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Purpose: A previous investigation (Lee & Iverson, 2012) found that English and Korean stop categories were fully distinguished by Korean–English bilingual children at 10 years of age but not at 5 years of age. The present study examined vowels produced by Korean–English bilingual children of these same ages to determine whether and when bilinguals establish distinct vowel categories across their 2 languages.

Method: Both English and Korean vowels produced by 40 Korean–English bilingual children (5 and 10 years of age) were examined in terms of 1st formant frequency (F1) and 2nd formant frequency (F2), vowel duration, and F1 and F2 formant trajectories.

Results: Formant frequencies of vowels produced by the bilingual children were similar to those of monolingual English and Korean children. The bilinguals distinguished vowel categories across languages using both the assimilation and dissimilation mechanisms as identified by Flege, Schirru, and MacKay (2003).

Conclusions: Vowel categories developed earlier than stops in bilingual children because vowels were typically acquired earlier than consonants. The results of this study suggest that detailed phonetic categories do not form across-the-board and that bilingual children may invoke multidimensional representations of phonetic categories.

Key Words: bilingualism, vowel productions, Korean–English bilingual children

One of the long-standing theoretical issues in simultaneous bilingualism is whether bilingual children develop one or two linguistic systems in the learning of their respective languages. The one-system hypothesis (Swain, 1972; Volterra & Taeschner, 1978) suggests that children initially posit linguistic rules common to both languages; then they differentiate the two as they master higher linguistic knowledge. The two-system hypothesis (Genesse, 1989; Goodz, 1989; Padilla & Liebmann, 1975), on the other hand, holds that children in bilingual environments differentiate both systems at an early age and that children are capable of keeping the two linguistic systems separate as these develop. Though the one-system hypothesis has been challenged on both methodological and empirical grounds (see Paradis & Genesee, 1996, for more information), most research on this issue has dealt with the lexical, syntactic, and phonological domains; however, whether bilingual children develop one or two distinct phonetic systems has not been fully explored. The present study, accordingly, examined English and Korean vowels produced by Korean–English bilingual children to provide evidence bearing on whether children distinguish detailed phonetic categories for two languages.

Phonetic Category Formation in Adult Bilingual Speakers and Second Language (L2) Learners

The organization of phonetic systems employed by bilingual speakers has been extensively examined among adult bilingual or L2 learners (for more information, see Bohn & Munro, 2007; Flege, 1995). Flege’s (1995) speech learning model, in particular, holds that phonetic elements of the first language (L1) and L2 are related to each other at the level of allophones, with language-specific aspects of speech sounds formed in long-term representation called phonetic categories (Yeni-Komshian, Flege, & Liu, 2000). Thus, it is of interest to investigate whether bilinguals can produce detailed phonetic differences for two languages when two phones fall into the same phonological category, a process termed phonetic
category formation (Flege & Eefting, 1987). For example, one may examine whether Spanish–English bilinguals produce English /b/ (short lag) and Spanish /b/ (voicing-lead) distinctively inasmuch as these two phonemes are articulated with different phonetic (acoustic) values in the L1.

Flege and colleagues (Flege, Schirru, & MacKay, 2003; Yeni-Komshian et al., 2000) proposed two mechanisms for forming phonetic categories: assimilation and dissimilation. Assimilation may occur when the learning of a sound in L2 is blocked by a similar L1 sound, resulting in a single, merged phonetic category (e.g., the positing of one type of /p/ for both the English aspirated and the French unaspirated voiceless bilabial plosive). Phonetic category dissimilation, on the other hand, may occur when a sound in one language is produced in a (typically exaggerated) way so as to distinguish it maximally from a similar sound in the other language. For example, early Italian–English bilingual speakers have been observed to produce the English vowel /e/ with more formant movement than monolingual English speakers, indicating that the bilinguals established a new category in differentiating between phonetically diphthongal English /e/ (/[e]/) and monophthongal Italian /e/ ([ɛ]) (Flege et al., 2003; Munro, 1993).

Phonetic Category Formation and Adaptation Mechanisms Among Bilingual Children

Although phonetic category formation has been frequently addressed for adult bilingual speakers, the question of how bilingual children form detailed phonetic categories has been explored in only a limited number of studies, and these results have not been consistent (Deuchar & Clark, 1996; Johnson & Wilson, 2002; Kehoe, Lleo, & Rakow, 2004; Khattab, 2000; Watson, 1982). For example, Deuchar and Clark (1996) claimed that an infant as young as 2 years of age began to distinguish the voicing systems between two languages, whereas Watson (1982) reported that early bilinguals implement two separate systems after 5 years of age. Most of these studies included only a single participant per age and offered insufficient statistical analysis to evaluate the strength of assertions about the phonetic systems of bilingual children.

Recently, Lee and Iverson (2012) conducted a study in which Korean and English stops produced by 30 Korean–English bilingual children at 5 and 10 years of age were compared with those of age-matched monolingual English- and Korean-speaking children. The results of this study provided a more comprehensive understanding of phonetic category formation in bilingual children because they included relatively larger numbers of homogenous bilingual participants and their productions were compared both within and between groups. The 10-year-old bilinguals were found to distinguish all stop categories across two languages, making use of both assimilation and dissimilation, whereas the 5-year-olds failed to differentiate phonetic details between English and Korean, employing chiefly the assimilation mechanism. The results of this study suggested that bilingual children at around 5 years of age do not yet have fully separate stop systems, consistent with Watson (1982), but that the systems continue to evolve during the developmental period. The question remains, however, as to whether the patterning of vowels, which develop earlier than stop consonants (Stoel-Gammon & Herrington, 1990), parallels those of stops in Korean–English bilingual children.

