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Title
Korean Fricatives: Production, Perception, and Laryngeal Typology

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Abstract

Four experiments were conducted to investigate the contrast between the two voiceless sibilant fricatives of Korean. The results of Experiment 1 show that before /a/, the two fricatives differ in total segment duration, aspiration duration, F1 onset, intensity buildup, and voice quality. The results of Experiment 2 indicate that while segmental duration is not a significant cue in perception, aspiration duration is; the most important cues, however, are qualities of the following vowel. Experiments 3 and 4 replicated Experiments 1 and 2 with the vowel /u/. The results of Experiment 3 confirm those of Experiment 1, except there is no difference in F1 onset or intensity buildup in the high vowel /u/. The results of Experiment 4 show a similar hierarchy of cues, but a much greater deviance from the vocalic cues, suggesting that F1 onset and intensity buildup play an important role in perception. Thus, in spite of consonantal cues distinguishing the fricatives, vocalic cues are dominant in their perception. In having a fricative contrast without a voiced member, Korean constitutes an exception to the laryngeal typology of Jansen (2004). The classification of the non-fortis fricative may require the addition of an aspirated voiceless lenis category to this typology.

1. Introduction

The three-way laryngeal contrast in Korean among lenis, fortis, and aspirated[1] plosives and affricates has been the subject of much phonetic research. The two-way contrast between fortis and non-fortis[2] fricatives, however, has received much less attention despite being an arguably more unusual contrast.

This paper thus has two main objectives. The first is to arrive at an analysis of

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[1] These laryngeal series have acquired a variety of names in the literature. The lenis series is also called 'lax', 'weak', 'plain', 'slightly aspirated', and 'breathy'; the fortis series is also called 'tense', 'strong', 'glottalized', 'long', 'unaspirated', and 'forced'; and the aspirated series is also called 'heavily aspirated', 'strongly aspirated', and 'super aspirated'. In this paper they will be referred to as lenis, fortis, and aspirated, respectively.

[2] The latter fricative is usually called lenis or aspirated, depending on how it is categorized. Here it will be referred to as non-fortis in order to remain neutral on its categorization.

laryngeal contrast in Korean fricatives on the basis of acoustic and perceptual data. How do the two fricatives differ acoustically? What cues are important in the perception of this contrast? The second objective is to put this analysis in typological perspective. What do acoustic and perceptual data suggest about the proper classification of the fricatives? Is the non-fortis fricative lenis, aspirated, both, or neither?

2. Laryngeal contrast in Korean

2.1. Plosives

A great deal of previous research has investigated the articulatory, aerodynamic, and acoustic characteristics of the three-way laryngeal contrast in Korean plosives. From the results of these studies, it is generally known that the three laryngeal series (lenis, fortis, and aspirated) are differentiated from each other along a number of dimensions word- and phrase-initially: linguopalatal contact, glottal configuration, subglottal and intraoral pressure, laryngeal and supralaryngeal articulatory tension, voice onset time (VOT), fundamental frequency (f_0) of vowel onset, intensity of vowel onset, and voice quality of vowel onset.[3]

2.1.1. Articulatory and aerodynamic differences among the plosives

Articulatorily the lenis, fortis, and aspirated plosives differ from each other in several ways. One notion often employed to capture the distinction is "strength" or "tension", with the fortis and aspirated plosives thought to be stronger and to involve greater articulatory tension than the lenis plosives. This tension is realized in the form of greater amplitude, duration, and buildup of high pressure; faster glottal vibration upon the onset of periodicity; and a greater degree of articulatory muscle activity (cf. C.-W. Kim 1965, Hardcastle 1973). Linguopalatal contact has also been shown via electropalatographic techniques to be much more robust for fortis and aspirated plosives than for lenis ones (Cho and Keating 2001).

In addition, glottal configuration has been found to differ significantly across these three series, with the aperture being widest for aspirated plosives, intermediate for lenis plosives, and narrowest for fortis plosives (cf. C.-W. Kim 1970, Kagaya 1974). Kagaya in particular argued that the fortis and aspirated

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[3] The somewhat complementary dimensions of closure duration and vowel length also appear to be important cues to the laryngeal distinction, but primarily in postvocalic and intervocalic environments. The duration of fortis and aspirated plosives is much longer than that of lenis plosives; conversely, vowels are longer before lenis plosives than before aspirated or fortis plosives. While the closure duration characteristics also appear to hold in word-initial position (cf. Cho and Keating 2001), they are unlikely to serve as a cue here, since it would be difficult for a listener to separate the silence of (voiceless) closure from normal pre-utterance silence. As this paper focuses on the laryngeal contrast in prevocalic position, these factors are not discussed further here. For further details, see Silva (1992), Kim (1994), Han (1996), Cho and Keating (2001), and references cited therein.

plosives are associated with "positive inherent laryngeal gestures"—the fortis series being associated with glottal adduction and stiffening, abrupt glottal relaxation near the onset of voicing, increasing subglottal pressure, and glottal lowering before release; and the aspirated series being associated with glottal abduction and increased subglottal pressure. The lenis plosives, however, constitute the unmarked member of the trio, not being associated with any of these gestures.

In an electromyographic study, Hirose et al. (1974) made more concrete the notion of "tension" by demonstrating a spike in thyroarytenoid muscle activity prior to the release of fortis plosives (resulting in increased inner glottal tension and constriction at the time of the oral closure) as compared to aspirated and lenis plosives. Aspirated plosives were instead associated with total suppression of the adductor muscles before release (followed by a sharp increase in adductor muscle activity with the onset of periodicity), while lenis plosives were associated with less marked suppression of the adductor muscles and no sharp increase in thyroarytenoid muscle activity prior to release. In a study of lenis and fortis plosives, Dart (1987) also expanded upon the notion of "tension" by concluding that the production of fortis plosives involves greater vocal tract wall tension than lenis plosives.

Aerodynamic differences between lenis and fortis plosives constituted another one of Dart's (1987) findings. According to her results, the main difference between these two series aerodynamically appears to be a "higher intraoral pressure before release, yet a lower oral flow after release." As noted by Cho et al. (2002), this is unexpected, since higher pressure is normally built up precisely to be released, resulting in higher instead of lower oral flow.

2.1.2. *Acoustic differences among the plosives*

Acoustic differences among lenis, fortis, and aspirated plosives are numerous as well. VOT as well as several attributes of the following vowel have been pointed to as cues to the laryngeal status of the preceding plosive. In actuality none of these cues alone differentiates all three series from each other due to a high degree of overlap between two or sometimes all three categories with respect to their range of realizations of these phonetic dimensions. Instead, the combination of two or more cues is necessary to make a full three-way division.

Among these cues, VOT and f_0 have usually been considered the most salient ones (cf. M. Kim 2004). With respect to VOT, the fortis series has the shortest and the aspirated series the longest, with the lenis series in between. Han and Weitzman (1970) claim that the VOT difference between lenis and fortis is not perceptually significant and, thus, that VOT serves to distinguish aspirated from lenis and fortis. A similar conclusion is reached by Lisker and Abramson (1964). However, many others (e.g. Hardcastle 1973, Hirose et al. 1974, J.-I. Han 1996, Cho et al. 2002, Choi 2002) have noted that the VOT ranges of the aspirated series and the lenis series overlap to a large degree, and as such M. Kim (2004) has argued that VOT is actually a more reliable cue for setting apart fortis from

lenis and aspirated. As for f_0, the lenis series has the lowest and the aspirated series the highest, with the fortis series in the middle. Again, however, the f_0 distributions of the fortis and aspirated series overlap to a large degree (cf. J.-I. Han 1996, Choi 2002, M. Kim 2004, among others).

Other qualities of the following vowel have been noted to distinguish the three series as well. Intensity buildup is quicker following fortis plosives than lenis or aspirated plosives (Han and Weitzman 1970). In addition, vowels following lenis plosives are accompanied by breathiness (cf. N. Han 1998, Kim and Duanmu 2004), as indicated by positive differences between the first and second harmonics of the spectrum (H1-H2, cf. Ladefoged 2003). Conversely, it has been claimed that vowels following fortis plosives have characteristics of creaky voice (Abberton 1972), but this result has not been duplicated by other researchers (N. Han 1998).

2.2. Fricatives

While much of the literature has concentrated on the nature of the three-way contrast among the plosives, comparatively few studies have investigated the two-way contrast between the fricatives. The identification of the first fricative as a fortis sibilant /s*/ has been relatively uncontroversial, but there is disagreement over the proper analysis of the non-fortis fricative. In some phonological processes such as Post-Obstruent Tensing (cf. S. Kim 2003, Park 2004), it patterns with the lenis plosives (becoming fortis following an obstruent just as the lenis plosives do). However, in other processes such as Intervocalic Lenis Stop Voicing (cf. Jun 1993), it patterns with the aspirated plosives (remaining voiceless intervocalically just as the aspirated plosives do).

2.2.1. Phonetic differences between the fricatives
Aspects of the non-fortis fricative's phonetic realization are similarly equivocal. Some bear more similarities to the features of the aspirated plosives than the lenis plosives. For instance, the f_0 onset associated with it is close to that of the fortis fricative, in keeping with the closeness in f_0 onset between the fortis and aspirated plosives, and its duration word- and phrase-initially is similar to that of the aspirated plosives (cf. K.-S. Kang 2000). In addition, the glottal configuration associated with it is similar to that of the aspirated plosives (cf. Kagaya 1974), with an opening that is significantly larger than that for the fortis fricative (cf. Jun et al. 1998). The fricative is thus heavily aspirated like the aspirated plosives (cf. K.-S. Kang 2000, Cho et al. 2002). Yoon's (1999) acoustic analyses further suggest that before mid and low vowels the duration of the aspiration interval is the only consistent difference between the two fricatives, and thus he concludes that "the duration of the aspirated segment alone can act as the primary cue for the aspirated/[fortis] distinction" (1999:iv).

On the other hand, the non-fortis fricative has significantly less linguopalatal contact than the fortis fricative (cf. S. Kim 2001), a difference similar to that

between lenis and fortis plosives, and its shortened intervocalic duration is similar to that of the lenis plosives (cf. K.-S. Kang 2000, Cho et al. 2002). With respect to initial duration, Cho et al. (2002) report that including aspiration the non-fortis fricative is actually longer than the fortis fricative (which makes it seem more like the aspirated plosives than the lenis plosives); on the other hand, excluding aspiration it is much shorter than the fortis fricative (which makes it seem more like the lenis plosives than the aspirated plosives). Their data also showed that the non-fortis fricative's f_0 onset is generally lower than that associated with the fortis fricative (which makes it seem like the lenis plosives vis-à-vis the fortis plosives), but this was not a statistically significant trend; when they compared its f_0 onset to the f_0 distributions of lenis and aspirated plosives, in fact they found that it was similar to neither and fell in between. Moreover, when the non-fortis fricative is flanked by voiced sounds, though it remains voiceless it undergoes vocal fold slackening similar to that seen in the lenis plosives in the same environments (cf. Iverson 1983). Cho et al. (2002) go further in claiming that it even becomes voiced in this environment as often as 46% of the time, though the voicing they found was gradient and did not appear to be phonologized in the same way it is for lenis plosives (also, this result has not been duplicated by other researchers). Finally, H1-H2 and H1-F2 values for the non-fortis fricative are significantly higher than those for the fortis fricative (Cho et al. 2002), which indicates breathy phonation similar to that seen after lenis plosives. However, it should be noted that it is not clear that breathy phonation can be said to exclusively characterize the lenis plosives. Cho et al. (2002) themselves demonstrate that while H1-H2 and H1-F2 values are highest for the lenis plosives among the three series, these values are next highest for the aspirated plosives (with those for the fortis plosives being the lowest). Consequently, this sort of evidence has also been used to argue in favor of analyzing the non-fortis fricative as aspirated (cf. Park 1999).

Not surprisingly, then, the non-fortis fricative has been analyzed in various ways in the literature—as aspirated by some (e.g. Kagaya 1974; Park 1999, 2002; Yoon 1999, 2002), as lenis by others (e.g. Iverson 1983, Cho et al. 2002, H. Kang 2004), and as both aspirated and lenis by others still (e.g. K.-S. Kang 2000, 2004).

2.2.2. *Perception of the fricatives*

In addition to exploring the acoustics of these fricatives, a few studies have examined their perception in some detail. Yoon (1999) conducted an experiment in which he synthesized syllables with an aspirated fricative /s^h/ as onset and the vowel /a/ as nucleus. He found that when the aspiration interval was shortened or removed, perception shifted from aspirated to fortis for most speakers at around 37 ms of aspiration. In another experiment, Yoon (1999, 2002) took natural utterances of words beginning with /s^h/ and generated stimuli by incrementally reducing the aspiration noise interval by 10 ms. Here, too, he found that perception shifted from aspirated to fortis, but only for some listeners:

> It was sometimes the case that perception did not shift from aspirated to [fortis]

> even when the same amount of aspiration as for the [fortis] fricative was present. In cases such as this, more aspiration reduction was necessary for the expected perception shift, indicating that the aspiration noise duration was not the only parameter for the aspirated/[fortis] distinction. (2002:184)

What might the other parameters for the distinction be? The characteristics of the laryngeal distinction in the plosives have been summarized in §2.1 above. One point that becomes evident from this discussion is that many of the cues to the laryngeal contrast among the plosive consonants are actually contained in the adjacent vowels. It follows that the vowels are the next logical place to look for information signaling the laryngeal contrast between the fricatives.

2.3. The relative contribution of vocalic information

Vowels carry so much of the information about the laryngeal distinction that some studies have demonstrated that perception of the contrast is quite good on the basis of vocalic information alone. M.-R. Kim et al. (2002), for example, found in a series of perception experiments that vowels extracted from syllables with lenis onsets largely sufficed to cue lenis plosives, while vowels extracted from syllables with aspirated and fortis onsets both tended to draw fortis identifications.

Among the cues provided by the vowel as to the laryngeal state of a consonant are f_0, intensity, and voice quality, as discussed above. Kluender (1991) adds first formant (F1) onset to this list. In experiments with both human listeners and Japanese quail, he found that among the various aspects of the vowel onset related to F1, F1 onset frequency was the best predictor of voiced/voiceless labeling judgments. Later work by Benkí (2001, 2005) involving English and Spanish speakers confirmed the role of F1 onset frequency in the perception of voicing and emphasized the role of the F1 transition pattern as well.

In the case of a consonant articulated with the tongue body high and a vowel articulated with the tongue body low, a higher F1 onset and flatter F1 transition pattern are associated with the category having the longer VOT (i.e. the voiceless consonants). Since F1 increases in frequency as the tongue lowers from the point of consonantal occlusion to the position for vocalic articulation, this correlation is the natural result of the longer delay between consonantal release and voicing onset. In other words, with a long VOT, the tongue has more time to get into position for the vowel and thus is closer to the target position by the time the vocal folds start vibrating. Conversely, when the VOT is short, the tongue has little time to get into position for the vowel and the vocal folds may start vibrating well before the tongue reaches its target position; thus, the F1 onset is lower and the F1 transition pattern steeper.

Park (2002) investigated the time courses of F1 and F2 as realized in the three laryngeal types in some detail. Her results indicated significant differences in F1 trajectory among the three laryngeal series. Specifically, F1 peaks earlier and higher in the aspirated series than in the fortis or lenis series (not an unexpected

result, given that the aspirated series has the longest VOT). Data for F2 trajectories also showed some differences, but was less conclusive.

