5. Coefficients in a logistic mixed-effects model of the probability of a 'fortis' response in the perception experiment.

Predictor	**β**	**s.e.**	**df**	**t-value**	***p*-value**	
(Intercept)	−1.667	0.320	12889	−5.213	<0.001	***
VAff: fortis	5.524	0.468	12889	11.799	<0.001	***
VQual: /i/	0.583	0.270	12889	2.157	0.031	*
VQual: /ɯ/	2.870	0.277	12889	10.359	<0.001	***
VQual: /u/	0.926	0.278	12889	3.329	<0.001	***
AspDur: mid	−3.216	0.299	12889	−10.758	<0.001	***
AspDur: long	−3.489	0.321	12889	−10.862	<0.001	***
F0Ons: mid	0.512	0.273	12889	1.874	0.061	
F0Ons: high	1.376	0.261	12889	5.275	<0.001	***
FricDur: mid	0.259	0.073	12889	3.543	<0.001	***
FricDur: long	0.747	0.074	12889	10.060	<0.001	***
VAff: fortis x VQual: /i/	−3.660	0.520	12889	−7.043	<0.001	***
VAff: fortis x VQual: /ɯ/	−3.347	0.598	12889	−5.596	<0.001	***
VAff: fortis x VQual: /u/	−3.869	0.525	12889	−7.367	<0.001	***
VQual: /i/ x AspDur: mid	1.829	0.349	12889	5.239	<0.001	***
VQual: /ɯ/ x AspDur: mid	0.552	0.361	12889	1.530	0.126	
VQual: /u/ x AspDur: mid	−0.393	0.399	12889	−0.986	0.324	
VQual: /i/ x AspDur: long	1.477	0.375	12889	3.936	<0.001	***
VQual: /ɯ/ x AspDur: long	0.963	0.379	12889	2.540	0.011	*
VQual: /u/ x AspDur: long	0.050	0.408	12889	0.124	0.902	
VAff: fortis x AspDur: mid	3.294	0.552	12889	5.966	<0.001	***
VAff: fortis x AspDur: long	3.489	0.558	12889	6.254	<0.001	***
VAff: fortis x F0Ons: mid	−0.434	0.539	12889	−0.805	0.421	
VAff: fortis x F0Ons: high	−1.376	0.525	12889	−2.618	0.009	**
VQual: /i/ x F0Ons: mid	−0.201	0.343	12889	−0.586	0.558	
VQual: /ɯ/ x F0Ons: mid	0.210	0.327	12889	0.642	0.521	
VQual: /u/ x F0Ons: mid	−0.220	0.363	12889	−0.606	0.544	
VQual: /i/ x F0Ons: high	0.108	0.325	12889	0.332	0.740	
VQual: /ɯ/ x F0Ons: high	0.657	0.324	12889	2.030	0.042	*
VQual: /u/ x F0Ons: high	−0.608	0.350	12889	−1.736	0.083	
VAff: fortis x VQual: /i/ x AspDur: mid	−2.377	0.604	12889	−3.934	<0.001	***
VAff: fortis x VQual: /ɯ/ x AspDur: mid	−3.012	0.680	12889	−4.428	<0.001	***
VAff: fortis x VQual: /u/ x AspDur: mid	−1.146	0.636	12889	−1.802	0.072	

Table 5. (*continued*)

Predictor	β	S.E.	df	t-value	*p*-value	
VAff: fortis x VQual: /i/ x AspDur: long	−2.664	0.614	12889	−4.342	<0.001	***
VAff: fortis x VQual: /ɯ/ x AspDur: long	−3.001	0.687	12889	−4.368	<0.001	***
VAff: fortis x VQual: /u/ x AspDur: long	−1.285	0.636	12889	−2.021	0.043	*
VAff: fortis x VQual: /i/ x F0Ons: mid	−0.054	0.599	12889	−0.090	0.928	
VAff: fortis x VQual: /ɯ/ x F0Ons: mid	0.388	0.613	12889	0.634	0.526	
VAff: fortis x VQual: /u/ x F0Ons: mid	0.412	0.612	12889	0.674	0.501	
VAff: fortis x VQual: /i/ x F0Ons: high	0.021	0.584	12889	0.036	0.971	
VAff: fortis x VQual: /ɯ/ x F0Ons: high	0.114	0.606	12889	0.188	0.851	
VAff: fortis x VQual: /u/ x F0Ons: high	1.188	0.599	12889	1.984	0.047	*

[a] * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

identification lower than chance. The probability of fortis identification increased with FricDur (Figure 8a), but decreased with AspDur (Figure 8b). The impact of AspDur on perception was substantially larger than that of FricDur. However, the strongest influence belonged to VAff: a fortis VAff increased the probability of fortis identification by nearly 50% overall (Figure 8c).

