Phonological systems in bilinguals: Age of learning effects on the stop consonant systems of Korean-English bilinguals[a)]

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Interaction of Korean and English stop systems in Korean-English bilinguals as a function of age of acquisition (AOA) of English was investigated. It was hypothesized that early bilinguals (mean AOA=3.8 years) would more likely be native-like in production of English and Korean stops and maintain greater independence between Korean and English stop systems than late bilinguals (mean AOA=21.4 years). Production of Korean and English stops was analyzed in terms of three acoustic-phonetic properties: voice-onset time, amplitude difference between the first two harmonics, and fundamental frequency. Late bilinguals were different from English monolinguals for English voiceless and voiced stops in all three properties. As for Korean stops, late bilinguals were different from Korean monolinguals for fortis stops in voice-onset time. Early bilinguals were not different from the monolinguals of either language. Considering the independence of the two stop systems, late bilinguals seem to have merged English voiceless and Korean aspirated stops and produced English voiced stops with similarities to both Korean fortis and lenis stops, whereas early bilinguals produced five distinct stop types. Thus, the early bilinguals seem to have two independent stop systems, whereas the late bilinguals likely have a merged Korean-English system. © *2006 Acoustical Society of America.* [DOI: 10.1121/1.2166607]

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I. INTRODUCTION

Many studies have demonstrated that the two languages of a bilingual may influence each other in speech production. For example, production characteristics of the first language may be inappropriately transferred to the second language or acquisition of a second language may influence the production of the first language. Furthermore, the influence between a bilingual's two languages may increase with age of learning of the second language (L2). There is emerging evidence that earlier bilinguals may have more independent segmental systems for their two languages than later bilinguals. The current study investigates this possibility with an analysis of segmental speech production by Korean-English bilinguals who learned English early (M=3.8 years old) or late (M=21.4 years old). Specifically, the acoustic properties of Korean and English stops produced by early and late bilinguals are investigated. The early bilinguals are predicted to show less mutual influence between the two stop systems than the late bilinguals. That is, the early bilinguals are predicted to be native-like in both English and Korean due to a greater independence of their two languages. The late bilinguals, on the other hand, are predicted to have non-native-like production of some aspects of both English and Korean due to greater mutual influence of their two languages.

It has been well demonstrated that later learners show more first language (L1) effects on L2 in segmental speech production than early learners. For example, in a study investigating Spanish learners of English, Flege (1991) has shown that early learners' voice-onset time (VOT) values for English /t/ are not distinctive from those of English monolinguals, whereas late learners produce /t/ with values that are intermediate between the short-lag values of Spanish (L1) and the long-lag values of English (L2). Additionally, MacKay *et al.* (2001) examined the production of English /b/ and found that late Italian (L1)-English (L2) bilinguals produced English /b/ with prevoicing more often than the early bilinguals, who, in turn, produced more prevoicing than the English monolinguals. In a study investigating L2 vowel production, Piske *et al.* (2002) examined Italian-English bilinguals' production of 11 English vowels. The production of late bilinguals was significantly less authentic than early bilinguals, whose vowels did not differ from those of English monolinguals. Other studies also have confirmed that early learners are more likely to be native-like in L2 segmental speech production than late learners (e.g., Flege, Mackay, and Meador, 1999; Munro, Flege, and Mackay, 1996, for vowels; Flege, Munro, and MacKay, 1995, for consonants).

In addition to L1 effects on L2, several studies have reported that L2 can affect L1 speech production. MacKay *et al.* (2001) found that both early and late Italian learners of English differed in their Italian stop production from Italian monolinguals. Specifically, they produced Italian /b/ with full prevoicing less often than Italian monolinguals. Several other studies have also found that sequential bilingual children as well as highly proficient late second language learners produce stops in their native language differently from monolingual speakers of that language (Flege, 1987b; Flege and Eefting, 1987a, 1987b; Flege and Hillenbrand, 1984;

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Mack, 1990; Williams, 1979; see Guion, 2003 for a review of studies reporting L2 effects on L1 production).

Findings that L2 and L1 can mutually affect each other in speech production have been interpreted as an indication that bilinguals may have a combined L1-L2 phonological system. For example, Harada (2003) reported the effect of an interaction between English and Japanese stop systems in early Japanese (L1)-English (L2) bilinguals. The Japanese-English bilinguals produced Japanese voiceless stops with longer VOT values than Japanese monolinguals but had native-like VOT values for English voiceless stops. These results were interpreted to be an effect of an effort to maintain phonetic contrast between Japanese voiceless stops and English voiced stops in the bilinguals' common phonological space.

Also investigating the proposal that the L1 and L2 may be combined in a single phonological system in bilinguals, Flege, Schirru, and Mackay (2003) examined the interaction of Italian (L1) and English (L2) vowels in bilinguals. Early bilinguals (who used L1 rarely) produced English /eɪ/ with greater formant movement than English native speakers, whereas late bilinguals produced this vowel with less movement. The production with greater formant movement was attributed to an effort to dissimilate the acquired phonetic category for English /eɪ/ from the Italian /e/. The production with less formant movement was attributed to an assimilation of the English /eɪ/ with the Italian /e/.

It also seems that the mutual effects of L1 and L2 on speech production in bilinguals are related to age of learning. There is some evidence that earlier bilinguals may have greater independence between their two phonological systems than later bilinguals. First, later bilinguals may be more likely to use the same phonetic categories in both the L1 and L2, a type of equivalence classification, whereas earlier bilinguals may be more likely to acquire new categories for the L2 that are distinct from the L1 categories (Flege, 1987a, 1987b, 1995).

Second, there is also some evidence that the independence of the acquired L2 phonetic categories from the L1 phonetic categories varies with age. Guion (2003) investigated age of learning effects on the independence of phonological systems by assessing the vowel production ($F1$ and $F2$) of Quichua-Spanish bilinguals. Simultaneous bilinguals were found to have a more finely partitioned vowel space than early bilinguals, such that L1 and L2 front and back vowels were distinct from one another and similar to (near-) monolingual speakers. On the other hand, bilinguals who began learning Spanish in early to late childhood produced Spanish L2 vowels in a native-like way but produced their Quichua (L1) vowels differently from (near-) monolingual speakers. This difference in vowel production was interpreted to be a result of a reorganization which served to enhance perceptual distinctiveness between the vowels of the combined Quichua-Spanish vowel system. Finally, the late bilinguals were found to have merged Spanish and Quichua vowels and seemed to be using their Quichua vowels in Spanish production. These results indicated that simultaneous bilinguals were more likely to have two independent vowel systems than early and late bilinguals. Early and late bilinguals demonstrated interaction between their two vowel systems: the early bilinguals due to interaction between the L1 and L2 systems and the late bilinguals due to the use of the L1 system for L2 production.

However, not all studies have found the two phonological systems of simultaneous bilinguals to be independent. Sundara, Polka, and Baum (in press) investigated the production of coronal stops (/t/ and /d/) in Canadian English and Canadian French by adult simultaneous English-French bilinguals. They found that the bilinguals produced the target stops with language-specific differences between Canadian English and Canadian French but that the bilinguals were not completely identical to monolinguals, indicating possible interaction between the two language systems. Developmental studies also suggest that the phonological systems of simultaneous bilinguals may not develop with full independence from one another (Kehoe, Lleó, and Rakow, 2004; Khattab, 2002).