2.4. Summary

While the two-way contrast between the fortis and non-fortis fricatives bears similarities to the three-way contrast among the plosives, there are significant differences, one of which is precisely the binary nature of the distinction. The categorization of the non-fortis fricative has consequently become a puzzling question. The literature has also drawn attention to the fact that cues to the laryngeal status of a consonant are largely carried on the following vowel. Four experiments were thus conducted to reexamine the distribution of the Korean fricatives along the acoustic dimensions discussed above as well as the relative contribution of these consonantal and vocalic cues to the perception of these fricatives.

3. Experiment 1: Production before /a/

The first part of the present study investigates a number of acoustic features of fricatives in Seoul Korean—specifically, total segment duration, aspiration duration, f_0 onset, F1 onset, intensity buildup, voice quality, and length of the following vowel.

3.1. Methods

3.1.1. Materials
A list of Korean CV monosyllables was constructed such that obstruents of all places of articulation and phonation types occurred before the three vowels /a, i, u/. Some of these syllables later served as stimuli for Experiment 2.

3.1.2. Subjects
The subjects in the production study were five native speakers of Korean, three males and two females in their 20s and 30s. The first and second male speakers (S2, S4) and first and second female speakers (S1 and S3) were born and grew up in Seoul, and the third male speaker (S5) was born and grew up in Daejeon. Thus, all speakers spoke relatively standard dialects containing the fortis/non-fortis fricative contrast.

3.1.3. Procedure
The sound files for speakers S1, S2, and S3 were recorded in quiet rooms as mono sound files in Praat 4.2.17 (Boersma and Weenink 2004) using a Sony Vaio PCG-TR5L laptop computer and a Shure C608 microphone. The sound files for speakers S4 and S5 were recorded using a Marantz PMD660 solid state recorder and an AKG C420 microphone. For all subjects and target words, three tokens

were collected in isolation at a sampling rate of 22050 samples per second and a bit rate of 16 bits per sample.

All measurements were taken in Praat. Segmental duration of the fricative was measured from the onset of high frequency noise to the onset of periodicity in the vowel; aspiration duration[4] was measured from the onset of a more distributed spectrum with low frequency noise after the sibilant fricative to the onset of periodicity; f_0 was measured over the first three pitch points in the vowel resulting from the default autocorrelation method used by Praat; F1 was measured at the first visible glottal cycle; intensity was measured at the beginning of each of the first ten glottal cycles as well as across the whole vowel; H1-H2 values were calculated across a spectrum of the first four glottal cycles; and vowel length was measured from the first glottal cycle to the end of visible periodicity.

With regard to other relevant settings, the spectrogram method was Fourier and the window shape was Gaussian, with a window length of 5 ms, bandwidth of 200 Hz, dynamic range of 70 dB, and pre-emphasis of 6 dB/octave.

Below are two spectrograms of /s^{h}a/ 'buy' and /s*a/ 'wrap'. The portions of the spectrogram corresponding to the sibilant fricative, aspiration, and vowel have been demarcated to exemplify the transition points used to measure the duration of these sections.
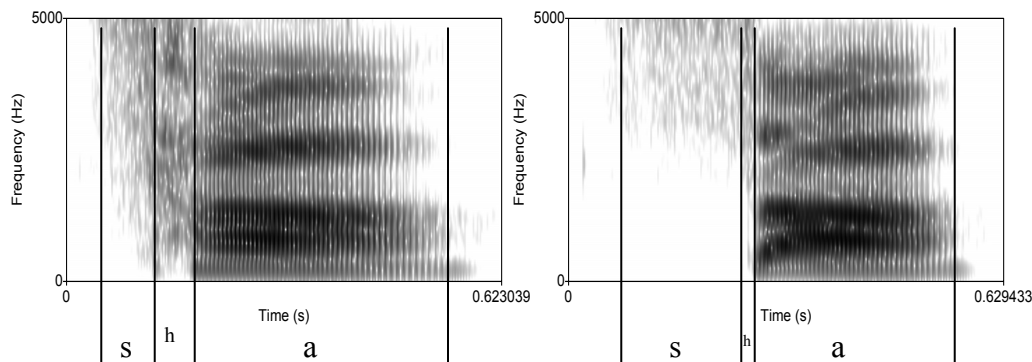

Fig. 1. Wide-band spectrograms of /s^{h}a/ 'buy' (L) and /s*a/ 'wrap' (R)

As acknowledged by Yoon (2002), taking measurements by hand leaves open the possibility of human error, but the dividing line between the high frequency energy of the sibilant and the low frequency energy of the aspiration interval is distinct enough that measurements can be taken with a high degree of consistency.

3.2. Results

3.2.1. Segmental duration

The durational data for the five subjects' productions of /s^{h}a/ and /s*a/ are given

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[4] Since fricatives do not have a release burst that can serve as the initial measurement point of VOT, aspiration duration was measured instead as an analog of VOT.

in the tables below, as well as graphed in terms of means and ranges.[5]

Table 1
Duration of /sʰ/ in /sʰa/ 'buy' (in ms)

Token	S1	S2	S3	S4	S5
1	120	158	114	179	161
2	105	127	110	180	146
3	105	173	102	141	151
Average	**110**	**153**	**109**	**167**	**153**
StDev	9	23	6	22	8

Table 2
Duration of /s*/ in /s*a/ 'wrap' (in ms)

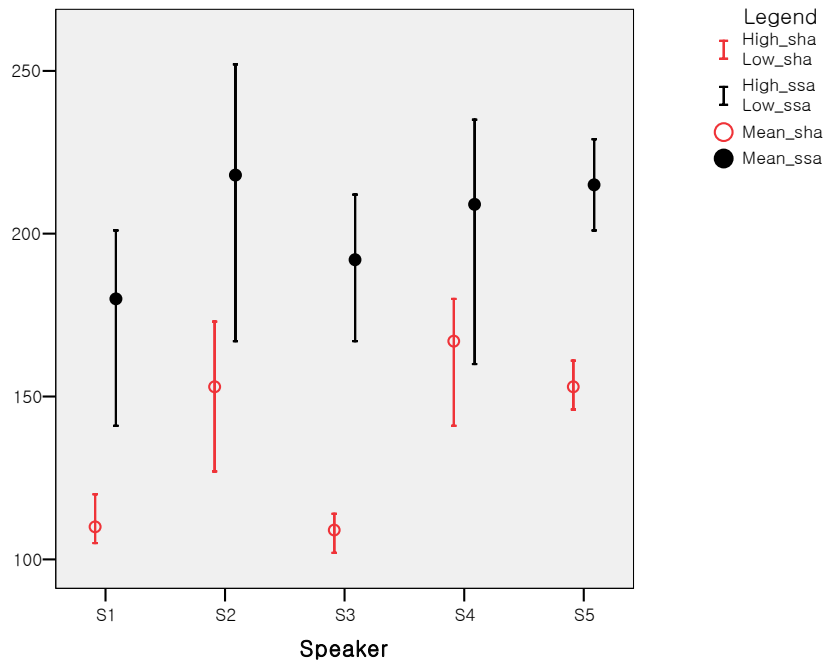| Token	S1	S2	S3	S4	S5
1	141	167	167	235	215
2	199	252	198	160	201
3	201	236	212	233	229
Average	**180**	**218**	**192**	**209**	**215**
StDev	34	45	23	43	14

Fig. 2. Segmental duration of /sʰ/ vs. /s*/ before /a/ (in ms)

For all subjects the fortis fricative is longer than the non-fortis fricative, and the difference between the two is highly significant ($t = -9.680$, df = 4, $p = 0.001$). A

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[5] Abbreviations: StDev = standard deviation, S1 = Speaker S1, S2 = Speaker S2, etc.

repeated-measures analysis of variance (ANOVA) shows a main effect of fricative identity on segmental duration ($F(1, 2) = 20.595$, $p = 0.045$), with no effect of subject ($F(1.5, 3.0) = 5.914$, $p > 0.05$) and no interaction between fricative identity and subject ($F(1.4, 2.8) = 0.414$, $p > 0.6$). Note that these data contradict the results of Cho et al. (2002), who claimed that the non-fortis fricative including aspiration was longer than the fortis fricative. On the contrary, the data above indicate that the fortis fricative can be nearly twice as long as the non-fortis fricative for some speakers.

3.2.2. Aspiration duration

The data for aspiration duration in the five subjects' productions of /s^{h}a/ and /s*a/ are given below.

Table 3
Aspiration duration in /s^{h}a/ 'buy' (in ms)

Token	S1	S2	S3	S4	S5
1	95	54	43	64	59
2	62	32	15	61	70
3	76	44	29	54	39
Average	**78**	**43**	**29**	**60**	**56**
StDev	17	11	14	5	16

Table 4
Aspiration duration in /s*a/ 'wrap' (in ms)

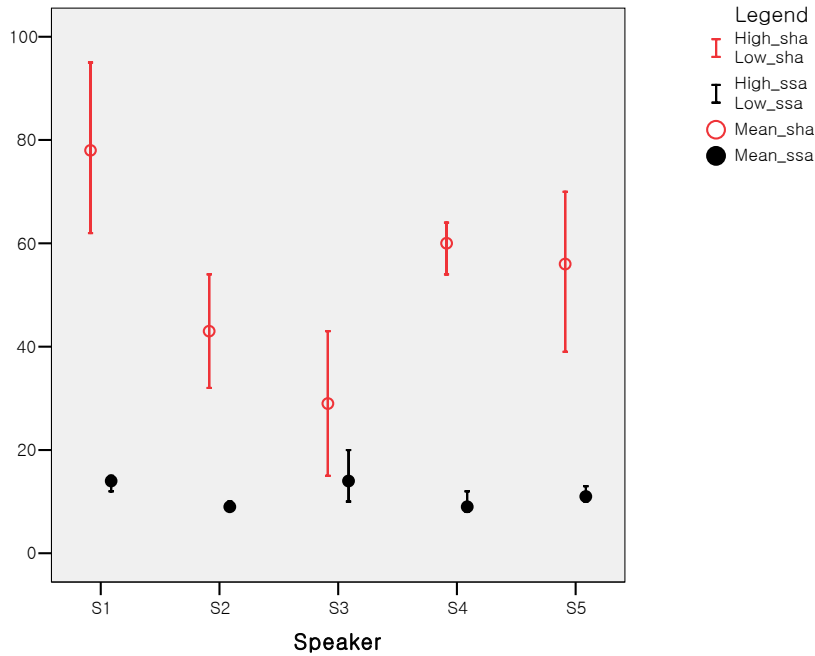| Token	S1	S2	S3	S4	S5
1	15	9	20	8	10
2	12	9	10	12	13
3	15	10	11	8	11
Average	**14**	**9**	**14**	**9**	**11**
StDev	2	1	6	2	2

Fig. 3. Aspiration duration in /sʰ/ vs. /s*/ before /a/ (in ms)

These data corroborate the results of previous studies. For all subjects the aspiration interval is much longer in the non-fortis fricative than in the fortis fricative, and the difference is highly significant ($t = 5.056$, df = 4, $p = 0.007$). A repeated-measures ANOVA again shows a main effect of fricative identity on aspiration duration ($F(1, 2) = 85.333$, $p = 0.012$), with no effect of subject ($F(1.5, 3.0) = 5.993$, $p > 0.05$). Here, however, there is an interaction between fricative identity and subject ($F(1.9, 3.9) = 10.414$, $p = 0.028$), reflecting some variation between subjects in the degree to which they differentiate the two fricatives in aspiration. The aspiration interval in the non-fortis fricative is always longer than that in the fortis fricative, but varies between being two to five times longer (15-64 ms longer in raw duration).

3.2.3. F_0 onset

The fundamental frequency data for the five subjects' productions of /sʰa/ and /s*a/ are given below.

Table 5
F_0 onset in /s^{h}a/ 'buy' (in Hz)

Token	S1	S2	S3	S4	S5
1	244	167	303	141	176
2	249	162	301	134	159
3	241	158	285	134	157
Average	**245**	**162**	**296**	**136**	**164**
StDev	4	5	10	4	10

Table 6
F_0 onset in /s*a/ 'wrap' (in Hz)

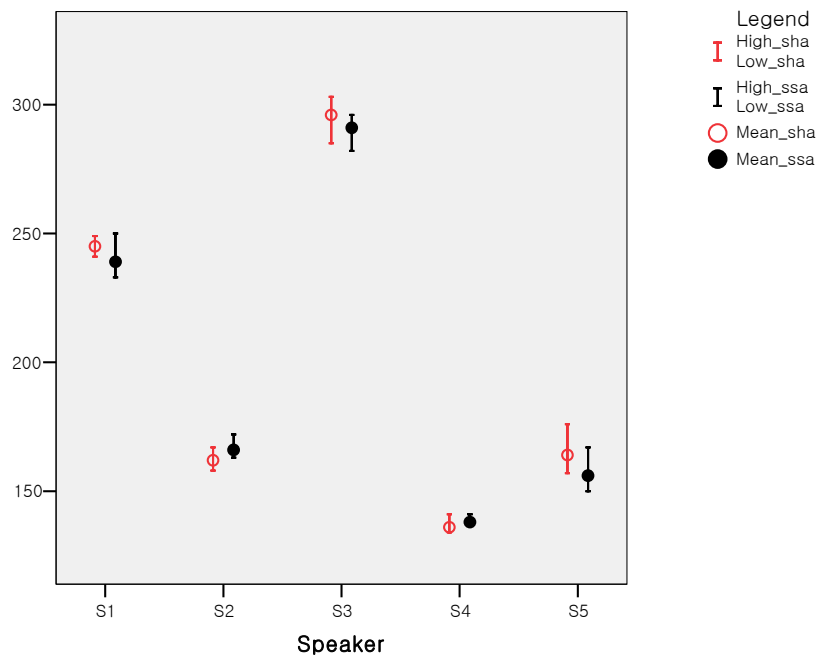| Token	S1	S2	S3	S4	S5
1	250	172	295	137	167
2	235	163	296	137	151
3	233	163	282	141	150
Average	**239**	**166**	**291**	**138**	**156**
StDev	9	5	8	2	10

Fig. 4. F_0 onset in /a/ following /s^h/ vs. /s*/ (in Hz)

Like Cho et al. (2002), who did not find a statistically significant difference between the non-fortis and fortis fricatives in f_0, these data also do not show a significant difference between the two fricatives (t = 1.103, df = 4, p > 0.3). Moreover, the general trend in Cho et al. (2002) for the non-fortis fricative to be associated with a lower f_0 than the fortis fricative is not reflected here. These data do not form any sort of trend, failing to fall in the same direction across speakers.

A repeated-measures ANOVA shows a main effect of subject on f_0 ($F(4, 8) = 651.054$, $p < 0.0005$), reflecting the variation between subjects in terms of which fricative had a higher f_0, but shows no effect of fricative identity ($F(1, 2) = 6.418$, $p > 0.1$) and no interaction between fricative identity and subject ($F(1.1, 2.3) = 2.354$, $p > 0.2$).

3.2.4. F1 onset

The first formant data for the five subjects' productions of /s^{h}a/ and /s*a/ are given in the tables below.