The other vocalic parameters also had significant, though smaller, effects. Compared to stimuli with the low vowel /a/, stimuli with the high vowels /i/ and /u/ were less likely overall to be labeled as fortis, whereas stimuli with the high vowel /ɯ/ were more likely overall to be labeled as fortis (Figure 8d), a result consistent with a Ganong effect introducing a bias against the non-word /s_{NF}ɯ/. F0Ons had a significant effect on perception as well: higher F0Ons resulted in a higher probability of fortis identification (Figure 8e).

The effects of VAff and VQual interacted significantly with each other as well as with the effects of AspDur and F0Ons. Whereas stimuli with high vowels were more likely than stimuli with /a/ to be labeled as fortis when VAff was non-fortis, the opposite was true when VAff was fortis (Figure 9a). In the latter case, stimuli with /i/, /ɯ/, and /u/ were less likely to be labeled as fortis compared to stimuli with /a/, as seen in the negative coefficients in Table 5. This result was consistent with the prediction of a bias against fortis identification with high vowels and followed from the comparatively small phonetic disparity between fortis- and non-fortis-affiliated high vowel onsets. The [VAff x VQual] interaction was attributable primarily to the pronounced effect of VAff in a low vowel environment, where responses followed VAff very closely: stimuli with non-fortis-affiliated /a/ were overwhelmingly labeled as non-fortis, while stimuli with fortis-affiliated /a/ were overwhelmingly labeled as fortis. VAff also interacted with AspDur in that longer levels of AspDur lowered the probability of fortis identification less when VAff was

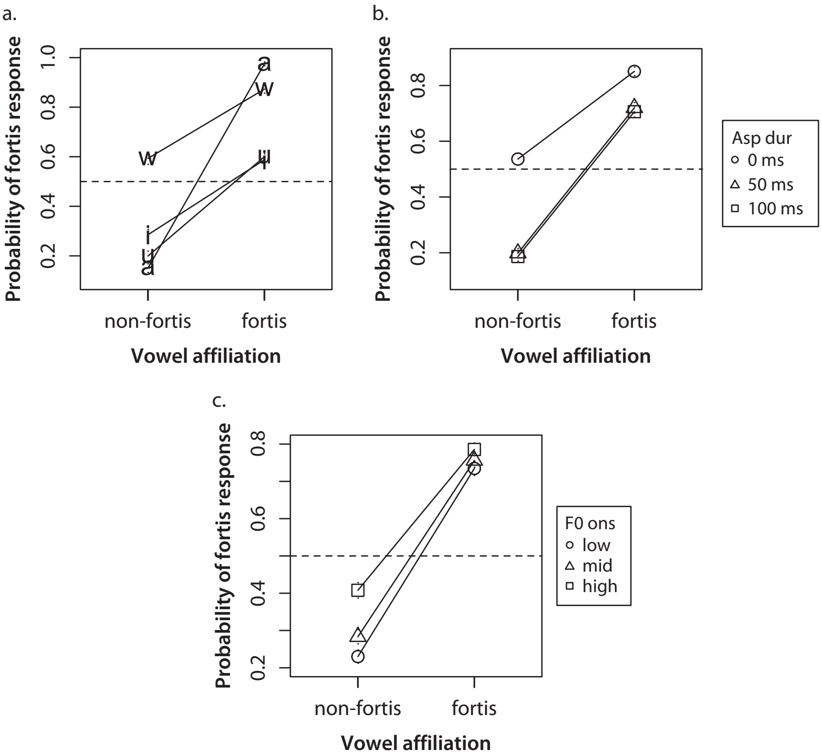

Figure 9. Interactions of VAff with: (a) VQual ('w' = /ɯ/); (b) AspDur; (c) F0Ons. Dotted lines mark chance (50%).

fortis than when VAff was non-fortis (Figure 9b). VAff interacted with F0Ons in a similar way: lower levels of F0Ons lowered the probability of fortis identification less when VAff was fortis as opposed to non-fortis (Figure 9c).

Interactions of VQual with AspDur and F0Ons were obtained largely because in each case one vowel quality behaved differently from the others, as shown in Figure 10. In the case of AspDur, stimuli with the vowels /a/, /ɯ/, and /u/ showed a decline in fortis identification only with the increase of AspDur from short to mid, whereas stimuli with the vowel /i/ showed declines with both the increase from short to mid and the increase from mid to long. In the case of F0Ons, /ɯ/ was the vowel that stuck out, showing larger overall increases in fortis identification with the raising of F0Ons than did the other vowels.