Thus, although late bilinguals are usually found to have merged phonological systems, the extent of independence between the two phonological systems for early or simultaneous bilinguals is not fully understood. The current study continues investigation into age of learning effects on the interaction of two phonological systems in bilinguals by assessing the interaction of the Korean and English stop systems in early and late Korean-English bilinguals. Specifically, the production of Korean and English stops by early and late Korean (L1)-English (L2) bilinguals is investigated. It is predicted that early bilinguals are more likely to be native-like in their production of English and Korean stop consonants than late bilinguals, and also that early bilinguals have more independent stop systems for their two languages than late bilinguals.

TABLE I. Korean stop consonants.

	Bilabial	Alveolar	Velar
Aspirated	p^h	t^h	k^h
Lenis	p	t	k
Fortis	p^*	t^*	k^*

II. THE STOP CONSONANTS OF KOREAN AND ENGLISH

The consonant system of the Korean language contrasts three types of stops. All three are voiceless in word-initial position, but differ from each other in terms of degree of aspiration and quality of the following vowel. The first type, referred to as *aspirated*, is generally described as strongly aspirated. The second type, referred to as *lenis*, is generally described as slightly aspirated with an onset of breathy phonation in the following vowel. The third type, referred to as *fortis*, is generally described as unaspirated, with an onset of tense phonation in the following vowel. All three stop types occur at three places of articulation: bilabial, alveolar, and velar. Table I presents these stop consonants. The voiceless fortis stops are designated with the diacritic " * " and the voiceless lenis stops are left unmarked, following the con-

ventions used by Cho, Jun, and Ladefoged (2002) and Kim, Beddor, and Horrocks (2002).

Acoustic characteristics of these stops have been well documented in numerous studies. First, regarding voice-onset time (VOT), it has been reported that mean VOT values in word-initial position are shortest for fortis, longer for lenis, and longest for aspirated stops: 15–40, 50–70, and 80–120 ms, respectively (e.g., Cho *et al.*, 2002; Han and Weitzman, 1970; Kim, 1965; 1994; Lisker and Abramson, 1964; Silva, 1992). However, recent work by Silva and colleagues (Silva, 2002; Silva, Choi, and Kim, 2004) suggests that younger Korean speakers may be shortening the VOT for aspirated stops, such that the VOT is similar to lenis stops.

As for the relative difference in amplitude across first harmonic (H1) and higher harmonics (H2 and above) at the onset of a following vowel, lenis and aspirated stops show greater values than fortis stops (Ahn, 1999; Cho *et al.*, 2002; Kagaya, 1974). Generally, the values for lenis and aspirated stops are positive, and negative for fortis stops. This difference indicates that vowels following lenis and aspirated stops are produced with a more breathy quality and vowels following fortis stops are produced with a more creaky quality.

As for *F*0, it is generally agreed that *F*0 at the onset of the following vowel is lowest for lenis, higher for fortis, and highest for aspirated stops (Kim *et al.*, 2002). Ahn (1999), Cho *et al.* (2002), and Shimizu (1996) found that *F*0 for lenis stops was significantly lower than aspirated and fortis stops.

English contrasts two stop categories: voiceless and voiced stops. These categories are reliably differentiated by VOT word initially. For example, Klatt (1975) reported the average VOT of 61 ms for English voiceless stops and 18 ms for voiced stops in stressed monosyllabic words. Lisker and Abramson (1964) also found a great difference between English voiceless (about 80 ms) and voiced (about 15 ms) stops (see also Flege and Eefting, 1986, 1988; Williams, 1977).

As for the H1-H2 measure of the initial portion of the vowels following stops, Ahn (1999) found significantly greater values (a more breathy phonation) for English voiceless stops than English voiced stops. A normalized H1-H2 difference showed a significant difference during the first 1/4 of the total length of the vowel.

As in the case of Korean stops, there are some studies suggesting that *F*0 difference at the onset of the following vowel may play an important role in differentiating English voiceless stops from English voiced stops: *F*0 at the onset of the following vowel is higher for aspirated voiceless stops than for voiced stops (Abramson and Lisker, 1985; Lehiste and Peterson, 1961; Ohde, 1985; Shimizu, 1996).

When investigating age of learning effects in the production of stop consonants, previous studies have mostly considered a single phonetic property, namely VOT (e.g., Flege, 1991; Harada, 2003; Kehoe *et al.*, 2004; Khattab, 2002, 2003; MacKay *et al.*, 2001, with the notable exception of Sundara *et al.*, in press). As described above, Korean stops exploit multiple acoustic cues, such as VOT, voice quality of the following vowel (as indexed by H1-H2 difference), and fundamental frequency of the following vowel (*F*0). Accordingly, the present study measured these various acoustic properties for Korean and English stop consonants.

Also, previous studies have investigated VOT production of bilinguals whose two languages differed in that one of the languages had stops with lead voicing and the other did not (e.g., Khattab, 2002 for English and Arabic, and Kehoe *et al.*, 2004, for German and Spanish). In contrast with these studies, the current study examines two stop systems, both with primarily lag voicing on stops. English voiceless stops and Korean aspirated and lenis stops fall into the category of long-lag VOT, and English voiced stops and Korean fortis stops fall into the category of short-lag VOT. Thus, the current study examines language learners who need to partition their VOT range in a fine-grained way if they are to accommodate Korean and English stops.

III. METHODS

A. Participants

The data were collected from 40 adult participants. None of the participants reported being diagnosed with a language or reading disorder. All participants passed a pure-tone hearing test in both ears from 500 to 4000 Hz at octave intervals (38 at 20 dB and 2 at 25 dB). The participants were divided into four groups of 10 each: native monolingual speakers of English (NE group), native monolingual speakers of Korean[1] (NK group), early Korean-English bilinguals (Early group) and late Korean-English bilinguals (Late group). The NK and the bilingual groups all consisted of 7 female and 3 male participants, and the NE group consisted of 6 female and 4 male participants. The English monolinguals were students or affiliates of the University of Oregon (mean age =28.8 years). The Korean monolinguals were all students at the American English Institute at the University of Oregon who had lived, at the time of the experiment, in an English-speaking country for less than 5 months (mean age =24.8 years).

The bilingual participants all spoke Korean as their first language and had lived in the United States for at least 6 years. The Early group had begun learning English between 1 and 6 years, typically when they started school or preschool ($M=3.8$ years). The age of acquisition for the Late group ranged from 15 to 34 years old and was determined by age of first massive exposure to English when they moved to the United States ($M=21.4$ years). Even though the Late group had some exposure to English in middle school and high school in Korea, they had received very limited exposure to native English speakers. Speakers in both bilingual-groups used English regularly on a daily basis at the time of the study.

Although the two groups of bilinguals differed from each other principally in the age at which they were first immersed in English, the two groups differed in other ways as well. The Late group was older at the time of testing (31 vs 20 years) and used English less overall on a daily basis according to self-report (54% vs 81%). Also, their average length of residence in the U.S. was shorter than the Early group, although both groups had been in the U.S. for a considerable amount of time (9.8 vs 18.2 years).