Table 7
F1 onset in /s^{h}a/ 'buy' (in Hz)

Token	S1	S2	S3	S4	S5
1	927	635	1201	753	591
2	926	473	907	637	498
3	902	658	947	655	586
Average	**918**	**589**	**1018**	**682**	**558**
StDev	14	101	159	62	52

Table 8
F1 onset in /s*a/ 'wrap' (in Hz)

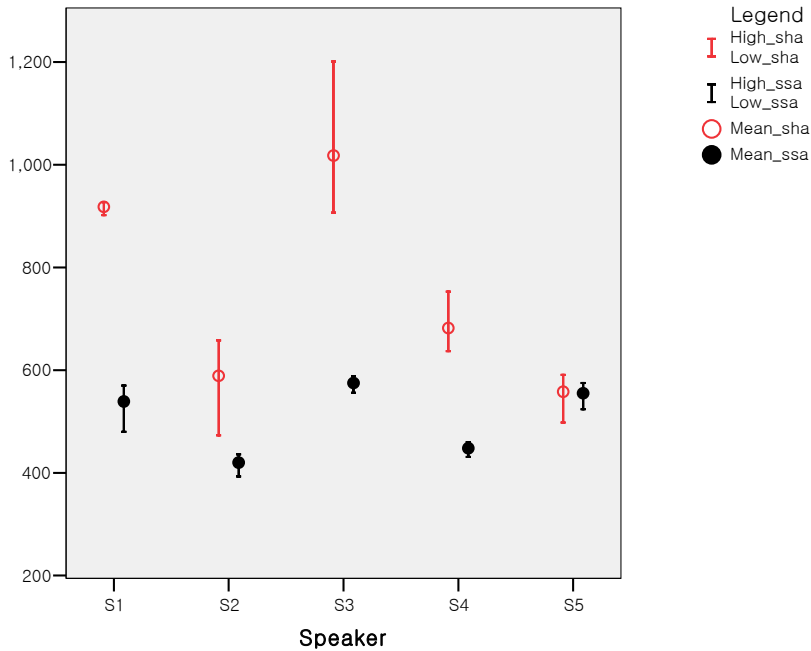| Token	S1	S2	S3	S4	S5
1	480	436	581	431	524
2	570	432	556	454	565
3	566	393	588	460	575
Average	**539**	**420**	**575**	**448**	**555**
StDev	51	24	17	15	27

Fig. 5. F1 onset in /a/ following /sʰ/ vs. /s*/ (in Hz)

These data also corroborate the results of previous studies. For nearly all subjects the first formant starts much lower after the fortis fricative than the non-fortis fricative (cf. Fig. 6), and the difference is significant ($t = 3.150$, df = 4, $p = 0.035$), approaching 500 Hz for some subjects (cf. S1, S3). A repeated-measures ANOVA shows a main effect of fricative identity ($F(1, 2) = 28.408$, $p = 0.033$), a main effect of subject ($F(2.6, 5.3) = 26.690$, $p = 0.001$), and an interaction between the two ($F(4, 8) = 19.456$, $p < 0.0005$).
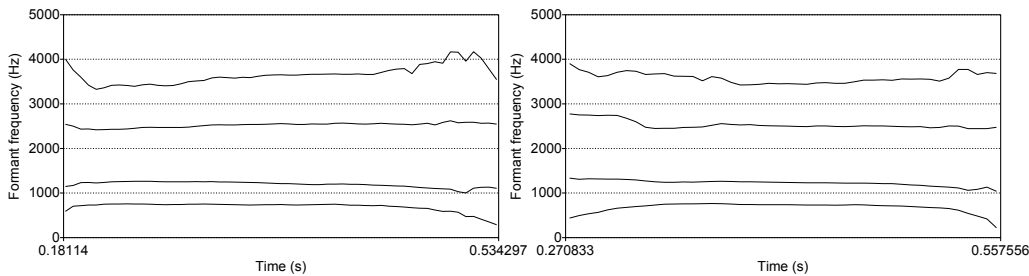

Fig. 6. Formant tracks in the vowel of /sʰa/ 'buy' (L) and /s*a/ 'wrap' (R)

3.2.5. Intensity buildup

The next acoustic dimension explored was intensity buildup. Han and Weitzman (1970) found that intensity buildup is quicker following fortis plosives than following lenis or aspirated plosives. This difference is indeed reflected in the intensity buildup following the two fricatives, as seen in Figure 7 (drawn from the two tokens used in Experiment 2, cf. §4). As with the plosives, intensity appears

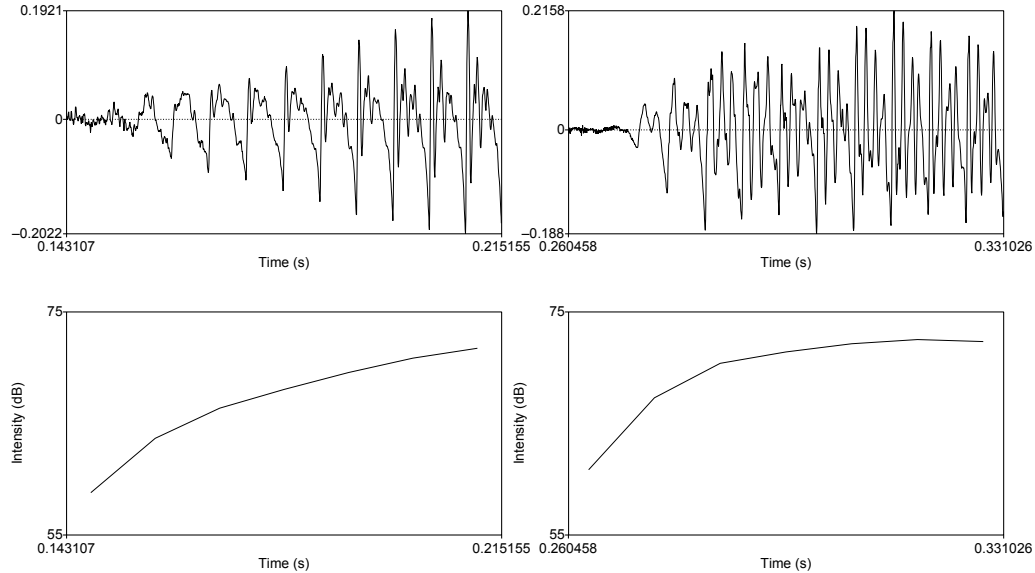to increase more sharply and peak earlier following a fortis fricative than following a non-fortis fricative.

Fig. 7. Waveforms and intensity contours of the first ten glottal cycles in /sʰa/ 'buy' (L) and /s*a/ 'wrap' (R)

In order to confirm the significance of these apparent differences, intensity buildup was measured. In the absence of a standard measure, the rate of change was approximated via differences between individual intensity measurements (intensity was measured at the beginning of each of the first ten glottal periods, and the intensity difference between adjacent periods was then calculated as the intensity of one period minus the intensity of the preceding period). Thus, in the data that follows, greater (i.e. more positive) intensity differences indicate sharper intensity buildup, while less positive differences indicate more gradual intensity buildup (with negative values indicating an intensity decrease instead of an increase). These data are given below for the two tokens of /sʰa/ and /s*a/ used in Experiment 2.

Table 9
Intensity buildup in /s^{h}a/ 'buy' and /s*a/ 'wrap' (in dB)

Difference between periods	/s^{h}a/ [S2, token 1]	/s*a/ [S2, token 2]
Period 2 – Period 1	2.0	2.3
Period 3 – Period 2	1.8	1.4
Period 4 – Period 3	1.3	1.1
Period 5 – Period 4	1.2	0.4
Period 6 – Period 5	0.9	0.5
Period 7 – Period 6	0.8	0.4
Period 8 – Period 7	0.6	0.2
Period 9 – Period 8	0.5	0.1
Period 10 – Period 9	0.4	-0.1

There are marked differences between /s^{h}a/ and /s*a/, and a period-by-period comparison shows that these differences are significant ($t = 3.653$, df = 8, $p = 0.006$). In /s*a/, intensity increases sharply at first, levels off rapidly, and then decreases, while in /s^{h}a/, intensity increases fairly gradually and does not begin to decrease until after the tenth glottal cycle. These results confirm the findings of Han and Weitzman (1970) regarding intensity buildup: intensity increases more rapidly following a fortis consonant than following a non-fortis consonant. Thus, it appears that intensity buildup might also serve as a cue to the fricative distinction.

Change in intensity was measured as above for the first four glottal periods of all tokens produced by each subject. The average change across tokens of the same word also reveals differences approaching significance ($t = 2.539$, df = 4, $p = 0.064$). As expected, average change in intensity for these early periods is lower for /s*a/ because intensity levels off and begins decreasing sooner than in /s^{h}a/.

Table 10
Average change in intensity per period in /s^{h}a/ 'buy' and /s*a/ 'wrap' (in dB)

Word	S1	S2	S3	S4	S5
/s^{h}a/	0.8	1.5	1.1	0.9	1.3
/s*a/	0.7	1.1	1.1	0.3	0.5

In addition to measuring intensity buildup, average intensity across the whole vowel was measured to see if there might be a basic difference in average intensity between the two fricatives. Measurements for all fifteen tokens of /s^{h}a/ and /s*a/ are given below.

Table 11
Average vowel intensity in /sʰa/ 'buy' (in dB)

Token	S1	S2	S3	S4	S5
1	66.6	67.3	69.4	79.1	76.4
2	66.3	67.1	69.5	78.3	74.8
3	66.9	68.6	69.6	78.7	72.4
Average	**66.6**	**67.7**	**69.5**	**78.7**	**74.5**
StDev	0.3	0.8	0.1	0.4	2.0

Table 12
Average vowel intensity in /s*a/ 'wrap' (in dB)

Token	S1	S2	S3	S4	S5
1	65.9	68.0	72.1	77.6	75.6
2	67.8	68.3	73.6	78.1	75.3
3	65.5	65.5	71.0	77.8	75.9
Average	**66.4**	**67.3**	**72.2**	**77.8**	**75.6**
StDev	1.2	1.5	1.3	0.3	0.3

While the data for intensity change show some significant differences, the data for average intensity do not ($t = -0.708$, df = 4, $p > 0.5$). A repeated-measures ANOVA shows a main effect of subject ($F(4, 8) = 345.664$, $p < 0.0005$), but no effect of fricative identity ($F(1, 2) = 0.947$, $p > 0.4$) and no interaction between the two ($F(1.3, 2.5) = 2.213$, $p > 0.2$).

3.2.6. Spectral tilt

The voice quality of the vowel onset has also been shown to differ between the two fricatives, as indicated by more positive differences between the first and second harmonics (H1-H2) following non-fortis obstruents. This difference is illustrated in representative spectra of /sʰa/ and /s*a/ (taken from the tokens used in Experiment 2). As seen below, the spectrum of /sʰa/ descends much more steeply from the first harmonic to the second harmonic than the spectrum of /s*a/.
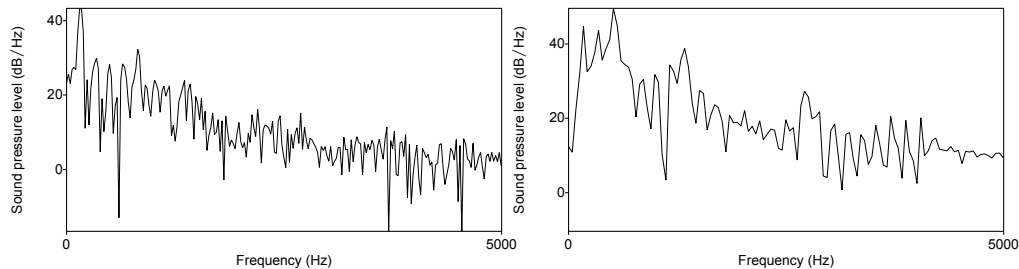

Fig. 8. Spectrum of vowel onset in /sʰa/ 'buy' (L) and /s*a/ 'wrap' (R)

The H1-H2 values for the five subjects' productions of /sʰa/ and /s*a/ were thus measured, and these data are given in the tables below.

Table 13
H1-H2 differences in /sʰa/ 'buy' (in dB)

Token	S1	S2	S3	S4	S5
1	21.5	6.1	10.2	5.3	-1.2
2	24.2	14	6.5	13.2	-0.6
3	25.1	6	11.5	17.9	0.1
Average	**23.6**	**8.7**	**9.4**	**12.1**	**-0.6**
StDev	1.9	4.6	2.6	6.4	0.7

Table 14
H1-H2 differences in /s*a/ 'wrap' (in dB)

Token	S1	S2	S3	S4	S5
1	-3.8	0.2	-10.4	-1.7	-0.9
2	0.3	-1.7	-7.2	-2.5	1.4
3	1.4	0.2	-11.6	-2.9	-1.7
Average	**-0.7**	**-0.4**	**-9.7**	**-2.4**	**-0.4**
StDev	2.7	1.1	2.3	0.6	1.6

These data agree with the results of previous studies. H1-H2 values are generally more positive in /sʰa/ than in /s*a/, and this difference is significant ($t = 3.904$, df = 4, $p = 0.017$). A repeated-measures ANOVA shows a main effect of fricative identity ($F(1, 2) = 1765.243$, $p = 0.001$), a main effect of subject ($F(4, 8) = 35.721$, $p < 0.0005$), and an interaction between the two ($F(1.5, 3.0) = 11.328$, $p = 0.041$).

3.2.7. *Vowel length*

The final acoustic dimension explored in the production study was vowel length. Although vowel length has not usually been claimed to differ following initial obstruents in Korean, some (e.g. K.-S. Kang 2000) argue that the non-fortis fricative's shortened duration intervocalically triggers compensatory lengthening of the following vowel. In addition, studies such as Cho and Keating (2001) have shown that closure duration differs significantly between fortis and non-fortis plosives even in word-initial position; it follows that there could be a complementary effect of "compensatory shortening" resulting in significantly shorter vowels following the longer fortis fricatives than the shorter non-fortis fricatives. Thus, vowel length in /sʰa/ and /s*a/ was also measured, and the durational data are given below.

Table 15
Vowel length in /sʰa/ 'buy' (in ms)

Token	S1	S2	S3	S4	S5
1	455	401	394	270	243
2	428	382	413	283	248
3	391	287	353	251	215
Average	**425**	**357**	**387**	**268**	**235**
StDev	32	61	31	16	18

Table 16
Vowel length in /s*a/ 'wrap' (in ms)

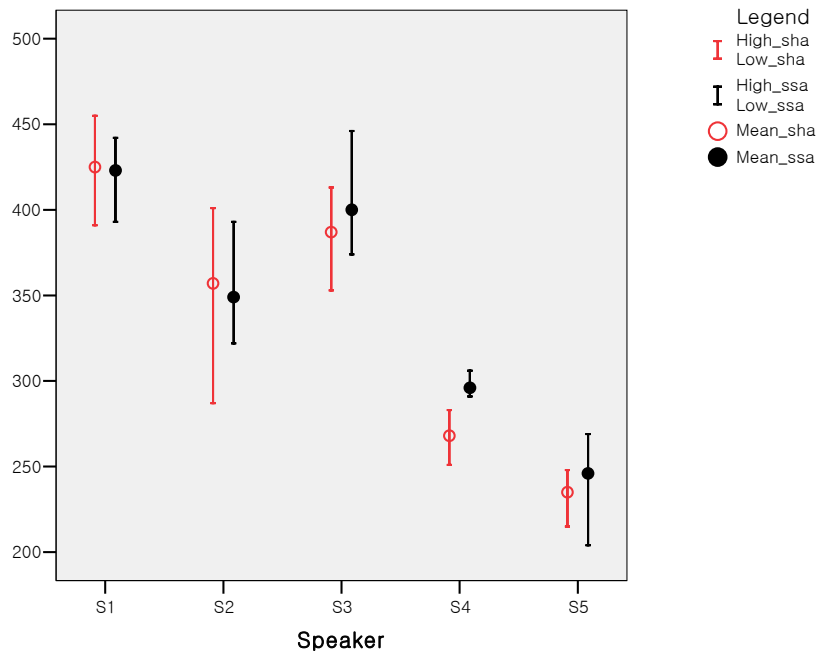| Token	S1	S2	S3	S4	S5
1	433	393	379	291	265
2	442	322	374	291	269
3	393	331	446	306	204
Average	**423**	**349**	**400**	**296**	**246**
StDev	26	39	40	9	36

Fig. 9. Vowel length of /a/ following /sʰ/ vs. /s*/ (in ms)

Similar to the data for f_0 onset, there does not seem to be a trend present here. For some subjects (cf. S1, S2), the vowel following the fortis fricative is slightly shorter than following the non-fortis fricative, while for other subjects (cf. S3, S4, S5), the vowel following the fortis fricative is actually longer. These differences are not significant (t = -1.337, df = 4, p > 0.2). A repeated-measures ANOVA shows a main effect of subject ($F(2.1, 4.2)$ = 38.094, p = 0.002), but no effect of

fricative identity ($F(1, 2) = 0.332$, $p > 0.6$) and no interaction between the two ($F(2.1, 4.1) = 0.409$, $p > 0.6$).