Three-way interactions of VAff and VQual with AspDur and F0Ons arose from the fact that the disparate effects of AspDur and F0Ons across vowel contexts were often isolated to one VAff level. In the case of AspDur, the monotonic decline in fortis identification of stimuli with /i/ was consistent across both levels of VAff. However, there was a marked disparity in stimuli with /a/: stimuli with

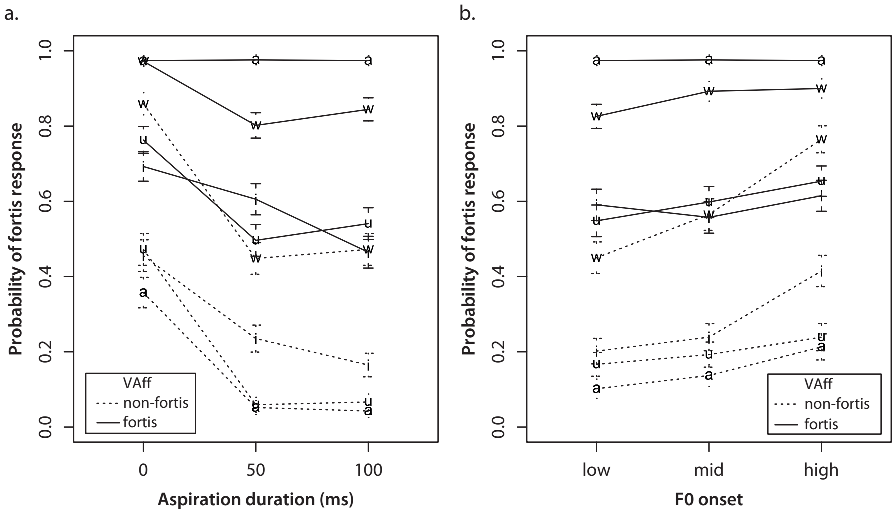

Figure 10. Interaction of VAff and VQual with: (a) AspDur; (b) F0Ons. VAff is divided by line type (dotted: non-fortis; solid: fortis). VQual is represented with standard IPA symbols (except 'w' = /ɯ/).

non-fortis-affiliated /a/ showed a sharp decline in fortis identification with the increase of AspDur from short to mid, whereas stimuli with fortis-affiliated /a/ were unaffected by increases in AspDur, being labeled as fortis nearly all of the time (Figure 10a).

A similar pattern occurred in the case of F0Ons. While stimuli with non-fortis-affiliated /a/ showed modest increases in fortis identification with the raising of F0Ons, stimuli with fortis-affiliated /a/ were unaffected by F0Ons modulation and labeled as fortis nearly all of the time (Figure 10b). As mentioned above, as F0Ons was raised the vowel /ɯ/ also showed larger increases in fortis identification than the other vowels; however, this was the case only when VAff was non-fortis. The imperviousness of stimuli with fortis-affiliated /a/ to modulations in stimulus parameters was found in the influence of FricDur as well: while nearly all stimuli including those with non-fortis-affiliated /a/ showed a small effect of lengthened FricDur on fortis identification, stimuli with fortis-affiliated /a/ were consistently labeled as fortis regardless of FricDur level.

In summary, responses in the perception experiment were jointly influenced by FricDur, AspDur, VAff, VQual, and F0Ons, and the effects of AspDur and F0Ons differed significantly across levels of VAff as well as VQual. Switching VAff from non-fortis to fortis had the strongest net effect on perception, resulting in a sharp increase in the probability of fortis identification, especially for the low vowel /a/. Lengthening FricDur and raising F0Ons each slightly increased the probability of fortis identification, while lengthening AspDur — in particular, from no aspiration to a mid level of aspiration — sharply reduced the probability of fortis identification. However, the effects of AspDur and F0Ons modulations were attenuated when VAff was fortis as opposed to non-fortis. In fact, these effects were hardly apparent for stimuli with a fortis-affiliated low vowel, which consistently resulted in a fortis percept regardless of FricDur, AspDur, or F0Ons level.

4.3 Discussion

The results of the perception experiment supported the hypothesis that the influence of vocalic cues in perception of the Korean fricative contrast would be weaker in high vowel environments than in low vowel environments. As seen in Figure 9a, responses in the perception experiment closely followed the vowel's original onset affiliation when the vowel was /a/. In fact, perceptual judgments on stimuli with /a/ deviated from VAff only 15% of the time when VAff was non-fortis and less than 3% of the time when VAff was fortis, suggesting that the cohort of cues present in a low vowel onset exerted a powerful influence on perception. When the stimulus vowel was a high vowel, however, responses followed VAff less closely, though they were still more strongly influenced by VAff than any other individual stimulus parameter. Perceptual judgments on stimuli with non-fortis-affiliated high vowels were consistent in showing greater deviation from VAff than stimuli with non-fortis-affiliated /a/ (29%, 59%, and 20% for /i/, /ɯ/, and /u/, respectively). Similarly, perceptual judgments on stimuli with fortis-affiliated high vowels showed greater deviation from VAff than stimuli with fortis-affiliated /a/ (41%, 13%, and 40% for /i/, /ɯ/, and /u/, respectively). Thus, while there was an overall tendency for perception to match VAff, the influence of VAff and the cohort of associated vocalic cues was weaker for the high vowels than for /a/. This result accords with the pattern of acoustic differences between fricatives found in the following vowel onset, which were generally smaller in high vowel environments (Section 3.2).

