말소리와 음성과학 제2권 제3호 (2010)
pp. 37~46

An Acoustic Study of Korean and English Voiceless Sibilant Fricatives

Sung, Eunkyung[1)] · Cho, Yunjeong[2)]

ABSTRACT

This study investigates acoustic characteristics of English and Korean voiceless sibilant fricatives as they appear before the three vowels, /i/, /ɑ/ and /u/. Three measurements - duration, center of gravity and major spectral peak - are employed to compare acoustic properties and vowel effect for each fricative sound. This study also investigates the question of whether Korean sibilant fricatives are acoustically similar to the English voiceless alveolar fricative /s/ or to the palato-alveolar /ʃ/. The results show that in the duration of frication noise, English /ʃ/ is the longest and Korean lax /s/ the shortest of the four sounds. It is also observed that English alveolar /s/ has the highest value, whereas Korean /s/ shows the lowest value in the frequency of center of gravity. In terms of major spectral peak, while English /s/ reveals the highest frequency, English /ʃ/ shows the lowest value. In addition, evidence indicates that there is a strong vowel effect in the fricative sounds of both languages, although the vowel effect patterns of the two languages are inconsistent. For instance, in the major spectral peak, both Korean lax /s/ and tense /s*/ show significantly higher frequencies before the vowel /ɑ/ than before the other vowels, whereas both English /s/ and /ʃ/ exhibit significantly higher frequencies before the vowel /i/ than before the other vowels. These results indicate that Korean sibilant fricatives are acoustically distinct from both English /s/ and /ʃ/.

Keywords: voiceless sibilant fricatives, duration, center of gravity, major spectral peak

1. Introduction

Fricatives are produced with a very narrow constriction in the oral cavity. There is a rapid flow of air through the constriction, creating turbulence in the flow. While stops present a relative lack of spectrographic activity, fricatives are accompanied by aperiodic vibrations in the higher frequencies (Stevens, 1971, 1998).

In early studies, fricatives are characterized by a number of acoustic parameters such as spectral shape, duration and overall intensity (Hughes & Halle, 1956; Strevens, 1960; Jassem, 1965). More recent research adds other acoustic parameters to our knowledge about fricatives such as spectral moments - centroid, variance, skewness and kurtosis (Forrest, Weismer, Milenkovic & Dougall, 1988; Nittrouer, 1995; McFarland, Baum & Chabot, 1996; Tabain, 1998; Jongman, Wayland & Wong, 2000), locus equations (Sussman, 1994; Fowler, 1994; Sussman & Shore, 1996; Yeou, 1997), and relative amplitude (Stevens, 1985; Hedrick & Ohde, 1993).

Among fricatives, the alveolars /s, z/ and palato-alveolars /ʃ, ʒ/ are called sibilants because of the hissing noise produced during articulation (Jongman et al. 2000). The voiceless sibilant fricatives /s/ and /ʃ/ are the most frequently occurring fricative sounds in the languages of the world (Maddieson, 1984). Although both English and Korean have two-way contrasts in sibilant fricatives, they contrast in different aspects of articulation. In English, two sibilant fricative sounds contrast with each other in tongue position, whereas in Korean, the sounds are differentiated by tenseness. In English, alveolar /s/ and palato-alveolar /ʃ/ are generally distinguished on the basis of the spectral properties of frication noise. That is, /s/ has a greater energy concentration at higher frequencies than /ʃ/. Major spectral

1) Cyber Hankuk University of Foreign Studies eks@cufs.ac.kr, corresponding author
2) Hankuk University of Foreign Studies cyj@hufs.ac.kr
This work was supported by the Cyber Hankuk University of Foreign Studies Research Fund of 2010.

Received: August 13, 2010
Revision received: September 14, 2010
Accepted: September 27, 2010

peaks appear around 3,000 Hz for /ʃ/ and around 4,000 Hz for /s/ (Stevens, 1971; Behrens & Blumstein, 1988; Davenport & Hannahs, 1998). The spectral properties of /s/ examined in several languages show considerable interspeaker variation despite the consistently high frequency of peaks relative to /ʃ/. This interspeaker variation is related to variation in constriction locati on, tongue shape and tongue position (Gordon, Barthmaier & Sands, 2002). The difference in energy distribution between /s/ and /ʃ/ can also be shown by the center of gravity, the first moment when the power spectrum is treated as a probability distribution (Forrest et al., 1988; Jongman et al., 2000). Furthermore, Proctor, Shadle & Iskarous (2006) argue that the articulatory and acoustic properties of English /s/ and /ʃ/ depend on vowel context. For example, the place of articulation of /s/ varies from dental to post-alveolar depending on the vocalic environment, in some cases shifting according to the frontness or backness of the adjacent vowel.

In Korean, there are two voiceless sibilant fricatives, lax /s/ and tense /s*/.[3] Korean /ʃ/ and /ʃ*/ are allophonic variants of s/ and /s*/ because Korean /s/ and /s*/ are palatalized in front of /i/ or /y/, e.g., *tasi* /tɑʃi/ 'again' (Sohn, 1999). The place of articulation of the fricatives is controversial, having been alternatively classified as - dental (Cheng, 1987; Maddieson, 1984), alveolar (Jung, 1962) and denti-alveolar (Cho, Jun & Ladefoged, 2002; Choo & O'Grady, 2003). Schmidt and Meyers (1995) indicate that this disagreement on the description of tongue placement is due to the fact that Korean, with only three fricatives, including /h/, has fewer fricatives than English, which has nine.

The status of the Korean tense fricative /s*/ is rigid because its phonetic and phonological properties are very similar to those of Korean tense stops and affricates. However, categorization of the lax fricative /s/ varies from lax (Cho et al., 2002) to aspirated (Park, 1999). Kang, Kochetov and Go (2009) indicate that the lax fricative /s/ shows characteristics of both lax and aspirated obstruents. They found that the fricative /s/ patterns with lax obstruents in terms of fricative duration and center of gravity, while it patterns with aspirated obstruents in fundamental frequency (F0). It is also known that Korean lax /s/ and tense /s*/ contrast in duration. Lax /s/ has shorter duration of frication than tense /s*/ (Kim, 1999; Kim & Curtis, 2002). However, Kang (2008) argues that the duration difference between these two sounds is consistent only in the word-medial position, and not in the word-initial position. Cho et al. (2002) calculate center of gravity (centroid) in front of the vowel /ɑ/ in order to investigate spectral characteristics of Korean sibilant fricatives. They show that the tense fricative has a significantly higher centroid than the lax one.