TABLE II. Korean stops recorded for acoustic measurements.

Aspirated	Lenis	Fortis
/p^{h}ɑtɑ/ "to dig"	/pɑtɑ/ "sea"	/p*ɑtɑ/ "to grind"
/t^{h}ɑtɑ/ "to ride"	/tɑto/ "tea ceremony"	/t*ɑtɑ/ "to pick"
/k^{h}ɑdɨ/ "card"	/kɑtɑ/ "to go"	/k*ɑtɑ/ "to peel"

As the goal of the present study was to compare early and late bilinguals, and early bilinguals were likely to be highly proficient in English, it was critical to recruit late bilinguals who were also highly proficient in English. To this end, bilinguals who had long lengths of residence (at least 6 years in the U.S.) and high levels of education (all had at least some college education in the U.S.) were recruited. In addition to this, a standardized test of English proficiency, the Test of Adolescent and Adult Language (TOAL), was administered to the bilinguals. This test was chosen because it was designed to test highly proficient English speakers at adult levels (Hammill *et al.*, 1994). Two of the TOAL subtests, those focusing on listening vocabulary and listening grammar, were administered and scores were recorded as number correct from a low of zero to a high of 35. Performance on the tests was comparable between the two bilingual groups. There was no significant difference between the two bilingual groups for the TOAL Test 1 (25.0 vs 21.1) $[F(1,18)=2.3, p>0.05]$ or Test 2 (27.2 vs 25.3) $[F(1,18)=0.51, p>0.05]$.

B. Speech material

Due to the cross-linguistic nature of this study, the target sounds, English voiceless and voiced stops, and Korean voiceless aspirated, lenis, and fortis stops, were matched for phonological environment in the words to be analyzed: utterance initial, and preceding a low vowel /ɑ/. Tables II and III present the word lists in a phonemic transcription.

Each target word was presented on a flashcard in the orthography of each language in two ways. First, to help facilitate the understanding of the meaning of the words and thus, to record production of known words, a sentence contextualizing the target word was presented. (For example, the contextualizing sentence for "pot" was "We made soup in the pot.") Second, in order to record the target words in a constant prosodic environment, each word was presented in a carrier sentence in an utterance initial position. The English carrier sentence was "__*is the word*," and the Korean one was "[__hɑsɛjo]." ("Say__"). The words in the carrier sentences were analyzed.

Each of the participants was recorded using a high-quality, head-mounted microphone and a Sony DAT recorder in a sound-attenuated room. The speakers read the cards three times in randomized blocks, three for each language (stop types were mixed within each block). The two groups of Korean-English bilinguals (Early and Late) first read the English cards three times and then the Korean cards three times. As control groups, the NE group and the NK group read the English and the Korean cards, respectively. A total of 1350 word productions was analyzed (9 Korean words $\times 3$ repetitions $\times 10$ participants $\times 3$ groups and 6 English words $\times 3$ repetitions $\times 10$ participants $\times 3$ groups).

TABLE III. English stops recorded for acoustic measurements.

Voiceless	Voiced
/p^{h}ɑt/ "pot"	/bɑt/ "bot"
/t^{h}ɑt/ "tot"	/dɑt/ "dot"
/k^{h}ɑt/ "cot"	/gɑt/ "got"

The participants were instructed, in English, to read the cards at a comfortable speaking rate and loudness level and to repeat any utterance when they were unsatisfied with their production. Before the recording session began, speakers were given a chance to rehearse the cards. All speakers reported familiarity with the target words. The utterances were digitally recorded at a sampling rate of 32 000 Hz and digitally transferred to a personal computer as wave files with the same sampling rate using the Kay Elemetrics's COMPUTERIZED SPEECH LAB (CSL). The acoustic measurements were performed using PCQUIRER by SCICON, a speech analysis program.

C. Measurements

1. Voice-onset time (VOT)

The VOT of the initial stop in each target word was measured to the nearest 1 ms from the beginning of the stop-burst release to the onset of the periodic portion of the waveform. The onset of the vowel in the waveform was determined by the onset of the first full glottal pulse of the vowel. The onset of the voicing energy in the second formant shown in a time-locked spectrogram was used to help determine voicing onset in conjunction with the waveform. In the few productions with prevoicing, the VOT was measured as a negative number as the time interval between the onset of periodic pulsing during the closure up to the stop release (Lisker and Abramson, 1964). As is common practice in VOT studies (Lisker and Abramson, 1964; MacKay *et al.*, 2001), the negative values for occasional prevoiced stops were not included in calculating the mean VOT values for a given stop type. The English voiced stops were prevoiced by the NE group 17% of the time and the Early and the Late groups 3% and 0% of the time, respectively. Other stop types were not prevoiced by any of the groups.

2. H1-H2 difference

The amplitudes (dB) for the first (H1) and the second (H2) harmonics were measured at the beginning of the vowel. A Hamming window was centered after the first full glottal pulse in the waveform and a narrow-band FFT spectrum (1024 points) was calculated. Zero padding was used to smooth the spectral peaks. The difference in intensity between H1 and H2 is thought to be an indicator of voice quality (Cho *et al.*, 2002). Breathy voicing is characterized by relatively more energy in the fundamental frequency (measured as H1), with a steep falling off in spectral slope. On the other hand, creaky voicing is produced with relatively more energy in H2 and the higher harmonics. Thus, a greater H1-H2 difference would indicate a more breathy voicing

quality, and a smaller or negative H1-H2 difference would indicate a more creaky quality of the voicing. The values submitted to the statistical analyses were obtained by subtracting the values of H2 from values of H1.

The amplitudes of H1 and H2 are affected by formant frequencies of the vowel (Fant, 1960). Only low vowels were measured; thus, formant frequencies should be relatively comparable across the data set. However, as place of articulation of the preceding stop varied, the formant frequencies at the vowel onset, especially *F*2, would be affected differently by the transition from the consonant into the stable portion of the vowel (Delattre, Liberman, and Cooper, 1955). Thus, some effect of formant transitions on the H1 and H2 measures would be expected for the data. However, this effect does not pose a serious problem to the data analysis presented here: All comparisons had equal numbers of tokens for the three places of articulation in each of the groups being compared. In other words, the effect of formant transitions likely introduced some variance in the data, but the variance was introduced equally for each group being compared.

Another consideration about the H1 and H2 measures relates to gender differences. Studies with English speakers have found that female speakers have a greater difference between H1 and H2 than male speakers, indicating that female speakers tend to have more breathy voicing (Hanson and Chuang, 1999; Klatt and Klatt, 1990). Thus, the female speakers in the current study may have greater H1-H2 values than the male speakers. However, as roughly equal numbers of male and female speakers were included for each of the four participant groups (4/6 for one and 3/7 for the other three), gender differences should not confound comparisons between the groups.

3. Fundamental frequency (F0)

The effect of consonant type on the fundamental frequency (*F*0) of the following vowel was also measured. Due to the common occurrence of irregular glottal pulses from creaky voicing after Korean fortis stops, reliable measures for *F*0 at vowel onset were not possible. Therefore, the effect of a consonant on the following vowel's *F*0 was estimated by taking a measure at vowel midpoint. By vowel midpoint, the creaky voicing found for Korean fortis stops had subsided and it was possible to obtain reliable *F*0 measures.