Although the perception experiment was not designed to tease apart the cues in the vowel onset from one another, three facts suggest that the discrepancy in fricative perception between high and low vowel contexts is largely attributable to the marked between-fricative differences in F_1 onset specific to the low vowel environment — in particular, the low F_1 onset and steep F_1 transition in /a/ following /s_F/. First, Holliday (2010) found intensity to have a relatively small effect on native perception of the fricatives. Second, in the production experiment, low and high vowel contexts were found to differ to a greater degree with respect to between-fricative distances in F_1 onset than with respect to between-fricative distances in spectral tilt (Figure 7). Finally, in the perception experiment, the high vowel /ɯ/, despite patterning relatively closely with /a/ in terms of spectral tilt differences, did not elicit fortis identifications with nearly the same uniformity that /a/ did when

VAff was fortis (e.g., Figure 10). Together these facts imply that F_1 onset played an especially large role in listeners' perception, in accordance with other findings indicating a strong effect of F_1 onset in the perception of laryngeal contrast (e.g., Kluender 1991, Benkí 2001). Future work should attempt to test the effect of F_1 onset on perception of the fricatives directly.

As for the influence of consonantal cues on perception, FricDur had only a modest effect, whereas AspDur had a marked effect that was mediated by an interaction with VAff and VQual.[4] Lengthening the aspiration interval of a stimulus made it less likely to be perceived as /s_F/ across vowel affiliations and vowel qualities with one exception: fortis-affiliated /a/. Although stimuli with non-fortis-affiliated and fortis-affiliated high vowels both showed effects of lengthened aspiration on perception, a disparity between vowel affiliations was apparent in stimuli with /a/, where only non-fortis-affiliated vowels showed effects of lengthened aspiration. Stimuli with fortis-affiliated /a/ were uniformly labeled as /s_F/ irrespective of FricDur, AspDur, and F0Ons. This result is consistent with an explanation in terms of relative consonant-vowel compatibility: the influence of audible aspiration in leading to a non-fortis percept was stronger when the following vowel onset was relatively compatible with a non-fortis percept. Given that the vowel onset of fortis-affiliated high vowels is phonetically closer to that of the corresponding non-fortis-affiliated vowels than the vowel onset of fortis-affiliated /a/ is close to that of non-fortis-affiliated /a/, it follows that aspiration in a fortis-affiliated vowel context would have been able to exert more influence with a high vowel. Fortis-affiliated /a/, on the other hand, is grossly incompatible with a non-fortis percept, largely due to its distinctive F_1 onset. As a consequence, conflicting consonantal and vocalic cues in this case were resolved in favor of the more salient vocalic ones.

Two findings of the perception experiment did not follow from findings of the production experiment, the first being the null effect of the FricQual parameter. Recall that the production experiment showed a significant difference between the fricatives in centroid frequency, which held true across all vowel contexts. Taken together with the findings of Holliday (2010), this result supports the prediction that centroid frequency would influence responses in the perception experiment,

4. An anonymous reviewer suggested that aspiration be considered vocalic, in accordance with the idea that aspiration is a vowel-like interval contributing to the distinction of consonant categories (Fischer-Jørgensen 1954, Fant 1958). In order to facilitate comparison with prior findings, this study followed previous studies in defining the vowel interval in terms of periodicity and assigning non-periodic aspiration to the consonant. However, if aspiration were instead included in the vowel and considered a vocalic cue, it would actually strengthen the claim that vocalic cues are dominant in the perception of the Korean fricatives, since of the three consonantal stimulus parameters (FricQual, FricDur, AspDur), AspDur was found to have the largest effect on perception.

but FricQual had no significant effect. This suggests that despite their reliability, centroid cues were not used to distinguish the fricatives perceptually in a consistent manner, although this null effect may have arisen as an artifact of the experimental procedure.[5]