Extensive acoustic studies have been done on Korean and English fricative sounds separately. However, there has been little investigation of direct comparisons between Korean and English fricative sounds in front of various vowels through the same acoustic measurements.

This study compares acoustic characteristics and vowel effect of frication noise in Korean and English voiceless sibilant fricatives using three acoustic measurements - duration, center of gravity and major spectral peak. This study also investigates the question of whether Korean sibilant fricatives are acoustically more similar to English alveolar /s/ or to English palato-alveolar /ʃ/.

In this study, three acoustic measurements - duration, center of gravity and major spectral peak - were employed. The two acoustic measurements, major spectral peak and center of gravity, were chosen because these measurements have been used to capture the differences between English voiceless sibilant fricatives in much previous research (Stevens, 1971; Behrens & Blumstein, 1988; Forrest et at., 1988; Jongman et al., 2000). These measurements were also employed to differentiate between Korean lax and tense fricatives (Cho et al, 2002; Hwang, 2004; Kang et al., 2009). Another measurement, duration of frication noise, was taken because in the previous studies duration was found to be a significant acoustic characteristic for Korean fricative contrast (Kim, 1999; Kim & Curtis, 2002; Cho et al., 2002; Chang, 2008). Duration was also measured in order to determine acoustic similarity between English and Korean voiceless sibilants (Cheon & Anderson, 2008).

The following questions will be addressed: 1) Are Korean and English voiceless sibilant fricatives distinguished based on the acoustic measurements?; 2) Do Korean sibilant fricatives present a greater acoustic similarity to the English alveolar fricative /s/ than to the English palato-alveolar fricative /ʃ/?; 3) Do Korean and English voiceless sibilant fricatives show consistent vowel effect?

2. Methods

2.1 Subjects

Twenty native Korean speakers (ten male and ten female) and twenty native English speakers[4] (fifteen male and five female)

3) Diacritic '*' is used to indicate tenseness in this study.

4) All of them are American English speakers.

participated in this study. The data from one English speaking subject of this group was excluded because of a recording error. All the Korean subjects (mean age: 26.6 years, mean length of stay in an English speaking country: 3.6 months) were graduate students at H University, in Seoul, Korea. The English speaking subjects (mean age: 37.4 years, mean length of stay in Korea, 5 years) were English professors or instructors at the same university. None of the subjects reported any history of speech or hearing impairments.

2.2 Stimuli

The stimuli consisted of English /s/, English /ʃ/, Korean /s/ and Korean /s*/ followed by the vowels /i/, /ɑ/ and /u/. English and Korean words which include these sequences in word-initial position were used as test words. The test words were embedded in two carrier sentences; "Please say _____ three times" or "Jigeumbuteo _____ sebeon malhaseyo." The English speaking subjects read the English sentences and the Korean subjects read the Korean sentences. Korean orthography was provided for the Korean sentences. The test words were randomized for each subject. Each test word had three repetitions. Thus, the total number of test words was 702 (19 English subjects x 2 fricatives x 3 vowels x 3 repetitions and 20 Korean subjects x 2 fricatives x 3 vowels x 3 repetitions). The following shows the target items used for acoustic analyses.

(1) a. English /s/ before /i/, /ɑ/, /u/
season, sock, soup
b. English /ʃ/ before /i/, /ɑ/, /u/
sheep, shock, shoot

(2) a. Korean /s/ before /i/, /ɑ/, /u/
sigan 'time'
sagwa 'apple'
sugap 'handcuff'
b. Korean /s*/ before /i/, /ɑ/, /u/
ssireum 'wrestling'
ssagae 'wrapper'
ssusigae 'pick'

2.3 Recording

Recording was conducted in a sound-proof room at the Language Research Institute of H University using an audio-interface (Tascam, Model US-122), which converts analogue into 16-bit digital signals at a sampling rate of 16,000 Hz, and directs it to the computer to be stored on the hard disk using software called Cool Edit (version 2.1). The subjects read test words in carrier sentences which were presented one by one on a computer screen prompted by *ProRec* software. In order to analyze and measure acoustic properties, a publically available speech analysis tool called *Praat* (version 5.1.4.1) was used.

2.4 Measurements

2.4.1 Duration

In total, 342 English items produced by English subjects and 360 Korean items produced by Korean subjects were employed for acoustic analyses. All measurements were taken by hand with *Praat*. For precise boundary locations and measurements, a waveform and a spectrogram were considered together. Frication was identified by the presence of high frequency noise. The duration of frication was measured from the beginning of high frequency noise to the zero-crossing of the end of the visible frequency noise preceding the onset of periodicity. If there was a portion of aspiration before the periodicity of the vowel portion, the portion of aspiration was not included in the duration of frication noise. Figure 1 shows an example of segmentation for measuring frication duration.

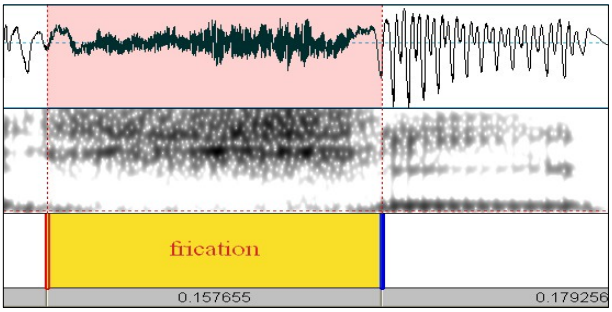

Figure 1. Wavefrom and Spectrogram of *sheep* produced by EM2.

2.4.2 Center of gravity

Another measurement used in this study to compare the acoustic properties of English and Korean voiceless sibilant fricatives was center of gravity of frication noise. Center of gravity is the centroid of a defined part of the spectrum, each frequency being weighed according to its amplitude (Forrest et al., 1988; Zsiga, 2000). The values for center of gravity were taken from a series of Fast Fourier Transforms (FFT) spectra, and measured over a spectrum of the entire fricative portion with *Praat*.