Fundamental frequency was measured at the temporal midpoint of the vowel by obtaining the frequency of the first harmonic from a narrow-band FFT spectrum (1024 points). The frequency of the glottal pulse at the temporal midpoint of the vowel was also obtained by measuring the duration of the relevant period in milliseconds and dividing it into 1000. This measure was checked against the frequency measured for the first harmonic. When the measures differed, the hand-measured frequency was recorded.

Because *F*0 varies according to each individual, especially across age and gender groups, the measured raw *F*0 values for each participant were normalized. Each *F*0 value produced by a given participant was divided by the mean value of all the midpoint measurements for that participant. Mean values were obtained separately for English stops (voiceless, voiced) and for Korean stops (aspirated, lenis, fortis). Thus, a normalized value more than 1 represents a *F*0 higher than the mean *F*0 for that speaker for that language, and a value less than 1 represents a lower *F*0 than the mean *F*0 for that speaker for that language. These normalized *F*0 values were used for between-group analyses. However, the raw *F*0 values were used for within-group analyses, in which stops produced by the same individuals were compared.

IV. RESULTS

In order to examine age of learning effects on segmental production of English and Korean stops and to examine the interaction of the English and Korean stop systems, two kinds of analyses were conducted. First, between-group analyses were carried out for English and Korean stops separately to investigate differences between the monolingual groups and the early and late bilingual groups in the production of English and Korean stops. Two separate analyses were performed, one for English stops and one for Korean stops. Second, within-group analyses were performed to examine how the stop systems of the two languages were organized in the bilinguals. In these analyses, the difference between the early and late bilinguals in the extent to which the stop systems were held independent from each other was investigated. The alpha level is set at 0.05 for the statistical tests reported here unless otherwise indicated, as in the case of multiple comparisons.

Table IV presents the mean values of the Korean and English stops by group for the acoustic measures analyzed here. The measures of VOT, H1-H2, and normalized *F*0 will be examined in between-group comparisons and the measures of VOT, H1-H2, and raw *F*0 will be examined in within-group comparisons.

A. Age of learning effects on the production of English stops: Between-groups analysis

The results of a three-way, group (NE, Early, Late) by stop type (English voiceless, voiced) by place (labial, alveolar, velar) multivariate repeated measures analysis with the dependent measures of VOT, H1-H2, and normalized *F*0 returned significant main effects for group $[F(6,294)=5.892, p<0.001]$, stop type $[F(3,147)=353.683, p<0.001]$, and place $[F(6,294)=7.455, p<0.001]$. The analysis also revealed interactions of group × stop type $[F(6,294)=7.165, p<0.001]$ and stop type × place $[F(6,294)=2.352, p=0.031]$. The results indicate that the group effect depended on stop type.

MANOVAs on each stop type returned a significant effect of group for English voiceless stops $[F(6,158)=6.225, p<0.001]$ and for English voiced stops $[F(6,132)=6.804, p<0.001]$ (alpha level was adjusted for two tests, $\alpha=0.025$). Pairwise comparisons conducted separately for the English voiceless and voiced stops revealed differences between the Late and the NE groups. In the case of both the voiceless and voiced stops, the Late group was different from the NE group for all three measures. As can be seen in Fig. 1, the Late group produced the voiceless stops differently from the NE group. As shown in Fig. 1(a), the Late group had

TABLE IV. Mean and standard errors in parentheses for the production of Korean and English stops for four acoustic measures: voice-onset time (VOT), the difference between the first two harmonics at the following vowel onset (H1-H2), raw fundamental frequency of the following vowel midpoint (*F*0raw), and normalized fundamental frequency of the following vowel midpoint (*F*0norm; see Sec. III C 3 for method of calculation). The Korean stops were produced by three groups of ten speakers each: early Korean-English bilinguals (Early), late Korean-English bilinguals (Late), and native monolingual speakers of Korean (NK). The English stops were produced by three groups of ten speakers each: Early, Late, and native monolingual speakers of English (NE). The numbers in each group column header indicate the number of male (first) and female (second) speakers.

Stop type	Measure	Early 3/7	Late 3/7	NK 3/7	NE 4/6
Korean	VOT (ms)	82 (3)	79 (4)	68 (3)	
aspirated	H1-H2 (dB)	2.9 (0.5)	2.7 (0.5)	2.3 (0.5)	
	*F*0raw (Hz)	219 (13)	214 (11)	234 (12)	
	*F*0norm	1.113 (0.011)	1.128 (0.017)	1.119 (0.011)	
Korean	VOT (ms)	67 (3)	61 (4)	63 (4)	
lenis	H1-H2 (dB)	1.7 (0.1)	2.3 (0.8)	1.2 (0.6)	
	*F*0raw (Hz)	166 (8)	160 (8)	173 (8)	
	*F*0norm	0.844 (0.010)	0.851 (0.011)	0.844 (0.010)	
Korean	VOT (ms)	14 (1)	16 (2)	11 (1)	
fortis	H1-H2 (dB)	−1.9 (1.4)	−1.2 (0.9)	−3.6 (1.3)	
	*F*0raw (Hz)	205 (13)	194 (11)	216 (11)	
	*F*0norm	1.042 (0.013)	1.021 (0.016)	1.036 (0.008)	
English	VOT (ms)	77 (4)	86 (4)		72 (3)
voiceless	H1-H2 (dB)	−0.2 (0.6)	2.8 (0.6)		0.2 (0.6)
	*F*0raw (Hz)	170 (10)	193 (11)		167 (9)
	*F*0norm	1.036 (0.011)	1.081 (0.017)		1.021 (0.011)
English	VOT (ms)	17 (2)	19 (2)		14 (1)
voiced	H1-H2 (dB)	−1.6 (0.6)	−0.2 (0.7)		−2.9 (0.4)
	*F*0raw (Hz)	160 (9)	162 (9)		161 (8)
	*F*0norm	0.963 (0.012)	0.918 (0.018)		0.979 (0.008)

longer VOT values, as shown in Fig. 1(b), the Late group had greater H1-H2 values, and as shown in Fig. 1(c), the Late group had higher normalized *F*0 values. The Late group also differed from the NE group in the production of the voiced stops. As shown in Fig. 1(a), the Late group had longer VOT values, as shown in Fig. 1(b), the Late group had greater H1-H2 values, and as shown in Fig. 1(c), the Late group had lower normalized *F*0 values.

The Early group, on the other hand, was not significantly different from the NE group for either English voiceless or voiced stops (Tukey's HSD, $p<0.05$). As can be seen in Fig. 1, the Early group's production of the English stops was similar to the NE group's for the three measures examined.

To summarize, the Late group was different from the NE group in the production of English stops for VOT, H1-H2, and *F*0. For the voiceless stops, the VOT was longer, the following vowel had a greater positive difference between the first two harmonics (more breathy phonation), and the normalized *F*0 was higher. For the voiced stops, the VOT was longer, the following vowel had a smaller negative difference between the first two harmonics (less creaky), and the normalized *F*0 was lower. In contrast, the Early group was not different from the NE group for either English voiceless or voiced stops.

