ACOUSTIC AND PERCEPTUAL SIMILARITIES BETWEEN ENGLISH AND KOREAN SIBILANTS: IMPLICATIONS FOR SECOND LANGUAGE ACQUISITION

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Abstract. Foreign accent has been assumed to be closely related to the degree of articulatory, acoustic and perceptual similarity between L1 and L2 sounds. This study examined cross-language acoustic and perceptual similarities between Korean and English sibilant fricatives: Korean [−tense] /s/ and [+tense] /s*/ vs. English alveolar /s/ and palato-alveolar /ʃ/. To determine acoustic similarity, two parameters were measured: duration and spectral peak frequency. A Same-Different (AX) discrimination task investigated listeners' perceived similarity judgments between pairs of sibilants. In most cases, the acoustic characterizations led to correct predictions about differences in listeners' perceptions. However, results showed several disparities between acoustic similarity and perceived similarity. These cases necessarily involve acoustic dimensions other than the two measured here; probable candidates are voice quality on a following vowel, and lip rounding, with its spectral lowering effects. Cases of mismatch between acoustic and perceptual characterizations are fruitful areas for examining additional acoustic characteristics that may be responsible for listeners' ability to distinguish sounds. Acoustic and perceptual characterizations in tandem provide the best method of establishing areas of difference between the sounds of different languages, and in turn of establishing ways to teach L2 sounds to learners.

Keywords: Phonetic similarity, English, Korean, sibilants, second language acquisition

1. INTRODUCTION

The task of mastering a second language (L2) phonology is difficult because languages differ both in their systems of phonological contrasts and in the

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precise phonetic implementations of those contrasts. Researchers make a variety of predictions concerning the areas of difficulty in learning L2 sounds. Lado (1957) claims that L2 sounds that are similar to sounds in the first language (L1) will be easy to acquire due to positive transfer from L1, while new L2 sounds will be difficult to acquire due to negative transfer from L1. On the other hand, Flege (1987) suggests that a new L2 sound may be acquired more easily than a similar L2 sound, because small differences between the equated L1 and L2 sounds are overlooked by learners. Best (1995) also grapples with the problem of similarities and discrepancies among native and non-native sounds. In classifying sounds as similar or dissimilar, phonetic criteria such as articulatory, acoustic, and perceptual descriptions as well as phonological criteria such as sound structure, distinctive features, or orthographic evidence have been used (Major 2001). However, there are no agreed-upon definitions or metrics that determine the degree of similarity and dissimilarity between native and non-native sounds (Major 2001: 39; Flege 2005).

Korean and English both make use of two voiceless sibilant fricative phonemes. Korean has /s/ and /s*/, while English has /s/ and /ʃ/. The goal of the present study is to compare acoustic characterizations with listeners' perceived similarity judgments of English and Korean voiceless sibilants, in order to illuminate what features of the fricatives are salient to L1 speakers, and to inform the development of pedagogy for L2 learners.

The organization of the paper is as follows. In section 2, we review and compare descriptions of English and Korean sibilants in the literature. Section 3 presents our research methodology, including research questions, predictions, and results of two experiments. Section 4 discusses the disparity between the results of perceived similarity and acoustic similarity found in the experiments.

2. ENGLISH AND KOREAN SIBILANTS IN THE PHONETIC LITERATURE

2.1. English sibilants

Table 1 shows distinctive features for the two English voiceless sibilants /s/ and /ʃ/ using Jakobson, Fant, & Halle's system (1963). /s/ and /ʃ/ are distinguished only by the feature [diffuse], which differentiates sounds that lack prominent spectral resonance peaks ([+diffuse]) from those that contain such peaks ([-diffuse]). In terms of articulation, [+diffuse] is associated with sounds made in the anterior portion of the oral cavity, such as labials, dentals, and alveolars, which involve minimal vocal tract filtering. Sounds made behind the alveolar ridge, such as palato-alveolars, palatals and velars are typically [-diffuse]. /s/ has a constriction in the middle or forward part of the alveolar ridge, while /ʃ/ is made by a narrowing of the vocal tract between the blade of the tongue and the back part of the alveolar ridge (Stevens 1998; Ladefoged 2001).

TABLE 1. Jakobson, Fant, & Halle's distinctive feature values for English voiceless sibilants.

	[±diffuse]	[±grave]	[±cont]	[±strid]	[±tense]
s	+	−	+	+	+
ʃ	−	−	+	+	+

Olive et al. (1993), Ladefoged & Maddieson (1996), and Ladefoged (1962; 2001) have all contrasted the acoustics of the English sibilants /s/ and /ʃ/. These studies produced similar results (as follows). The voiceless sibilants /s/ and /ʃ/ have relatively strong acoustic intensity as compared to labial or interdental (non-sibilant) fricatives. The difference between /s/ and /ʃ/ is that /s/ has its greatest energy concentration at higher frequencies than /ʃ/. The spectrograms in Figure 1 show typical high-amplitudes for frequencies above about 6,000 Hz for /s/, and between about 3,000 Hz and 5,000 Hz for /ʃ/ (Ladefoged 1962; 1996). English [ʃ] is produced with some lip protrusion, which enhances the low frequencies in the frication noise. Figure 2 shows sample spectra of English /s/ and /ʃ/, illustrating that /ʃ/ has its energy concentration at lower frequencies than /s/. English sibilants /s/ and /ʃ/ are taken to be allophones by Korean speakers (Eckman & Iverson 1997).

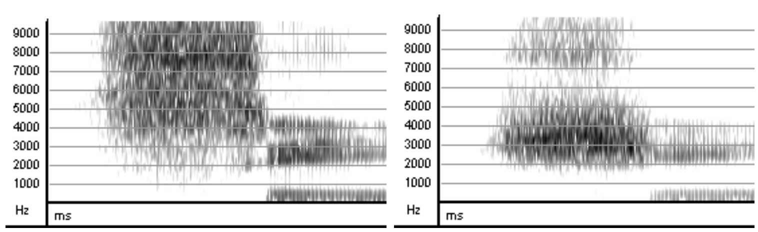

FIGURE 1. Spectrograms of "see" (left) and "she" (right) as produced by one of the American English speakers who participated in the present study.

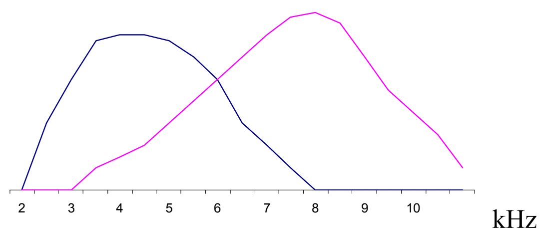

FIGURE 2. Sample spectra of the English sibilants /ʃ/ (left) and /s/ (right). The horizontal scale gives the frequency in kHz; the vertical dimension represents the amplitude of frication at given frequencies. Adapted from Ladefoged (1962; 1996, p. 53).

