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Effects of Sound Change on the Weighting of Acoustic Cues to the Three-Way Laryngeal Stop Contrast in Korean: Diachronic and Dialectal Comparisons

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Abstract

Both segmental and suprasegmental properties of the South Kyungsang dialect of Korean have changed under the influence of standard Seoul Korean. This study examines how such sound change affects acoustic cues to the three-way laryngeal contrast among Korean stops across Kyungsang generations through a comparison with Seoul Korean. Thirty-nine female Korean speakers differing in dialect (Kyungsang, Seoul) and age (older, younger) produced words varying in initial stops and lexical accent patterns, for which voice onset time and fundamental frequency (F0) at vowel onset were measured. This study first confirms previous findings regarding age and dialectal variation in distinguishing the three Korean stops. In addition, we report age variation in the use of voice onset time and F0 for the stops in Kyungsang Korean, with younger speakers using F0 more than older speakers as a cue to the stop distinction. This age variation is accounted for by the reduced lexical tonal properties of Kyungsang Korean and the increased influence of Seoul Korean. A comparison of the specific cue weighting across speaker groups also reveals that younger Kyungsang speakers pattern with Seoul speakers who arguably follow the enhancing F0 role of the innovative younger Seoul speakers. The shared cue weighting pattern across generations and dialects suggests that each speaker group changes the acoustic cue weighting in a similar direction.

Keywords

Korean stop production, sound change, VOT, F0, Kyungsang dialect

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Introduction

The utilization of multiple acoustic cues is language-specific. For example, whereas the voicing contrast in Spanish stop consonants consists of a distinction between lead voice onset time (VOT) and short-lag VOT, the VOT difference is sub-phonemic in English within the [+ voice] category; the short-lag VOT is the primary cue for the [− voice] category in Spanish, but for the [+ voice] category in English. The different phonetic realization of the consonant voicing contrast between the two languages affects the secondary fundamental frequency (F0) cue to the voicing distinction according to its phonological category, such that Spanish short-lag VOT [− voice] stops have a significantly higher onset F0 than English short-lag VOT [+ voice] stops (e.g., Dmitrieva, Llanos, Schultz, & Francis, 2015). Cue weighting patterns also vary across dialects of the same language; for instance, the tense-lax vowel pair /i/-/ɪ/ is primarily distinguished in terms of duration and spectral properties in Southern and Scottish English, respectively (Escudero & Boersma, 2004). The fact that language learners acquire the cue weighting strategies specific to their languages or dialects (e.g, Nittrouer & Burton, 2005) indicates that language experience plays a role in shaping speakers' selective reliance on multiple acoustic cues.

The purpose of this study is to elucidate the specific cue weighting across different groups of speakers of the same language in the context of sound change. Specifically, this study examines the effect of age in the use of multiple acoustic cues, VOT and F0, to the three-way laryngeal contrast among voiceless stops in Kyungsang Korean, a dialect whose segmental and suprasegmental features are currently changing. Both external and internal linguistic conditions in Kyungsang Korean lead us to predict age-related differences in the acoustic cue weighting for the stop contrast. First, under the increased influence of Seoul Korean, both phonetic and phonemic properties of Kyungsang Korean have become similar to those of Seoul Korean (Lee, 2008; Lee & Jongman, 2015, 2016; Lee, Jongman & Zhang, 2016). Therefore, under such external language influence it is hypothesized that the specific cue weighting pattern for Kyungsang Korean stops (Lee & Jongman, 2012) might also become similar to that in Seoul Korean. This would reduce the dialectal difference in the use of the multiple acoustic cues to the stop distinction. Second, the dialectal difference in cue weighting is due to the different tonal systems between Seoul and Kyungsang Korean (Lee & Jongman, 2012). However, the changing internal condition of Kyungsang Korean whose tonal system is currently undergoing a sound change also raises the question whether younger speakers use VOT and F0 for the laryngeal distinction in a manner that is similar to older speakers.