B. Age of learning effects on the production of Korean stops: Between-groups analysis

The results of a three-way, group (NK, Early, Late) by stop type (Korean aspirated, lenis, fortis) by place (labial, alveolar, velar) multivariate repeated measures analysis with dependent measures of VOT, H1-H2, and normalized *F*0 returned significant main effects for group [$F(6,482)=3.182, p=0.005$], stop type [$F(6,482)=383.125, p<0.001$], and place [$F(6,482)=9.761, p<0.001$]. There was no interaction between these factors ($p>0.05$). These results indicate that the groups differed from one another in their production of Korean stops in a consistent manner across stop type. To address the research question of whether there were differences in the production of Korean stops by age of English acquisition, planned comparisons investigating the effect of group for each stop type were conducted.

MANOVAs on each stop type returned a significant effect of group for Korean fortis stops only [$F(6,158)=4.607, p<0.001$]. The effect of group was not significant for the aspirated and lenis stops (alpha level was adjusted for three tests, $\alpha=0.016$). Pairwise comparisons (Tukey's HSD tests, $p<0.05$) investigating the three measures separately for the Korean fortis stops revealed a difference between the groups for VOT only. The Late group produced the fortis stops with longer VOT values than the NK group. As can be seen in Fig. 2(a) on the right-hand side, the VOT produced by the Late group for the fortis stops was only slightly longer, but the difference was significant. Although there was not a significant effect of group for the MANOVA investigating the Korean aspirated stops, as can be seen in Fig. 2(a) left-hand side, both the Early and Late groups tended to have longer VOT values than the NK group. On the other hand,

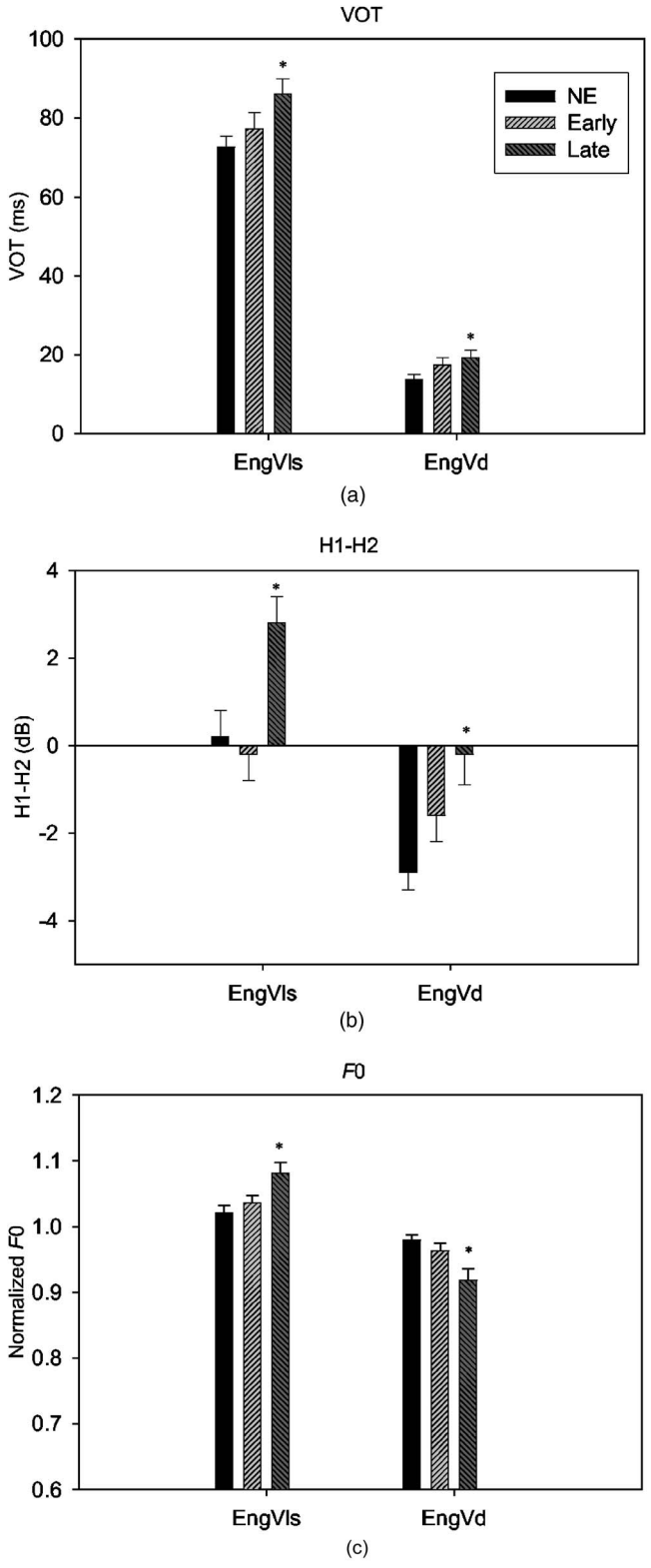

FIG. 1. Mean values with standard errors for the production of English stops (voiceless and voiced) for three acoustic parameters [(a) VOT; (b) H1-H2; (c) normalized *F*0] by three groups of ten speakers each (NE, early bilinguals, and late bilinguals). *=statistically different from the NE group.