The second finding of the perception experiment that did not follow from production facts was the significant effect of the F0Ons parameter. In the production experiment, the fricatives were found not to differ in f_0 onset in any vowel context examined, in accordance with previous findings. Nevertheless, there was a small, but significant, effect of f_0 onset on perception in every vowel context. There are three reasons why listeners may have cued in to f_0 to distinguish between the fricatives even though this is not a useful cue in their dialect. First, although the fricatives do not differ in f_0 in Seoul Korean, they have been found to differ in f_0 in other dialects such as Jeju Korean (Cho et al. 2002). It is unclear whether the listener population investigated in this study (college-age Korean speakers in Seoul) receives enough exposure to dialects where the fricatives differ in terms of f_0 for their speech perception to be affected, but substantial exposure to such dialects could account for why study participants used f_0 as a perceptual cue. Second, while the fricatives are consistently realized as voiceless at the beginning of an utterance, /s_{NF}/ has been reported to undergo intervocalic voicing anywhere between 20% to 46% of the time (Cho et al. 2002). Given the f_0 lowering effect associated with voiced obstruents (see, e.g., Hombert 1978), this implies that intervocalically /s_F/ and /s_{NF}/ may sometimes differ in terms of f_0 onset, and it is reasonable to think that listeners might (erroneously) apply such an intervocalic f_0 difference, however occasional, to their perception of the contrast in initial position. Third, it is possible that listeners, perhaps influenced by Korean orthography (which affiliates /s_{NF}/ with the lenis stops), simply analogized the non-fortis/fortis fricative contrast to the lenis/fortis stop contrast. Since the stop contrast is realized with a distinction in f_0 onset, it follows that such an analogy would lead to the use of f_0 in perception of the fricative contrast. In short, if data from other dialects and from other prosodic positions are considered, it can be said that there is a probabilistic difference in f_0 between /s_F/ and /s_{NF}/. Such an f_0 difference, along with orthographically-influenced analogy, helps to explain why listeners used the unreliable cue of f_0 in perception of initial fricatives.

5. A potentially significant difference between the study of Holliday (2010) and the current study is that the former used naturally produced, excised speech, whereas the latter used non-excised, but manipulated speech. As such, it is possible that centroid cues are normally used to distinguish between the fricatives, but were ignored in the current study due to the resynthesized nature of the stimuli.

5. Discussion and conclusions

The production and perception experiments reported here yielded results that exemplified the dual nature of /s_{NF}/ in Korean. Eight potential dimensions of contrast were examined (frication quality, frication duration, aspiration duration, and the duration, intensity profile, spectral tilt, F_1 onset, and f_0 onset of the following vowel). In most cases, the results of the present study were in agreement with those reported by other researchers. Below we review these results in light of previous studies of the Korean fricative contrast and discuss the implications for the analysis of Korean laryngeal contrast.

5.1 Review of the phonetic evidence

Frication quality differences between the fricatives are most consistent with a lenis analysis of /s_{NF}/. In agreement with Cho et al. (2002) and others, the centroid frequency of frication was found to be significantly lower in /s_{NF}/ than in /s_F/, a spectral difference reflecting linguopalatal contact differences reported by Kim (2001): a relatively narrow area of contact in /s_{NF}/ results in a wider channel area relative to /s_F/ and, thus, lower-frequency noise. In this respect, /s_{NF}/ is produced with less articulatory 'tension' than /s_F/, similar to the way in which lenis stops are produced in comparison to the fortis stops. However, it was also found that frication quality differences between the fricatives are quite small (with centroids differing by hundreds, rather than thousands, of Hz); moreover, they did not seem to be utilized as a perceptual cue to the contrast.

Frication duration differences are most consistent with a lenis analysis of /s_{NF}/ as well. The production experiment showed frication duration to be reliably shorter in /s_{NF}/ compared to /s_F/, in accordance with Cho et al. (2002). This difference parallels the difference in closure duration between the lenis and fortis stops (whereby the lenis stops are characterized by the shorter closure), but was found to vary significantly by vowel context, with a substantial difference for /a/, yet hardly any difference for /i/. Nevertheless, frication duration was used as a perceptual cue, and its effect on perception was similar across vowel environments.

Intensity buildup in the following vowel also points toward a lenis classification of /s_{NF}/. Consistent with previous results, intensity was found to increase significantly more slowly following /s_{NF}/ than /s_F/, echoing the difference in intensity buildup between the lenis and fortis stops, although the between-fricative differences were found to vary significantly across vowel environments.

Two other properties of the following vowel do not provide clear evidence in favor of one particular analysis of /s_{NF}/: voice quality and F_1 onset. In agreement with several prior studies, spectral tilt measures in this study indicated that the vowel onset following /s_{NF}/ is consistently breathier than that following /s_F/, although the difference is smaller in high vowel contexts. Furthermore, F_1 onset was found to be significantly higher following /s_{NF}/ than /s_F/, but only in a low vowel context. For both of these acoustic properties, the patterning of /s_{NF}/ relative to /s_F/ resembles the patterning of both the lenis stops and the aspirated stops relative to the fortis stops. Consequently, these production data fail to adjudicate between lenis and aspirated analyses of /s_{NF}/.