2.4.3 Major spectral peak

The frequency of major spectral peak of voiceless sibilant fricatives was also measured. The samples were preemphasized

from 50 Hz and the power spectra were made with the power of 2.0. Spectra were LPC smoothed for better visibility. For LPC, 12 peaks were used. Figure 2 shows an example of the spectrum for measuring the major spectral peak of English /ʃ/.

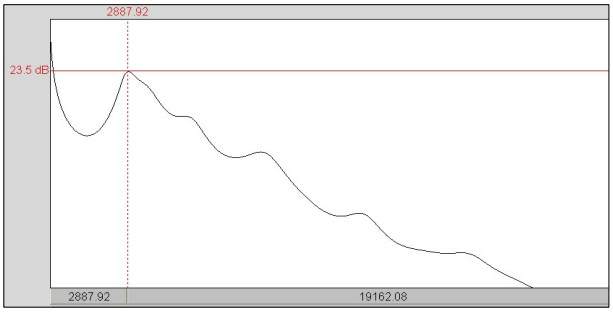

Figure 2. Spectrum of /ʃ/ shown in *sheep* produced by EM2.

3. Results

3.1 Frication duration

The following figure shows a graphic representation of mean frication duration for Korean and English fricatives. Each subject's scores were averaged over the three repetitions.

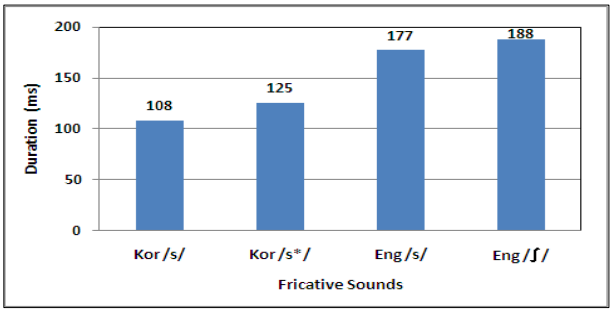

Figure 3. Mean frication duration of Korean /s/, Korea /s*/, English /s/ and English /ʃ/

As seen in Figure 3, English /ʃ/ reveals the longest frication noise (188 ms) and Korean /s/ is the shortest frication noise (108 ms) of the four sounds. The detailed individual data are given in Appendix 1.

According to a two-factor ANOVA (language, fricative sound), there was a significant effect among English /s/, English /ʃ/, Korean /s/ and Korean /s*/ sounds [$F(3, 230) = 63.390$ $p < .001$], as well as a significant language effect for Korean and English sounds [$F(1, 230) = 181.285$, $p < .001$].

A post hoc test revealed that the duration of Korean /s/ and Korean /s*/ was significantly shorter than that of English /s/ and English /ʃ/. Korean tense /s*/ was longer than Korean lax /s/ [$p < .001$]. Furthermore, English palato-alveolar /ʃ/ was longer than English alveolar /s/ [$p = .001$].

3.2 Center of gravity

The following figure displays the mean frequencies of center of gravity for Korean and English fricatives.

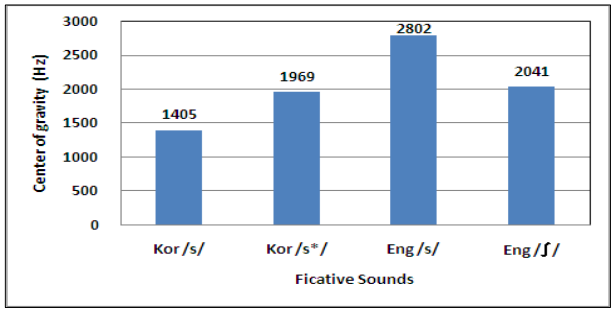

Figure 4. Mean frequencies of center of gravity of Korean /s/, Korean /s*/, English /s/ and English /ʃ/

As shown in Figure 4, English /s/ has the highest value (2802 Hz) whereas Korean /s/ has the lowest value (1405 Hz) of the four fricative sounds. The detailed individual data are shown in Appendix 2.

According to a two-factor ANOVA (language, fricative sound), there was a significant effect for English /s/, English /ʃ/, Korean /s/, and Korean /s*/ sounds [$F(3, 230) = 13.337$, $p < .001$], as well as a significant language effect for Korean subjects and English speaking subjects [$F(1, 230) = 21.918$, $p < .001$). A post hoc test revealed that the center of gravity of Korean /s/ was significantly lower than that of Korean /s*/ and English /ʃ/. English /s/ presented significantly higher values than the other fricative sounds.

3.3 Major spectral peak

The following figure illustrates the mean frequencies of major spectral peak shown in Korean and English fricatives.

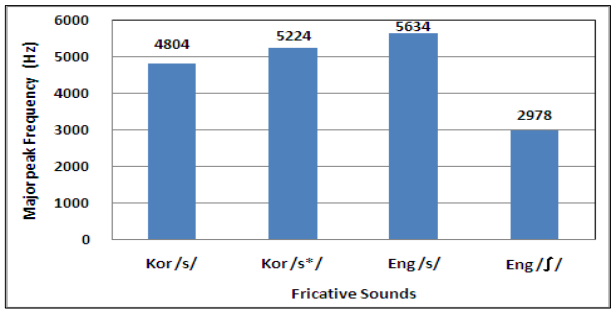

Figure 5. Mean frequencies of major spectral peak of Korean /s/, Korean /s*/, English /s/ and English /ʃ/

As shown in Figure 5, the major peak value of English /ʃ/

(2978 Hz) was much lower than that of the other fricative sounds, and English /s/ (5634 Hz) had a greater energy concentration at higher frequencies than Korean /s/ and /s*/. The individual data are shown in Appendix 3.