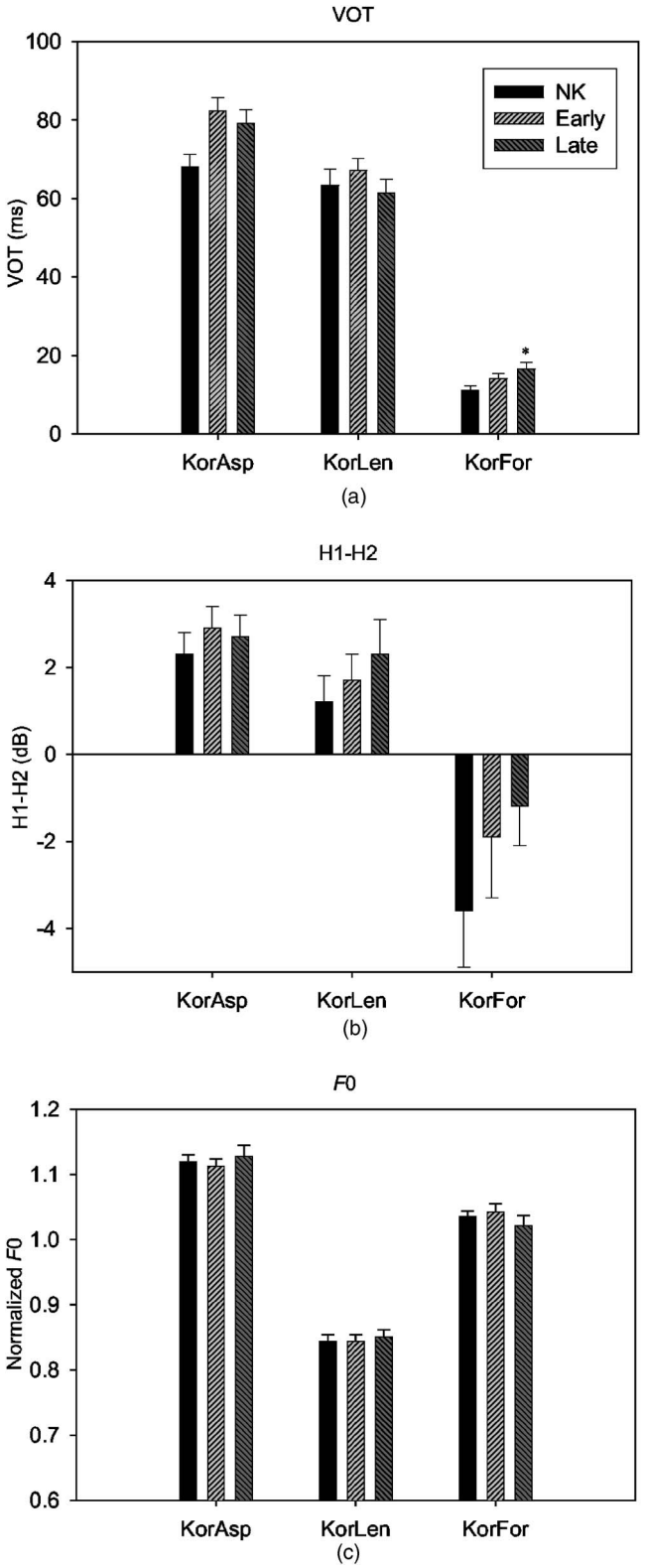

FIG. 2. Mean values with standard errors for the production of Korean stops (aspirated, lenis, and fortis) for three acoustic parameters [(a) VOT; (b) H1-H2; (c) normalized *F*0] by three groups of ten speakers each (NK, early bilinguals, and late bilinguals). *=statistically different from the NK group.

there was no significant difference between the three groups for the H1-H2 and normalized *F*0 measures for any of the three stop types. As can be seen in Fig. 2(b), there were no clear group differences for the H1-H2 measure. As can be seen in Fig. 2(c), there was very little difference between the groups for the normalized *F*0 values.

C. Age of learning effects on the degree of independence between English and Korean stop systems: Within-group analyses

This section addresses the question of whether age of learning differences between early and late bilinguals affect

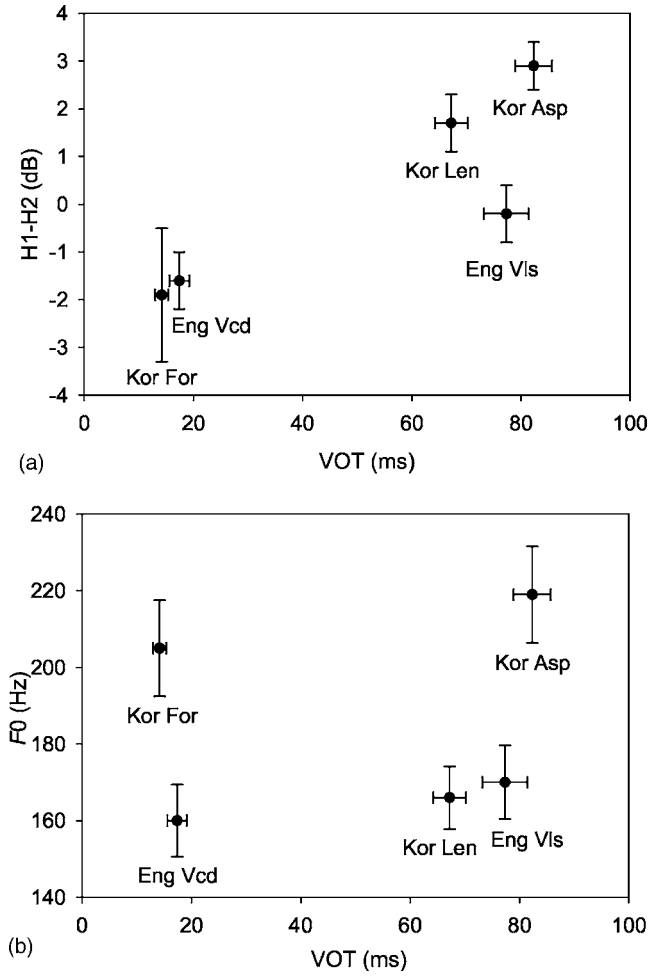

FIG. 3. The early bilingual group's production of English (voiceless, voiced) and Korean (aspirated, lenis and fortis) stops. Mean values with standard errors for three acoustic parameters (VOT, H1-H2, raw *F*0). The values for H1-H2 and VOT are shown in (a) and *F*0 and VOT are shown in (b).

the extent to which their two phonological systems are held independent from each other. To this end, the grouping patterns of the five stop categories of Korean and English were examined as a function of age of learning. For each group, ten pairwise comparisons were made: one comparison for the English stop types, three comparisons for Korean stop types, and six combined comparisons for English and Korean stop types. The results of this analysis indicate the number of independent stop types for each group.

1. Early group

Ten multivariate pairwise comparisons (i.e., all possible combinations of the English and Korean stops) with the dependent variables of VOT, H1-H2, and raw *F*0 were made. For the Early group, all ten comparisons were significantly different ($p \leqslant 0.005$, alpha level was adjusted to 0.005 for ten tests). These results suggest that the English and the Korean stop categories were separated from one another within their own stop systems and, at the same time, the five stop categories of Korean and English were all separated from one another.

Figure 3 displays the VOT, H1-H2, and raw *F*0 values for the five stops produced by the Early group (see Table IV for exact values). The three Korean stops are clearly distinguished from each other by the three measures. In Fig. 3(a), note that the three Korean stops are well-distinguished from each other in terms of VOT (horizontal axis) and that the Korean fortis stops are set apart in terms of H1-H2 (vertical axis). In Fig. 3(b), note that the Korean lenis stops have a much lower *F*0 (vertical axis) than the other two Korean stops. Moving to the English stops, as shown in Fig. 3(a), the two English stops are distinguished from each other primarily by VOT, and secondarily by H1-H2. As shown in Fig. 3(b), the English stops are not well-differentiated by *F*0. As for the Korean-English stop comparisons, the Korean fortis stops, as shown in Fig. 3(b), are primarily distinguished from the English voiced stops by *F*0. The Korean aspirated stops, as shown in Figs. 3(a) and 3(b), are distinguished from English voiceless stops by H1-H2 and *F*0. The Korean lenis stops, as shown in Fig. 3(a), are distinguished from the English voiceless stops primarily by H1-H2 and secondarily by VOT.

In summary, the Early bilingual group had five distinct stop types in their combined Korean English systems. English voiceless, English voiced, Korean aspirated, Korean lenis, and Korean fortis stops each formed a group that could be statistically distinguished from the other stop types.

2. Late group

The multivariate pairwise comparisons with the dependent variables of VOT, H1-H2, raw *F*0 for the Late group revealed no significant differences between the English voiced and Korean fortis stops and between the English voiceless and Korean aspirated stops. The other eight comparisons returned significant differences for the pairing of the other stop types ($p < 0.005$). These results suggest that, in the stop system of the late bilinguals, the English stop categories are distinguished from each other and the Korean stops are also distinguished from each other. However, the English voiced and Korean fortis stops, on the one hand, and the English voiceless and Korean aspirated stops, on the other hand, are not separated from each other.