2.2. Korean sibilants

Korean has three fricative phonemes, all voiceless: the sibilants /s/ and /s*/ and the non-sibilant /h/. Normally, these fricatives can be distinguished by Korean speakers in identical phonetic contexts, regardless of whether these contexts constitute meaningful utterances in Korean (as in *sa* 'to buy', *s*a* 'to wrap', and *ha* 'to do'), or are nonsense syllables. Both sibilants have palatalized allophones before /i/ and /j/ (Sohn 1999).

Unlike the English voiceless sibilants, the articulatory contrast between the Korean sibilants is not primarily one of place. According to Choo & O'Grady (2003), in both Korean sibilants the tongue blade articulates with the "front part of the dental ridge". In a palatographic study, Anderson *et al*. (2004) find that Korean /s/ and /s*/ are both denti-alveolar. Rather, the major differences between the sibilants show parallels with the laryngeal contrasts among Korean stops.

Korean has a well-known three-way phonemic contrast among voiceless stops. Ahn (1998:19) represents stop contrasts in terms of the features [aspirated] and [tense], as in Table 2.

Table 2. Distinctive feature specifications for Korean stops (Ahn 1998)

Tense	[+tense, -aspirated]
Plain(=lax)	[-tense, -aspirated]
Aspirated	[+tense, +aspirated]

Because Korean sibilants only employ a two-way phonological opposition, the question arises as to whether the contrast involves the feature [tense] or [aspirated]. Table 3 displays Kim-Renaud's (1974) distinctive feature specifications for /s/ and /s*/, which she distinguishes by the feature [tense]; both sibilants are classified as [-aspirated]. Iverson (1983) also takes the contrast to be [±tense], observing that /s/ undergoes the same intervocalic slacking process as do the lax stops (glottal width is reduced when between vowels). Moreover, /s/ patterns with the lax stops in undergoing tensification after obstruents (Iverson 1983, Sohn 1999; Cheon 2000), as shown in Table 4. Korean aspirated obstruents do not undergo tensification, arguing that /s/ is phonologically [-aspirated].

Table 3. Kim-Renaud's (1974) distinctive feature system for Korean sibilants

	[±son]	[±cons]	[±ant]	[±cor]	[±pal]	[±tense]	[±asp]	[±strid]
s	−	+	+	+	−	−	−	+
s*	−	+	+	+	−	+	−	+

Table 4. Post-obstruent tensification (Data from Cheon 2000:197-198)

/p/	→	[p*]	kukpap	→	[kukp*ap]	'soup & rice'
/t/	→	[t*]	siktang	→	[sikt*aŋ]	'restaurant'
/c/	→	[c*]	capci	→	[capc*i]	'magazine'
/k/	→	[k*]	ipko	→	[ipk*o]	'wear and'
/s/	→	[s*]	kuksu	→	[kuks*u]	'noodle soup'

The phonetic findings of Cho, Jun, & Ladefoged (2000) support claims that Korean /s/ is lax while /s*/ is tense. First, /s/ shows some amount of phonetic aspiration in the spectrogram, just as lax stops do. Second, the onset of the vowel after /s/ has a breathy voice quality similar to that of vowels after lax stops. Third, the fundamental frequency (F0) of the vowel onset after /s*/ is similar to that after tense stops, while the F0 of the vowel onset after /s/ is intermediate between lax and aspirated stops. Fourth, /s/ loses its aspiration word-medially as do the lax stops. Finally, although it has been generally assumed that /s/ does not become voiced intervocalically, about 48% of tokens produced in the Cho *et al.* study were fully voiced intervocalically (i.e., they behaved like lax stops in undergoing intervocalic voicing).

To summarize, Korean [-tense] /s/ involves less muscular tension than /s*/, is breathy, and is (phonetically) slightly aspirated (Cho *et al*. 2000), while [+tense] /s*/ is characterized by tight glottal closure, non-aspiration (Kagaya

1974; Iverson 1983), greater subglottal pressure, and tenser vocal tract walls (Ladefoged & Maddieson 1996:95).

3. EXPERIMENTS

3.1. Research questions

Two experiments were conducted in order to examine the degree of similarity between Korean (Kor) and English (Eng) voiceless sibilants. Experiment 1 involved a production task that focused on measurements of acoustic similarity. Experiment 2 was a Same-Different (AX) discrimination task that investigated listeners' perceived similarity judgments. The following questions were addressed:

1) To what extent can speakers of English and Korean distinguish Korean and English sibilants before /a/ and /i/ in perception?
2) To what extent does cross-language perceived similarity correspond with cross-language acoustic similarity for the two acoustic dimensions measured here?

We predict that greater acoustic similarity between sibilants will correlate with a greater tendency for them to be perceived as the same sound by non-native listeners.

In Experiment 1, the acoustic parameters *duration* and *spectral peak frequency* were measured in Korean and English sibilants produced by native speakers. In Experiment 2, native speakers of both languages were asked to decide whether paired auditory stimuli containing the sibilants were the same or different. In the current study, we interpret a low degree of perceived similarity to mean that listeners find it relatively easy to perceive differences between the compared sounds. Conversely, we interpret a high degree of perceived similarity to indicate that listeners have difficulty in perceiving differences between the compared sounds. American English (AE) and Korean listeners were tested for the following comparisons (summarized in Table 5): 1) Kor /sa/ versus Eng /sa/; 2) Kor /s*a/ vs. Eng /sa/; 3) Kor /si/ vs. Eng /si/; 4) Kor /si/ vs. Eng /ʃi/; 5) Kor /s*i/ vs. Eng /si/; 6) Kor /s*i/ vs. Eng /ʃi/; 7) Kor /sa/ vs. Kor /s*a/; 8) Kor /si/ vs. Kor /s*i/; 9) Eng /si/ vs. Eng /ʃi/.[1] Pairs 1 through 6 examined perceived

[1] Comparisons such as KO /sa/ and EN /ʃa/; KO /s*a/ and EN /ʃa/; EN /sa/ and EN /ʃa/; were excluded from this study because Korean does not have phonemic /ʃ/ (only allophonic [ʃ] before /i/) to compare with English /ʃ/.

similarity between an English and a Korean sibilant. Pairs 7 through 9 examined perceived similarity of language-internal sibilant contrasts.