Vowel Development in Monolingual and Bilingual Children

The literature on vowel development confirms that vowels emerge and are acquired earlier than consonants. Although there is a degree of variability, studies report that vowel production is reasonably accurate by 3 years of age in both English and Korean. For example, Paschall (1983) and Hare (1983) examined the vowels of English-learning children who were younger than 3 years of age. Children 16–18 months of age produced /i ɪ ɨ a/ with more than 70% accuracy, but the non-high-front vowels /æ e ɛ/ were produced with 50% or less accuracy. The two r-colored vowels /ɜ ɹ/ (as in butter and bird) were misarticulated frequently and were produced with only 5% accuracy. Children 21–24 months of age showed a dramatic increase, with all vowels except /e ɛ ɪ/ produced with more than 90% accuracy, and even these three vowels were produced at relatively high accuracy rates ranging from 84% to 89%. The two r-colored vowels, however, were still produced with less than 50% accuracy at this age level. By contrast, Larkins (1983) examined more than 15,000 vowel productions from children 34–38 months of age. At this later point in development, all English monophthongs except for /ɪ, ɜ/ were produced with 100% accuracy, and even /ɪ, ɜ/ were produced with 99% accuracy. By way of confirmation, Otomo and Stoel-Gammon (1992) investigated six unrounded vowels /ɪ ɛ ɛ ɛ æ ɚ/ from six English-learning children at 22, 26, and 30 months. General findings were similar to those of previous studies, albeit with overall lower percentages of accuracy. For example, at 30 months of age, /ɪ ɚ/ were produced with relatively high accuracy (91% and 82%, respectively), /ɛ ɚ/ with midlevel accuracy (79% and 70%, respectively), and /ɛ ɛ/ with comparatively low accuracy (40% and 49%, respectively).

Relatively few studies have explored the native acquisition of Korean vowels. Modern Standard (Seoul)
Korean contrasts seven monophthongal vowels (see details below). Kwon (1982) evaluated 20 Korean children whose ages ranged from 3;3 (years;months) to 5;5. At age 3;3, /a e/ were produced with 100% accuracy, whereas the other vowels were at 94% or higher: /i/ (97%), /u/ (99%), /æ/ (96%), /ø/ (94%), and /i/ (94%). At age 5;5, /a i u e/ were produced with 100% accuracy, the others better than 95%; /a/ (98%), /ø/ (95%), and /i/ (97%). Similar to English-learning children, then, L1 learners of Korean fully acquire their vowels before 3 years of age.

Several vowel studies of bilingual children have also been undertaken (Garlandt, 2001; Gildersleeve-Neumann, Kester, Davis, & Pena, 2008; Gildersleeve-Neumann, Pena, Davis, & Kester, 2009; Gildersleeve-Neumann & Wright, 2010; Johnson & Lancaster, 1998; Kehoe, 2002; Schnitzer & Krasinski, 1994, 1996; Whitworth, 2000), but these mainly explored vowel inventories based on transcriptions, or they examined acoustically only vowel length. Among the most recent studies, Gildersleeve-Neumann and Wright (2010) evaluated the English vowels of 3- to 5-year-old Russian–English bilingual children compared with age-equivalent monolingual English-speaking children; irrespective of age, both groups produced English monophthongal vowels with 100% accuracy. On the other hand, Gildersleeve-Neumann et al. (2008, 2009) evaluated the vowel accuracy of 3-year-old Spanish–English bilingual children at two time points, that is, in the 1st month and 8 months after they were enrolled in a Head Start program. Here it was found that, whereas the accuracy of English vowels increased between the two time points for both monolingual and bilingual groups, the percentage correct decreased from 93% to 87% for Spanish vowels, suggesting that the influence of the L2 became more prominent at this age with increased exposure to the more complex vowel system of English. Further studies are warranted to investigate the vowel productions of older bilingual children to determine whether similar “phonetic drift” effects occur parallel to those that have been observed in young adults (cf. Chang 2010).

To the best of our knowledge, there is only one study that examined acoustic vowel categories in bilinguals that focused on Korean–English (Baker & Trofimovich, 2005). Bilinguals were divided into two groups, on the basis of the duration of their exposure to English: short (M = less than 1 year) and long (M = 8 years). Baker and Trofimovich (2005) found, consistent with previous studies (Flege et al., 2003; Guion, 2003), that the earlier the exposure to two languages, the more likely a bilingual will produce distinct acoustic realizations of L1 and L2 sounds. Specifically, bilingual children with longer exposure distinguished English /h/ from /i/ /æ/ from /e/, and /u/ from /ø/ better than children with shorter exposure duration. Moreover, a significant influence of L1 on L2, and vice versa, was also found. Thus, Korean /u/ as produced by the longer exposure group was somewhat centralized, with higher F2 values than found in monolingual Korean /u/, and new or unshared English vowels such as /æ/ /i/ showed higher values of both first formant frequency (F1) and second formant frequency (F2). Baker and Trofimovich provided important findings for how bilinguals organize their phonetic systems and the complex interactions between L1 and L2. However, as they examined bilinguals who arrived in the United States after they had fully acquired the L1 (i.e., between 7 and 13 years of age), it is still not known how phonetic categories are formed in children who learn two languages at young ages. In addition, because they examined only high and front vowels, a full scope of vowel production should be conducted to get a more comprehensive picture of the phonetic categories of vowel production.

**Purpose and Significance of This Study**

The main purpose of the present study, then, is to (a) investigate whether Korean–English bilingual children at 5 and 10 years of age form distinctive vowel categories and (b) identify the underlying mechanisms in this process. We also investigate the overall characteristics of vowels produced by Korean–English bilingual children by comparing them with their monolingual English and Korean counterparts. The study focuses on three questions. First, are the vowels of Korean–English bilingual children different from those of their monolingual counterparts, and, if so, how? Second, do Korean–English bilingual children establish fully distinct vowel systems for each language? Third, what mechanisms (i.e., assimilation vs. dissimilation) do bilingual children employ in their developmental process?

Investigating speech abilities of bilingual children provides not only a basis for theorizing about the nature of speech development in bilingual children but also useful information for correct diagnosis and developing appropriate treatment for bilingual children with speech sound disorders. According to the U.S. Bureau of the Census (2008), more than 10 million children were raised in homes with languages other than English. Of these bilingual children, approximately 10%–15% have diagnosable speech sound disorders in childhood, on the basis of the prevalence rate in the general population (American Speech-Language-Hearing Association, 2008).