Although this linguistic situation in Kyungsang Korean leads us to expect age-conditioned variation in stop contrasts, it is unclear how age factors into the interaction between tonal and segmental properties under the ongoing sound change. Therefore, this study examines how younger Kyungsang speakers maintain the three-way laryngeal contrast among the voiceless stops by testing if and how the changing lexical tonal property of the regional dialect affects speakers' use of multiple acoustic cues in the stop distinction. We compare the acoustic properties of the stops between non-tonal Seoul and tonal South Kyungsang Korean[1] as produced by both conservative older and innovative younger speakers. This sound change in Kyungsang Korean provides an ideal experimental condition to observe speaker-specific cue weighting related to sound change. Accordingly, this investigation will contribute to our understanding of the relationship between sound change in one phonological component (i.e., pitch accent) and acoustic cue weighting in the other component (i.e., laryngeal distinction).

1.1 Dialectal variations in the use of VOT and F0 in the three-way stop contrast between Seoul and Kyungsang Korean

Korean has a typologically rare three-way laryngeal contrast among voiceless stops, namely fortis, lenis, and aspirated stops, occurring at bilabial, alveolar, and velar places of articulation (/p', p, p^h/, /t', t, t^h/, /k', k, k^h/). Although the three-way laryngeal stop contrast has drawn much attention among phoneticians and phonologists due to its typological uniqueness (e.g., Cho, Jun, & Ladefoged, 2002; Han & Weitzman, 1970; Kim, 1965; Kim, Beddor, & Horrocks, 2002; Lisker & Abramson, 1964), researchers have recently focused on the stop contrast for its sound change observed in standard Seoul Korean (e.g., Kang, 2014; Kang & Guion, 2006, 2008; Kim & Duanmu, 2004; Kong, Beckman, & Edwards, 2011; Silva, 2006). Classic studies had identified VOT as the primary cue to the stop distinction, with onset F0 after the stop release, breathiness measured by H1-H2 in the following vowel, and closure duration reported as secondary cues. However, more recent apparent-time studies have consistently shown that whereas the importance of the VOT cue has diminished (e.g., Silva, 2006), that of the F0 cue has increased (e.g., Kang, 2014; Kang & Guion, 2006; Lee, 2016a). Specifically, although the mean VOT value was shortest for the fortis and greatest for the aspirated stop, the VOT difference between the lenis and aspirated stops has decreased over decades. Silva (2006) reported that whereas Seoul Korean speakers born before 1965 showed well-separated VOT values for the three Korean stops, those born after 1965 revealed an overlap in VOT for the lenis and aspirated stops. Kang and Guion (2008) also found overlapping VOT values for aspirated and lenis stops in their conversational condition for younger speakers, but not for older speakers. Despite the overlap in VOT, however, these studies have noted that the F0 distinction across the three stops has increased over time, with significantly lower F0 values after the lenis stop compared to the other two stop categories among younger Seoul speakers. Replicating the earlier findings, Kang (2014) also noted gender-related variation as well as age variation for the Seoul Korean stops. Kang (2014) showed that the enhanced F0 distinction spread further into a phrase and that this effect was stronger for younger female speakers than younger males. The changing roles of VOT and F0 over decades suggested that the phonemic contrast was maintained by the innovative Seoul speakers using different phonetic properties, that is, by enhancing the F0 distinction among the stops while reducing the VOT distinction.