Table 5. Nine pairs of English and Korean sibilants before /i/ and /a/.

<table>
<tr><th colspan="2">Pairs 1-6 (English versus Korean sibilants)</th></tr>
<tr><td>Korean</td><td>English</td></tr>
<tr><td>sa</td><td rowspan="2">sa</td></tr>
<tr><td>s*a</td></tr>
<tr><td rowspan="2">si</td><td>si</td></tr>
<tr><td>ʃi</td></tr>
<tr><td rowspan="2">s*i</td><td>si</td></tr>
<tr><td>ʃi</td></tr>
<tr><th colspan="2">Pairs 7-8 (Korean versus Korean sibilants)</th></tr>
<tr><td colspan="2">Korean sa-s*a</td></tr>
<tr><td colspan="2">Korean si-s*i</td></tr>
<tr><th colspan="2">Pair 9 (English versus English sibilants)</th></tr>
<tr><td colspan="2">English si -ʃi</td></tr>
</table>

3.2. Experiment 1: Acoustic similarities between English and Korean sibilants

3.2.1. Participants

Ten subjects participated in Experiment 1: five male native speakers of Korean, and five male native speakers of American English. The AE speakers were recruited from graduate programs in various departments at the University of Hawai‘i at Mānoa, and had no exposure to the Korean language. The Korean speakers were all from Seoul, and were recruited from English as a Second Language programs at the University of Hawai‘i at Mānoa. All the Korean speakers were new arrivals in the United States, and thus had little exposure to advanced levels of English. All participants were recorded on high-bias audio tape in a sound-attenuated booth at the University of Hawai‘i at Mānoa. Recordings were digitized onto computer using PCQuirer, with a sample rate of 22.1 kHz and a bit rate of 16.

The stimuli consisted of Kor /s/, Kor /s*/, and Eng /s/ in syllable-initial position followed by /a/; and Kor /s/, Kor /s*/, Eng /s/, and Eng /ʃ/ in syllable-initial position followed by /i/. The one-syllable English words Eng /sa/, Eng /si/, and Eng /ʃi/ were placed in the English carrier sentence ‘I’m saying ____ now’ and each was written on a separate notecard. The randomized stack of notecards was read by each AE speaker five times. Similarly, the one-syllable

Korean words Kor /sa/, Kor /s*a/, Kor /si/, and Kor /s*i/ were placed in the Korean carrier sentence *Nanŭn chigŭm malhako issŏyo* 'I'm saying ____ now' and each was written in Korean on a separate notecard. The randomized stack of notecards was read by each Seoul Korean speaker five times.

3.2.2. Acoustic measurements

For Eng /sa/, Kor /sa/, and Kor /s*a/, *duration of frication* and *duration of aspiration* were measured. Figure 3 displays a spectrogram window showing durations of Korean stimuli /sa/ and /s*a/ as produced by a Seoul speaker. As shown, frication was determined by the presence of high-frequency, high amplitude noise in the spectrogram. Aspiration duration was measured from offset of high-frequency noise to onset of the following vowel, and was identified by low amplitude, low frequency noise.

The sibilants in Eng /sa/, Kor /sa/, and Kor /s*a/ were acoustically characterized by duration because Cheon (2001) showed that in this vowel context, learners of Korean tended to rely on temporal parameters more heavily than spectral or other acoustic parameters. Spectral peak frequency in the context of the vowel /a/ was not examined here because Cheon (2001) showed no statistically significant differences among these sibilants in this context.

Conversely, the sibilants in Eng /si/, Eng /ʃi/, Kor /si/, and Kor /s*i/ were not measured for duration in this study. Kagaya (1974) finds no difference in aspiration duration between Kor /s/ and Kor /s*/ when the following vowel is /i/. Similarly, Yoon's (1998) acoustic study of Korean sibilants reports that aspiration duration distinguishes Kor /s/ from Kor /s*/ only in mid and low vowel contexts; /s*/ has much shorter aspiration duration than /s/ before /a/. However, in the context of /i/ or /u/, Yoon finds no difference in aspiration duration between Kor /s/ and Kor /s*/; aspiration is brief in both. These results are similar to findings by Cheon (2006).

Eng /si/, Eng /ʃi/, Kor /si/, and Kor /s*i/ were acoustically characterized by spectral peak frequency. In previous experimental studies, Eng /s/ is distinguished from Eng /ʃ/ on the basis of the distribution of spectral energy. In a study of correlations between speech production and perception, Newman (2003) used three types of acoustic measurements to characterize participants' productions of English /s/ and /ʃ/: frication centroid, skewness, and location of

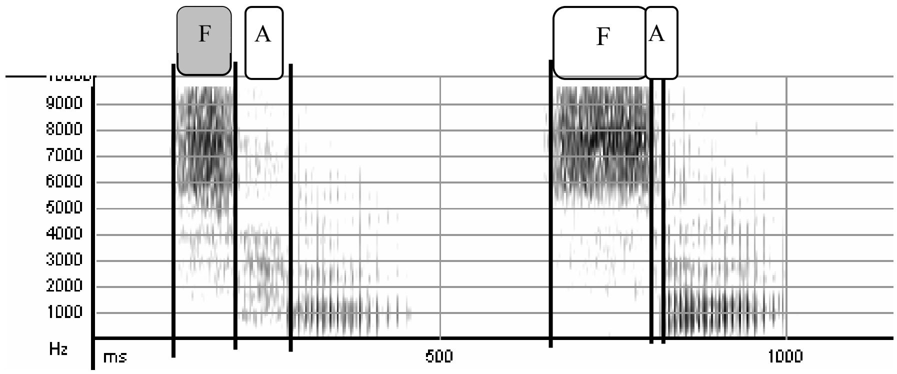

*FIGURE 3. Sample of Korean stimuli /sa/ (left) and /s*a/ (right) as produced by a Seoul speaker. The spectrogram window shows durations of frication (F) and aspiration (A).*

spectral peaks. Newman found that only the acoustic measurements based on spectral peaks appeared to be related to listeners' goodness ratings. This result is comparable with findings by Jongman *et al.* (2000) that spectral peaks are better cues to sibilant discrimination than are spectral moments. Similarly, Behrens & Blumstein (1988) report that /s/ is distinguished from /ʃ/ on the basis of the distribution of spectral peaks. For the present study, FFT spectra were measured at a midpoint in the frication noise, as shown in Figure 4.