Although identification techniques and appropriate treatments for monolingual English-speaking children have been established, those for bilingual children are based mainly on monolingual milestones. Bilinguals are more than the sum of two monolinguals, however, with unique patterns of language behavior (Grosjean, 1985). To identify and provide appropriate treatment for bilingual children with speech disorders, it is necessary
to establish the developmental characteristics of speech production in bilingual children without speech and language impairments.

## Vowel Systems of Korean and English

As reviewed by Ahn and Iverson (2007) and Kim-Renaud (2009), the basic vowel system in colloquial Korean today is symmetrical. In addition to one low vowel (central unrounded /a/), there are three mid and three high monophthongs: two front unrounded (/i, /e/), two central/back unrounded (/u, /o/), and two back rounded (/a, /o/). An additional mid-front unrounded vowel, /e/, still prevails in the formal standard (phonetically as well as orthographically), but the contrast between non-high-front vowels has been merged in the speech of most Koreans throughout the country now, resulting in an evenly balanced seven-vowel inventory: /i e a u o a/.

This symmetrical system of monophthongs is complemented by a skewed set of nine on-glide diphthongs consisting of /wi, /we, /wa, /ja, /je, /ja, /je, /ja, /we/ with a labial onset and /ju, /jo, /je, /ju, /jo, /je, /ju, /jo, /je/ with a palatal onset. Marginally, a diphthong /ij/ with a central or back unrounded onset and palatal off-glide also occurs for some speakers in word-initial position (e.g., in euisa [jsa] “medical doctor”), but this is typically reduced to monophthongal /i/ ([jsal]), and to /i/ elsewhere in the word (haneui [hani] “oriental medicine”); see Park, Iverson, and Park (2011) for a neuroimaging characterization of the relative complexity and special status of /ij/ in Korean. Additionally, the diphthongs /we/ and /wa/, in medial position in careful speech, are sometimes pronounced as the front rounded monophthongs /y/ and /o/, respectively, reflecting their historical source.

Tables 1 and 2 lay out the vowel system that has emerged in today’s Korean, reflecting the recent coalescence of /e/ and /a/. The parenthetical front rounded monophthongs generally no longer appear as such phonetically, having been broken into new on-glide diphthongs with /w, /wi, and /we/. Furthermore, although the diphthong /ij/ occurs sporadically in word-initial position, its status in the system remains marginal and so is indicated in brackets.

Though expression of the vowel system of English varies considerably by region and social factors, the variety to which the participants in this study were exposed is uniformly that of an upper Midwest dialect of American English as spoken specifically in the Milwaukee metropolitan area of southeastern Wisconsin. This system comprises 11 phonemic monophthongs, /i e æ a u o a/, and three phonemic diphthongs, /ai au /e/, and /æ/ is low-front unrounded, as in cat, whereas low central unrounded /a/ may be phonetically more retracted for some speakers, toward low-back unrounded /a/, but there is no contrast between /a/ and /e/. Mid-low-back unrounded /æ/ occurs per se under stress, elsewhere as schwa, as exemplified in transcription of the word above (’is’bav).

Lee and Iverson (2009) established cross-linguistic similarities and differences between Korean and English vowels produced by monolingual Korean- and English-speaking children at 5 and 10 years of age. Lee and Iverson measured formant frequencies of seven vowels in both languages that are typically transcribed using the same IPA symbols, /i e æ a u o a/; though, as mentioned, for Korean, the orthographically distinguished /e/ and /æ/ are now merged in speech. We found that the F1 values were similar between English- and Korean-speaking children, except for the vowels /æ, o, /e. Among monolinguals, English speakers showed higher F1 for /æ, o, /e than Korean speakers, whereas Korean speakers produced higher F1 for /æ/ than English speakers, reflecting the merger in Korean of /æ, /e/ with /æ/. On the other hand, F2 values for all vowels except for /i/ were significantly different between the languages. English-speaking children produced higher F2 values for the vowels /æ, o, /e, whereas Korean-speaking children produced higher F2 for /æ/. On the basis of these findings, the question that arises here is whether bilingual children also manifest formant frequency distinctions between the two languages.

### Table 1. Modern Korean monophthongs.

<table>
<thead>
<tr>
<th>-back</th>
<th>+back</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>y</td>
</tr>
<tr>
<td>e</td>
<td>o</td>
</tr>
</tbody>
</table>

### Table 2. Modern Korean diphthongs, categorized according to backness of nuclear vowel.

<table>
<thead>
<tr>
<th>-back</th>
<th>+back</th>
</tr>
</thead>
<tbody>
<tr>
<td>ju</td>
<td>wi</td>
</tr>
<tr>
<td>ja</td>
<td>wa</td>
</tr>
</tbody>
</table>

A total of 120 children (40 Korean–English bilingual, 40 monolingual English-speaking, and 40 monolingual

### Method

**Participants**

A total of 120 children (40 Korean–English bilingual, 40 monolingual English-speaking, and 40 monolingual...
The monolingual English-speaking children were from monolingual families in which Midwestern American English was spoken. The particular variety to which these children were exposed is an upper Midwest dialect of American English as spoken in the Milwaukee metropolitan area of southeastern Wisconsin. In recruiting monolingual English-speaking children, classroom teachers were asked to forward invitation letters to parents of children in their classes who speak only English and who had not, to their knowledge, received any L2 education. The invitation letter stated, “Your child was selected for this study because she/he speaks only English.” The experimenter asked 10-year-old children whether they speak and/or understand other languages, particularly Spanish, before data collection began. For the 5-year-olds, the experimenter contacted the parents to ask about their child’s knowledge of other languages. The interviews confirmed that all of the monolingual children had little or no knowledge of languages other than English. The monolingual Korean children, on the other hand, lived in the Seoul metropolitan and surrounding area and used standard Korean (Seoul dialect) at home and school. Invitation letters were sent to parents of children who speak only Korean without having knowledge of other languages. Before data collection began, the 10-year-olds and the parents of the 5-year-olds were asked whether the children had been to a foreign country or had learned English or other languages. Interviews with the children as well as their parents indicated that the monolingual Korean children did not know, or had little knowledge of, languages other than Korean. Some Korean children had learned only the names of the letters of the Roman alphabet as used in English (e.g., [bi] for B), but they were not able to read or understand English words, and they did not show awareness of English phonemes when they were asked to answer the question, “What is the first sound of the word CAT?”