Dialectal variation has also been demonstrated for the relative importance of the VOT and F0 cues in distinguishing the stops (Kenstowicz & Park, 2006; Lee & Jongman, 2012; Lee, Politzer-Ahles, & Jongman, 2013). Unlike standard Seoul Korean that does not use pitch differences to convey lexical meaning, the South Kyungsang dialect of Korean is a pitch accent language where F0 properties differentiate word meaning (e.g., *kaci* (HL) "type," *kaci* (HH) "branch," and *kaci* (LH) "eggplant"). Given the fact that speakers of tonal and non-tonal languages differ in the extent of F0 perturbation due to consonant voicing (e.g., Abramson & Lisker, 1985; Oglesbee, 2008; Francis, Ciocca, Wong, & Chan, 2006; Gandour, 1974; Hombert, 1978), the different tonal systems between Seoul and Kyungsang Korean motivated the previous studies to test if tonal Kyungsang speakers used the VOT and F0 cues in the same way as non-tonal Seoul speakers (Lee & Jongman, 2012; Lee et al., 2013). Lee and Jongman (2012) showed that whereas non-tonal Seoul speakers relied on the combination of the VOT and F0 cues in distinguishing the three stops, tonal Kyungsang speakers relied mainly on the VOT cue. For the Kyungsang speakers, F0 was not a reliable acoustic cue, which was related to the presence of the lexical pitch accent of their dialect. Specifically, although the mean F0 measured after the stop release at vowel onset was highest for the aspirated stop and lowest for the lenis stop, consistent with Seoul Korean, the F0 difference across the three stop categories was less distinct for Kyungsang than Seoul speakers. In addition, a comparison of F0 as a function of the

stop distinction across lexical tonal patterns revealed no difference; that is, F0 between the lenis stop with the HH accent and the fortis stop with the LH accent and between the fortis stop with the HH accent and the aspirated stop with the LH accent was the same. In a follow-up perception study, Lee et al. (2013) confirmed the acoustically observed dialectal variation, reporting that F0 was less important for Kyungsang listeners than for Seoul listeners in identifying the lenis and the aspirated stops. The previous acoustic and perception studies suggested the different tonal systems as important factors for the dialect-specific cue weighting, and argued that the use of F0 for the purpose of contrasting lexical pitch accent words made the F0 cue less reliable for the stop distinction purpose in tonal Kyungsang Korean. Given that the different tonal system between Seoul and Kyungsang Korean is a crucial factor in the dialect-specific cue weighting of VOT and F0 in distinguishing the three-way laryngeal contrast, the ongoing sound change in the lexical tonal properties of Kyungsang Korean casts doubt on the validity of the observed dialect-specific cue weighting, and raises the question if the cue weighting pattern unique to Seoul Korean is maintained across generations of Kyungsang speakers.

1.2 Sound change in Kyungsang Korean

Under increased influence of standard Seoul Korean, phonetic and phonological properties of Kyungsang Korean have shifted toward those of Seoul Korean at both the segmental and suprasegmental levels (Lee, 2008; Lee & Jongman, 2015; Lee, 2016a, 2016b; Lee et al., 2016). The speech of younger Kyungsang speakers who have been exposed to standard Seoul Korean more than older speakers has become similar to Seoul Korean, which makes the dialect-specific cue weighting for the stop contrast doubtful. Given that the contact with other languages is an important factor influencing cue-weighting patterns, younger Kyungsang speakers under greater influence of standard Seoul Korean would be more likely to adopt the cue-weighting strategies of Seoul Korean stops. Along with the influence of Seoul Korean, another important reason to question the dialect-specific cue weighting across Kyungsang generations is the role of age variation observed in the lexical pitch accent of Kyungsang Korean; the F0 scaling and durational properties contrasting Kyungsang's pitch accent words were less distinct for younger speakers compared to older speakers (Lee & Jongman, 2015; Lee et al., 2016). That is, the loss of F0 distinction in contrasting the lexical pitch accent in the speech of younger Kyungsang speakers is another reason to suspect the re-organization of cue weighting in stop contrast by the younger generation.