Figure 4 displays the VOT, H1-H2, and raw *F*0 values for the five stops produced by the Late group (see Table IV for exact values). The three Korean stops are clearly distinguished from each other by the three measures. As shown in Fig. 4(a), the Korean fortis stops have lower H1-H2 values than the other Korean stops and all three Korean stops are distinguished by VOT. As shown in Fig. 4(b), the Korean lenis stops have a lower *F*0 than the other Korean stops. The two English stops are also clearly distinguished from each other by the three measures: The English voiced stops have lower H1-H2 and VOT values [see Fig. 4(a)], as well as lower *F*0 values [see Fig. 4(b)].

In contrast, the Korean aspirated stops are not well-distinguished from the English voiceless stops by any of the three measures. Note the very close H1-H2 and VOT mean values in Fig. 4(a) and overlapping distributions of *F*0 values in Fig. 4(b). The Korean fortis and English voiced stops, though not significantly different from each other in the MANOVA reported above, do exhibit some separation with

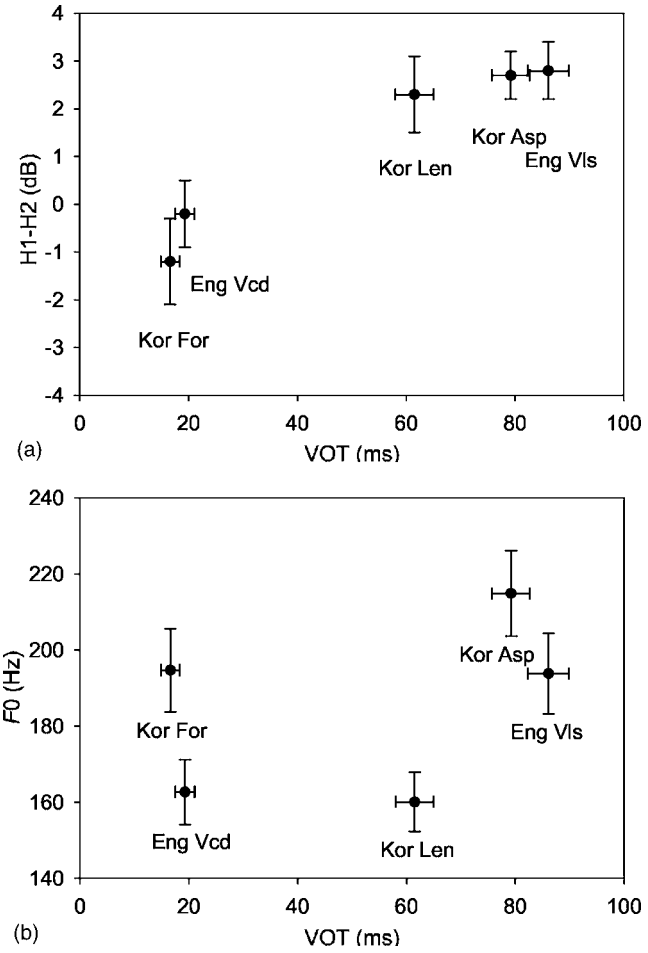

FIG. 4. The late bilingual group's production of English (voiceless, voiced) and Korean (aspirated, lenis and fortis) stops. Mean values with standard errors for three acoustic parameters (VOT, H1-H2, raw *F*0). The values for H1-H2 and VOT are shown in (a) and *F*0 and VOT are shown in (b).

regard to *F*0 [see Fig. 4(b)]. Specifically, the English voiced stops have lower *F*0 values, which are similar to the Korean lenis stops. Thus, the English voiced stops are similar to the Korean fortis stops in terms of VOT and H1-H2 [see Fig. 4(a)] but similar to the Korean lenis stops in terms of *F*0.

In summary, the Late bilingual group had three distinct stop types in their combined Korean-English systems. English voiceless and Korean aspirated stops formed one group. English voiced and Korean fortis stops formed another group, though demonstrating a trend towards different *F*0 values. Finally, the Korean lenis stops formed a group by themselves.

V. DISCUSSION

The results reported here suggest that there exist age of learning effects between the early bilinguals and the late bilinguals in the production of English and Korean stops and in the extent of independence between the Korean and English stop systems. The early bilinguals were not different from the English monolinguals for either English voiced or voiceless stops, nor were they different from the Korean monolinguals for any of the three Korean stops. At the same time, the early bilinguals maintained five distinct stop types in their stop systems (see Fig. 3). Thus, the early bilinguals seem to have established English voiced and voiceless stop categories independent from the Korean stop categories. In other words, there was no apparent interaction between the L1 and L2 stop system, as all productions were monolingual-like.

In contrast, the late bilinguals produced English voiceless and voiced stops differently from English monolinguals in terms of VOT, as well as H1-H2 and *F*0 of the following vowel. They also produced Korean fortis stops slightly differently from Korean monolinguals in terms of VOT. Whether or not these differences are perceptually salient to native monolingual speakers of the respective languages is an open question. Further research will be needed to make this determination. Nonetheless, the productions of the late bilinguals were found to be significantly different from monolingual speakers in this investigation.

Thus, the late bilinguals were found to produce both English and, to a lesser extent, Korean stops differently than monolingual speakers. At the same time, the late bilinguals had fewer distinct stop types in their combined Korean-English stop system. Their Korean aspirated and English voiceless stops were not distinguished from each other in production by any of the three acoustic measures (see Fig. 4). Their English voiced stops did not form a distinct category, but exhibited similarities with both the Korean fortis and lenis stops (see Fig. 4).

The apparent merger between Korean aspirated and English voiceless stops did not seem to influence the production of Korean aspirated stops, but did seem to influence the production of English stops. As can be seen in Fig. 1 and Table IV, the English voiceless stops produced by the late bilinguals had longer VOT values (86 ms) than the English monolinguals (72 ms), a greater difference between the first two harmonics of the following vowel (2.8 dB) than the English monolinguals (0.2 dB), and higher normalized *F*0 values of the following vowel (1.08) than the native English monolinguals (1.02). The values for the late bilinguals' English voiceless stops were similar to the values for their Korean aspirated stops (VOT 79 ms, H1-H2 2.7 dB, and normalized *F*0 values 1.12; see Fig. 2). Additionally, the late Korean bilinguals did not produce Korean aspirated stops differently from the Korean monolinguals. Thus, it seems that the late bilinguals were using their Korean aspirated stops when speaking English. The L1 category seemed to be used for both the L1 and L2, with no effect on L1 pronunciation.

The status of English voiced stops produced by the late bilinguals is not as clear as the status of voiceless stops. While it seems likely that the late bilinguals had transferred the production characteristics of Korean aspirated stops to English voiceless stops, this same group's production of English voiced stops is not fully equivalent to either Korean fortis or Korean lenis stops (see Fig. 4). On the one hand, the values for VOT and H1-H2 of the following vowel are similar for English voiced and Korean fortis stops (19 vs 16 ms and −0.2 vs −1.2 dB, respectively). On the other hand, the values for *F*0 of the following vowel are similar for English voiced and Korean lenis stops (162 vs 160 Hz, respectively).