The bilingual children, who lived in the greater Milwaukee metropolitan area of southeastern Wisconsin and in the Chicago metropolitan area of northern Illinois, were carefully selected when they met the following criteria: (a) were exposed to both English and Korean for at least 5 years in the case of the 10-year-olds (M = 5.6 years), and at least 2 years in the case of the 5-year-olds (M = 2.1 years); (b) used both English and Korean on a daily basis; (c) attended Korean language school at least 4 years for the 10-year-olds and 1 year for the 5-year-olds; (d) demonstrated no heavy accent and were able to use complex syntactic structures when speaking Korean and English on the basis of the primary investigator’s observation and the reports of Korean language teachers; (e) had parents who used the Seoul dialect of Korean; and (f) grew up learning the same variety of Midwestern American English.

**Stimuli**

Picture naming tasks were used to elicit target vowels. The same target words used in a previous study (Lee & Iverson, 2009) were adopted to make the bilingual data comparable with those elicited from monolingual children. For English, the words containing target vowels were eat (/i/), in (/ɪ/), cake (/keɪ/), egg (/ɛɡ/), cat (/kæt/), gum (/ɡʌm/), car (/kɑɹ/), goose (/ɡuʊs/), book (/bʊk/), the letter (/oʊ/), and call (/ɔːl/); for Korean, the targets were the first vowels in the (Yale-romanized) words i “teeth” (/i/), kay “dog” [which is homophonous with key “crab”] (/ɛk/), kurim “picture” (/kiɾɨm/), kemi “spider” (/kekim/), kapang “bag” (/ka.pan/), kuwlum “cloud” (/kuwlum/), and o “five” (/o/). These words were selected because of their similar initial consonant context (either null or velar stop). The words were also chosen because, similar to previous studies of vowel productions in young children (Baker & Trofimovich, 2005; Busby & Plant, 1995; Eguchi & Hirsh, 1969; Whiteside & Hodgson, 2000), they are ones that children as young as 5 years of age would likely know without being given any auditory cues, although this necessarily sometimes resulted in vowels not appearing in the exact same consonantal contexts. Picture cards displaying each word were presented in random order.

**Recordings**

The monolingual data were collected at schools or kindergartens in a quiet room. The bilingual data were collected at Korean language schools, churches, or participants’ homes. The same procedures were employed for all children. A digital flash recorder (Marantz Model PMD670) was connected to a stand-mounted, omnidirectional dynamic microphone (Electro-Voice 635A/B) positioned on a table. Speech was recorded at a sampling speed of 16,000 Hz. Each recording session lasted approximately 30 minutes. 1

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1 Part of the data on monolingual English- and Korean-speaking children was reported in our previous study (Lee & Iverson, 2009), in which we examined cross-linguistic similarities and differences with respect to seven vowels shared between monolingual English- and Korean-speaking children.

2 The extent of use for each language was determined via interviews with participants and parents. Overall, 5-year-olds used Korean in 20%–25% of their daily language interactions (English was used 75%–80% of the time), whereas 10-year-olds used Korean 15%–18% of the time (English was used 82%–85% of the time). All participants reported that they used Korean at home with parents and/or grandparents and at Korean language schools, but they used English with their siblings at home and with English-speaking peers at English-speaking schools.
rate of 44 kHz. The children sat at the table and spoke the test items.

Data Collection and Selection Procedure

The primary investigator, a fluent Korean–English bilingual speaker, collected all Korean and English data from the bilingual children. When English words were being elicited, all conversation with the experimenter was in English only, and when Korean words were elicited, all conversation was in Korean. Children were asked to say each word three times in a row in isolation. Most bilingual children knew all target words. However, when a child did not know a target word, the experimenter used a delayed imitation technique. Similar to our previous study (Lee & Iverson, 2009), the best two (usually the first and second) out of the three productions of each word for each participant were chosen for analysis.

Perceptual Analysis

Before the acoustic analyses were conducted, two native speakers of English and two of Korean independently listened to all target word productions in their respective languages to render native speaker judgments as to the correctness of the children’s productions. The native listeners indicated any substitution or distortion errors when the target vowel was categorized as incorrect. The percentage of correct productions was averaged across the two native listeners for each language.

Acoustic Analysis

Computerized Speech Lab (Model 4300, Kay Elemetrics) software was used to analyze the recordings. Speech recordings were down-sampled to 10 kHz. A spectrogram of each word was made using a 512-point discrete Fourier transform analysis with a 20-ms Hamming window. Three measurements were made: formant frequencies (F1 and F2), vowel duration, and formant trajectory. First, F1 and F2 values were taken at the midpoint of the steady state portion of vowel between vowel onset and offset points and were computed automatically by linear predictive coding analysis with the order of 12 and were visually verified using the spectrographic display. Formant frequencies obtained were converted to Bark scale to normalize for gender and age differences in vowel production by using the following formula: Bark = 26.81/[1 + (1960/F)] – 0.53 (Traunmüller, 1988). Second, the durations of five vowels common to English and Korean (/i, e, a, u, o/) were measured through visual inspection of the acoustic waveform and were confirmed through auditory confirmation of the vowel segment. Vowel onset was defined as the point where waveform periodicity ceases and waveform amplitude decreases markedly. Third, following the practice of Fl ege et al. (2003), formant trajectories for English phonetically diphthongal /e/ and /o/ were obtained after F1 and F2 were measured at the beginning (10%) and end (90%) of vowels. The Euclidean distance between the two points defined by these measurements in an F1 × F2 space was calculated.