A two-factor ANOVA (language, fricative sound) revealed that there was a significant effect of fricative sounds for English /s/, English /ʃ/, Korean /s/ and Korean /s*/ [$F(3, 230) = 70.978$, $p < .001$], as well as a significant language effect between Korean and English sounds [$F(1, 230) = 26.497$, $p < .001$]. A post hoc test exhibited that the mean frequency of major spectral peak of English /ʃ/ was lower than that of Korean /s*/ and Korean /s/. Furthermore, the mean spectral peak frequency of Korean /s*/ was higher than that of Korean /s/ ($p=.001$). English /s/ showed the highest spectral peak frequency.

The following table summarizes statistical differences for the four fricative sounds across vowels.

Table 1. Statistical differences in three acoustic measurements

Dur	English /ʃ/ > English /s/ > Korean /s*/ > Korean /s/
CG	English /s/ > Korean /s*/ & English /ʃ/ > Korean /s/
MSP	English /s/ > Korean /s*/ & Korean /s/ > English /ʃ/

(Dur=duration, CG=center of gravity, MSP=major spectral peak)

3.4 Vowel effect

In each measurement, the vowel effect of each sound was investigated. For frication duration, the following figure represents the general patterns of duration shown in Korean /s/, Korean /s*/, English /s/ and English /ʃ/ in front of the three vowels, /i/, /ɑ/ and /u/.

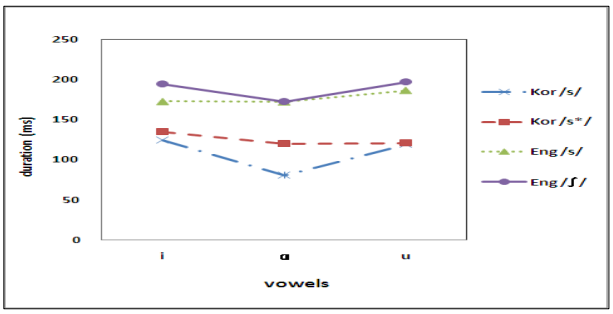

Figure 6. Mean frication duration of Korean /s/, Korean /s*/, English /s/ and English /ʃ/ before three vowels

As depicted in Figure 6, the duration of English /s/ and /ʃ/ was longer than that of Korean /s/ and /s*/. Statistical analysis was performed for each sound in order to check the vowel effect. A repeated measures ANOVA revealed that there was a significant vowel effect for all four fricative sounds [$F(19, 40) = 15.539$, $p < .001$ for Korean /s/; $F(19, 40) = 8.662$, $p = .002$ for Korean /s*/; $F(18, 38) = 6.301$, $p = .009$ for English /s/; $F(18, 38) = 13.167$, $p < .001$ for English /ʃ/]. Post hoc pairwise comparisons for each fricative sound indicated that the duration of Korean /s/ before /ɑ/ was significantly shorter than that of Korean /s/ before /i/ or /u/ ($p = .002$ and $p < .001$, respectively). Also, the duration of Korean /s*/ before /i/ was significantly longer than that of Korean /s*/ before /ɑ/ or /u/ ($p = .012$ and $p = .003$, respectively). In addition, the duration of English /s/ before /u/ was marginally longer than that of English /s/ before /i/ or /ɑ/ ($p = .016$ and $p = .035$, respectively). Furthermore, the duration of English /ʃ/ before /ɑ/ was significantly shorter than that of English /ʃ/ before /i/ or /u/ ($p = .011$ and $p < .001$, respectively). In terms of the duration of frication noise, the vowel effect patterns were not consistent among the sounds, but in general, the fricative noise was shorter before /ɑ/ than before other vowels. This pattern was more prominent in Korean /s/ compared to the other sounds as the percentage of aspiration occurrence was high (about 80%) and the duration of aspiration was relatively long in this sound.

The following figure illustrates the aspiration shown in Korean /s/ before /ɑ/.

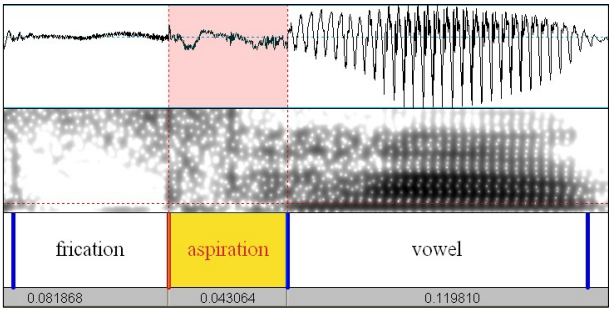

Figure 7. Waveform and spectrogram shown in *sagwa* 'apple' produced by KF2.

For the mean frequencies of center of gravity, the following figure depicts the general patterns shown in Korean /s/, Korean /s*/, English /s/ and English /ʃ/ in front of the three vowels, /i/, /ɑ/ and /u/.

When we compared the mean frequencies of center of gravity, English /s/ and /ʃ/ were higher than Korean /s/ and /s*/, and Korean /s/ revealed the lowest frequency of center of gravity. Statistical analysis was performed for each sound in order to

check the vowel effect. A repeated measures ANOVA revealed that there was a significant vowel effect for Korean /s/, Korean /s*/ and English /ʃ/ [F(19, 40) = 15.539, p < .001; F(19, 40) = 6.870, p = .006; F(18, 38) = 7.280, p < .001, respectively]. There was no vowel effect in English /s/. Post hoc pairwise comparisons for each fricative sound indicated that the center of gravity of Korean /s/ before /ɑ/ was significantly lower than that of Korean /s/ before /i/ or /u/ (p < .001, and p = .002, respectively). Also, the center of gravity of Korean /s*/ before /ɑ/ was significantly lower than that of Korean /s*/ before /i/ (p = .006). There was no significant difference for the other vowels. In addition, the center of gravity of English /ʃ/ before /ɑ/ was significantly lower than that of English /ʃ/ before /i/ or /u/ (p < .001 for both comparisons). In terms of the center of gravity of frication noise, the vowel effect patterns were consistent among the sounds. That is, in general, the center of gravity for frication noise was shorter before /ɑ/ than before the other vowels.