In South Kyungsang Korean, disyllabic words are contrasted by HL, HH, and LH surface tonal patterns[2] (Chang, 2007, 2008, 2013; Jun, Kim, Lee, & Jun, 2006; Kim & Jun, 2009; Lee, 2008; Lee & Davis, 2009; Lee & Zhang, 2014; Ramsey, 1975; Schuh & Kim, 2007). The location of the high peak distinguishes segmentally similar words; a peak is located in the first and the second syllables for HL and LH words, respectively, and across two syllables for HH words forming a peak plateau. In addition, the three accent patterns also differ in pitch values. That is, both temporal and spectral properties distinguish the lexical pitch accent words of South Kyungsang Korean, similar to other pitch accent languages (e.g., Arvaniti, Ladd, & Mennen, 1998; Bruce, 1977; Chang, 2007; Lee, 2008; Prieto, van Santen, & Hirschberg, 1995; Xu, 1993). In the temporal domain, accent words can be defined by F0 maximum duration (or F0 peak timing), the interval between F0 onset and peak F0, and F0 minimum duration (or F0 fall timing), the interval between F0 onset and minimum F0. In the spectral domain, F0 is characterized by its maximum and minimum values. These four acoustic measurements characterize the HL, HH, and LH disyllabic tonal patterns in Kyungsang Korean; the F0 maximum/minimum duration is longest for LH and shortest for HL (Chang, 2007; Lee, 2008); the F0 maximum/minimum values tend to be greatest for

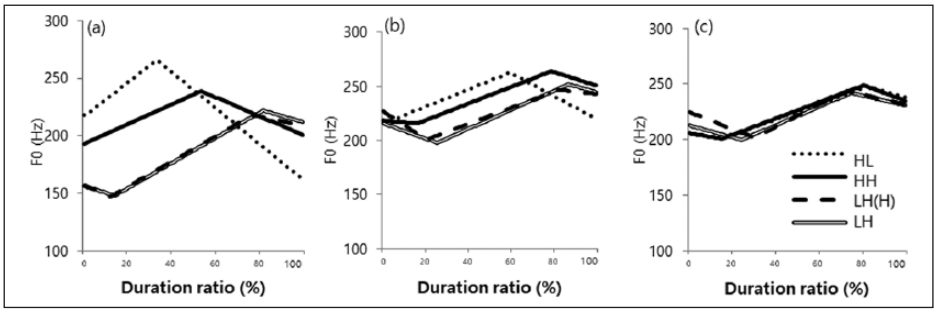

Figure 1. Comparison of schematic pitch contours of disyllabic HL, HH, LH(H), and LH accents in isolation for (a) older Kyungsang, (b) younger Kyungsang, and (c) younger Seoul speakers (adapted from Lee & Jongman (2015): 30).

HL and lowest for LH, although Lee (2008) observed consistent F0 maximum/minimum values across HL, HH, and LH words.

Lee and Jongman (2015), however, showed that younger Kyungsang speakers born after 1988 exhibited phonetic properties for the accent words that differed from those of older speakers born before 1950 and from the previous literature. Figure 1, adapted from Lee and Jongman (2015), illustrates the age variation observed for Kyungsang speech as well as a comparison with (younger) Seoul Korean. Two major findings in Lee and Jongman (2015) were a reduced acoustic distinction across contrastive accent words and a substantial peak delay for all accent types for the speech of younger speakers compared to that of older speakers. Comparing Fig. 1 (b) and Fig. 1 (c), the changed phonetic realization made the disyllabic accent pattern look similar to the prosodic pattern of non-tonal Seoul Korean, which has an LH pattern for disyllabic words.

In Figure 1, older speakers' production of the three contrastive accent words is clearly distinct in both F0 timing and scaling properties, showing the longest and shortest F0 minimum/maximum duration for LH and HL, respectively, and the greatest and smallest F0 minimum/maximum value for HL and LH, respectively. In contrast, the productions of younger speakers are acoustically less distinct compared to the older; the F0 minimum/maximum duration was not significantly different between LH and HH, and the F0 maximum values were not different across three accent patterns, though the F0 minimum value of LH was lower than that of the other two patterns. In addition to the lack of the acoustic distinction, a substantial peak delay is observed for the speech of younger speakers. The peak delay results in consistently locating the peak on the second syllable for HL, HH, and LH words; as a result, the F0 values of the first syllable as a function of accent are less distinct for younger than older speakers.