Results

Perceptual Analysis

Out of the total of 1,320 English vowels and 840 Korean vowels, more than 99% of Korean and English vowel productions were judged by native speakers as phonetically accurate, for both monolingual and bilingual children. In English, some monolingual as well as bilingual children produced /e/ for /æ/ in “egg” and /e/ for /i/ in “in.” These pronunciation patterns are common regional variants of standard English (Purnell, 2008), however, resulting from a high-front glide transition between /e/ and voiced velars, rendering /æg/ as [æg] = /æg/, and the raising of /e/ to /i/ before nasals, rendering pen homophonous with pin. Thus, these variants were considered as phonemically correct productions. Distortion or other substitutions were rare in both English and Korean.

Acoustic Analysis: Formant Frequencies

Comparisons Between Monolingual and Bilingual Children in English and Korean

To investigate whether the vowel productions of bilingual children are similar to those of corresponding monolinguals, multivariate analyses of variance (MANOVAs) were conducted for F1 and F2, separately between monolingual and bilingual children in English and Korean. Using Bonferroni correction, an alpha level was set at .0125 by dividing .05 by 4 (F1 and F2 for each language).

English. Figures 1 and 2 show the English vowel space between monolingual English and bilingual children for 10-year-olds (see Figure 1) and 5-year-olds (see Figure 2). MANOVAs indicated significant differences between the two language groups for both F1 and F2— for F1, $F(11, 66) = 3.64, p = .007$; for F2, $F(11, 66) = 2.66, p = .007$ — and between the two ages for both F1 and F2: for F1, $F(11, 66) = 3.84, p < .001$; for F2, $F(11, 66) = 12.78, p < .001$. There were no significant interaction effects between language groups and age for both F1 and F2: for F1, $F(11, 66) = 1.08, p = .386$; for F2, $F(11, 66) = 0.66, p = .765$.

Table 3 shows $F$ and $p$ values of univariate analysis of variance (ANOVA) for each vowel. Bilingual children showed significantly lower F1 for /æ/ and lower F2 for /æ/ than monolingual English-speaking children. In terms of age, as expected, F1 values of younger children
(5-year-olds) were higher than those of older children (10-year-olds) for /e æ a o/. F2 values for the younger children were again higher than those for the older children, except for /u o/.

Korean. Figures 3 and 4 show the Korean vowel space between monolingual Korean and bilingual children at 10 years of age (see Figure 3) and 5 years of age (see Figure 4). MANOVAs indicated no significant differences between the two language groups, F(7, 70) = 2.14, p = .046, but significant differences between the two ages, F(7, 70) = 9.53, p < .001, in terms of F1 values, whereas significant differences were found between the two language groups, F(7, 70) = 4.91, p = .001, and the two ages, F(7, 70) = 12.35, p < .001, in terms of F2 values. There were significant interaction effects between language groups and age for F1, F(7, 70) = 4.08, p = .001, but not for F2, F(7, 70) = 1.81, p = .042. Specifically, language group and age interactions were significant for F1 values of /i e æ/ vowels (p = .002 for /el/, and p = .003 for /i e/).

Table 3. F and p values for univariate analysis of variance (ANOVA) statistics of first formant frequency (F1) and second formant frequency (F2) in English.

<table>
<thead>
<tr>
<th>Vowel</th>
<th>F1 Language</th>
<th>F1 Age</th>
<th>F2 Language</th>
<th>F2 Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>3.96</td>
<td>.05</td>
<td>.95</td>
<td>.02</td>
</tr>
<tr>
<td>ë</td>
<td>3.52</td>
<td>.07</td>
<td>.27</td>
<td>.03</td>
</tr>
<tr>
<td>æ</td>
<td>6.49</td>
<td>.01</td>
<td>24.40</td>
<td>&lt;.001*</td>
</tr>
<tr>
<td>ø</td>
<td>1.19</td>
<td>.28</td>
<td>1.35</td>
<td>.25</td>
</tr>
<tr>
<td>æ</td>
<td>4.34</td>
<td>.04</td>
<td>6.48</td>
<td>.01</td>
</tr>
<tr>
<td>ë</td>
<td>0.50</td>
<td>.48</td>
<td>0.65</td>
<td>.42</td>
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<tr>
<td>a</td>
<td>0.33</td>
<td>.57</td>
<td>16.97</td>
<td>&lt;.001*</td>
</tr>
<tr>
<td>u</td>
<td>0.41</td>
<td>.53</td>
<td>0.82</td>
<td>.37</td>
</tr>
<tr>
<td>û</td>
<td>4.73</td>
<td>.03</td>
<td>0.36</td>
<td>.55</td>
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<tr>
<td>o</td>
<td>3.50</td>
<td>.07</td>
<td>7.91</td>
<td>.06*</td>
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<tr>
<td>ë</td>
<td>0.05</td>
<td>.82</td>
<td>5.72</td>
<td>.02</td>
</tr>
</tbody>
</table>

Note. Values are statistically significant at α = .0125 using Bonferroni correction.

*p < .05.

Table 4 shows F and p values of univariate ANOVA for each vowel. Bilinguals produced significantly higher F2 for /u o/ than did monolingual Korean speakers. With respect to age, F1 values of the younger children were higher than those of the older children, except for /i/, and the F2 values of the 5-year-olds were higher than those of the 10-year-olds, except for /el/.

Comparisons Between English and Korean in Bilingual Children

So far, we have compared formants between monolingual and bilingual children. To answer the question of whether bilingual children employ one or two separate...
phonetic systems, comparison of both English and Korean vowel productions within bilingual children is needed. Figures 5 and 6 show vowel spaces between English and Korean in two groups of bilingual children: 10-year-olds (see Figure 5) and 5-year-olds (see Figure 6). The vowels were divided into four categories (high-front, non-high-front, high-back, and non-high-back). Accordingly, four sets of repeated measure mixed ANOVAs were conducted to examine whether bilingual children manifest distinct phonetic categories across languages for each vowel category. Using Bonferroni correction, an alpha level was set at .006 by dividing .05 by 8 (four sets of F1 and F2 comparisons).