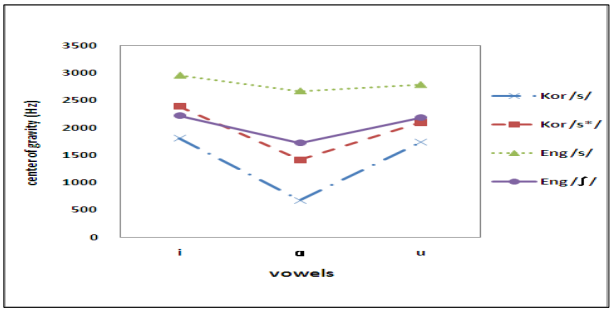

Figure 8. Mean frequencies of center of gravity of Korean /s/, Korean /s*/, English /s/ and English /ʃ/ before three vowels

For the major spectral peak of frication, the following figure shows the general patterns of Korean /s/, Korean /s*/, English /s/ and English /ʃ/ in front of the three vowels, /i/, /ɑ/ and /u/.

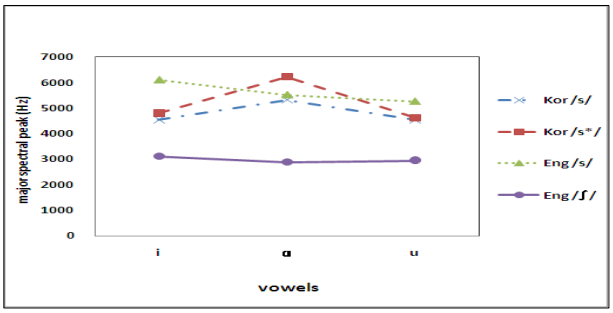

Figure 9. Mean frequencies of major spectral peak of Korean /s/, Korean /s*/, English /s/ and English /ʃ/ before three vowels

Figure 9 displays that the frequency of major spectral peak of English /ʃ/ was lower than that of Korean /s/, Korean /s*/ and English /s/.

Statistical analysis was performed for each sound in order to check the vowel effect. A repeated measures ANOVA revealed that there was a significant vowel effect for all four fricative sounds [F(19, 40) = 9.241, p = .002 for Korean /s/; F(19, 40) = 1.726, p < .001 for Korean /s*/; F(18, 38) = 7.530, p = .005 for English /s/; F(18, 38) = 8.324, p = .003 for English /ʃ/]. Post hoc pairwise comparisons for each fricative sound indicated that the spectral peak frequency of Korean /s/ before /ɑ/ was significantly higher than that of Korean /s/ before /i/ or /u/ (p = .003 and p = .008, respectively). Also, the spectral peak frequency of Korean /s*/ before /ɑ/ was significantly higher than that of Korean /s*/ before /i/ or /u/ (p < .001 for both comparisons). In addition, the spectral peak frequency of English /s/ before /i/ was significantly higher than that of English /s/ before /ɑ/ or /u/ (p = .024 and p = .007, respectively). Furthermore, the spectral peak frequency of English /ʃ/ before /i/ was significantly higher than that of English /ʃ/ before /ɑ/ or /u/ (p = .016 and p = .008, respectively). In terms of the major spectral peak frequency of frication noise, the vowel effect patterns of the two languages were different. That is, in Korean the vowel /ɑ/ was different from the other vowels, whereas in English, the vowel /i/ showed a different pattern from the other vowels.

The following figure shows the waveforms and spectrograms of Korean /s/ before three different vowels.

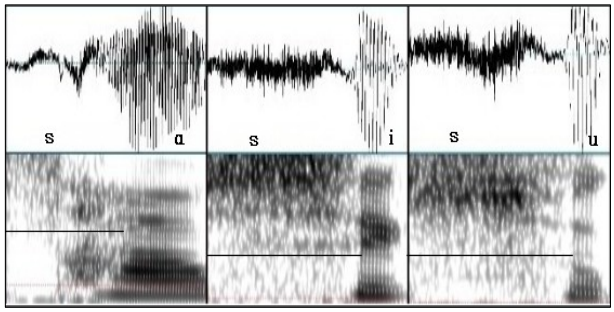

Figure 10. Spectrograms of /sɑ/, /si/, and /su/ produced by KF2

Figure 10 shows the different energy distribution of Korean /s/ before the three vowels. Korean /s/ before /ɑ/ consists of frication noise, aspiration, and the vowel /ɑ/, whereas that before /i/ or /u/ has no aspiration, hence a sequence of frication noise and the vowel. Moreover, the boundary of frequency of /s/ before /i/ or /u/ is around 2000 Hz, whereas the boundary of frequency of /s/ before /ɑ/ is around 3500 Hz, as illustrated by horizontal lines. The mean value of major spectral peak of Korean /s/ before /a/ is higher than that before /i/ or /u/ by about 1000-1500 Hz (refer to the table in appendix).

The following table summarizes the statistical differences for the four fricative sounds before the three vowels.

Table 2. Statistical differences involving vowel effect in three acoustic measurements

	Kor /s/	**Kor /s*/**	**Eng /s/**	**Eng /ʃ/**
Dur	/i/ or /u/ > /ɑ/	/i/ > /ɑ/ or /u/	/u/ > /ɑ/ or /i/#	/i/ or /u/ > /ɑ/
CG	/i/ or /u/ > /ɑ/	/i/ > /ɑ/	no vowel effect	/i/ or /u/ > /ɑ/
MSP	/ɑ/ > /i/ or /u/	/ɑ/ > /i/ or /u/	/i/ > /ɑ/ or u/	/i/ > /ɑ/ or /u/

(Dur=duration, CG=center of gravity; MSP=major spectral peak, # Difference is marginal.)

4. Discussion and conclusion

This study compared acoustic properties of the English voiceless sibilant fricatives, /s/ and /ʃ/, and the Korean fricatives, /s/ and /s*/, as they occurred before the three vowels, /i/, /ɑ/ and /u/ at the word-initial position. Three acoustic measurements - duration, center of gravity, and major spectral peak of frication noise - were used in order to investigate acoustic characteristics and vowel effect. The results showed that a strong fricative sound effect and a language effect appeared in all three measurements.