3.3. Summary

In comparing the acoustic features of /s^h/ and /s*/, it is apparent that these segments are produced with (i) different durations (the fortis fricative being longer than the non-fortis fricative), (ii) different aspiration intervals (the non-fortis fricative's being longer than the fortis fricative's), (iii) different F1 trajectories (F1 after the fortis fricative starting lower than after the non-fortis fricative), (iv) different patterns of intensity buildup (intensity increasing more rapidly after the fortis fricative than after the non-fortis fricative), and (v) different voice onset qualities (a more breathy quality after the non-fortis fricative than after the non-fortis fricative, as indicated by a more steeply declining spectral tilt). On the other hand, f_0 onset, average vowel intensity, and vowel length do not appear to be distinguishing factors. With these acoustic facts in mind, the contributions of the first five factors to the percepts of the two fricatives were investigated in a perception experiment.

4. Experiment 2: Perception before /a/

The goal of this experiment was to examine how the cues of segmental duration, aspiration duration, F1 onset, intensity buildup, spectral tilt, and f_0 onset are merged in the percept of Korean fricatives. The first five cues were seen above to show significant differences across the two fricatives; the sixth cue, f_0 onset, did not show significant differences across the two fricatives, but was included as well since it has been shown to play a significant role in differentiating the plosives (cf. §2.1.2).

4.1. Methods

4.1.1. Experimental design
There were four within-groups factors in this experiment: (i) segmental duration (of the fricative), (ii) aspiration duration, (iii) f_0 onset, and (iv) vowel quality (i.e. F1 onset/intensity buildup/spectral tilt). The details of the experimental design are summarized below.

Table 17
Design of Experiment 2: Perception before /a/

Factor	Range	Levels	Values of levels
SEGMENTAL DURATION	125 ms ~ 250 ms	4	125 ms 165 ms 205 ms 250 ms
ASPIRATION DURATION	10 ms ~ 60 ms	3	10 ms 35 ms 60 ms
F_0 ONSET	145 Hz ~ 185 Hz	5	145 Hz 155 Hz 165 Hz 175 Hz 185 Hz
F1 ONSET / INTENSITY BUILDUP / SPECTRAL TILT (≈ original affiliation of V)	/sʰa/ V ~ /s*a/ V	2	high / gradual / steep low / sharp / shallow

Note that F1 onset, intensity buildup, and spectral tilt were combined into one factor due to the difficulty of manipulating these dimensions individually in a program like Praat.

Since it was ultimately S2's recordings that were used in this experiment (because of the lowest amount of background noise and most consistent amplitude levels), the range for the first three factors was based on the range present in S2's production data (cf. §3.2.1-3.2.3 above) and, when possible, expanded within reasonable limits. Thus, his 127-252 ms range in segmental duration translated to a 125-250 ms range in the segmental duration factor; his 9-54 ms range in aspiration duration translated to a 10-60 ms range in the aspiration duration factor; and his 158-172 Hz range in f_0 onset was expanded to a 145-185 Hz range in the f_0 onset factor.

The whole experiment contained 120 critical fricative stimuli (4 levels of segmental duration x 3 levels of aspiration duration x 5 levels of f_0 onset x 2 levels of F1 onset/intensity buildup/spectral tilt), as well as 120 filler stimuli for a total of 240 stimuli.

4.1.2. Stimuli

Six words were used for all the stimuli in the experiment. These are listed with glosses in the table below.

Table 18
Stimuli for Experiment 2: Perception before /a/

	Orthography	IPA[6]	Gloss
Fricatives	사	/sʰa/	'buy', 'four'
	싸	/s*a/	'wrap', 'be cheap'
Fillers	다	/da/	'all'
	따	/t*a/	'pluck'
	타	/tʰa/	'ride', 'burn'
	아	/a/	'Ah!'
Pretest	자	/ʤa/	'ruler, measure'
	짜	/ʧ*a/	'wring', 'be salty'
	차	/ʧʰa/	'tea', 'car'

   The first token of /sʰa/ and the second token of /s*a/ recorded by S2 in Experiment 1 provided the basic building blocks for the 120 fricative stimuli. The most difficult step in the generation of the fricative stimuli was the first step undertaken—namely, the generation of the aspiration duration continuum.[7] Aspiration was shortened by removing a central portion of the aspiration noise interval and lengthened by inserting additional aspiration noise into the center of the aspiration noise interval; in both cases, care was taken to avoid producing a sudden break in any visible formant structure (thus, in removing aspiration noise where there was formant structure, a portion with level formants was removed, and in inserting aspiration noise, the point of insertion was always before any section with formant structure). Additional (formant-less) aspiration noise was copied from the center of S2's /sʰa/ token.

   Second, the stimuli in the aspiration duration continuum were manipulated to form parallel segmental duration continua, either by removing a central portion of the sibilant's high frequency noise interval (to shorten the duration) or inserting high frequency noise into the center of the sibilant's high frequency noise interval (to lengthen the duration). Additional high frequency noise was copied from the center of S2's /s*a/ token.

   Third, the stimuli in the two-dimensional [segmental duration x aspiration duration] matrix were then expanded along the dimension of f_0 onset via Praat's 'Shift pitch frequencies' function, with the entire pitch contour of a given stimulus either raised or lowered in 10 Hz steps.

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[6] Transcriptions follow the conventions of H. Lee (1996) and H. B. Lee (1999).

[7] M. Kim (2004) conducted a similar perception study looking at the interrelationship of VOT and f_0 in the perception of plosives and affricates, but she looked at a naturally wide range of VOT variation in a much larger corpus of recorded tokens rather than manipulating the aspiration noise, which she was careful not to alter due to the fact that it is "not a homogeneous period" and that its "spectral character changes constantly." While this circumspection is well-motivated, it seems that it is precisely the irregular, heterogeneous nature of aspiration noise that permitted it to be spliced without the production of audible artifacts in the stimuli for this experiment.

Finally, the preceding three steps were carried out starting from both original syllables. In other words, aspiration duration was lengthened and shortened starting from the basic /s^{h}a/ recording and then a second time starting from the basic /s*a/ recording. In this way, the stimuli ultimately varied along the four dimensions summarized in Table 17. It should be noted that neither of the original fricative recordings used as the basis for the other stimuli happened to have exactly the right specifications for any of the first three dimensions; thus, all 120 fricative stimuli were manipulated in at least one way.

As for the filler stimuli, these were produced from fifteen of S2's recordings: three tokens of a minimal triplet containing plosive onsets at the alveolar place of articulation (like the fricatives) and three tokens of /s^{h}a/ and /s*a/. The alveolar plosive tokens were simply manipulated in terms of f_0 to produce 10-11 filler stimuli from each original token spread evenly across a range of 110-210 Hz. In the case of the fricative tokens, the fricative portion was first removed, and then f_0 was manipulated to produce five filler stimuli from each original token spread across a range of 145-185 Hz. The end result was 90 alveolar plosive fillers and 30 'onset-less' fillers for a total of 120 filler stimuli.

4.1.3. Subjects

Sixteen native speakers of Korean (eight females and eight males) ranging in age from 20 to 40 participated in the perception trials. All spoke a dialect with the fortis/non-fortis fricative contrast (eleven of the subjects were from Seoul or the surrounding Gyeonggi Province, and the other five were from Jeolla Province, Chungcheong Province, and Gangwon Province). None reported any history of hearing disorders.

4.1.4. Procedure

Subjects were asked to take a test in which they would listen to words and identify them out of a set of six choices by clicking buttons on a computer screen. They were initially told that the goal of the experiment was to see how emotional speech affected intelligibility and that they would thus be hearing many instances of one speaker saying the same words in different emotional states. They were informed that they could only listen to each stimulus once, that they would not hear the following stimulus until they made a decision about the current one, and that they could not go back to a previous stimulus. Thus, the task was essentially forced-choice identification.

Stimuli were presented to subjects via Praat's listening test function on a Sony Vaio PCG-TR5L computer over Direct Sound EX-29 headphones. The screen display contained six buttons labeled in Korean orthography (<사>, <싸>, <아>, <다>, <따>, <타>). Subjects made their responses via mouse by clicking the button on screen labeled with the word they thought they heard. The stimuli were arranged in a different random order for each subject and presented in four blocks of 60 stimuli, with a one-second inter-stimulus interval and a break period after each block (the length of which was controlled by the subject via mouse click).

The experiment lasted approximately 20 minutes in all, and subjects were compensated for their time.

A short, two-minute pretest containing eighteen presentations of nine stimuli was conducted prior to the real test in order to familiarize the subject with the test procedure. The nine stimuli in the pretest comprised three tokens each of three words recorded by S2 that were not included in the real test (see Table 18 above for a full list of fricative, filler, and pretest stimuli). Subjects' responses were coded in integers from 1 to 6.

4.2. Results

Mean identification functions for each experimental factor are shown in Figure 10 (percent /s^{h}a/ responses indicated by the solid lines, percent /s*a/ responses indicated by the dotted lines). As can be seen in these graphs, labeling shifts slightly towards /s*a/ with increasing segmental duration and towards /s^{h}a/ with increasing aspiration duration; slightly favors /s^{h}a/ regardless of f_0 onset; and reverses almost entirely from /s^{h}a/ to /s*a/ with a corresponding change in F1 onset, intensity buildup, and spectral tilt.
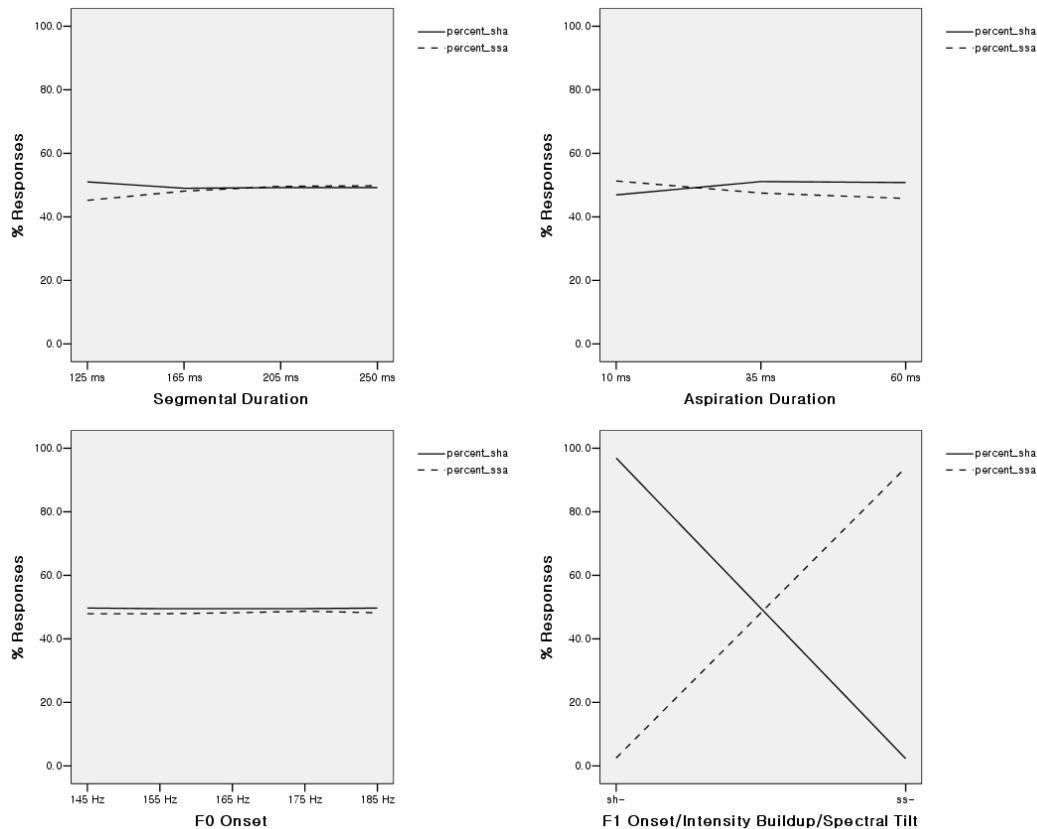

Fig. 10. Individual effects of experimental factors on labeling of stimuli as /s^{h}a/ vs. /s*a/

A repeated-measures ANOVA performed on the data indicates a main effect of F1 onset/intensity buildup/spectral tilt and an interaction between F1 onset/intensity buildup/spectral tilt and aspiration duration, but no main effect of segmental duration, aspiration duration, or f_0 onset and no other interactions between factors. These results are summarized below, where significant main effects and interactions have been placed in boldface and highlighted with stars.[8]

Table 19
Results of repeated-measures ANOVA (Huynh-Feldt corrected[9])

SD	AD	F_0	F1/IB/ST	Main effects
•				$F(1.5, 22.0) = 1.900, p > 0.1$
	•			$F(1.8, 27.3) = 1.693, p > 0.2$
		•		$F(2.5, 38.2) = 0.241, p > 0.8$
			☆	**$F(1, 15) = 139.439, p < 0.0005$**

SD	AD	F_0	F1/IB/ST	Interactions
•	•			$F(2.2, 33.7) = 2.178, p > 0.1$
•		•		$F(6.2, 92.6) = 0.583, p > 0.7$
•			•	$F(2.0, 30.6) = 1.348, p > 0.2$
	•	•		$F(5.4, 80.8) = 1.334, p > 0.2$
	☆		☆	**$F(1.8, 26.7) = 7.059, p = 0.005$**
		•	•	$F(3.6, 53.4) = 0.063, p > 0.9$
•	•	•		$F(9.0, 134.2) = 1.111, p > 0.3$
•	•		•	$F(2.9, 44.1) = 2.819, p > 0.05$
•		•	•	$F(5.4, 81.5) = 1.095, p > 0.3$
	•	•	•	$F(4.6, 69.1) = 1.297, p > 0.2$
•	•	•	•	$F(8.1, 121.2) = 0.980, p > 0.4$

The ANOVA results are largely confirmed by non-parametric tests for repeated measures such as the Friedman test,[10] the results of which are summarized below.

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[8] SD = segmental duration, AD = aspiration duration, F_0 = f_0 onset, F1 = F1 onset, IB = intensity buildup, ST = spectral tilt.

[9] Sphericity has not been assumed in these data, so in all cases the Huynh-Feldt corrected figures have been reported (see Max and Onghena 1999 for further details).

[10] One of the assumptions underlying ANOVA is that the data are continuous. However, the judgment data here are nominal and not interval or ordinal scores, so the most appropriate test is a non-parametric test for repeated measures, which does not make the same assumptions as ANOVA regarding data continuity.