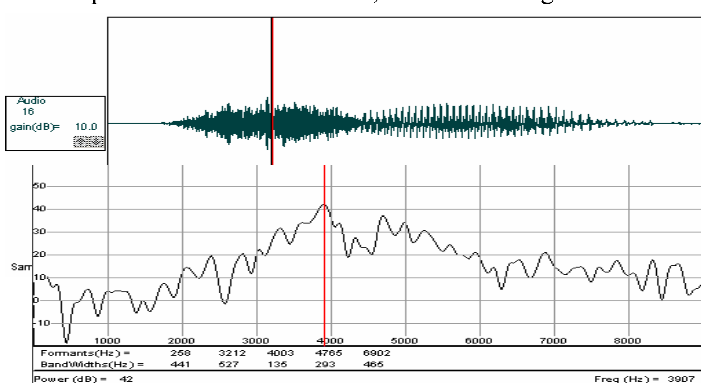

FIGURE 4. Sample of Kor /si/ as produced by a Seoul Korean speaker. Waveform window (top) shows the midpoint of the frication (measurement was taken at the cursor). FFT window (bottom) shows the spectral peak frequency at around 4000 Hz.

3.2.3. Results of Experiment 1

*Duration: Kor /sa/, Kor /s*a/, and Eng /sa/.* Figure 5 shows mean durations of frication and aspiration for Korean and English sibilants before /a/. Each subject's scores were averaged over the five repetitions prior to statistical analysis. Statistical comparisons were made between sibilants in a pairwise fashion. Unpaired T-tests were used to discern the differences between Korean and English sibilants (i.e., Kor /sa/ vs. Eng /sa/; Kor /s*a/ vs. Eng /sa/). A two sample T-test was used to discern the differences between the two Korean sibilants (i.e., Kor /sa/ vs. Kor /s*a/).

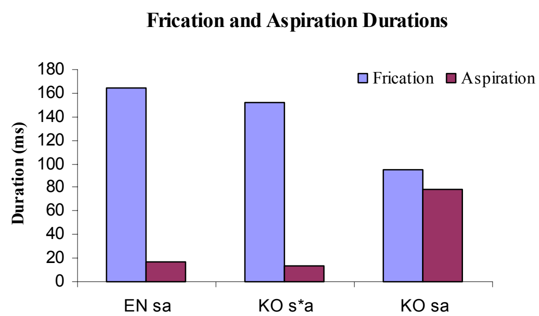

*FIGURE 5. Mean frication and aspiration durations of Eng /sa/, Kor /sa/, and Kor /s*a/.*

T-test output showed that Kor /sa/ was significantly shorter in frication duration than both Eng /sa/ and Kor /s*a/ (frication duration: Kor /sa/ < Eng /sa/, t (8) = 5.11, p = 0.0009; Kor /sa/ < Kor /s*a/, t(4) = 8.199, p = 0.0012). Eng /sa/ and Kor /s*a/ did not differ significantly in frication duration (Kor /s*a/ ≡ Eng /sa/, t(8) = 0.692, p = 0.5083).

On the other hand, Kor /sa/ was significantly longer in aspiration duration than both Eng /sa/ and Kor /s*a/ (aspiration duration: Kor /sa/ > Eng /sa/, t(8) = -10.091, *p* <.0001; Kor /sa/ > Kor /s*a/, t(4) = 8.846, *p* = 0.0009.) Eng /sa/ and Kor /s*a/ did not differ significantly in their aspiration duration (Eng /sa/ ≡ Kor /s*a/, t(8) = 1.242, *p* = 0.2492). There were no statistically significant differences in total (i.e., frication-plus-aspiration) duration among Kor /sa/, Kor /s*a/ and Eng /sa/.

*Spectral peak frequency: Kor /si/, Kor /s*i/, Eng /si/, and Eng /ʃi/.* Figure 6 illustrates differences in mean spectral peak frequency (Hz) between English and Korean sibilants before /i/. Again, unpaired T-tests were used to discern differences between Korean and English sibilants (i.e., Kor /s*i/ vs. Eng /ʃi/, Kor /si/ vs. Eng /ʃi/, Kor /si/ vs. Eng /si/, Kor /s*i/ vs. Eng /si/). Two sample T-tests were used to discern the differences: 1) between the two Korean sibilants (i.e., Kor /si/ vs. Kor /s*i/) and 2) between the two English sibilants (i.e., Eng /si/ vs. Eng /ʃi/).

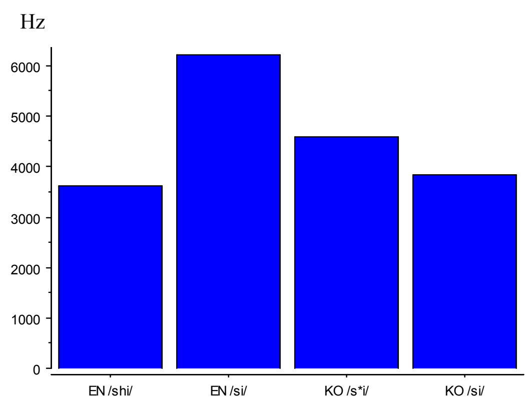

FIGURE 6. Mean spectral peak frequencies of Eng /ʃ/, Eng /s/, Kor /s/and Kor /s/ before /i/ as produced by native speakers of English and Korean respectively.*

Mean spectral peak frequency of Eng /si/ is quite substantially (and significantly) higher than that of the three other categories (Eng /si/ > Eng /ʃi/, t(4) = 8.275, p = 0.0012; Eng /si/ > Kor /si/, t(8) = 3.716, p = 0.0059; Eng /si/ > Kor /s*i/, t(8) = 2.639, p = 0.0298). In turn, mean spectral peak frequency of Kor /s*i/ is significantly higher than that of Kor /si/ and Eng /ʃi/ (Kor /s*i/ > Kor /si/, t(4) = 3.498, p = 0.0249; Kor /s*i/ > Eng /ʃi/, t(8) = -2.338, p = 0.0476). However, Kor /si/ is not significantly different in mean spectral peak frequency from Eng /ʃi/ (Kor /si/ ≡ ENG /ʃi/, t(8) = -0.481, p = 0.6435).

3.2.3. Summary: Acoustic comparison between English and Korean sibilants

Based on previous characterizations of Korean and English sibilants in the acoustic literature, two types of acoustic parameter were measured in order to determine the degree of acoustic similarity between Korean and English sibilants: 1) durations of frication and aspiration of Korean and English sibilants before /a/; and 2) spectral peak frequency of Korean and English sibilants before

/i/. With respect to duration, Kor /sa/ was significantly shorter in frication duration and significantly longer in aspiration duration than either Eng /sa/ or Kor /s*a/. Eng /sa/ and Kor /s*a/ however, were very similar to each other on these measures; they did not differ significantly from each other in either frication duration or aspiration duration.