In the duration of frication noise, English /s/ and /ʃ/ were significantly longer than Korean /s/ and /s*/. Korean tense /s*/ was longer than Korean lax /s/, while English palato-alveolar /ʃ/ was longer than English alveolar /s/. Thus, English /ʃ/ exhibited the longest frication and Korean /s/ showed the shortest fricaiton of the four fricative sounds. When the frequency of center of gravity in frication noise was measured, English /s/ had the highest value whereas Korean /s/ showed the lowest value. There was no significant difference between Korean /s*/ and English /ʃ/. In each language, Korean /s*/ showed significantly higher frequency than Korean /s/, and English /s/ presented higher frequency than English /ʃ/. These results are consistent with the previous research exploring spectral moments (McFarland et al., 1996; Shadle & Mair, 1996; Cho et al., 2002; Hwang, 2004). In the frequency of major spectral peak in frication noise, English /s/ showed the highest frequency whereas English /ʃ/ revealed the lowest frequency. The frequency of Korean /s*/ was higher than Korean /s/. Therefore, a distinction among the four fricative sounds was shown in all three measurements.

Vowel effect was also explored in each measurement. In the duration of frication, there was a vowel effect for all four fricatives. In general, the fricative sounds before /ɑ/ were shorter than those before /i/ or /u/. Specifically, Korean lax /s/ before /ɑ/ was much shorter in frication duration than before the other vowels. This pattern can be explained by the high percentage of occurrence of aspiration, some instances of which were accompanied by a strong burst. This phenomenon is also consistent with previous studies. Cheon & Anderson (2008) reported that Korean /s/ before /ɑ/ was significantly longer in aspiration duration than both English /s/ and Korean /s*/ before /ɑ/, and Korean /s/ before /ɑ/ was significantly shorter in frication duration than the other sounds before /ɑ/. Kang, Kochetov & Go (2009) also demonstrated that Korean lax /s/ had a significant VOT difference only before /ɑ/ in the word-initial position.

In terms of center of gravity, the three fricative sounds, Korean /s/, Korean /s*/ and English /ʃ/ showed significantly lower frequencies before /ɑ/ than before the other vowels. However, English /s/ did not reveal any vowel effect.

For the major spectral peak frequency, English and Korean fricative sounds did not show consistent patterns. For Korean, both /s/ and /s*/ were significantly higher before /ɑ/ than before the other vowels, whereas both English /s/ and /ʃ/ were significantly higher before /i/ than before the other vowels. Thus, the Korean /s/-palatalization rule involving the vowel /i/ was not clearly shown in this study as the frequencies of major spectral peak were lower before both /i/ and /u/ than before /ɑ/. In other words, the place of articulation of Korean /s/ and /s*/ moved backwards before both /i/ and /u/ compared to those sounds before /ɑ/.

In summary, Korean and English voiceless sibilant fricatives are distinguished from one another based on the three acoustic measurements. Furthermore, Korean sibilant fricatives are acoustically differentiated from both English /s/ and /ʃ/. This implies that Korean learners of English should be aware of acoustic differences in temporal and spectral aspects between Korean and English voiceless sibilant fricatives. Moreover, a strong vowel effect is shown for all the fricative sounds in both languages except English /s/, which does not exhibit vowel effect in center of gravity. However, vowel effect is not consistent between the two languages. For example, both Korean /s/ and /s*/ display longer duration and higher frequency of major spectral peak before /ɑ/ than before /i/. This pattern, however, is not revealed for the English sounds.

Future study is needed to compare the acoustic characteristics of Korean and English voiceless sibilant fricatives at word-medial or final position. In order to investigate L2 acquisition, a comparison of English voiceless sibilant fricatives produced by English native speakers and native Korean speakers should be

considered. That is, whether Korean speakers and English speakers show similar acoustic characteristics when they pronounce English voiceless sibilant fricatives is a question to be examined. In addition, perception tests involving the continuum between /s/ and /ʃ/ are needed to see whether native Korean speakers reveal the same perception categorization as native English speakers.

References

Ahn, H. (1999) "An acoustic investigation of the phonation types of post-fricative vowels in Korean", *Harvard Studies in Korean Linguistics,* Vol. 7, pp. 57-71.

Behrens, S. J. & Blumstein, S. E. (1988). "Acoustic characteristics of English voiceless fricatives: a descriptive analysis", *Journal of Phonetics*, Vol. 16, pp. 295-298.

Chang, B. C. (2008) "The acoustics of Korean fricatives revisited", *Harvard Studies in Korean Linguistics*, Vol. 12, pp. 134-150.

Cheng, L. (1987). *Assessing Asian language performance,* Rockville, MD: Aspen Press.

Cheon, S. & Anderson, V. (2008). "Acoustic and perceptual similarities between English and Korean sibilants: implications for second language acquisition", *Korean Linguistics*, Vol. 14, pp. 41-64.

Cho, T., Jun, S. & Ladefoged, P. (2002). "Acoustic and aerodynamic correlates to Korean stops and fricatives", *Journal of Phonetics*, Vol. 29, pp. 193-228.

Choo, M. & O'Grady, W. (2003). *The sounds of Korean : A pronunciation guide,* Honolulu: University of Hawaii Press.

Davenport, M. & Hannahs, S. J. (1998). *Phonetics and phonology*, New York: Oxford University Press.

Forrest, K., Weismer, G., Milenkovic, P. & Dougall, R. (1988). "Statistical analysis of word-initial voiceless obstruents: preliminary Data.", *Journal of the Acoustical Society of America*, Vol. 84, No. 1, pp. 115-123.

Fowler, C. A. (1994). "Invariants, specifiers, cues: An investigation of locus equations as information for place articulation", *Perception and Psychophysics*, Vol. 55, pp. 597-611.

Gordon, M., Barthmaier, P. & Sands, K. (2002). "A cross-linguistic acoustic study of voiceless fricatives", *Journal of the International Phonetic Association*.

Hedrick, M. S. & Ohde, R. N. (1993). "Effect of relative amplitude of frication on perception of place of articulation", *Journal of Acoustical Society of America*, Vol. 94, pp. 2005-2026.

Hughes, G. W. & Halle, M. (1956). "Spectral properties of fricative consonants", *Journal of Acoustical Society of America*, Vol. 28, pp. 303-310.