1.3 This study

The purpose of this study is to explore the interaction between segmental and suprasegmental cues to the three-way laryngeal contrast among the Korean voiceless stops for various speaker groups under sound change. We examine if and how the VOT and F0 cues to the laryngeal contrast are weighted differently between conservative older and innovative younger Kyungsang speakers, and also re-visit age-related variation in the production Seoul Korean stops, which allows us to directly compare cue weighting across the different speaker groups. Given that (a) the lexical pitch accent of Kyungsang Korean, a crucial factor in the dialectal variation in cue weighting, is changing toward the prosody of Seoul Korean, and (b) the phonetic and phonological properties of Kyungsang

Korean are shifting toward Seoul Korean under the increased influence of the standard dialect, it is hypothesized that the younger Kyungsang generation does not have the same cue weighting pattern as the older generations for the laryngeal distinction. Instead, we expect the reliance on the VOT and F0 cues to be similar to those of Seoul Korean speakers. The specific hypotheses regarding the reliance on VOT and F0 as a function of the stop laryngeal distinction in relation to F0 as a function of the pitch accent distinction are as follows.

First, based on Lee and Jongman (2015), we expect that younger Kyungsang speakers make less use of F0 temporal and spectral cues as compared to older speakers to distinguish lexical pitch accent words. With the reduced use of F0 for the purpose of the accent distinction, the use of F0 for the laryngeal distinction is hypothesized to be less affected by the accent classes, and accordingly, F0 would be a more reliable acoustic cue to the laryngeal contrast for the younger speakers than for the older speakers. Second, considering trading relations among multiple cues (Repp, 1982), it is also expected that the importance of the VOT cue differs between the two generations of Kyungsang speakers according to the varying importance of F0 for the stop contrast. If younger Kyungsang speakers rely more on F0 for the stop distinction than older speakers, their reliance on VOT would be smaller compared to older speakers.

2 Methods

2.1 Participants

Thirty-nine female Korean speakers (19 Kyungsang speakers; 20 Seoul speakers) participated in this acoustic study; the Kyungsang speaker group has 9 older and 10 younger speakers, and the Seoul group has 10 older and 10 younger speakers. This study recruited Kyungsang speakers in the city of Pusan where the South Kyungsang dialect of Korean is used, and recruited Seoul speakers in the Seoul metropolitan area where standard Korean is spoken. For both dialectal groups, we included only subjects who were born and educated in the target dialect region, and did not have experience with other dialects for more than one year. For the Kyungsang group, the year of birth ranged from 1936 to 1950 for the older group, and from 1988 to 1992 for the younger group. For the Seoul group, the range was from 1943 to 1950 for the older speakers, and from 1985 to 1993 for the younger speakers. At the time of recording in 2011, the participants' age ranged from 61 to 75 for older Kyungsang speakers (mean = 66.40, *SD* = 5.98) and from 19 to 23 for younger Kyungsang speakers (mean = 21, *SD* = 1.15). For the Seoul group, older speakers ranged from 61 to 68 (mean = 65.8, *SD* = 3.79), and younger speakers ranged from 18 to 26 (mean = 20.7, *SD* = 2.58).

2.2 Speech materials and procedure

Disyllabic nouns including all nine stops in word-initial position were selected. Each of the fortis, lenis, and aspirated stops at bilabial, alveolar, and velar places of articulation also differed in their accent patterns, HL, HH, and LH, providing a total of 27 unique stimulus words (3 laryngeal stops × 3 places of articulation × 3 accent patterns). All initial stops were followed by the low vowel /a/, except for two words, /k^{h}oil/ "coil" and /t^{h}ɨm-i/ "gap." If there was no disyllabic word with an appropriate stop consonant and accent pattern, we used a monosyllabic word followed by the nominative case marker "-i" with the proper accent pattern. Because one of foci of this study is to examine the interaction between the lexical tone and the F0 perturbation due to the laryngeal distinction, we categorized all test words according to tonal Kyungsang Korean. For example, we treated the stimulus /pal-i/ "a foot," which has a HH pitch pattern in Kyungsang Korean, equally between the two dialects, as if Seoul Korean also has the same HH tonal pattern for the word

Table 1. Speech materials.