**High-front vowels**. High-front vowels include English /i/ and Korean /i/. English /e/ was categorized as high-front on the basis of acoustic results for the productions of Korean–English bilingual children. In terms of F1, there were significant differences among these four high-front vowels, $F(3, 114) = 11.75, p < .001$, and the interaction effect between vowels and age, $F(3, 113) = 4.76, p = .004$. However, no significant difference on age, $F(1, 38) = 0.13, p = .74$, was found. With respect to F2, there were also significant differences among these four vowels, $F(3, 114) = 143.94, p < .001$, and difference on age, $F(1, 38) = 0.45, p < .001$. However, there was no significant interaction effect between vowels and age, $F(3, 114) = 1.03, p = .37$. Pairwise post hoc comparisons indicated that the F1 value of English /e/ in 5-year-old bilingual children was significantly different from the other three vowels, whereas F1 values of all high-front vowels in 10-year-old bilingual children did not differ from each other. However, the F2 values of all high-front vowels were significantly different in both age groups. Thus, the four high-front vowels were distinguished on the basis of F2 values. None of the vowels were produced with the same values of both F1 and F2.

**Non-high-front vowels**. Non-high-front vowels include English /æ/ and Korean /e/. In terms of F1, there were also significant differences among these four vowels, $F(3, 114) = 15.54, p < .001$, and the interaction effect between vowels and age, $F(3, 113) = 4.76, p = .004$. However, no significant difference on age, $F(1, 38) = 0.13, p = .74$, was found. With respect to F2, there were also significant differences among these four vowels, $F(3, 114) = 3.89, p < .001$, and difference on age, $F(1, 38) = 0.45, p < .001$. However, there was no significant interaction effect between vowels and age, $F(3, 114) = 0.52, p = .74$. Pairwise post hoc comparisons indicated that the F1 value of English /æ/ in 5-year-old bilingual children was significantly different from the other three vowels, whereas F1 values of all high-front vowels in 10-year-old bilingual children did not differ from each other. However, the F2 values of all non-high-front vowels were significantly different in both age groups. Thus, the four non-high-front vowels were distinguished on the basis of F2 values. None of the vowels were produced with the same values of both F1 and F2.

**Table 4.** $F$ and $p$ values for univariate ANOVA statistics of F1 and F2 in Korean.

<table>
<thead>
<tr>
<th>Vowel</th>
<th>Language</th>
<th>Age</th>
<th>Language</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F$</td>
<td>$p$</td>
<td>$F$</td>
<td>$p$</td>
</tr>
<tr>
<td>$i$</td>
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<td>.006</td>
<td>0.24</td>
<td>.63</td>
</tr>
<tr>
<td>$e$</td>
<td>0.17</td>
<td>.67</td>
<td>15.54</td>
<td>&lt;.001*</td>
</tr>
<tr>
<td>$i$</td>
<td>0.08</td>
<td>.92</td>
<td>23.79</td>
<td>&lt;.001*</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.17</td>
<td>.68</td>
<td>13.55</td>
<td>&lt;.001*</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.13</td>
<td>.71</td>
<td>29.55</td>
<td>&lt;.001*</td>
</tr>
<tr>
<td>$u$</td>
<td>0.54</td>
<td>.46</td>
<td>9.53</td>
<td>&lt;.001*</td>
</tr>
<tr>
<td>$o$</td>
<td>5.41</td>
<td>.02</td>
<td>14.23</td>
<td>&lt;.001*</td>
</tr>
</tbody>
</table>

Note. Values are statistically significant at $\alpha = .0125$ using Bonferroni correction.

*p < .05.
there were significant differences among the three vowels, F(2, 76) = 50.20, p < .001. However, there were no significant differences on age, F(1, 38) = 0.41, p = .53, or interaction effect between vowels and age, F(2, 76) = 1.28, p = .28. With respect to F2, there were significant differences among the three vowels, F(2, 76) = 16.26, p < .001, and age, F(1, 38) = 47.73, p < .001. However, no significant interaction effect between vowels and age, F(2, 76) = 0.54, p = .59, was found. Pairwise post hoc comparisons indicated that both F1 and F2 values of English /e/ were similar to Korean /e/ in both age groups, but they were significantly different from English /æ/.

**High-back vowels.** High-back vowels here include English /u û/ and Korean /u ë/, on the basis of the acoustic results for Korean–English bilingual children. In terms of F1, there were significant differences among the six vowels, F(5, 190) = 21.37, p < .001. However, no significant differences on age, F(1, 38) = 4.84, p = .03, or interaction effect between vowels and age, F(5, 190) = 1.50, p = .21, were found. With respect to F2, there were significant differences among the six vowels, F(5, 190) = 63.93, p < .001, as well as on age, F(1, 38) = 12.28, p = .001. Again, no significant interaction effect was found, F(5, 190) = 0.97, p = .43. Pairwise post hoc comparisons indicated that either F1 or F2 values were significantly different from each other. In other words, none of vowels were the same with respect to both F1 and F2 values.

**Non-high-back vowels.** Non-high-back vowels include English /æ a œ/ and Korean /æ a œ/. In terms of F1, there were significant differences among the five vowels, (4, 152) = 48.43, p < .001, and significant interactions between vowels and age, F(4, 152) = 8.53, p < .001. However, no significant differences on age, F(1, 38) = 1.37, p = .25, were found. With respect to F2, there were significant differences among the five vowels, F(4, 152) = 82.44, p < .001, and on age, F(1, 38) = 12.35, p = .001, but there were no significant interaction effects between vowels and age, F(4, 152) = 2.26, p = .07. Pairwise post hoc comparisons indicated that either F1 or F2 values of all vowel comparisons were significantly different except for one. Both F1 and F2 values of Korean /œ/ and English /œ/ were similar for 10-year-old children.