With respect to spectral peak frequency, Kor /si/ and Eng /ʃi/ were statistically indistinguishable, and had the lowest mean spectral peak frequency among the categories. Kor /s*i/ had a significantly higher mean spectral peak frequency than these two groups, while Eng /si/ had the highest mean spectral peak frequency.

3.3. Experiment 2: Perceived similarities between English and Korean sibilants[2]

3.3.1. Methods

Subjects. Seventy-two subjects participated in Experiment 2. Thirty subjects were native speakers of Korean from either Seoul or Kyunggi province. As before, Korean speakers were recruited from English as a Second Language programs at the University of Hawai‘i at Mānoa, and were new arrivals in the United States. Forty-two subjects were native speakers of American English, again recruited from among graduate students at the University of Hawai‘i at Mānoa. AE speakers had no exposure to the Korean language.

Stimuli and Procedures. The stimuli used in Experiment 2 were the same as those in Experiment 1 (refer to Table 5); i.e., Kor /s/, Kor /s*/ and Eng /s/ followed by /a/ in syllable-initial position; and Kor /s/, Kor /s*/, Eng /s/ and Eng /ʃ/ followed by /i/ in syllable-initial position.

Two Korean and two AE speakers from Experiment 1 produced the Korean and English stimuli respectively. Stimuli were recorded as single syllables in isolation, in order to tightly control for prosody and amplitude. Six pairs of sibilant stimuli before /a/ in syllable-initial position were created (refer to Table 6). Similarly, ten pairs of sibilant stimuli before /i/ in syllable-initial position were created (refer to Table 8). Within a pair, the two stimuli were always spoken by different speakers, in order to avoid listeners judging “same” or “different” on the basis of speaker, rather than sibilant.

[2] According to Flege (2005), the best way to measure perceived cross-language phonetic similarity or dissimilarity is to present L1 and L2 sounds together in pairs for direct scaling. The measurement that was chosen here was “the same-different discrimination” (AX) which is a 2-alternative forced-choice task.

Each stimulus was presented for discrimination four times. That is, 24 pairs of sibilants in the context of /a/ (6 pairs x 4 repetitions) and 40 pairs of sibilants in the context of /i/ (10 pairs x 4 repetitions) were constructed.

In terms of L1 and L2, two types of paired stimuli were presented to listeners. The first involved L1-L2 (or L2-L1) pairs; the second involved L1-L1 pairs (produced by different speakers). The second type was included to detect any response biases from the native language, and to ensure that the participant was properly attending to the task. For example, phonemically identical Eng /sa-sa/ and Eng /ʃi-ʃi/ pairs were expected to produce a "same" response from English native speakers, while the Eng pair /si-ʃi/ were expected to produce a "different" response. Similarly, phonemically identical Kor /sa-sa/ and Kor /s*a-s*a/ pairs were expected to be perceived as the "same" by Korean native listeners, while Kor /sa-s*a/ was expected to be perceived as "different". If a subject responded incorrectly to more than two of the four pairs of the phonologically identical stimuli in their native language, their data were excluded from results. English L1-L1 sound pairs consisted of 25% of the total stimuli set (e.g., Eng /sa-sa/ pairs, Eng /si-ʃi/ pairs and Eng /ʃi-ʃi/ pairs) and Korean L1-L1 sound pairs consisted of about 25% of the total stimuli set (e.g., Kor /sa-sa/ pairs and Kor /s*a-s*a/ pairs).

An interval of 1,000 milliseconds was placed between members of a pair. The discrimination task was conducted on a Power Macintosh G4 running PsyScope with a button-box. Each subject was tested individually in a sound-attenuated booth at the Phonetics Lab at the University of Hawaiʻi at Mānoa. Subjects heard stimuli over headphones. The experiment began with a familiarization task. Subjects were asked to listen to a pair of stimuli and then to press either the button labeled "same" (on the left) or the button labeled "different" (on the right) on the button box. Subjects could take as much time as needed to make a decision, but were required to make a judgment for every pair that was presented.

3.3.2. Specific predictions based on acoustic study

Based on the results of Experiment 1, Tables 6 and 7 summarize our specific predictions regarding perceived similarity between the Korean and English sibilants. Table 6 shows predictions for the /a/ environment. We predict that AE listeners will judge each pair to be the same, based on the lack of a contrast that involves relative proportion of frication-to-aspiration in English fricatives. Conversely, we take the significantly different relative durations of frication and aspiration in Kor /sa/ and Kor /s*a/ to be auditory cues to the distinction for Korean listeners. Thus, because the fricative in Eng /sa/ patterns with that in Kor

/s*a/ in its durations of frication and aspiration, we predict that Korean listeners will judge this pair to be the same, and will judge Eng /sa/ and Kor /sa/ to be different.

TABLE 6. Predictions regarding perceived similarity between sibilants in Korean and English before /a/.

	Prediction	
Comparison	AE listeners	Korean listeners
Eng /sa/ vs. Kor /sa/	same	different
Eng /sa/ vs. Kor /s*a/	same	same
Kor /sa/ vs. Kor /s*a/	same	(different phonemes)

Table 7 summarizes predictions for the /i/ environment. Because the contrast between Eng /si/ and Eng /ʃi/ relies on differences in the distribution of spectral energy between the fricatives, we predict that AE listeners will find Eng /si/ and Kor /si/ to be different (Experiment 1 shows them to be highly statistically distinguishable on this measure). By the same reasoning, Eng /ʃi/ and Kor /si/ should be perceived by AE listeners as the same (this pair were found not to differ significantly in spectral peak frequency in Experiment 1.) As for the other paired comparisons, AE listeners' reactions are harder to predict, because even though each pair involves statistically significant differences in spectral peak frequency, the differences between Eng /si/ vs. Kor /s*i/, Eng /ʃi/ vs. Kor /s*i/, and Kor /si/ vs. Kor /s*i/ are not numerically as great as in the English Eng /si/—/ʃi/ contrast (refer to Figure 6). Since AE listeners may require this larger difference in spectral energy distribution when distinguishing English sibilants, we predict that each of the other pairs will be judged to be the same.

TABLE 7. Predictions regarding perceived similarity between sibilants in Korean and English before /i/.