Table 20
Results of Friedman test

SD	AD	F_0	F1/IB/ST	Asymptotic significance		
			☆	**_p < 0.0005_**		
•				_p > 0.4_	_p > 0.5_	/s^{h}a/ F1/IB/ST
					_p > 0.2_	/s*a/ F1/IB/ST
	☆			**_p = 0.001_**	**_p < 0.0005_**	/s^{h}a/ F1/IB/ST
					_p = 0.009_	/s*a/ F1/IB/ST
		•		_p > 0.9_	_p > 0.8_	/s^{h}a/ F1/IB/ST
					_p > 0.9_	/s*a/ F1/IB/ST

Similar to the ANOVA, the Friedman test indicates a highly significant effect of F1 onset/intensity buildup/spectral tilt. The Friedman test indicates a significant effect of aspiration duration as well. Furthermore, aspiration duration again seems to interact with F1 onset/intensity buildup/spectral tilt to some degree, as suggested by the different *p*-values of data subsets sorted by F1 onset/intensity buildup/spectral tilt. This interaction can be seen in Figure 11, a graph of the identification functions related to the three levels of the aspiration duration factor. An increase in aspiration duration results in a higher percentage of /s^{h}a/ responses only with the F1 onset/intensity buildup/spectral tilt of /s^{h}a/ (as seen in the space between the 10-ms identification function and the other two).
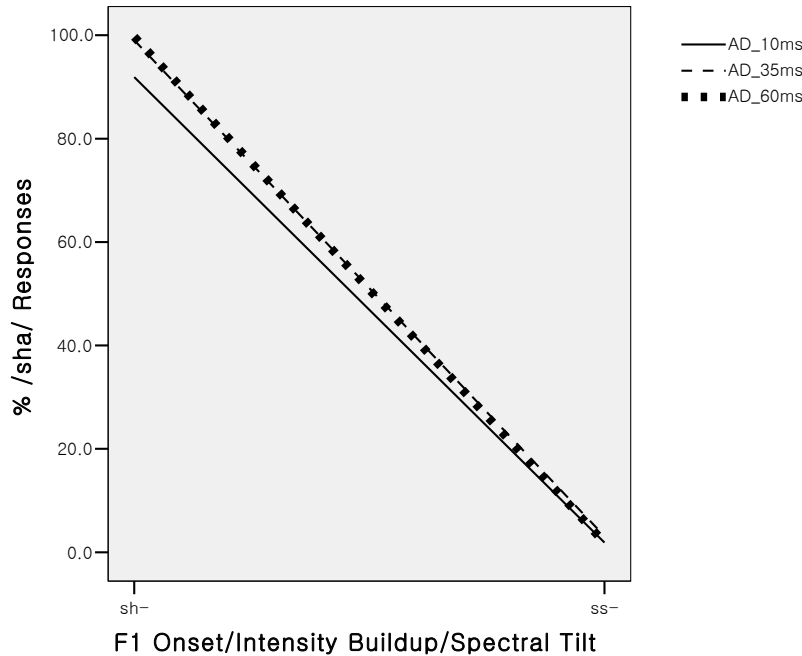

Fig. 11. Interaction between aspiration duration and F1 onset/intensity buildup/spectral tilt

4.3. Summary

Subjects' response patterns in Experiment 2 closely follow the quality of the vowel. In fact, their perceptual judgments deviate from the vowel's original onset affiliation only 5% of the time. Aspiration duration appears to have its own effect on responses as well, but this effect is stronger when the F1 onset, intensity buildup, and spectral tilt are characteristic of the non-fortis fricative (i.e. high F1 onset, gradual intensity buildup, positive H1-H2). It appears that subjects are more willing to identify heavy aspiration with the non-fortis fricative when the vowel quality also matches that of the non-fortis fricative; when the vowel quality is incompatible, subjects usually resolve the conflict between cues by following vowel quality.

It remains a question, however, whether F1 onset, intensity buildup, and spectral tilt all play a role in cuing the laryngeal status of the preceding fricative. Out of these, F1 is the cue most commonly cited as signaling phonation contrast (cf. Kluender 1991; Benkí 2001, 2005), so there is reason to believe that F1 may be the predominant cue. Indeed, F1 trajectory is significantly different between phonation categories when the vowel is low and the F1 target is consequently high, but what happens with a high vowel where the F1 target is low and F1 thus does not have to travel very far out of the fricative? This question motivated the replication of Experiments 1 and 2 with the vowel /u/.

5. Experiment 3: Production before /u/

Experiment 3 was replicated to see if the significant differences found in Experiment 1 extend to a high vowel environment.

5.1. Methods

The materials, procedure, and subjects were the same as in Experiment 1. Below are two spectrograms of /s^{h}u/ 'number' and /s*u/ 'cook'. Note that the differences between these two parallel those seen in Fig. 1 for /s^{h}a/ 'buy' and /s*a/ 'wrap', but are smaller in magnitude.
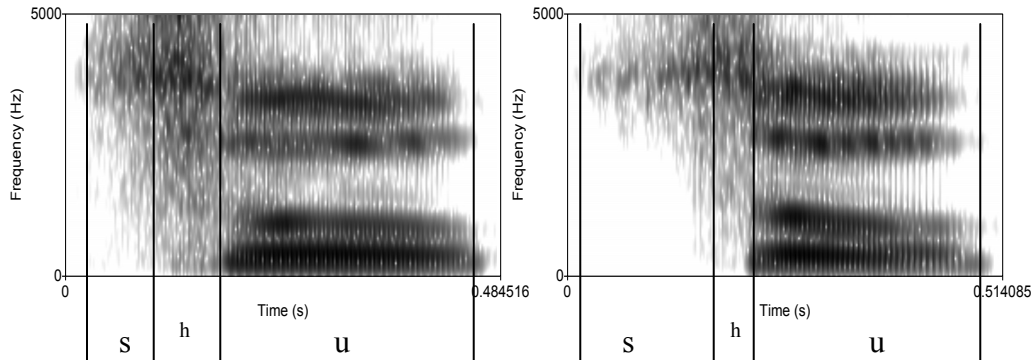
Fig. 12. Wide-band spectrograms of /sʰu/ 'number' (L) and /s*u/ 'cook' (R)

5.2. Results

5.2.1. Segmental duration

The durational data for the five subjects' productions of /sʰu/ and /s*u/ are given below.

Table 21
Duration of /sʰ/ in /sʰu/ 'number' (in ms)

Token	S1	S2	S3	S4	S5
1	129	157	157	180	195
2	151	148	134	233	190
3	134	155	142	189	175
Average	**138**	**153**	**144**	**201**	**187**
StDev	12	5	12	28	10

Table 22
Duration of /s*/ in /s*u/ 'cook' (in ms)

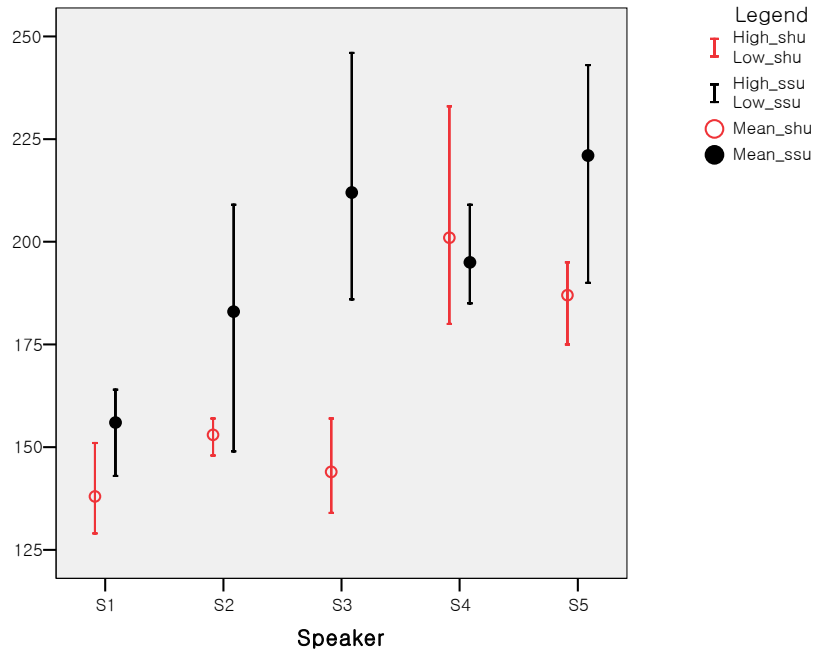| Token	S1	S2	S3	S4	S5
1	162	149	186	192	190
2	164	190	205	185	231
3	143	209	246	209	243
Average	**156**	**183**	**212**	**195**	**221**
StDev	12	31	31	12	28

Fig. 13. Segmental duration of /s^h/ vs. /s*/ before /u/ (in ms)

For nearly all subjects the fortis fricative is longer than the non-fortis fricative, with this difference approaching significance (t = -2.395, df = 4, p = 0.075). A repeated-measures ANOVA, however, does not show an effect of fricative identity ($F(1, 2)$ = 6.361, p > 0.1). There is an effect of subject ($F(3.8, 7.6)$ = 16.424, p = 0.001), though there is no interaction between fricative identity and subject ($F(4, 8)$ = 2.496, p > 0.1).

5.2.2. Aspiration duration
The data for aspiration duration in /s^{h}u/ and /s*u/ are given below.

Table 23
Aspiration duration in /s^{h}u/ 'number' (in ms)

Token	S1	S2	S3	S4	S5
1	46	59	61	56	44
2	65	68	40	46	44
3	74	59	41	49	40
Average	**62**	**62**	**47**	**50**	**43**
StDev	14	5	12	5	2

Table 24
Aspiration duration in /s*u/ 'cook' (in ms)

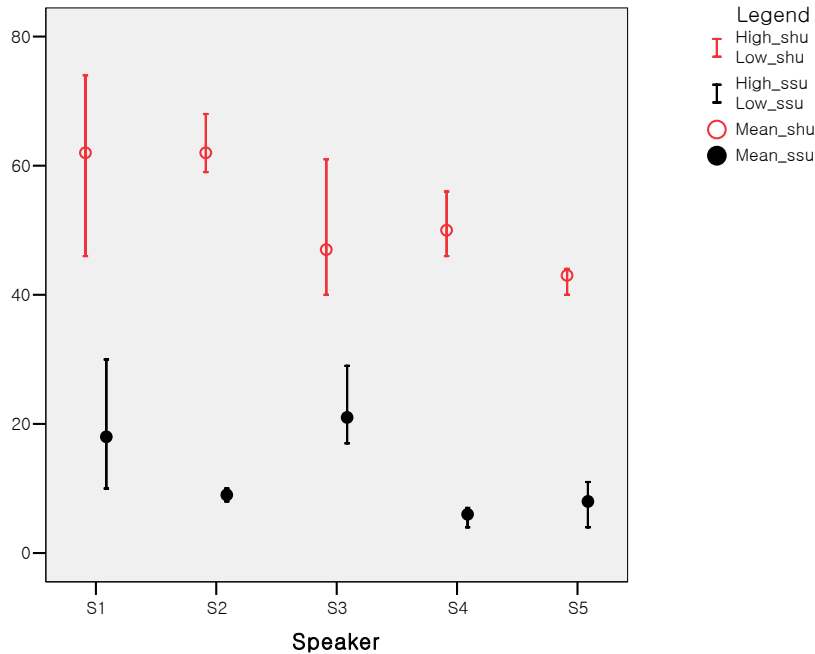| Token	S1	S2	S3	S4	S5
1	15	9	29	4	10
2	30	10	17	7	4
3	10	8	18	6	11
Average	**18**	**9**	**21**	**6**	**8**
StDev	10	1	7	2	4

Fig. 14. Aspiration duration in /s^h/ vs. /s*/ before /u/ (in ms)

In keeping with the results of Experiment 1, for all subjects the aspiration interval is much longer in the non-fortis fricative than in the fortis fricative, and the difference is highly significant ($t = 8.803$, df = 4, $p = 0.001$). A repeated-measures ANOVA shows a main effect of fricative identity ($F(1, 2) = 2015.558$, $p < 0.0005$), but no effect of subject ($F(1.3, 2.6) = 2.412$, $p > 0.2$) and no interaction between fricative identity and subject ($F(4, 8) = 2.977$, $p > 0.05$).

5.2.3. F_0 onset

The fundamental frequency data for the five subjects' productions of /s^{h}u/ and /s*u/ are given below.

Table 25
F_0 onset in /s^{h}u/ 'number' (in Hz)

Token	S1	S2	S3	S4	S5
1	244	204	341	172	164
2	242	188	308	166	155
3	242	188	311	165	155
Average	**243**	**193**	**320**	**168**	**158**
StDev	1	9	18	4	5

Table 26
F_0 onset in /s*u/ 'cook' (in Hz)

Token	S1	S2	S3	S4	S5
1	243	218	290	172	182
2	239	181	312	162	172
3	235	192	308	161	165
Average	**239**	**197**	**303**	**165**	**173**
StDev	4	19	12	6	9
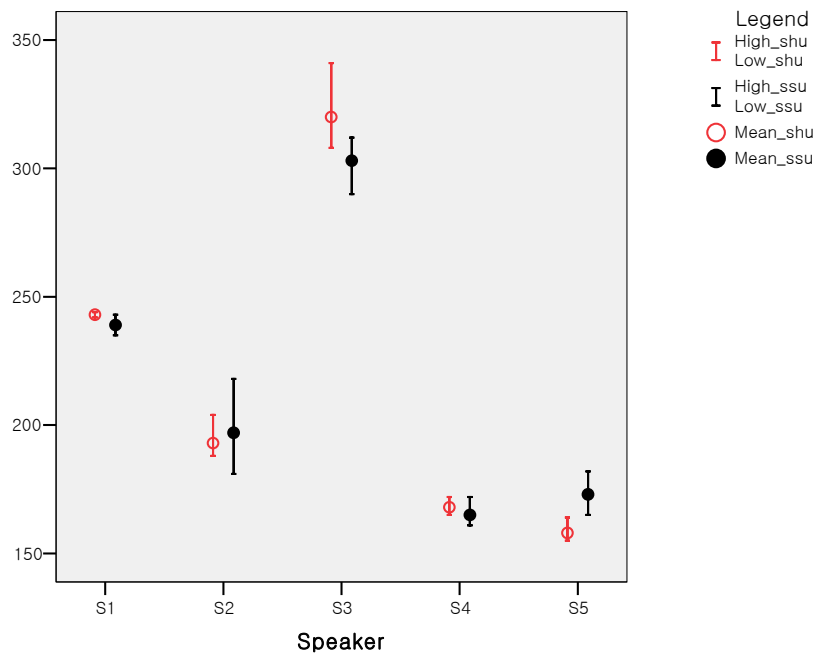
Fig. 15. F_0 onset in /u/ following /s^h/ vs. /s*/ (in Hz)

The differences seen above are again not statistically significant ($t = 0.191$, df = 4, $p > 0.8$) and do not fall in the same direction across speakers. A repeated-measures ANOVA shows a main effect of subject ($F(1.3, 2.7) = 488.685$, $p < 0.0005$), reflecting the variation between subjects in terms of which fricative had a higher f_0, but shows no effect of fricative identity ($F(1, 2) = 0.287$, $p > 0.6$) and no interaction between fricative identity and subject ($F(1.3, 2.7) = 1.597$, $p > 0.3$).

5.2.4.   F1 onset

The first formant data for the five subjects' productions of /s^{h}u/ and /s*u/ are given in the tables below.