### Acoustic Analysis: Vowel Duration

The durations of five vowels (/i e a u o/) in English and Korean were measured and compared between monolingual and bilingual children using MANOVAs. Using Bonferroni correction, an alpha level was set at .025 by dividing .05 by 2 (English and Korean). Means and standard deviations for English and Korean vowels are shown in Table 5. For English, no significant differences were found between the monolingual and bilingual groups, F(5, 72) = 0.57, p = .72, or between the two ages, F(5, 72) = 0.71, p = .62, and there was no interaction between group and age, F(5, 72) = 2.32, p = .05. English vowel duration was similar for all five vowels for both monolingual and bilingual children. However, there were significant differences in Korean vowel durations between the two groups, F(5, 72) = 3.96, p = .004, but not age, F(5, 72) = 2.48, p = .04, and there was no interaction between group and age, F(5, 72) = 2.13, p = .06. Univariate ANOVA indicated that durations for two Korean vowels /e œ/ were significantly longer for bilingual children than for monolingual Korean children: for /e/ F(1, 76) = 17.59, p < .001; for /œ/ F(1, 76) = 9.53, p = .003. No differences were found in the durations of Korean /i u a/ between the two groups.

### Acoustic Analysis: Formant Trajectory

Formant trajectories for phonetically diphthongal English /e œ/ were measured and compared between monolingual and bilingual children using mixed ANOVAs (see Figures 7 and 8). There was a significant difference on formant trajectory between /e/ and /œ/, F(1, 76) = 84.84, p < .001, and between monolingual English-speaking and bilingual children, F(1, 76) = 4.48, p = .038. Formant trajectory from vowel onset to offset was longer for vowel /œ/ than that of /e/ in both monolingual and bilingual children.
children. Bilingual children produced shorter trajectories for English /e o/ than monolingual English-speaking children. No significant differences, however, were found on formant trajectory between ages, $F(1, 76) = 1.66, p = .020$, as well as interactions between age and group, $F(1, 76) = 0.002, p = .96$; between vowel type and age, $F(1, 76) = 0.20, p = .65$; and among vowel type, age, and group, $F(1, 76) = 1.97, p = .16$.

**Discussion**

This study had three goals. The first goal was to compare the acoustic properties of vowels produced by Korean–English bilingual children with those of monolingual children at the same ages to examine the degree of influence of L1 on L2 vowels. The second goal was to investigate whether bilingual children employ distinct vowel systems across their two languages. If they do, the third goal was to identify the apparent adaptive mechanisms by which this happens.

Vowels are typically developed earlier than consonants and mastered before 3 years of age by L1 learners of English (Stoel-Gammon & Herrington, 1990), apparently because vowels are produced at uniformly higher amplitude than consonants and are typically associated with a well-defined formant pattern that generally remains constant for a longer time (Lee, Davis, & MacNeilage, 2010). In fact, children who learn a language such as Spanish may master their vowel system by 2 years of age because Spanish, with only five vowel phonemes, is relatively less complex in this respect (Goldstein & Pollock, 2000).

Gildersleeve-Neumann et al. (2009) reported an interesting observation on Spanish–English bilingual children’s vowel acquisition in that accuracy of L1 (Spanish) vowels decreased after they started to learn L2 (English), suggesting a negative effect of L2 on L1 vowel systems (cf. Chang, 2010). The authors explained this phenomenon using the united competition model (MacWhinney, 2005) and claimed that the higher percentage of vowel errors after 8 months exposure to English language would be attributed to conceptual reorganization on the part of bilingual children. Because Spanish and English have many similar consonant properties (despite their familiar voice onset time differences), strong consonant cue reliability may lead bilingual children successfully to acquire fine-grained phonetic distinctions. On the other hand, as vowels in the two languages differ considerably, cue reliability for Spanish vowels may not be as strong as for consonants—that is, the five Spanish vowels must be mapped onto 11 English vowels, requiring conceptual reorganization, whereas the consonants line up more isomorphically.

The findings of Gildersleeve-Neumann et al. (2009) should be verified with other types of bilingual children. A question raised here, however, was whether such reorganization still remains after a certain period of exposure irrespective of age. The results of the present study may provide an answer because Korean, similar to Spanish, has a relatively simpler basic vowel system than English. The current study found that 5-year-old Korean–English bilingual children who had exposure to English for 2 years did not produce any Korean vowel substitution errors. Subsequent acoustic analysis of Korean vowels confirmed perceptual judgments in that formant values of most Korean vowels produced by the bilingual children were not significantly different from those of monolingual Korean children. The two exceptions were the high- and mid-back vowels /u o/ in Korean, which revealed qualities of English influence in having somewhat higher F2 values. This overall finding suggests that reorganization in bilingual children...
may occur only during the initial period of learning the L2 and disappears after a certain duration of exposure to the L2. This phenomenon seems to be similar to the U-shaped learning in child cognitive and linguistic development, according to which there is a decrease in accuracy relative to the adult target (Stemberger & Bernhardt, 2001).

The 5-year-old Korean–English bilinguals accurately produced most English vowels after 2 years of exposure, as is consistent with previous studies of Spanish–English and Russian–English bilingual children (Gildersleeve-Neumann et al., 2008; Gildersleeve-Neumann & Wright, 2010). Acoustic analysis revealed no statistically significant differences in formant values between bilinguals and monolinguals, except for English /eɪ/ (for which F1 was lower) and /æ/ (for which F2 was lower). Thus, similar to monolingual children (Stoel-Gammon & Herrington, 1990), bilinguals appear able to acquire most aspects of the L2 vowel system after 2–3 years of exposure. We examined two groups of bilingual children who had different durations of exposure to English (2 vs. 5 years). We did not find different patterns between the two groups except that English /s/ and Korean /s/ were merged in 10-year-old bilingual children but not in 5-year-olds. These findings suggest that the vowel production of bilingual children remains stable once the vowels are fully acquired after 2–3 years of exposure.

These results contrast with those of Baker and Trofimovich (2005), who found that bilinguals with more than 7 years of exposure to English demonstrated the new or unshared vowels of English to be colored by Korean. In the current study, we did not find that formants of new or unshared English vowels (such as /ε/ and /æ/) produced by bilingual children were significantly different from those of monolingual English-speaking children. Baker and Trofimovich, however, examined bilinguals who had arrived in the United States between 7 and 13 years of age—that is, after they had fully acquired the L1—thus making their participants more like L2 learners than simultaneous bilinguals.