	Prediction	
Comparison	AE listeners	Korean listeners
Eng /si/ vs. Eng /ʃi/	(different phonemes)	different
Eng /si/ vs. Kor /si/	different	different
Eng /si/ vs. Kor /s*i/	same	different
Eng /ʃi/ vs. Kor /si/	same	same
Eng /ʃi/ vs. Kor /s*i/	same	different
Kor /si/ vs. Kor /s*i/	same	(different phonemes)

For Korean listeners, we predict that Eng /si/ vs. Eng /ʃi/ will be judged as different. Although this contrast does not exist in Korean, the Kor /si/ vs. Kor /s*i/ contrast does involve a reliable acoustic difference in spectral peak frequency, as results of Experiment 1 show. Thus, under the assumption that spectral energy is indeed an auditory cue for the Korean contrast, we argue that the much larger difference between the English sibilants will also be salient to Korean listeners. As for the pairs Eng /si/ vs. Kor /si/, and Eng /si/ vs. Kor /s*i/, the same argument applies: since these pairs of sibilants differ more in their spectral peak frequency values than Kor /si/ vs. Kor /s*i/ differ, Korean listeners will be able to hear them as different. However, we predict that Korean listeners will judge the pair Eng /ʃi/ vs. Kor /si/ to be the same, based on these fricatives' lack of significant difference in peak frequency in Experiment 1. Finally, we predict Eng /ʃi/ vs. Kor /s*i/ will be heard as different, since the difference in frequency is on the same order of magnitude as the difference between the two Korean sibilants before /i/.

3.3.3. Results of Experiment 2

Fifteen AE subjects' responses in the discrimination of sibilants before /a/ were excluded. Ten Korean subjects' responses in the discrimination of sibilants before /i/ were excluded. As mentioned above, subjects' responses were excluded if syllable pairs that were phonemically identical in their native language were not judged to be "the same" at least 50% of the time (such results would imply that the subject was not attending to the task at hand).

ENG /s/, KOR /s/, and KOR /s/ BEFORE /a/.* Table 8 summarizes percent mean perceived similarity for sibilants before /a/ by 27 AE speakers (before colon) and 30 Korean speakers (after colon). Each subject's scores for four repetitions were averaged prior to statistical analysis. T-tests were used to compare pairs of phonemically non-identical stimuli.

TABLE 8. Summary of percent mean perceived similarity between sibilants before /a/ by 27 AE speakers and 30 Korean speakers (AE speakers: Korean speakers).

	Eng /sa/	Kor /sa/	Kor /s*a/
Eng /sa/	100%:96%	56%:6%	77%:88%
Kor /sa/		83%:100%	60%:0%
Kor /s*a/			93%:100%

In comparing Eng /sa/ and Kor /sa/, AE speakers (standard deviation = 0.400) showed a significantly higher degree of perceived similarity than Korean speakers (SD = 0.126) (t(55) = 6.462, p <.0001). Mean perceived similarity was 56% for AE speakers, but only 6% for Korean speakers, who, as predicted, reliably perceived Kor /sa/ and Eng /sa/ as different sounds. These differences in perception can be attributed to the fact that the two sounds differ significantly in their respective durations of frication and aspiration, and that relative proportion of frication-to-aspiration is used in the Korean contrast between sibilants, but not in the English contrast.

English speakers and Korean speakers showed no significant difference in their ability to discriminate between Eng /sa/ and Kor /s*a/ (t(55) = -1.600, p = 0.1152). Mean perceived similarity was 77% for AE speakers (SD = 0.259) and 88% for Korean native speakers (SD = 0.243). Recall that in terms of frication and aspiration durations, these two fricatives are statistically indistinguishable.

In comparing Kor /sa/ and Kor /s*a/, AE speakers (SD = 0.369) showed a significantly higher degree of perceived similarity than Korean speakers (SD = 0) (t(55) = 8.952, p <.0001). Kor /s*a/ and Kor /sa/ are phonemically distinct in Korean (0% perceived similarity for Korean speakers) but are not reliably differentiated by AE speakers (60% perceived similarity). Again, the lack of a tense-lax distinction in English means that AE speakers do not recognize the durational differences in frication and aspiration related to this contrast.

Although AE speakers and Korean speakers were not statistically compared for sets of phonemically identical pairs (i.e., Eng /sa/ vs Eng /sa/; Kor /sa/ vs Kor /sa/; and Kor /s*a/ vs Kor /s*a/), the results merit some discussion. In Table 6, the 100% "same" judgments in these cells show native speakers' high level of ability to decide on the aptness of a phoneme's exemplar. Thus, AE listeners correctly find the two native speakers' renditions of Eng /sa/ to be 100% similar. Likewise, Korean listeners show 100% confidence that the two native speakers' renditions of Kor /sa/ are the same, and that the two renditions of Kor /s*a/ are the same. If we compare judgments by the non-native listeners, we find that in the first case, Korean listeners are also very confident (96%) that the two renditions of Eng /sa/ are the same. We speculate that this is because of the acoustic similarity between Eng /sa/ and Kor /s*a/. If Korean listeners equate Eng /sa/ with Kor /s*a/, and perceive the pair as /s*a/—/s*a/, then we expect them to perform with this high level of confidence. On the other hand, for the other two cases, while we do not know whether the respective 83% and 93% scores by AE listeners differ significantly from the 100% scores by Korean listeners, the larger differences imply that AE listeners may not be as confident about whether the two tokens of Kor /sa/ are different from each other, and whether the two tokens of Kor /s*a/ are different from each other. AE listeners perform better on the /s*a/—/s*a/ pair that has duration characteristics similar to those in English, but rather less well on the Kor /sa/—/sa/ pair, whose long period of aspiration has no counterpart among the English sibilants. The lower score of 83% may well reflect AE listeners' inexperience with what constitutes a good Kor /s/ phoneme, and how it relates to individual differences among speakers.

Table 9 summarizes predictions and results for perceived similarity between sibilants in Korean and English before /a/. The results of T-tests generally support our predictions. Korean speakers and AE speakers perceived L2 sounds in terms of their L1. Korean speakers perceived Kor /sa/ and Eng /sa/ as reliably different sounds (only 6% perceived similarity), probably because of the differences in the proportion of frication-to-aspiration between them. Korean speakers perceived Kor /s*a/ and Eng /sa/ as similar (88% perceived similarity), because of the fricatives' similarity in frication and aspiration durations. AE speakers perceived Kor /sa/ and Kor /s*a/ as somewhat similar sounds (60% perceived similarity), indicating that they did not reliably differentiate Kor /sa/ from Kor /s*a/. The likely reason for this is the lack in English of a voiceless sibilant contrast that depends on these duration differences.

TABLE 9. Summary of predictions and statistical results regarding perceived similarity between sibilants in Korean and English before /a/.