Hwang, H. (2004) "Spectral Characteristics of Frication Noise in Korean Sibilants", *Malsori*, vol. 49, pp. 31-50.

Jassem, W. (1965). "Formants of fricative consonants", *Language and Speech*, Vol. 8, pp.1-16.

Jongman, A., Wayland, R. & Wong, S. (2000). "Acoustic characteristics of English fricatives", *Journal of Acoustical Society of America*, Vol. 108, No.3, pp. 1252-1263.

Jung, M. W. (1962). "A contrastive study of English and Korean segmental phonemes with some suggestions toward pedagogical applications", Unpublished master's thesis, Georgetown University.

Kang, Y. (2008). "English voiced stops in Korean in the 1930s", A talk presented at the annual meeting of the Montreal-Ottawa-Toronto (MOT), Phonology workshop.

Kang, Y., Kochetov, A. & Go, D. (2009). "The acoustics of Korean fricatives", CRC-Sponsored Summer Phonetics/Phonology Workshop, Department of Linguistics, University of Toronto.

Kim, S. (1999). "Sub-phonemic duration differences in English /s/ and few-to-many borrowing from English to Korean", PhD Dissertation, University of Washington.

Kim, S. & Curtis, E. (2002). "Phonetic duration of English /s/ and its borrowing into Korean", *Japanese/Korean Linguistics,* Vol. 10, pp. 406-419.

Maddieson, I. (1984). *Patterns of sounds,* London: Cambridge University Press.

McFarland, D. H., Baum, S. R. & Chabot, C. (1996). "Speech compensation to structural modifications of the oral cavity", *Journal of Acoustical Society of America*, Vol. 100, pp. 1093-1104.

Morton, J. & Jassem, W. (1965). "Acoustic correlates of stress", *Language and Speech,* Vol. 8, pp. 148-158.

Nittrouer, S. (1995). "Children learn separate aspects of speech production at different rates: Evidence from spectral moments", *Journal of Acoustical Society of America*, Vol. 97, pp. 520-530.

Park, H (1999). "The phonetic nature of the phonological contrast between the lenis and fortis fricatives in Korean", in *Proceedings of the 14th international congress of phonetic sciences* (ICPS 99), Vol. 1, pp. 424-427.

Proctor, M., Shadle, S. & Iskarous K. (2006). "An MRI study of vocalic context effects and lip rounding in the production of English sibilants", in *proceedings of the 11th Australian international conference on speech science & technology*, pp. 307-312.

Schmidt, A. M. & Meyers, K. A. (1995). "Traditional and phonological treatment for teaching English fricatives and affricates to Koreans", *Journal of Speech and Hearing Research*, Vol. 38, pp. 828-838.

Shadle, C. H. & Mair, S. J. (1996). "Quantifying spectral characteristics of fricatives", *CSLP*, 1521-1524 (unpublished).

Sohn, H. (1999). *The Korean language,* Cambrige: Cambridge University Press.

Stevens, K. N. (1971). "Airflow and turbulence for noise for fricative and stop consonants: Static considerations", *Journal of Acoustical Society of America,* Vol. 50, pp. 1182-1192.

Stevens, K. N. (1985). "Evidence for the role of acoustic boundaries in the perception of speech sounds", in *Phonetic linguistics* edited by V. A. Fromkin, New York: Academic, pp. 243-255.

Stevens, K. N. (1998). *Acoustic phonetics,* Cambridge, MA: MIT Press.

Strevens, P. (1960). "Spectra of fricative noise in human speech", *Language and Speech*, Vol. 3, pp. 32-49.

Sussman, H. M. (1994). "The phonological reality of locus equations across manner class distinctions: Preliminary observations", *Phonetica*, Vol. 51, pp. 119-131.

Sussman, H. M., & Shore, J. (1996). "Locus equations as phonetic descriptors of consonantal place of articulation", *Perception and Psychophysics*, Vol. 58, pp. 936-946.

Tabain, M. (1998). "Nonsibilant fricatives in English: Spectral information above 10 kHz", *Phonetica,* Vol. 55, pp. 107-130.

Yeou, M. (1997). "Locus equations and the degree of coarticulation of Arabic consonants", *Phonetica*, Vol. 54, pp. 187-202.

Zsiga, E. C. (2000). "Phonetic alignment constraints: consonant overlap and palatalization in English and Russian", *Journal of Phonetics,* Vol. 28, pp. 69-102.

• **Sung, Eunkyung,** corresponding author
Department of English
Cyber Hankuk University of Foreign Studies
270 Imun-dong, Dongdaemun-gu, Seoul 130-791, Korea
Tel: 02-2173-2359
Email: eks@cufs.ac.kr
Research interests: Phonetics, Phonology, L2 acquisition

• **Cho, Yunjeong**
Department of English Linguistics
Hankuk University of Foreign Studies
270 Imun-dong, Dongdaemun-gu, Seoul 130-791, Korea
Email: cyj@hufs.ac.kr
Research interests: Phonetics, L2 acquisition

Appendix 1. Individual data in mean frication durations

Korean /s/ and /s*/ before three vowels (ms)

Kor Sub	/si/	/sɑ/	/su/	/s*i/	/s*ɑ/	/s*u/
KM1	114	123	114	103	115	94
KM2	168	68	81	136	90	125
KM3	124	57	91	124	124	131
KM4	156	48	99	136	113	124
KM5	130	123	78	136	100	90
KM6	136	110	152	156	127	116
KM7	136	96	123	112	120	114
KM8	156	81	133	121	122	81
KM9	89	96	124	137	116	139
KM10	75	75	93	126	116	127
KF1	152	65	133	135	157	146
KF2	134	62	130	124	117	122
KF3	173	81	133	203	158	185
KF4	187	78	153	155	164	133
KF5	101	58	113	143	121	124
KF6	158	65	152	121	101	123
KF7	109	55	104	128	131	104
KF8	51	59	119	122	96	109
KF9	86	108	121	147	116	121
KF10	47	98	133	133	96	105
Mean	124	80	119	135	120	121

English /s/ and /ʃ/ before three vowels (ms)