However, perception data favor an aspirated analysis of /s_{NF}/. The perception experiment reported here showed that the cohort of cues present in a following vowel had by far the strongest effect on native listeners' perception of the fricatives. The vowel following /s_{NF}/, moreover, has been shown to be perceptually more similar to vowels following aspirated stops than to vowels following lenis stops. When frication is cut away from /s_{NF}/, it is generally perceived as an aspirated stop, not as a lenis stop (Moon 1997, Park 1999). This pattern is at odds with intensity cues, which align more closely with the lenis stops, but is consistent with spectral tilt and F_1 onset cues, as well as with vowel duration and f_0 onset cues. Following vowel duration was found in the production experiment to be significantly shorter for /s_{NF}/ than /s_F/, while f_0 onset was found to be no different between the two. Both of these patterns were consistent across vowel contexts and align with the patterning of aspirated stops relative to fortis stops.

Aspiration duration provides additional support for an aspirated analysis of /s_{NF}/. Replicating a common finding in the literature, the production experiment showed /s_{NF}/ to be reliably more aspirated than /s_F/. Although the magnitude of the difference in aspiration was found to vary substantially by vowel context, the difference was significant in every vowel context examined. The results of Kim, Maeda, Honda, and Hans (2010) further indicated that /s_{NF}/ is significantly more aspirated than /s_F/ in intervocalic position and, moreover, that it is not usually voiced like lenis stops, which have a narrower glottal width than fortis stops in intervocalic position. Recent data from Kim et al. (2011), moreover, suggest that /s_{NF}/ has a wider glottal opening than /s_F/ and lenis stops in both initial and medial positions. In addition, /s_{NF}/ has been shown to be very similar acoustically to the voiceless aspirated /s^h/ of Burmese, the only language commonly cited as having contrastively aspirated sibilants (Chang 2007). Given these facts, it can be inferred that, unlike the lenis stops, /s_{NF}/ is characterized by a glottal width that is consistently wider than that of /s_F/, in similar fashion to the aspirated stops vis-à-vis the fortis stops. Furthermore, in the perception experiment aspiration duration was found to play a large role in contributing to the percept of /s_{NF}/. Taken together, these findings suggest that aspiration is not merely an incidental feature of /s_{NF}/, but rather a meaningful consequence of a phonologically specified spread glottal configuration.

In short, the picture that emerges from these production and perception data is of /s_{NF}/ resembling both the lenis stops and the aspirated stops of Korean. However, the properties of /s_{NF}/ align with those of the lenis and aspirated stops in a principled way: properties related to **articulatory tension** (e.g., linguopalatal contact, frication quality, frication duration) bear greater similarity to those of the lenis stops, while properties related to **glottal width** (e.g., aspiration duration, following vowel duration) bear greater similarity to those of the aspirated stops. In light of this dichotomy, it is logical to posit a unique representation of /s_{NF}/. The next section motivates this representation and shows how it fits into a novel analysis of Korean laryngeal contrast.

5.2 A new analysis of the non-fortis fricative

The Korean laryngeal system has been given many featural treatments in the phonological literature (for an excellent review, see Silva 2010). In one of the earliest treatments, Kim (1965) suggested that the contrast could be represented in terms of tension and aspiration, with lenis stops being [−tense, +aspirated], fortis stops [+tense, −aspirated], and aspirated stops [+tense, +aspirated]. This analysis would prove to be influential on later scholarship, which emphasized the importance of both tension and timing in the analysis of voicing and laryngeal contrast (e.g., Kohler 1984). Since Kim (1965), there have been several other analyses of Korean using different specifications (e.g., specifying the "slightly aspirated" lenis stops as [−aspirated]), different basic features (e.g., [±stiff vocal folds], [±slack vocal folds], [±voice]), and different assumptions regarding the hierarchical organization of the features.

Returning to the sort of specification presented in Kim-Renaud (1974), Kim (2005) proposed an analysis of the Korean stop types in terms of two features: [±tense] and [±spread glottis]. She observed that MRI data on intervocalic coronal stops showed two independent patterns distinguishing the stop types: coordinated tongue and larynx movements, as well as different degrees of glottal opening. Lenis stops were associated with a relatively small tongue blade movement and a narrow glottal opening; fortis stops, with a large tongue blade movement, glottal raising, and a narrow glottal opening; and aspirated stops, with a large tongue blade movement, glottal raising, and a wide glottal opening (Kim et al. 2005). Coordinated tongue and larynx movements were thus suggested to be the basis of the feature [±tense], and glottal opening, the basis of the feature [±spread glottis], such that lenis stops were specified as [−tense, −spread glottis]; fortis stops, as

[+tense, −spread glottis]; and aspirated stops, as [+tense, +spread glottis] (cf. Ahn 1998 for a similar proposal).[6]

Kim's (2005) analysis of Korean laryngeal categories differs from previous analyses in grounding the distinctive features used in two independent glottal and supraglottal articulatory patterns, but resembles previous analyses in the use of two features to distinguish three Korean laryngeal categories, a general characteristic of non-hierarchical analyses of the Korean laryngeal contrast that follows from assuming binary features. However, positing two binary features actually leads one to expect four, not three, categories. In other words, what most previous analyses of Korean have in common is the prediction of a fourth laryngeal category, yet few have provided a satisfactory explanation for why only three categories seem to exist.