	Perceived similarity				
	Prediction		Results		
Comparison	AE	Kor	AE	Kor	T-test
Eng /sa/ vs. Kor /sa/	same	different	56%	6%	AE > Korean
Eng /sa/ vs. Kor /s*a/	same	same	77%	88%	AE ≡ Korean
Kor /sa/ vs. Kor /s*a/	same	(different phonemes)	60%	0%	AE > Korean

Eng /s/, Eng /ʃ/, Kor /s/, and Kor /s/ before /i/.* Table 10 displays percent degree of perceived similarity between sibilants in English and Korean before /i/ by 42 AE speakers and 20 Korean native speakers. Each subject's scores for four repetitions were averaged prior to statistical analysis. T-tests were used to compare pairs of phonologically non-identical stimuli.

Again comparing phonologically non-identical pairs, for Eng /si/ vs. Eng /ʃi/, both AE speakers and Korean speakers reliably perceived the English sibilants as different sounds (0% and 4% perceived similarity respectively). Eng /si/ and Eng /ʃi/ are phonemically distinct for AE speakers, but as predicted, are also discriminated with very high accuracy by Korean speakers. (Recall from Figure 6 that the spectral difference between Eng /si/ and Eng /ʃi/ exceeds that between the two Korean sibilants in this environment.).

TABLE 10. Summary of percent mean perceived similarity between sibilants in English and Korean before /i/ by 42 AE speakers and 20 Korean speakers.

	Eng /si/	Eng /ʃi/	Kor /si/	Kor /s*i/
Eng /si/	100%:99%	0%:4%	1%:3%	55%:84%
Eng /ʃi/		100%:99%	80%:15%	48%:0%
Kor /si/			96%:95%	64%:5%
Kor /s*i/				73%:96%

For Eng /si/ and Kor /si/, no significant difference in perceived similarity was found between the two language groups (t(60) = -0.776, p= 0.4408). Both AE speakers (SD = 0.054) and Korean speakers (SD = 0.077) reliably perceived Kor /si/ and Eng /si/ as different sounds (1% and 3% perceived similarity respectively). For AE listeners, the difference between Eng /si/ and Kor /si/ is much like the difference between Eng /si/ and Eng /ʃi/ (since Kor /si/ and Eng /ʃi/ are statistically indistinguishable in their spectral peak frequencies). For Korean listeners, we again posit that since listeners are already adept at attending to the smaller spectral difference between the Korean sibilants in this environment, they have no difficulty with the larger spectral differences between Eng /si/ and either of the Korean sibilants.

However, in comparing Eng /si/ and Kor /s*i/, Korean listeners (SD = 0.296) showed a significantly higher degree of perceived similarity than AE listeners (SD = 0.284) (t (60) = -3.629, p = 0.0006). Contrary to our prediction that Korean listeners would judge these two syllables to be different, mean perceived similarity between Eng /si/ and Kor /s*i/ was 84% for Korean speakers; higher than the perceived similarity score of 55% for AE speakers. This pair shows larger differences in frequency than the two Korean sibilants, and yet Korean listeners found them more similar than the Korean sibilants. The strong implication of this result is that the important auditory cue(s) distinguishing Kor /s*i/ and Kor /si/ involve not (just) spectral peak frequency but another acoustic dimension.

In comparing Eng /ʃi/ with Kor /si/, AE listeners (SD = 0.332) showed a significantly higher degree of perceived similarity than Korean listeners (SD = 0.308) (t(60) = 7.339, *p* <.0001). Mean perceived similarity was 80% for AE listeners but only 15% for Korean listeners. Again, the result for Korean listeners is contrary to the prediction we made based on the dimension of spectral peak frequency. On this acoustic dimension, Eng /ʃi/ and Kor /si/ are not statistically non-differentiable, and yet Korean listeners judge them to be different. Thus, Koreans' ability to differentiate this pair must be based on another acoustic dimension.

As predicted, for Eng /ʃi/ vs. Kor /s*i/ AE listeners (SD = 0.357) showed a significantly higher degree of perceived similarity than Korean listeners (SD = 0) (t(60) = 5.939, *p*<.0001). Korean listeners never perceived the two to be the same (0% perceived similarity). Perceived similarity was 48% for AE listeners.

As expected, for Kor /si/ and Kor /s*i/, AE listeners (SD = 0.332) showed a significantly higher degree of perceived similarity than Korean listeners (SD = 0.103) (t(60) = 7.698, *p*<.0001). Mean perceived similarity was 64% for AE speakers but only 5% for Korean speakers, for whom the sounds are phonologically contrastive.

Again, although AE listeners and Korean listeners were not statistically compared for sets of phonemically identical pairs, the results are of interest. The two renditions of Eng /si/ were judged very accurately by both AE and Korean listeners (100% and 99% similar respectively), as were the two renditions of Eng /ʃi/ (100%:99%). The paired renditions of Kor /si/ were likewise perceived as the "same", with high accuracy (96%:95%). However, there was a substantial difference between perceived similarity scores for the two renditions of Kor /s*i/; 96% similarity for Korean listeners but only 73% for AE listeners. This difference is probably attributable to AE listeners' lack of exposure to different speakers' realizations of Kor /s*i/, and their resultant diffidence about what may constitute "same" and "different". What is striking is that Korean listeners are so accurate with their "same" judgments about the English phonemes. We return to this point in the discussion section.

Table 11 summarizes predictions and results for perceived similarity before /i/, with mismatches between predictions and results in shaded cells. AE listeners found Eng /si/ "different" from Kor /si/ (only 1% similarity), but were uncertain about Eng /si/ vs. Kor /s*i/ (55% similarity). This makes sense in view of the much larger frequency difference in the first pair than the second. AE listeners judged Eng /ʃi/ and Kor /si/ to be similar (80%); this is also in concert with the idea that AE listeners' major acoustic cue involves a large frequency difference. Judgments were at chance (48% similarity) for Eng /ʃi/ vs. Kor /s*i/, with their smaller difference in frequency, and the same reasoning explains results for Kor /si/ vs. Kor /s*i/ (64% similarity).

TABLE 11. Summary of predictions and results regarding perceived similarity between sibilants in Korean and English before /i/.