Table 27
F1 onset in /s^{h}u/ 'number' (in Hz)

Token	S1	S2	S3	S4	S5
1	280	261	364	339	348
2	301	306	344	383	346
3	299	284	343	355	287
Average	**293**	**284**	**350**	**359**	**327**
StDev	12	23	12	22	35

Table 28
F1 onset in /s*u/ 'cook' (in Hz)

Token	S1	S2	S3	S4	S5
1	330	301	382	345	366
2	343	248	369	246	389
3	380	308	403	332	365
Average	**351**	**286**	**385**	**308**	**373**
StDev	26	33	17	54	14
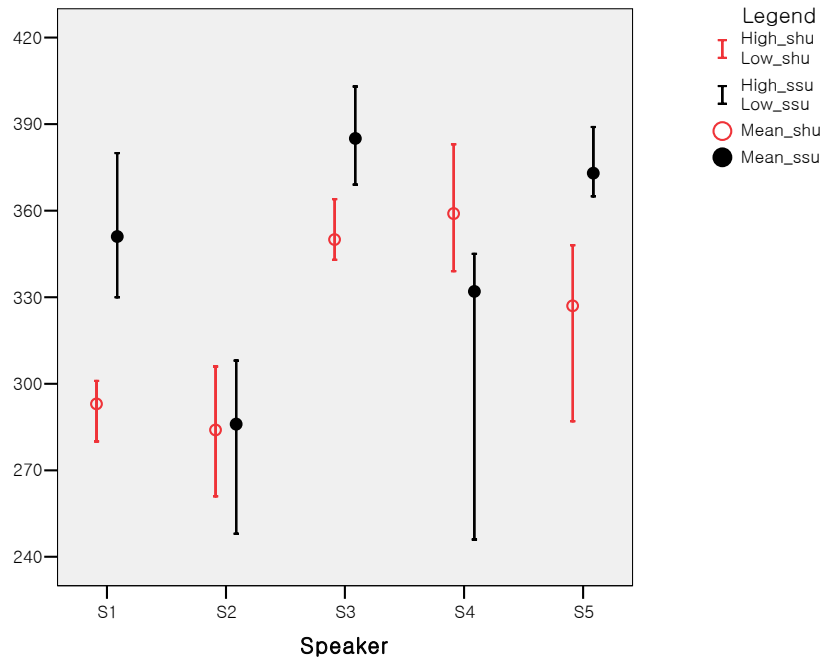
Fig. 16. F1 onset in /u/ following /s^h/ vs. /s*/ (in Hz)

For most subjects the first formant actually starts higher in the fortis fricative than in the non-fortis fricative, but this difference is not significant (t = -0.918, df

= 4, *p* > 0.4). Note below the similarly flat F1 contours in the tokens of /sʰu/ and /s*u/ used in Experiment 4 (cp. Fig. 6).
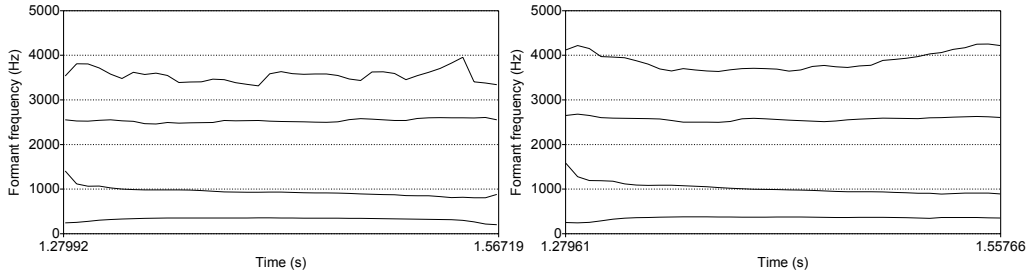

Fig. 17. Formant tracks in the vowel onset of /sʰu/ 'number' (L) and /s*u/ 'cook' (R)

A repeated-measures ANOVA shows a main effect of subject ($F(4, 8) = 10.348$, $p = 0.003$), reflecting the variation between subjects in terms of which fricative had a higher F1, but shows no effect of fricative identity ($F(1, 2) = 0.964$, $p > 0.4$) and no interaction between fricative identity and subject ($F(1.1, 2.1) = 4.290$, $p > 0.1$).

5.2.5. *Intensity buildup*

Below is a comparison of the waveforms and intensity contours of the first ten glottal cycles in /sʰu/ and /s*u/ (from the two tokens used in Experiment 4). Unlike Experiment 1, here there is no discernible difference in intensity buildup following the two fricatives.
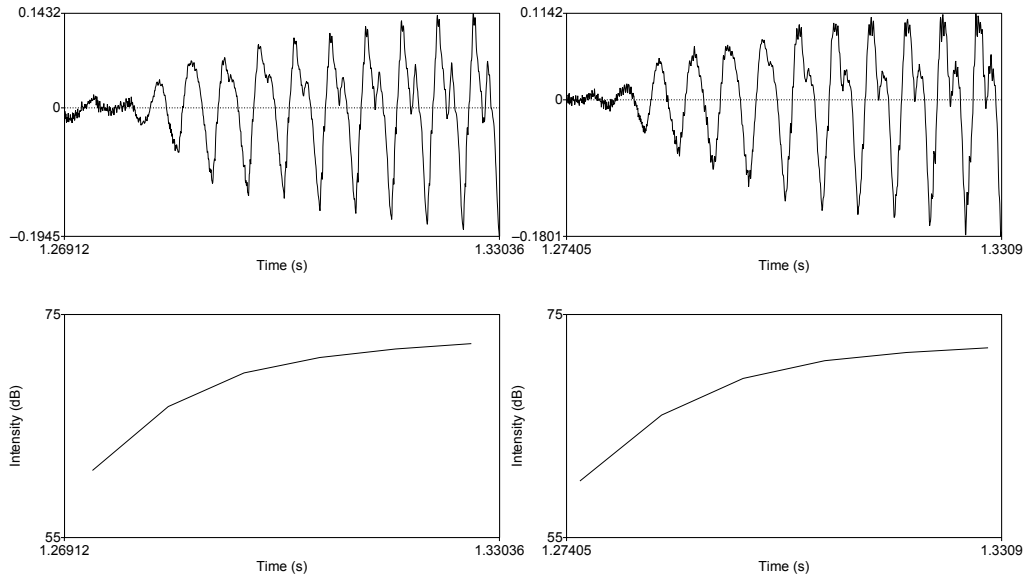

Fig. 18. Waveforms and intensity contours of /sʰu/ 'number' (L) and /s*u/ 'cook' (R)

The similarities between these intensity contours correspond to similarities in

intensity change measurements. These data are given below for the two tokens of /s^{h}u/ and /s*u/ used in Experiment 4. The differences between /s^{h}u/ and /s*u/ are not significant ($t = -0.459$, df = 8, $p > 0.6$).

Table 29
Intensity buildup in /s^{h}u/ 'number' and /s*u/ 'cook' (in dB)

Difference between periods	/s^{h}u/ [S2, token 1]	/s*u/ [S2, token 1]
Period 2 – Period 1	1.7	2.2
Period 3 – Period 2	1.7	1.4
Period 4 – Period 3	1.1	1.2
Period 5 – Period 4	0.8	0.9
Period 6 – Period 5	0.6	0.5
Period 7 – Period 6	0.4	0.5
Period 8 – Period 7	0.4	0.3
Period 9 – Period 8	0.3	0.3
Period 10 – Period 9	0.2	0.2

Measurements of average intensity across the whole vowel also show no basic difference in average intensity ($t = -0.261$, df = 4, $p > 0.8$). Measurements for all fifteen tokens of /s^{h}u/ and /s*u/ are given below.

Table 30
Average vowel intensity in /s^{h}u/ 'number' (in dB)

Token	S1	S2	S3	S4	S5
1	67.9	69.2	67.3	79.5	74.6
2	65.3	68.1	66.5	80.8	75.1
3	65.6	64.6	66.5	79.8	73.9
Average	**66.3**	**67.3**	**66.8**	**80.0**	**74.5**
StDev	1.4	2.4	0.5	0.7	0.6

Table 31
Average vowel intensity in /s*u/ 'cook' (in dB)

Token	S1	S2	S3	S4	S5
1	68.9	67.3	66.0	80.0	78.2
2	65.0	68.4	64.8	79.7	80.5
3	64.9	65.2	64.1	79.0	76.0
Average	**66.3**	**67.0**	**65.0**	**79.6**	**78.2**
StDev	2.3	1.6	1.0	0.5	2.3

A repeated-measures ANOVA shows no main effect of fricative identity ($F(1, 2) = 0.888$, $p > 0.4$), but does show a main effect of subject ($F(4, 8) = 106.385$, $p < 0.0005$), as well as an interaction between fricative identity and subject ($F(4, 8) = 9.118$, $p = 0.004$).

5.2.6. Spectral tilt

Representative spectra of /s^{h}u/ and /s*u/ are given below (from S2, token 1 and S2, token 3). The second harmonic is lower than the first harmonic in both cases, but the difference between the two is larger in the case of /s^{h}u/ (cp. Fig. 8).
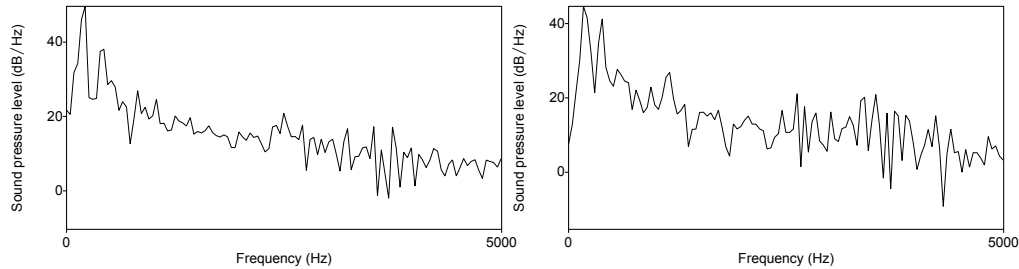

Fig. 19. Spectrum of vowel onset in /s^{h}u/ 'number' (L) and /s*u/ 'cook' (R)

The H1-H2 values for the five subjects' productions of /s^{h}u/ and /s*u/ were measured, and these data are given in the tables below.

Table 32
H1-H2 differences in /s^{h}u/ 'number' (in dB)

Token	S1	S2	S3	S4	S5
1	38.3	27.6	29.5	1.0	-5.6
2	30.3	26.1	29.6	-0.1	-2.0
3	31.7	24.1	29.2	-0.4	9.6
Average	**33.4**	**25.9**	**29.4**	**0.2**	**0.7**
StDev	4.3	1.8	0.2	0.7	7.9

Table 33
H1-H2 differences in /s*u/ 'number' (in dB)

Token	S1	S2	S3	S4	S5
1	30.8	29.4	20.9	-4.1	-2.2
2	32.6	0.0	11.0	-3.6	-3.7
3	3.9	29.0	24.3	-3.7	-3.0
Average	**22.4**	**19.5**	**18.7**	**-3.8**	**-3.0**
StDev	16.1	16.9	6.9	0.3	0.8

Although S4 and S5 have noticeably different H1-H2 values from S1, S2, and S3, similar to the results found in §3.2.6 H1-H2 values here are generally more positive in /s^{h}u/ than in /s*u/, and this difference is significant ($t = 4.537$, df = 4, $p = 0.011$). A repeated-measures ANOVA shows a main effect of fricative identity that approaches significance ($F(1, 2) = 12.929$, $p = 0.069$), as well as a main effect of subject ($F(4, 8) = 16.908$, $p = 0.001$), but no interaction between fricative identity and subject ($F(1.7, 3.4) = 0.258$, $p > 0.7$).

5.2.7. *Vowel length*

The final acoustic dimension examined in Experiment 3 was vowel length. The durational data for the vowels in /s^{h}u/ and /s*u/ are given below.

Table 34
Vowel length in /s^{h}u/ 'number' (in ms)

Token	S1	S2	S3	S4	S5
1	404	283	313	284	262
2	427	286	333	276	208
3	383	266	339	266	210
Average	**405**	**278**	**328**	**275**	**227**
StDev	22	11	14	9	31

Table 35
Vowel length in /s*u/ 'cook' (in ms)

Token	S1	S2	S3	S4	S5
1	390	292	323	293	271
2	417	270	288	259	210
3	361	285	291	233	199
Average	**389**	**282**	**301**	**262**	**227**
StDev	28	11	19	30	39
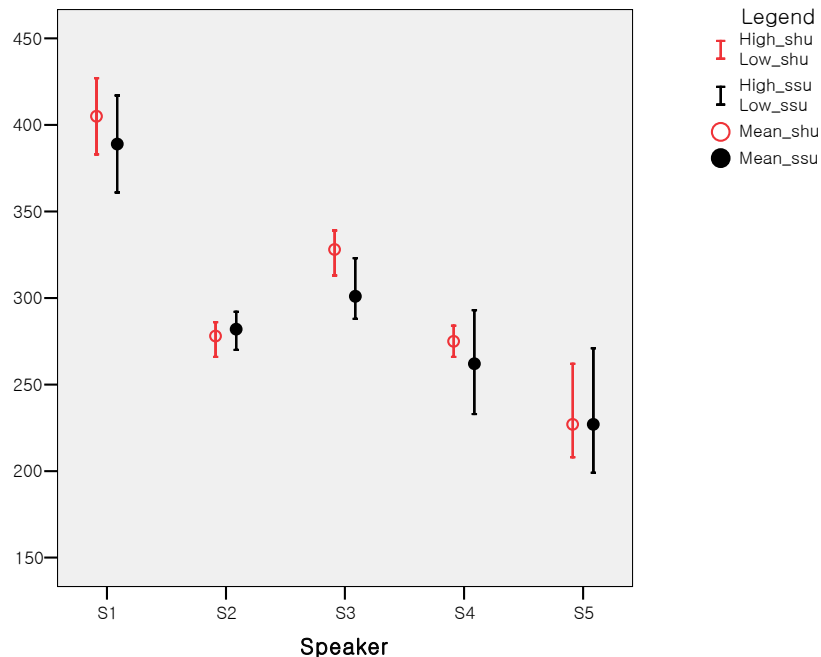
Fig. 20. Vowel length of /u/ following /s^h/ vs. /s*/ (in ms)

There is no significant difference between /s^{h}u/ and /s*u/ in vowel length ($t = 1.854$, df = 4, $p > 0.1$). A repeated-measures ANOVA shows a main effect of

subject ($F(4, 8) = 38.868$, $p < 0.0005$), reflecting some between-subject variation, but there is no effect of fricative identity ($F(1, 2) = 1.929$, $p > 0.2$) and no interaction between fricative identity and subject ($F(4, 8) = 1.740$, $p > 0.2$).

5.3. Summary

   Experiment 3 corroborates most of the results of Experiment 1. Before /u/ the non-fortis and fortis fricatives are produced with significantly different durations, aspiration intervals, and voice onset qualities. On the other hand, in contrast to the /a/ environment, in the /u/ environment there is no difference in F1 onset or intensity buildup (nor in f_0 onset, average vowel intensity, or vowel length, as in Experiment 1). Experiment 2 was therefore replicated to see what sort of effect the absence of the F1 and intensity buildup cues would have on perception of the contrast in the /u/ environment.

6. Experiment 4: Perception before /u/

   The goal of this experiment was the same as that of Experiment 2, except that the environment investigated was the /u/ environment.

6.1. Methods

6.1.1. Experimental design
   The design of Experiment 4 was the same as that of Experiment 2, except that there were fewer levels of the f_0 onset factor. Specific values of the parameters, which were again based upon the range of variation present in S2's production data, are summarized below.