The results of this study also have implications for bilingual children with speech sound disorders because the speech patterns of normally developing children are commonly considered to be diagnostic for functional speech disorders with no known etiology. The establishment of developmental speech milestones will be used as an important diagnostic device for identifying speech disorders and delays in bilingual children as well. The present findings suggest that bilingual children who demonstrate vowel errors even though they have 2–3 years of exposure to English may have a speech sound disorder rather than L2 learning difficulties. Of course, clinical judgment should be rendered only after the child’s abilities in general have been fully examined.

One Versus Two Linguistic Systems in Bilingual Children

In contrast to stop productions, the present study found that children as young as 5 years of age did make fine phonetic distinctions across English and Korean vowels, albeit with a few vowels showing the same F1 or F2 or both between the two languages. In terms of high-front vowels, the 5-year-old Korean–English bilinguals with 2 years of exposure to English distinguished English /ʌ/ from both English /i/ and Korean /i/. This finding for high-front vowels is consistent with a previous study (Baker & Trofimovich, 2005) that noted that Korean–English bilinguals who had learned English for 7 years distinguished English lax /ʌ/ from tense /i/ in ways that were similar to the monolingual speech of both children and adults (Baker & Trofimovich, 2005; Yang, 1996).

With respect to high-back vowels, Korean–English bilingual children were also able to distinguish all vowels across the two languages. In addition to contrasting English lax /ʌ/ with English tense /ʌ/, Korean–English bilingual children distinguished English /ʌ/ from Korean /ʌ/ by producing English /ʌ/ with higher F2 values than those of Korean /ʌ/. As Lee and Iverson (2009) reported, the F2 value of English /ʌ/ is significantly higher than Korean /ʌ/ in monolingual child speech. Thus, Korean–English bilingual children as young as 5 years of age manifested detailed phonetic differences in vowels between the two languages. These findings also indicate that, unlike adult L2 learners, early simultaneous bilingual children were able to produce the English tense-lax distinction under a relatively short period of English exposure.

Besides the high-front and high-back categories, English and Korean vowels in the non-high-front and non-high-back categories were regularly distinguished. Two exceptions were merger of the pairs English /ɛ/ and Korean /ɛ/ (which are phonetically identical between monolingual children in any case), and Korean /ʌ/ and English /ʌ/ for 10-year-olds. Korean /ʌ/ is phonetically close to English /ʌ/ in virtue of the fact that both vowels are rounded as well as non-high and back; the chief distinguishing property is that English /ʌ/ is somewhat more retracted than Korean /ʌ/ (which in turn is more retracted than English /ʌ/), a subtle difference that 5-year-old bilinguals appear to be sensitive to but that 10-year-olds disregard.

The results of this study indicate that detailed phonetic categories across languages are not formed holistically, in part because the learning of vowel patterns generally precedes that of consonants but also because, within these categories, learning proceeds progressively. As with our analysis of stop productions in Korean–English
bilingual children (Lee & Iverson, 2012), the results of this study suggest that the phonetic system of bilingual children continues to evolve during the developmental process and that bilingual children require different durations of exposure per speech category to develop detailed phonetic categories across languages. Generalized to phonetic category formation in bilingual children, this reflects a core assumption of Flege’s (1995) speech learning model, namely, that “the phonetic systems used in production and perception of vowels and consonants remain adaptive over the life span and that phonetic systems reorganize in response to sounds encountered in an L2 through the addition of new phonetic categories” (p. 233).

Adaptive Mechanisms Employed in Bilingual Development

The term assimilation as used here refers to the merging of phonetic categories across two languages (Flege, 1995). As mentioned, 10-year-old bilingual children merged Korean /ʌ/ with English /ə/. Although Korean /u o/ did not merge with the slightly more centralized English /u o/, the F2 values of the Korean vowels as produced by bilinguals were higher than those of monolingual Korean children, thus also pointing toward an influence of English on Korean. This centralized production of high-back Korean /u/ by bilinguals parallels the finding of Flege (1987) that adult English speakers produce French /u/ with higher F2 than is characteristic of native French.

Dissimilation, by contrast, refers to the maximizing or exaggeration of differences in acoustic values between similar sounds in the two languages (Flege, 1995). Korean–English bilingual children in the present study, especially 10-year-olds, produced the vowel /æ/ with higher F1 (although not significantly so after Bonferroni correction) than found among monolingual English speakers—a phonetic departure whose effect is to under-score the contrast with /e/ by exaggeratedly lowering the tongue in the production of /æ/. The Korean–English bilingual children, however, did not exhibit dissimilation, or exaggerated diphthongization, relative to the formant trajectory of English /el, as Flege et al. (2003) found with respect to Italian–English bilinguals. Finally, the greater duration of Korean vowels produced by bilingual as compared with monolingual Korean children points toward another acoustic influence of English on Korean, though this seems not to be an example of dissimilation inasmuch as vowel length plays no contrastive role in Korean (but of course does in English). In short, further study is warranted to establish the prevalence of assimilation versus dissimilation among bilingual children.

Acknowledgments

This study has been supported by National Institute of Child Health and Human Development Grant RHD061527A. We thank Ja Hyung Lee at Ewha Woman’s University in Seoul for her help with participant recruitment. We also thank the children who participated in the study, the parents who gave their consent, and the childcare centers and schools at which the data were collected. In particular, we are grateful to Ae-Young Paek at the Happy Children’s Center, Hwa-Sook Lee at the In-Wang Children’s Center, and Jung Hong at the Man-An and Ho-Sung elementary schools in Korea, as well as to the Korean Language and Culture School of Milwaukee in Wisconsin and, in Illinois, the Hasang Korean School and the Niles Korean School.

References


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cies obtained were converted…”: Please verify that we formatted the Bark equation correctly. Thanks.

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