The present proposal is that there actually are four laryngeal categories in Korean, and that the fourth is instantiated by /s_{NF}/. The dual nature of /s_{NF}/ seen above is argued to be a consequence of a tension/timing, or supraglottal/glottal, dichotomy: /s_{NF}/ is 'lenis' with respect to articulatory tension (which is mostly supraglottal), but 'aspirated' with respect to timing (in particular, the timing of glottal adduction relative to oral constriction). Given the supraglottal similarities of /s_{NF}/ to the lenis stops and its glottal similarities to the aspirated stops, it follows that the most appropriate representation of /s_{NF}/ is a blend of these two series: [−tense, +spread glottis].[7] This hybrid analysis echoes the reluctance of other researchers

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6. With regard to the fricatives, Kim et al. (2011) argued in favor of a lenis analysis of /s_{NF}/, but their study unfortunately suffered from serious conceptual and methodological problems that negated the force of their argument. Among these was the questionable premise that fricatives should by default have the same realization of articulatory parameters as stops (cf. Ohala 1997). Faulty speech materials also encouraged atypical fricative production, due to tendencies toward dissimilation between repeated obstruent types in the same word (e.g., Grassmann's Law; see Collinge 1985). The use of a non-naïve talker and the lack of a measure of variability made it still more difficult to interpret the data, which in the end were ambiguous in showing /s_{NF}/ to be intermediate in phonetic properties between the lenis and aspirated stops.

7. Two anonymous reviewers advocated an alternative account that reanalyzes the lenis stops and /s_{NF}/ both as [−tense, +spread glottis]. This account is more economical, and it may also represent the modern phonetic realization of the lenis stops in Seoul more accurately, given the recent lengthening of lenis stop VOT discussed in the literature (e.g., Silva 2006a,b). It is important to note, however, that while there has clearly been change in the VOTs of lenis and aspirated stops, this is a change in progress. Few adult speakers alive today can be said to completely merge the VOTs of the lenis and aspirated stops; consequently, a featural analysis of these stop types still needs to capture whatever difference in glottal width results in a difference in VOT. The question of when the sound change can be considered to have progressed far enough to provide cause for a change in featural specification (see, e.g., Wright 2007) is an interesting one, but lies far outside the scope of this study. An analysis of /s_{NF}/ and the lenis stops as both [−tense,

Table 6. Korean laryngeal contrast in terms of four categories.

	[−**spread glottis**]	[+**spread glottis**]
[−tense]	lenis stops	/s_{NF}/
[+tense]	fortis stops, /s_F/	aspirated stops

to classify /s_{NF}/ as lenis or aspirated (e.g., Kang 2000), but departs from previous studies by proposing an articulatorily grounded featural specification of /s_{NF}/ and, in so doing, identifying the fourth laryngeal category in Korean — essentially, a lenis-aspirated category.[8] The manner in which this category fits in with the three categories proposed by Kim (2005) is illustrated in Table 6, which shows that while /s_F/ is specified like the fortis stops, /s_{NF}/ is specified uniquely, with proximity to both the lenis stops and the aspirated stops.

Apart from filling out the predictions following from a two-feature analysis of Korean, the proposal of a fourth laryngeal category for /s_{NF}/ is well motivated on both phonetic and phonological grounds. A distinct laryngeal category for /s_{NF}/ is consistent with the fact that it does not pattern unilaterally with either the lenis stops or the aspirated stops, as discussed above. Moreover, the specific featural analysis proposed encodes the manner in which /s_{NF}/ phonetically resembles the lenis stops versus the aspirated stops. This analysis also correctly predicts the dual patterning of /s_{NF}/ with lenis stops in some alternations (i.e., the natural class of

+spread glottis] is, moreover, plagued by at least three problems alluded to in this section. First, it still generates the prediction of an apparently unattested fourth laryngeal category ([−tense, −spread glottis]). Second, under this account the similarity in f_0 onset between /s_{NF}/ and /s_F/ is unexpected. Third, it does not follow from this analysis how /s_{NF}/ could possibly pattern with the aspirated stops to the exclusion of the lenis stops. By affiliating /s_{NF}/ so closely with the lenis stops, this account shoots itself in the foot, as it were, because /s_{NF}/ actually needs to be specified in affiliation with both the lenis stops and the aspirated stops in order to predict the sort of dual patterning that has been observed in the literature.