Table 36
Design of Experiment 4: Perception before /u/

Factor	Range	Levels	Values of levels
SEGMENTAL DURATION	135 ms ~ 225 ms	4	135 ms 165 ms 195 ms 225 ms
ASPIRATION DURATION	10 ms ~ 70 ms	3	10 ms 40 ms 70 ms
F_0 ONSET	180 Hz ~ 230 Hz	2	180 Hz 230 Hz
SPECTRAL TILT ($\approx$ original affiliation of V)	/s^{h}u/ V ~ /s*u/ V	2	steep shallow

6.1.2. Stimuli

Six words were used for all the stimuli in the experiment. These are listed with glosses below.

Table 37
Stimuli for Experiment 4: Perception before /u/

	Orthography	IPA	Gloss
Fricatives	수	/sʰu/	'number', 'ability'
	쑤	/s*u/	'cook'
Fillers	두	/du/	'two', 'head'
	뚜	/t*u/	'hoot, honk'
	투	/tʰu/	'form, style'
	우	/u/	'right', 'fine'

The first token of /sʰu/ and the first token of /s*u/ recorded by S2 in Experiment 3 provided the basic building blocks for the 48 fricative stimuli. 75 fillers with alveolar onsets and without onsets were also produced according to the protocols used in Experiment 2.

6.1.3. Subjects

Twelve native speakers of Korean (six females and six males) ranging in age from 20 to 30 participated in the perception trials. All spoke a dialect with the fortis/non-fortis fricative contrast (eight were from Seoul or the surrounding Gyeonggi Province, and the other four were from Jeolla Province and Chungcheong Province). None reported any history of hearing disorders.

6.1.4. Procedure

The procedure followed was the same as in Experiment 2, except that subjects took a shorter test since there were fewer critical stimuli (due to the lower number of levels of the f_0 onset factor). Subjects took the same pretest as in Experiment 2 and were again compensated for their time.

6.2. Results

Mean identification functions for each experimental factor are shown in Figure 21 (percent /sʰu/ responses indicated by the solid lines, percent /s*u/ responses indicated by the dotted lines). With increasing segmental duration, stimulus labeling shifts away from /sʰu/ and towards /s*u/ (though it favors /sʰu/ at every level). With increasing aspiration duration, labeling shifts towards /sʰu/. With increasing f_0 onset, labeling shifts away from /sʰu/ and towards /s*u/ (though it favors /sʰu/ at both levels). Finally, labeling remains quite similar in the face of a change in spectral tilt, favoring /sʰu/ at both levels.
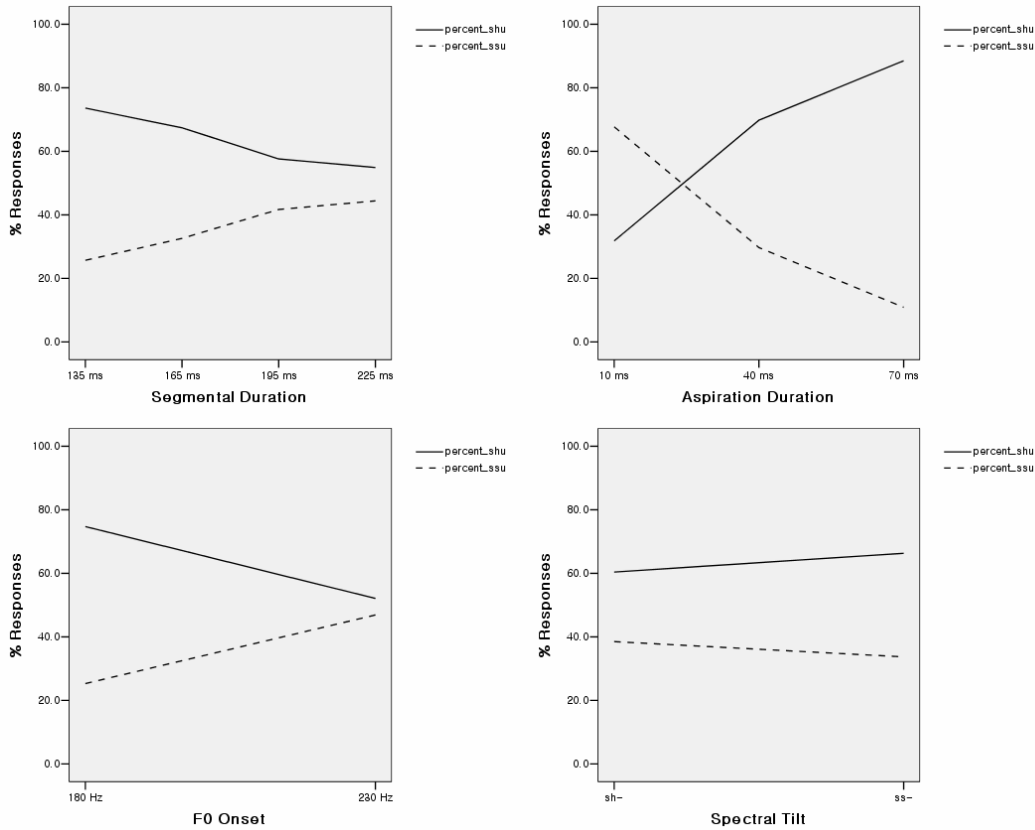
Fig. 21. Individual effects of experimental factors on labeling of stimuli as /sʰu/ vs. /s*u/

A repeated-measures ANOVA performed on the data indicates main effects of segmental duration, aspiration duration, and f_0 onset, as well as interactions between segmental duration and aspiration duration and between aspiration duration and spectral tilt. The ANOVA indicates no main effect of spectral tilt and no other interactions between factors. These results are summarized below.[11] Note that they differ from the results of Experiment 2 in that there are additional main effects/interactions evident here—namely, main effects of segmental duration and f_0 onset and an interaction between segmental duration and aspiration duration.

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[11] SD = segmental duration, AD = aspiration duration, F0 = f_0 onset, IB = intensity buildup, ST = spectral tilt.

Table 38
Results of repeated-measures ANOVA (Huynh-Feldt corrected)

SD	AD	F_0	ST	Main effects
☆				**$F(2.4, 26.2) = 6.975, p = 0.002$**
	☆			**$F(1.4, 15.3) = 45.563, p < 0.0005$**
		☆		**$F(1, 11) = 25.826, p < 0.0005$**
			•	$F(1, 11) = 1.760, p > 0.2$

SD	AD	F_0	ST	Interactions
☆	☆			**$F(6, 66) = 2.650, p = 0.023$**
•		•		$F(1.9, 21.0) = 0.751, p > 0.4$
•			•	$F(2.6, 28.3) = 1.979, p > 0.1$
	•	•		$F(2, 22) = 2.030, p > 0.1$
	☆		☆	**$F(2, 22) = 13.821, p < 0.0005$**
		•	•	$F(1, 11) = 0.058, p > 0.8$
•	•	•		$F(5.2, 57.5) = 1.442, p > 0.2$
•	•		•	$F(6.0, 65.9) = 0.748, p > 0.6$
•		•	•	$F(3, 33) = 1.503, p > 0.2$
	•	•	•	$F(1.8, 19.3) = 0.465, p > 0.6$
•	•	•	•	$F(5.9, 64.9) = 1.095, p > 0.3$

Similar to the ANOVA, the Friedman test indicates significant effects of aspiration duration and f_0 onset, though it is difficult to tell whether there is an interaction between aspiration and spectral tilt because of a floor effect in the *p*-values of data subsets sorted by spectral tilt. The Friedman test also indicates a significant effect of spectral tilt. These results are summarized below.

Table 39
Results of Friedman test

SD	AD	F_0	ST	Asymptotic significance		
			☆	**$p = 0.029$**		
•				$p > 0.3$	$p > 0.8$	/sʰu/ ST
					$p = 0.072$	/s*u/ ST
	☆			**$p < 0.0005$**	**$p < 0.0005$**	/sʰu/ ST
					$p < 0.0005$	/s*u/ ST
		☆		**$p < 0.0005$**	**$p < 0.0005$**	/sʰu/ ST
					$p < 0.0005$	/s*u/ ST

The interactions between segmental duration and aspiration duration and between aspiration duration and spectral tilt are shown in Figure 22 below. It is clear that a change in spectral tilt affects labeling differently depending on the length of the aspiration interval, as does an increase in segmental duration. In the latter case, increased duration results in an appreciably lower percentage of /sʰu/ responses only for the first two levels of aspiration duration; at 70 ms of

aspiration, responses remain at approximately 90% /s^{h}u/ regardless of the level of segmental duration.
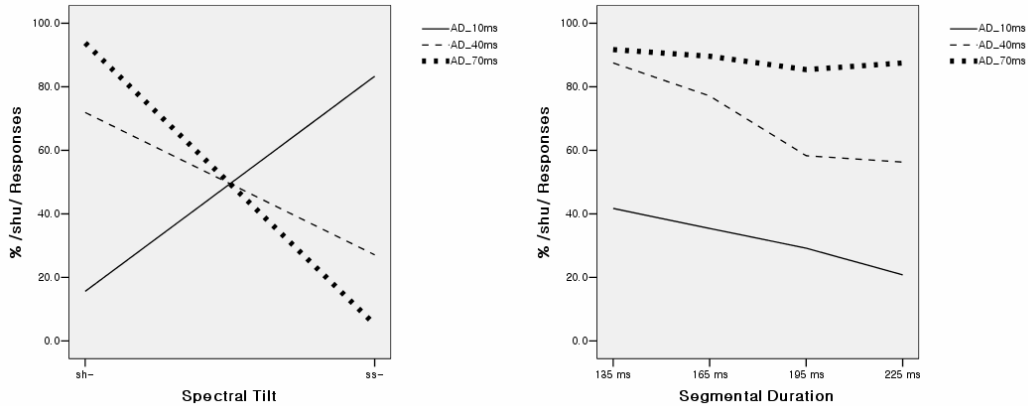

Fig. 22. Interactions between aspiration duration and spectral tilt (L) and
between aspiration duration and segmental duration (R)

It would be useful at this point to compare the results of this experiment to those of Experiment 2 in some detail. Unlike Experiment 2, there are significant effects of segmental duration and f_0 onset here. The latter is surprising since both Experiments 1 and 3 showed no difference in f_0 onset between the two fricatives. It is possible that subjects started attending to f_0 here because the salient F1 cue from Experiment 2 was now gone, and because f_0 serves as an important cue in the perception of the plosives. However, it is also possible that some effect of both segmental duration and f_0 onset was in fact present in Experiment 2, but washed out by the overriding effect of F1 onset/intensity buildup/spectral tilt. If the identification functions in Figure 21 are compared to those in Figure 10, it can be seen that the identification functions for segmental duration and f_0 onset (as well as aspiration duration) are actually quite similar in shape, but different in scale. This is probably due to the dominant effect of F1 onset/intensity buildup/spectral tilt in Experiment 2. When the factors of F1 onset and intensity buildup are taken away in Experiment 4, the lone effect of spectral tilt becomes much smaller. Thus, this dissipation of vocalic effects is most likely responsible for the emergence of the effects seen here.

What is most striking about Experiment 4 is that unlike Experiment 2, where the 'error' rate (the percentage of responses that deviated from the identity of the original onset of the vowel) is extremely low (5%), the error rate here is very high (53%). In Experiment 2, there is nearly no deviation, whereas here it appears that subjects have much more trouble following a vocalic strategy of onset identification.

6.3. Summary

Comparing the results of Experiment 4 to those of Experiment 2 leads to two main conclusions. First, there are again significant effects of spectral tilt and aspiration duration on subjects' response patterns. Second, in the absence of a significant difference in F1 onset or intensity buildup, subjects rely less on vocalic cues and more on the consonantal cues of segmental duration and aspiration duration to distinguish between the fricatives.

7. Discussion

This study has yielded several major findings. In Experiments 1 and 3, it was seen, contra Cho et al. (2002), that the fortis fricative is much longer in duration than the non-fortis fricative, and that there is no difference in f_0 onset between the two fricatives. The first point in particular is significant because it constitutes additional evidence in favor of a lenis categorization of the non-fortis fricative (cf. the difference in closure duration between the lenis and fortis plosives vs. the lack of a difference between the aspirated and fortis plosives). Experiments 1 and 3 also confirmed the results of previous studies which found that (i) aspiration duration is longer in the non-fortis fricative, (ii) F1 onset (in a low vowel) is lower following the fortis fricative, (iii) intensity buildup (in a low vowel) is quicker following the fortis fricative, and (iv) voice quality is breathier following the non-fortis fricative.

The results of Experiments 2 and 4 are even more interesting. It was found that out of all the acoustic cues examined, the combination of F1 onset/intensity buildup/spectral tilt had the strongest effect in perception. Aspiration duration was also a significant cue and appeared to have a stronger effect when a high F1 onset, gradual intensity buildup, and positive H1-H2 cuing the non-fortis fricative were present.

Two further, complementary findings emerge from Experiments 2 and 4. On the one hand, acoustic differences that could serve as potential cues to a contrast are not necessarily utilized in perception, as seen in subjects' apparent non-use of segmental duration as a cue in Experiment 2 despite significant differences between the two fricatives. On the other hand, an acoustic dimension may be used in perception that fails to reliably distinguish between segments in contrast, as seen in subjects' use of f_0 as a cue in Experiment 4 despite a lack of significant differences between the two fricatives. In short, perception can be "sloppy", failing to exploit useful cues while making use of unreliable ones.

Remember that Yoon (2002) found that not all listeners experienced a perception shift from aspirated to fortis in his categorical perception experiment. He states that a "comparison between the amount of aspiration in the perception test and the actual aspiration from the natural utterances leads us to suspect that other parameters or [a] synergistic effect of other parameters may exist" (184).

Indeed, F1 onset, intensity buildup, and voice quality would appear to be among these other parameters. Subjects' responses in Experiment 2 aligned almost invariably with the fricative category corresponding to the F1 onset, intensity buildup, and spectral tilt in any given stimulus. Subjects' responses in Experiment 4 further showed that the effect of this cohort of cues is greatly diminished when F1 onset and intensity buildup are removed. Together these results suggest that, for the fricatives at least, F1 onset, intensity buildup, and voice quality are important cues to the fortis/non-fortis distinction and that F1 onset and intensity buildup are the most salient of these cues.

In a way, the results of this study are similar to those of M.-R. Kim et al. (2002), who found that aspirated plosives cross-spliced with vowels from syllables with fortis plosive onsets were identified as fortis a surprisingly high percentage of the time. They observe, however, that the admittedly high variability in their data is due not to random factors, but to systematic differences in how individual subjects resolved the conflicting fortis and aspirated cues from the consonant and vowel: some subjects based their judgments on the consonantal cues, while others based their judgments on the vocalic cues. In both cases, though, they were strikingly consistent, leading Kim et al. to hypothesize that "listeners may have been aware of the conflicting cues for initial stop phonation type and consequently chose a consonant- or vowel-based strategy for responding to these stimuli" (2002:92). While the choice of a response strategy may have had an effect on Kim et al.'s results, if it were the case in Experiment 2 that subjects consciously chose a response strategy, then they all happened to choose the same strategy—namely, a vowel-based one. As this scenario seems rather unlikely, it appears that what is at work instead is a true hierarchy among the consonantal and vocalic cues to the laryngeal contrast in the fricatives: vocalic cues, in particular F1 onset and intensity buildup, outrank consonantal cues.