Eng Sub	/si/	/sɑ/	/su/	/ʃi/	/ʃɑ/	/ʃu/
EM1	179	151	187	174	139	194
EM2	138	142	158	151	148	165
EM3	167	175	181	198	202	198
EM4	133	128	149	161	123	164
EM5	162	159	206	202	173	227
EM6	160	153	155	202	177	168
EM7	196	184	209	217	172	210
EM8	213	273	254	235	270	274
EM9	160	185	153	185	177	168
EM10	149	157	151	165	139	176
EM11	239	222	266	243	261	281
EM12	181	185	211	183	195	203
EM13	180	154	180	160	138	183
EM14	148	129	162	174	143	171
EF1	252	286	301	293	250	291
EF2	197	169	180	196	159	176
EF3	162	134	175	147	136	161
EF4	165	193	183	218	178	226
EF5	97	88	78	185	94	102
Mean	173	172	186	194	172	197

cf) KM = Korean male speaker, KF = Korean female speaker
EM = English male speaker, EF =English female speaker
Each subject's scores were averaged over the three repetitions.

Appendix 2. Individual data in mean frequencies of center of gravity

Korean /s/ and /s*/ before three vowels (Hz)

Kor Sub	/si/	/sɑ/	/su/	/s*i/	/s*ɑ/	/s*u/
KM1	2384	327	3230	3105	2334	2932
KM2	553	160	1167	693	615	753
KM3	631	321	566	622	503	411
KM4	1646	294	1157	1768	1274	351
KM5	4179	532	3428	4168	2323	3729
KM6	1900	437	1533	1903	2849	823
KM7	1315	490	1681	542	797	1793
KM8	1893	368	128	3831	453	217
KM9	109	432	726	799	404	566
KM10	1722	242	1250	2672	1905	1875
KF1	1180	1394	3917	3108	1378	5259
KF2	3081	3584	2653	3271	548	1584
KF3	2532	727	2077	3340	1193	1745
KF4	4212	2539	3594	5115	3260	3746
KF5	2030	545	514	4440	1570	3248
KF6	1651	216	467	1259	217	769
KF7	1064	267	975	907	344	1271
KF8	2489	343	3226	2673	3713	3702
KF9	341	135	1926	879	781	4413
KF10	1174	168	510	2740	1869	2797
Mean	1804	676	1736	2392	1416	2099

English /s/ and /ʃ/ before three vowels (Hz)

Eng Sub	/si/	/sɑ/	/su/	/ʃi/	/ʃɑ/	/ʃu/
EM1	4799	3420	3456	1912	1003	2772
EM2	1644	1454	1358	1857	1233	1375
EM3	1259	1720	3679	3255	2632	3017
EM4	651	459	780	838	433	771
EM5	2187	3668	3386	2891	2184	2781
EM6	2661	2865	3191	1557	1739	2284
EM7	1381	1826	1187	1058	862	757
EM8	4564	4301	3938	3235	3590	3647
EM9	2661	1557	2865	1557	1739	2284
EM10	4018	4344	3132	1549	1093	1359
EM11	1908	1498	1579	2375	1971	2466
EM12	5014	3632	4173	2565	1756	2067
EM13	4619	4398	3921	3241	2235	3047
EM14	3440	3184	1898	1425	1382	1499
EF1	1651	1249	3486	2920	2498	3111
EF2	1599	1200	1639	1297	549	884
EF3	4796	1369	2330	3046	2226	2745
EF4	4783	4803	4592	3250	2391	2708
EF5	2515	3752	2315	2269	1226	1943
Mean	2955	2668	2784	2216	1723	2185

Appendix 3. Individual data in mean frequencies of major spectral peak

Korean /s/ and /s*/ before three vowels (Hz)

Kor Sub	/si/	/sɑ/	/su/	/s*i/	/s*ɑ/	/s*u/
KM1	4515	4940	3691	4397	6370	3691
KM2	4397	4433	3574	4162	4958	3809
KM3	2814	4352	3583	4687	4506	3655
KM4	3474	4470	4723	3872	4506	4813
KM5	4293	5786	5012	4334	6379	3167
KM6	4008	4813	3601	3786	5908	3728
KM7	4109	4370	3303	4515	5733	3351
KM8	4188	4828	4594	5063	4820	4350
KM9	4940	4671	6832	4126	6067	7437
KM10	3348	5038	3833	4510	6959	6911
KF1	5447	7329	6813	5175	6352	4361
KF2	4234	6388	3628	4270	8523	3927
KF3	4524	6270	4289	4632	6551	4831
KF4	5356	6080	4542	5094	5926	4967
KF5	5026	5908	5189	5374	6089	4560
KF6	4513	5355	4902	4824	6391	4462
KF7	4669	4728	4089	5211	6234	4180
KF8	6877	5330	4377	5984	7636	4425
KF9	5420	6216	4542	7401	7501	5266
KF10	4887	5094	5691	4759	7139	6840
Mean	4552	5320	4540	4809	6227	4637

English /s/ and /ʃ/ before three vowels (Hz)

Eng Sub	/si/	/sɑ/	/su/	/ʃi/	/ʃɑ/	/ʃu/
EM1	6976	5094	4687	3194	3004	3094
EM2	5456	5456	4582	2741	2397	2542
EM3	4958	4777	4822	3366	2587	3456
EM4	4542	4524	4524	2886	2651	2660
EM5	5899	5664	5411	3167	3139	3212
EM6	5040	5148	5121	3103	3167	2968
EM7	5646	5202	4397	2379	2379	2370
EM8	7062	6828	5203	3599	3661	3489
EM9	5040	3103	5148	3103	3167	2968
EM10	4931	4994	4415	3438	3176	3112
EM11	3715	3530	3235	2404	2816	2361
EM12	7564	4388	5139	2651	2416	2117
EM13	5546	4958	4451	2986	2226	2949
EM14	6677	6062	4334	2750	2651	2669
EF1	7428	7175	7772	3773	3519	3709
EF2	6542	6162	5999	2841	2578	2687
EF3	7075	5999	6551	3510	2768	2796
EF4	6686	6433	7582	3103	2868	3031
EF5	9335	9424	6718	3966	3585	3841
Mean	6111	5522	5268	3103	2882	2949