Comparison	Perceived similarity				
	Prediction		Results		
	AE	Kor	AE	Kor	T-test
Eng /si/ vs. Eng /ʃi/	(different phonemes)	different	0%	4%	AE < Kor
Eng /si/ vs. Kor /si/	different	different	1%	3%	AE ≡ Kor
Eng /si/ vs. Kor /s*i/	same	different	55%	84%	AE < Kor
Eng /ʃi/ vs. Kor /si/	same	same	80%	15%	AE > Kor
Eng /ʃi/ vs. Kor /s*i/	same	different	48%	0%	AE > Kor
Kor /si/ vs. Kor /s*i/	same	(different phonemes)	64%	5%	AE > Kor

For Korean listeners, the pairs Eng /si/ vs. Eng /ʃi/, Eng /si/ vs. Kor /si/, and Eng /ʃi/ vs. Kor /s*i/, were judged to be "different" (4%, 3%, and 0% similarity respectively); in the first two cases presumably because of the very large frequency difference between members of each pair, and in the third case possibly because of a frequency difference on par with the Korean phonemic distinction. Contrary to our predictions, however, the pair Eng /si/ vs. Kor /s*i/ were not considered "different" (84% similarity), but the pair Eng /ʃi/ vs. Kor /si/ were considered "different" (only 15% similarity).

4. DISCUSSION AND CONCLUSION

Phonemes in a second language are rarely phonetically identical to those found in a first language. Moreover, the allophonic and phonotactic behavior of phonemes can differ between languages. As Tables 8 and 10 summarize, the statistical analyses in this study indicate that except for three pairs (Eng /sa/ vs. Kor /s*a/, Eng /si/ vs. Eng /ʃi/, Eng /si/ vs. Kor /si/), the two groups of listeners differed in their judgments about the similarity of pairs of sibilants. Table 12 summarizes the results of Experiments 1 and 2.

Table 12. Summary of Experiments 1 and 2 regarding both perceived and acoustic similarities between English and Korean sibilants.

Comparison	Acoustic similarity		Perceived similarity	
	Frication duration	Aspiration duration	AE	Kor
Eng /sa/ vs. Kor /sa/	Eng /sa/ > Kor /sa/	Eng /sa/ < Kor /sa/	56% >	6%
Eng /sa/ vs. Kor /s*a/	Eng /sa/ ≡ Kor /s*a/	Eng /sa/ ≡ Kor /s*a/	77% ≡	88%
Kor /sa/ vs. Kor /s*a/	Kor /sa/ < Kor /s*a/	Kor /sa/ > Kor /s*a/	60% >	0%
	Spectral peak frequency (FFT)			
Eng /si/ vs. Eng /ʃi/	Eng /si/ > Eng /ʃi/		0% <	4%
Eng /si/ vs. Kor /si/	Eng /si/ > Kor /si/		1% ≡	3%
Eng /si/ vs. Kor /s*i/	Eng /si/ > Kor /s*i/		55% <	84%
Eng /ʃi/ vs. Kor /si/	Eng /ʃi/ ≡ Kor /si/		80% >	15%
Eng /ʃi/ vs. Kor /s*i/	Eng /ʃi/ < Kor /s*i/		48% >	0%
Kor /si/ vs. Kor /s*i/	Kor /si/ < Kor /s*i/		64% >	5%

In most cases, the acoustic differences measured in this study led to correct predictions about differences in listeners' perceptions. For the /a/ environment, predictions were based on duration ratios of frication-to-aspiration in the various sibilants, and predictions were confirmed for both groups of listeners. In the /i/ environment, spectral peak frequency differences (or lack of sufficient differences) explained the perceptual behavior of AE listeners. However, three unexpected results emerged for Korean listeners in the /i/ environment. First, despite a difference in spectral peak frequency between Eng /si/ and Kor /s*i/ that well exceeded the difference in the Korean contrast (Kor /si/ and Kor /s*i), Korean listeners judged Eng /si/ and Kor /s*i/ to be the same 84% of the time. Second, and conversely, despite the lack of a statistically significant difference in spectral peak frequency between Eng /ʃi/ and Kor /si/, Korean listeners judged this pair as different 85% of the time. Third, Korean listeners were unexpectedly very accurate in judging the English pairs Eng /si/ vs. Eng /si/, as well as Eng /ʃi/ vs. Eng /ʃi/, to be the "same".

The first two unexpected results strongly imply that spectral peak frequency is not the only perceptual cue, and perhaps not even the major cue, that Korean listeners use to distinguish tense vs. lax allophones of the sibilants before /i/. Another acoustic dimension must be involved. To investigate this, in a pilot study we cross-spliced the two vowels in Kor /si/ and Kor /s*i/ (i.e., /si$_1$/ and

/s*i_2/ were edited and presented as /si_2/ and /s*i_1/.) Native speakers of Korean often identified these edited syllables on the basis of the vowel. These preliminary results need to be pursued further, but suggest that voice quality on the following vowel may also constitute a major perceptual cue to the tense vs. lax distinction in this environment.

The third unexpected result concerns Korean phonotactics. Although Korean listeners are not routinely exposed to Eng /si/ and Eng /ʃi/ when speaking Korean, they are exposed to the sequence Kor /swi/. As a reviewer aptly points out, because Kor /swi/ involves lip rounding, it resembles Eng /ʃi/ in its phonetic implementation more than either Kor /si/ or Kor /s*i/ do. Korean listeners' high accuracy in judging Eng /ʃi/ vs. Eng /ʃi/ to be the "same" may have to do with their identification of Eng /ʃi/ with Kor /swi/.

Previous studies have often found disparities between acoustic characterizations and perceptual judgments (e.g., Cebrian 2002; Stevens *et al*. 1996; Flege 1991; 1995). Stevens *et al*. (1996) found that North German front rounded vowels are intermediate between American English front and back vowels in the F1–F2 acoustic space, but that in perceptual judgments, listeners categorize the German front rounded vowels as more similar to AE back vowels than to front vowels. Flege (1991) found in a comparison study of Spanish and English vowels that acoustically, Eng /i/ is similar to Spanish /i/ and Eng /ɪ/ to Spanish /e/, while perceptually, Spanish speakers identify Eng /i/ as Spanish /i/ (94% of the time) as predicted, but Eng /ɪ/ more often as Spanish /i/ (68% of the time) than as Spanish /e/ (19% of the time).

We take it that where acoustic differences and perceptual discrimination match, we can be fairly certain of having established the important cues that listeners use to differentiate between their language's sounds. However, cases in which acoustic and perceptual characterizations do not match are fruitful areas for examining additional acoustic characteristics that may be responsible for the ability of listeners to distinguish sounds. If we do not see acoustic differences along a given acoustic dimension, but listeners reliably tell the sounds apart, then we need to follow up with characterizations on other acoustic phonetic dimensions. If on the other hand we do see acoustic differences on a certain dimension, but listeners hear sounds as the same, then we can conclude that listeners are not using this particular acoustic dimension as a cue. Acoustic and perceptual characterizations in tandem provide the best method of establishing areas of difference between the sounds of different languages, and in turn of establishing ways to teach L2 sounds to learners.

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