Additional evidence for the high ranking of vocalic cues comes from subjects' judgments on the filler stimuli, the onset-less ones in particular. Remember that in Experiment 2 these were produced by removing the noise portions from the beginning of the original /s^{h}a/ and /s*a/ tokens, leaving behind only the vowel. Judgments on these stimuli show a clear pattern: the bare vowels from /s^{h}a/ were often identified as /a/, while the bare vowels from /s*a/ were nearly always identified as /t*a/. The difference in these two patterns of judgments is highly significant ($p < 0.0005$ in the Friedman test). It appears that the vocalic cues alone were enough to create the impression of a fortis plosive, even in the absence of a release burst and its cohort of cues.

7.1. Categorization of the non-fortis fricative

Do the results of this study support a particular categorization of the non-fortis fricative? To review, these are the facts that have been marshaled in previous research in favor of the two possible analyses.

Table 40
Summary of evidence for lenis vs. aspirated analyses of the non-fortis fricative

LENIS ANALYSIS	ASPIRATED ANALYSIS
subject to post-obstruent tensing	not subject to intervocalic voicing
less linguopalatal contact than fortis	not subject to phonological aspiration
vocal fold slackening intervocalically	open glottal configuration
loss of aspiration intervocalically	heavy aspiration in initial position
shorter duration than fortis	duration similar to aspirated
shortened duration intervocalically	high f_0 onset similar to aspirated

The findings of this study generally confirm the above facts, or otherwise do not directly contradict them (in the case of the phonological evidence). However, one result of Experiment 1 adds to the body of acoustic evidence supporting the aspirated analysis: the non-fortis fricative shows a high F1 onset, a property of the aspirated plosives.[12] Nonetheless, as can be seen in the table above there is quite a body of evidence that argues in favor of a lenis analysis. How can the major finding in this study regarding F1 onset be reconciled with these facts?

The answer to this question may lie in the generality of these facts and the interpretation of their underlying causes. First, with respect to linguopalatal contact and durational properties, it is unclear how similar the aspirated plosives are to the fortis plosives. Cho and Keating (2001) found a significant difference between the contact for lenis plosives on the one hand and that for aspirated and fortis plosives on the other, but they do not claim that the contact for aspirated and fortis plosives is in fact the same. If anything, the subordinate relation of the aspirated plosives to the fortis plosives in terms of closure duration[13] would suggest a similar relationship in terms of articulatory contact. Thus, neither the fact that the non-fortis fricative generally shows less linguopalatal contact than the fortis fricative nor the fact that the non-fortis fricative is generally shorter than the fortis fricative may actually constitute evidence that can adjudicate between a lenis analysis and an aspirated analysis in the first place. However, even supposing that the aspirated plosives and the fortis plosives were the same in terms of linguopalatal contact and that a similar parallelism should exist between an aspirated and a fortis fricative, it is not unreasonable to predict the aspirated fricative would have less contact anyway due to coarticulatory assimilation with the following aspiration gesture (essentially a glottal fricative, or voiceless vowel, with no oral contact).

With regard to the non-fortis fricative's intervocalic loss of aspiration, again it is

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[12] Note that neither gradual intensity buildup nor positive H1-H2 is evidence that can be brought to bear here, since both lenis and aspirated plosives show more gradual intensity buildup than fortis plosives (cf. Han and Weitzman 1970) as well as more positive H1-H2 values than fortis plosives (cf. Cho et al. 2002).

[13] Cho and Keating (2001) did not find a significant durational difference between aspirated and fortis plosive closures, but several other studies have found a difference (cf. Silva 1992, Kim 1994, J.-I. Han 1996).

not clear that this is evidence that can be said to support either analysis. As Han and Weitzman (1970) and others have shown, both the aspirated plosives and the lenis plosives lose a great deal of aspiration intervocalically. In addition, although it is true that in standard Seoul Korean the non-fortis fricative undergoes post-obstruent tensing like the lenis plosives, there are dialects (e.g. North Gyeongsang Korean) in which it does not and instead retains its salient aspiration.

Nonetheless, Iverson (1983) provides some convincing arguments for the lenis analysis of the non-fortis fricative. He observes that the vocal fold slackening, or glottal width reduction, in intervocalic environments is similar in magnitude ("a reduction by 10 or 15 on the glottal width scale [of 30]") to that seen in intervocalic lenis plosives. It is debatable whether a narrowing of a partly open glottis to a fully adducted glottis (in intervocalic lenis plosives) and a narrowing of a fully open glottis to a partly open glottis (in intervocalic non-fortis fricatives) amount to parallel gestures, but in any case the narrowing is indicative of some assimilation to the glottal requirements of the adjacent voiced vowels (i.e. a "weakened" articulation). Both this fact and the fact that intervocalic non-fortis fricatives are significantly reduced in duration (cf. K.-S. Kang 2000) provide the strongest evidence in favor of the lenis analysis.

In conclusion, the results of this study generally support analyzing the fricative distinction as an aspirated/fortis contrast, but do not refute much of the independent evidence offered in favor of a lenis/fortis contrast. It may be that the non-committal position of K.-S. Kang (2000, 2004) is ultimately the most justified: with both lenis and aspirated features, the non-fortis fricative may simply be both lenis and aspirated. In fact, this position becomes quite reasonable in the context of the laryngeal typology of Jansen (2004).

7.2. *The place of Korean in a laryngeal typology of fricatives*

To summarize points made in Jansen (2004), plosives across a wide variety of languages seem to divide into four types: (unaspirated) *prevoiced lenis*, (unaspirated) *passively voiced lenis*, *unaspirated voiceless fortis*, and *aspirated voiceless fortis*. The three-way contrast in Korean plosives fits well into this system. In terms of Jansen's categories, the 'lenis' series is passively voiced lenis; the 'fortis' series is unaspirated voiceless fortis; and the 'aspirated' series is aspirated voiceless fortis.

In contrast to the variety of plosive categories, Jansen observes that fricatives generally come in only two types: (unaspirated) *prevoiced lenis* and *unaspirated voiceless fortis*. He says that aspirated fricatives "only seem to occur in languages that already have distinctively voiced and plain voiceless fricatives" (2004:56). However, this is not an accurate characterization of the Korean fricative contrast, which appears to be typologically unusual (cf. Ladefoged and Maddieson 1996:176-179). The 'fortis' fricative can indeed be labeled unaspirated voiceless fortis, but the 'non-fortis' fricative cannot be prevoiced lenis since it is neither prevoiced nor passively voiced. Moreover, as summarized above, there is

considerable evidence grouping it with the lenis plosives. Therefore, it would appear that either we should look to the other plosive categories and classify the 'non-fortis' fricative as aspirated voiceless fortis, or admit that this fricative does not fit into any of Jansen's four categories and classify it as something else. As the former analysis must paradoxically categorize the 'non-fortis' fricative as fortis, the latter analysis seems superior. The non-fortis fricative appears to be an example of an entirely different category: *aspirated voiceless lenis*. This analysis not only avoids classifying the 'non-fortis' fricative as fortis, it also resolves the issue of whether the 'non-fortis' fricative is 'lenis' or 'aspirated', since in this classification it is both.

7.3. *Cross-linguistic comparisons with Burmese*

At this point it might be instructive to make some comparisons to the other language commonly cited as having aspirated fricatives, namely Burmese (Ladefoged and Maddieson 1996 cite only Burmese in mentioning aspirated fricatives, while Silverman 2004 notes that "Korean and Burmese are two of the few languages which possess [contrastively aspirated fricatives]", which are "quite rare cross-linguistically"). In having a three-way laryngeal contrast in its fricatives (voiced, voiceless unaspirated, and voiceless aspirated), Burmese already constitutes a counterexample to the two-way generalization in Jansen (2004). What is of interest here, however, is how similar these Burmese fricatives are to the fricatives of Korean. Though an in-depth acoustic analysis of these fricatives lies outside the scope of this paper, a brief inspection of the F1 onset, intensity, and spectral tilt characteristics follows in the interest of making cross-linguistic comparisons (all Burmese data comes from Chang 2003).

Spectrograms are given below of two Burmese words similar to the Korean words used in Experiment 2: /s^{h}á/ 'salt' and /sá/ 'eat'. These are presented alongside the Korean spectrograms from Fig. 1 for ease of comparison.
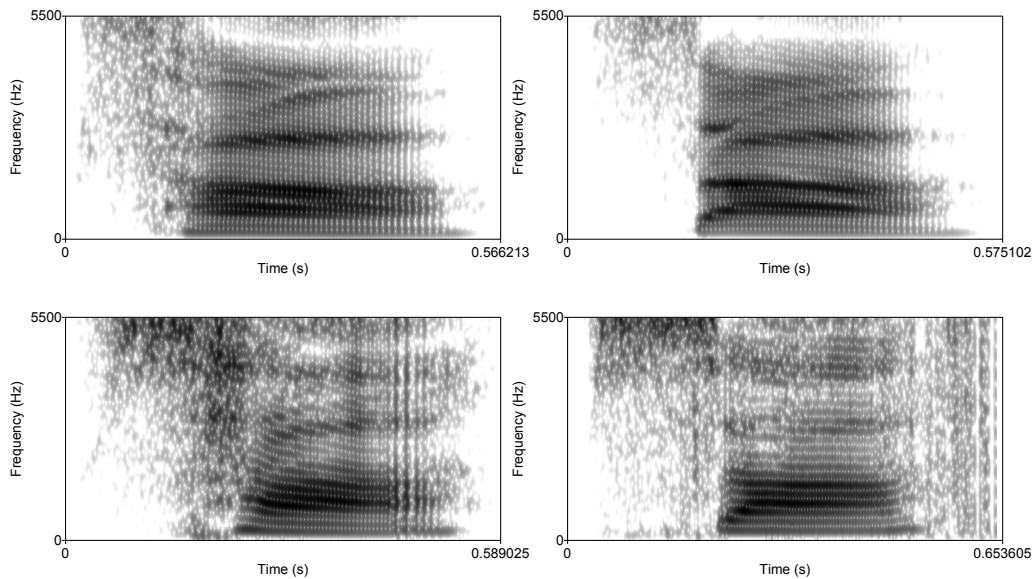
Fig. 23. Spectrograms of syllables with fricative onsets in Korean and Burmese: Korean /s^{h}a/ 'buy' (top L), Korean /s*a/ 'wrap' (top R), Burmese /s^{h}á/ 'salt' (bottom L), Burmese /sá/ 'eat' (bottom R)

Two features of the Burmese fricatives parallel properties of the Korean fricatives. First, the extended duration of low-frequency noise in the spectrogram of /s^{h}á/ is similar to that found in Korean /s^{h}a/. What stands out even more, though, is the similarity in the F1 trajectories. In both Korean and Burmese, the F1 following the aspirated fricative starts high, while the F1 onset following the unaspirated/fortis fricative starts low.

Similarities between the Korean and Burmese fricatives may also be found in their intensity profiles. Waveforms and intensity contours of the first ten glottal cycles of /s^{h}á/ 'salt' and /sá/ 'eat' are given below to illustrate the patterns in intensity buildup. In Figure 24 one can see that the aspirated and unaspirated fricatives differ from each other in a way that is similar to the difference between the Korean fricatives: intensity increases more quickly following the Burmese unaspirated fricative, just as it increases more quickly following the Korean fortis fricative (cf. Figure 7).
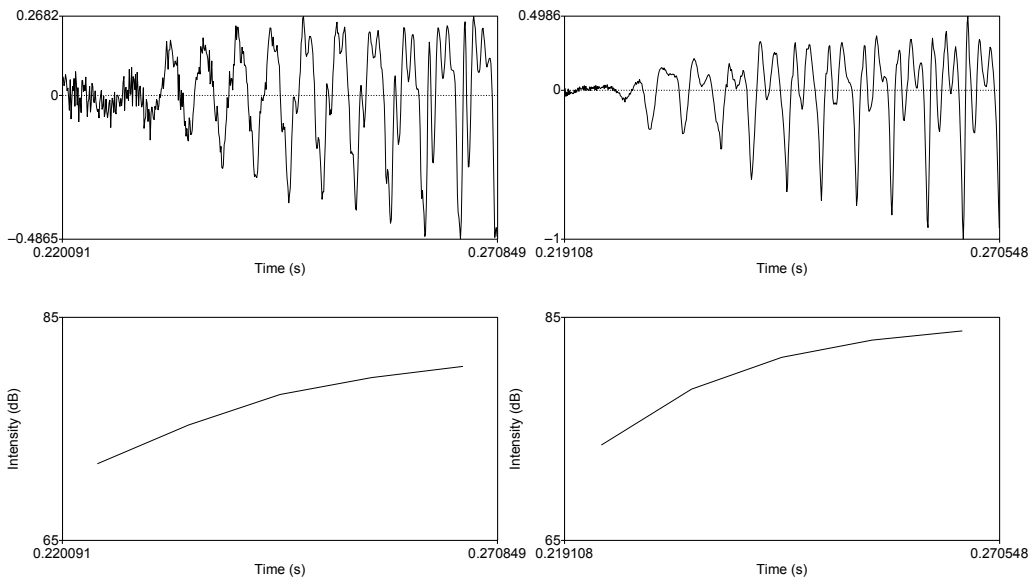
Fig. 24. Waveforms and intensity contours of /sʰá/ 'salt' (L) and /sá/ 'eat' (R)

A comparison of spectra of the first four glottal cycles in /sʰá/ 'salt' and /sá/ 'eat' also shows similarities with the Korean fricatives. Like the Korean fricatives, the Burmese fricatives differ substantially from each other in terms of spectral tilt, with the aspirated fricative having a much breathier voice onset.
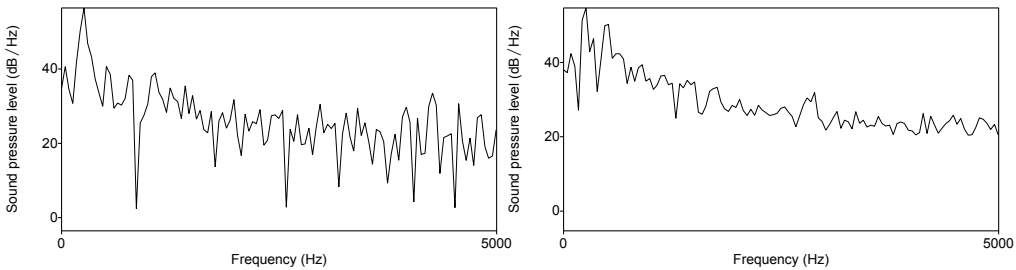

Fig. 25. Spectrum of vowel onset in /sʰá/ 'salt' (L) and /sá/ 'eat' (R)

The above facts suggest that aspiration is closely connected with gradual intensity buildup, breathy voice onset, and high F1 onset. This point is significant because it implies that these cues may be inevitable consequences of the glottal configuration required for aspiration. In this respect, it may make sense to consider these to be parts of the same cue rather than individual cues manipulable in their own right, at least in the environment of a low vowel.

8. Conclusion

In summary, this study examined the production and perception of the two-way laryngeal contrast in Korean sibilant fricatives in four experiments covering a low (/a/) and a high (/u/) vowel environment. Acoustic analyses show that in a low vowel environment, the two fricatives differ from each other in segmental duration, aspiration duration, F1 onset, intensity buildup, and voice quality; however, the F1 and intensity differences disappear in a high vowel environment. In both environments, there are no differences in f_0 onset, average intensity, or vowel length.

The results of the perception experiments demonstrate that the coalition of F1 onset, intensity buildup, and voice quality is important in the perception of this contrast. These vocalic cues appear to outrank the consonantal cues of segmental duration and aspiration duration, with F1 onset and intensity buildup being the most salient.

In having a fricative contrast without a voiced member, Korean constitutes an exception to Jansen's (2004) laryngeal typology. This contrast seems to be typologically unique and can only be accommodated by the addition of an aspirated voiceless lenis category to the set of possible laryngeal classifications.

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