A third anonymous reviewer alluded to another possible analysis of Korean laryngeal contrast in which [±spread glottis] is simply irrelevant in the case of Korean fricatives (e.g., Park 2002a). Given that there are only two fricatives, they can be distinguished featurally using only [±tense]. This would set up two classes of Korean obstruents: the plosives and affricates, which are also specified for [±spread glottis], and the fricatives, which are not. In this analysis, then, /s_{NF}/ would truly be non-fortis, as it would be specified strictly in opposition to /s_F/. While even more economical than the first alternative analysis described above, this second alternative analysis runs into the same problems: it accounts neither for the gap in the predicted four-way laryngeal system, nor for the similarities of /s_{NF}/ to the aspirated stops (in particular, its high f_0 onset).

8. Such a lenis-aspirated fricative might be well represented using the extended IPA diacritic for weaker articulation as /s͈ʰ/ (International Phonetic Association 1999: 189).

[−tense] obstruents) and with aspirated stops in other alternations (i.e., the natural class of [+spread glottis] obstruents).

In addition, the analysis of /s_{NF}/ as [−tense, +spread glottis] provides insight into the modulation of f_0 in the context of the Korean laryngeal system. As discussed in Section 2, f_0 elevation is one of the most salient acoustic reflexes of articulatory tension in Korean. Fortis and aspirated stops both show an elevated f_0 onset, which is consistent with their representation as [+tense]. However, the aspirated stops have repeatedly been found to show a higher f_0 onset than the fortis stops (e.g., Cho et al. 2002, Kim 2004, Chang 2010). This fact, together with the elevated f_0 onset associated with /s_{NF}/, suggests that f_0 raising in Korean results not only from articulatory tension, but also from active glottal spreading. This sort of positive association between glottal spreading and f_0 raising is consistent with the positive correlation between aspiration and elevated f_0 that has been observed in several other languages, such as Cantonese, Taiwanese, and Mandarin (Zee 1980, Francis et al. 2006, Lai & Jongman 2005, Lai et al. 2009, Lai & Chen 2011).[9] If f_0 elevation in Korean follows from being [+tense] or [+spread glottis], then, we can explain how [−tense] /s_{NF}/ can show an f_0 onset that is just as high as that of [+tense] /s_F/: it has an elevated f_0 onset by virtue of being [+spread glottis]. We can also account for why aspirated stops generally show a slightly higher f_0 onset than fortis stops: f_0 following fortis stops is raised by virtue of their being [+tense], while f_0 following aspirated stops is raised by virtue of their being [+tense] as well as their being [+spread glottis].[10]

9. Note, however, that the f_0 perturbation effects of glottal spreading may be language-specific (Thavisak 2004). Glottal spreading resulting in breathy phonation is generally associated with f_0 lowering (Gandour 1974, Hombert et al. 1979), and what is described as "aspiration" is sometimes found to be associated with f_0 lowering (e.g., Xu & Xu 2003) or with no effect (e.g., Hombert & Ladefoged 1977). The explanation for these differences in f_0 perturbation effects is unclear, although it is possible they stem from cross-linguistic disparities in the degree of tension held in spread vocal folds, which could result in differences in voice quality (Zhang 2009).

10. As for how the phonology operates to result in the f_0 elevation, the current analysis is amenable to the idea that fortis and aspirated obstruents are specified with underlying structure (e.g., an H tone), which gets realized domain-initially on the following vowel via spreading (Jun 1993, Ahn & Iverson 2004, Kim & Duanmu 2004, Silva 2006a). However, in order to account for the relative difference in f_0 elevation between fortis and aspirated stops, it must be assumed that the H tones are associated not with the entire feature bundles representing the stop types, but with the feature values [+tense] and [+spread glottis] specifically. If this is assumed, it follows that fortis stops would carry one H tone (from [+tense]), while aspirated stops would actually carry two H tones (one from [+tense] and one from [+spread glottis]), and the presence of this additional H tone for aspirated stops could then account for the slight "upstep" in their f_0 onset compared to that of the fortis stops.

In conclusion, a hybrid analysis of the non-fortis fricative as [−tense, +spread glottis] is ultimately the most empirically grounded. With properties of the lenis stops and the aspirated stops, the non-fortis fricative warrants a featural representation that reflects its dual nature as lenis and aspirated, and an analysis in terms of a lenis-aspirated category is consistent with phonetic facts as well as phonological patterning.

Received 27 June 2011;
revision received 22 August 2011;
accepted 18 October 2011

Acknowledgements

The author gratefully acknowledges funding from the U.S. Department of Education; the National Science Foundation; the Gates Cambridge Trust; Trinity College, Cambridge; and the Center for Advanced Study of Language, University of Maryland. The research represented in this article benefited from the helpful comments and logistical assistance of Taehong Cho, Andrew Garrett, Sharon Inkelas, Gregory Iverson, Keith Johnson, Hoyoung Lee, Brechtje Post, Rachel Smith, several anonymous reviewers, and audiences at Berkeley, Harvard, and LSA. Any errors are the author's. Preliminary stages of this work were reported in Chang (2007, 2008).

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