The incorporation of the English voiced stop into the phonological system of the late bilinguals may have influ-

enced the production of the Korean fortis stops. The late bilinguals produced Korean fortis stops differently from the Korean monolinguals. The longer VOT found for the Korean fortis stops produced by the late bilinguals (16 ms) is more like the VOT of English voiced stops produced by the English monolinguals (14 ms) than that produced for the Korean fortis stops by the Korean monolinguals (11 ms).[2]

The finding that the late bilinguals had merged L1 and L2 stops to varying degrees can be interpreted in light of models of L2 speech learning. Theoretical models have addressed the role of perceptual similarities between L1 and L2 sounds in second language speech learning. The Speech Learning Model (SLM) (Flege, 1995) posits that the greater the perceived phonetic distance between an L2 and L1 segment, the more likely that differences between these segments will be discerned and, thus, the more likely that an independent phonetic category for the L2 sound will eventually be established. Alternatively, if instances of an L2 category continue to be identified as instances of an L1 category, a "merged" category may develop over time. Similarly, the Perceptual Assimilation Model (PAM) (Best, 1995a, 1995b) predicts that some L2 segments will be more easily distinguished than others and that differences in similarity may ultimately affect L2 speech learning.

In a cross-language mapping experiment, Schmidt (1996) investigated Korean speakers' identification of English consonants in terms of Korean consonant categories. The study revealed that the native Korean speakers consistently labeled English voiceless stops as Korean aspirated stops with high similarity ratings. It also revealed that English voiced stops were labeled with roughly equal frequency as both Korean lenis stops and fortis stops and had lower similarity ratings than those between Korean aspirated and English voiceless stops. Thus, considering the findings of the present study, these cross-language mapping patterns may provide an explanation for the differences in acquisition of English voiceless and voiced stops for the late bilinguals. As mentioned earlier, the late bilinguals apparently used Korean aspirated stops to produce English voiceless stops. In the case of English voiced stops, their production was similar to their Korean fortis stops in terms of VOT and H1-H2 of the following vowel but similar to Korean lenis stops in terms of *F*0 of the following vowel. The apparent merger of the Korean aspirated stops and English voiceless stops may be because the late bilinguals identified instances of English voiceless stops as Korean aspirated stops and, therefore, established a fully merged L1-L2 category with the production characteristics of Korean aspirated stops. The less-complete merger of English voiced stops with any single Korean stop type may be due to a less-clear cross-language mapping between English voiced stops and a single Korean stop type. In other words, since the L2-L1 mapping for English voiced and Korean stops was of a two-category type (Best, 1995b), in that English voiced stops were mapped to both Korean fortis and Korean lenis stops, a fully merged category was not developed. Instead, English voiced stops may have developed as something of a hybrid between the two Korean stop types.

Let us now turn to the finding that the early bilinguals maintained independence between their two stop systems, whereas the late bilinguals evidenced a merger between the systems. Previous research has suggested that the degree of separation between the languages may be affected by age of L2 acquisition. Increased delays in L2 exposure have been related to increased influence between the L1 and L2 phonological systems. It has been well demonstrated that later learners show more L1 effects on L2 in segmental speech production than early learners (e.g., Flege, 1991; MacKay *et al.*, 2001; Piske *et al.*, 2002). Additionally, emerging evidence suggests that earlier bilinguals may have greater independence between their two phonological systems than late bilinguals. Later bilinguals may be more likely to merge L1 and L2 phonetic categories, whereas earlier bilinguals may be more likely to acquire new categories for the L2 (Flege, 1987a, 1987b, 1995).

However, the extent to which the two phonological systems of early bilinguals are separated is still not clear. Three previous studies have found non-monolingual-like production of either the L1 or L2 that was attributed to dissimilatory effects in a combined L1-L2 phonological system. Guion (2003) found that early bilinguals demonstrated an effect of the combined L1 and L2 systems on the production of L1 vowels in Quichua-Spanish bilinguals. Flege *et al.* (2003) also found an influence of the combined L1 and L2 systems on the production of L2 vowels in early Italian-English bilinguals. Finally, Harada (2003) found an effect on L1 stop production in early Japanese-English bilinguals that could be attributed to a mutual interaction of the L1 and L2 systems. On the other hand, in the current study, the early Korean-English bilinguals' stop production evidenced no influence from either language. In other words, they produced both the L1 and L2 stops like the monolingual speakers. There was no evidence of any sort of dissimilation between the stops in a combined L1-L2 system.

Given the results of the Guion (2003) study that early but not simultaneous bilinguals showed effects of merged phonological systems, the prediction was made that the younger the L2 learner, the more likely it would be for independent phonological systems to be developed. The early learners in the current study had an earlier age of acquisition than the early learners in the three studies mentioned above. In the current study, the average age of acquisition was 3.8 years (range 1–6). The early bilinguals reported by Guion had an average age of acquisition of 5.8 years (range 5–7). The early bilinguals reported by Flege *et al.* (2003) had an average age of acquisition of 7 years (range 2–13). The early bilinguals reported by Harada (2003) had an average age of acquisition of 5 years (range 4–6) (Harada, 2005 p.c.). Thus, the discrepancy between the current study and those reported previously may be due to variation in age of acquisition. Perhaps the onset of second language acquisition by the bilinguals in this study enabled the development of more fully independent phonological systems than was the case for the later onset of second language acquisition in the other studies.

A likely explanation for age effects on the separation of the L1 and L2 phonological systems may be found in an

"emergentist" view developed for general second language acquisition. As summarized in Hernandez, Li, and MacWhinney (2005), an "emergentist" model predicts that the degree of separation between a bilingual's languages is related to the development, or entrenchment, of the first language and how that entrenchment affects the acquisition of a second language. An entrenched language exhibits the property of resonance. In other words, a given language form can activate other language forms within the same language in a resonant interaction. When a new language is being learned, it is dependent on the L1 in a parasitic way in that it resonates with the L1. If the L2 is to be fully independent, it will have to set up its own language-internal resonance and not interact with the L1. It is proposed that the ability to set up a new resonant system is affected by the level of entrenchment of the first language. Thus, it is predicted that earlier, balanced bilinguals should have greater levels of separation between their two languages than later bilinguals.

The findings of the present study are consistent with these predictions. The early bilinguals established L2 phonetic categories for English stops independently from Korean stops, whereas the late bilinguals had merged categories of Korean and English stops. Thus, the findings of the present study suggest that age-related differences in the establishment, or entrenchment, of the L1 may affect the reorganization process of bilinguals' phonological systems.

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[1]The monolingual Korean had studied English in middle school and high school in Korea. However, they never used English on daily basis and did not have a functional command of English.

[2]The bilingual groups also tended to have longer VOT for Korean aspirated stops than the monolingual group. It is unclear, however, if this tendency is related to the acquisition of English. Silva (2002; 2004) has reported that young Korean speakers, such as those recorded for our Korean monolingual group, have shortened the VOT produced for aspirated stops. Further investigation with older monolingual speakers of Korean, who maintain longer VOT for aspirated stops, is warranted before drawing any conclusions.

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