	HL		HH		LH	
p’	p’aŋ-i	“jail”	p’al-ta	“to suck”	p’alɨm	“being fast”
p	paŋ-i	“room”	pal-i	“foot”	pantal	“a half-moon”
p^h	p^hal-i	“arm”	p^han-i	“board”	p^hacu	a city in Korea
t’	t’akwi	“slap face”	t’al-i	“daughter”	t’alɨm	“following”
t	tak-i	“chicken”	tal-i	“moon”	tali	“leg”
t^h	t^ham-i	“desire”	t^hɨm-i	“gap”	t^hal-i	“mask”
k’	k’aŋ-i	“unyielding courage”	k’aki	“to peel”	k’apul	“naughtiness”
k	kaci	“type”	kaci	“branch”	kaci	“eggplant”
k^h	k^han-i	“partition”	k^hal-i	“knife”	k^hoil	“coil”

/pal-i/. This allowed for consistent acoustic measurements and analyses across the two dialects. The word list used for this study is shown in Table 1.

The subjects in both dialectal and age groups produced the target words in isolation, and read stimuli written in Korean orthography on an index card twice in random order. To help the subject distinguish some segmental homonyms (e.g., /kaci/ “type,” /kaci/ “branch,” /kaci/ “eggplant”) and understand the meaning of the stimuli immediately, a picture was provided with the orthography. While the first author of this study, a 31-year-old female native Seoul speaker, carried out the Seoul Korean recording session, a native Kyungsang Korean language consultant, a 30-year-old female, assisted in the Kyungsang recording session to avoid any phonetic accommodation between the Seoul-speaking experimenter and the Kyungsang-speaking subjects. Each subject was recorded in a quiet place using a Marantz Digital Recorder (PMD 670) and SHURE head-mounted microphone. The stimuli were recorded at a sampling rate of 22,050 Hz and analyzed using the software package Praat (Boersma and Weenink, 2016). Overall, a total of 2106 tokens were obtained (27 target words × 2 repetitions × 39 speakers) for this investigation.

2.3 Measurements

VOT and F0 were measured using Praat. After manually identifying the target stop consonant and following vowel portions, VOT duration and F0 values at the midpoint of the following vowel were extracted using Praat scripts. VOT was measured from the point of the stop burst release to the onset of voicing as seen in both waveform and spectrogram. The onset of the first full pitch period was first defined as the onset of voicing in the waveform and additionally confirmed by the onset of the first formant in the spectrogram. For the midpoint F0 value, we identified the onset and offset of the vowel after the target stop, as determined by the onset of the first formant and the offset of the second formant in the spectrogram, respectively. The midpoint F0 values were first measured in Hertz. For the statistical comparisons they were later converted into semitones (St) relative to 100, which minimizes the inter-speaker variation across generations using $Log_2(Hz/100) * 12$ (Oh, 2011; Kang, 2014).

2.4 Data analysis

Prior to examining the effect of the sound change in Kyungsang’s lexical pitch accent on the use of F0 and VOT as cues to the three-way laryngeal stop contrast, this study first validated the

age-related tonal variation in Kyungsang Korean for these speech materials. We first tested if the younger Kyungsang speakers indeed produced the accent words differently (and in the expected direction) from the older speakers (see section 3.1). For this purpose, the midpoint F0 values were estimated based on mixed-effects regression models using the *lmer* function in the *lme4* package (Bates, Maechler, Bolker, & Walker, 2013) in R (R Core Team, 2015). Accent (HL vs. HH vs. *LH*), Age (young vs. *old*), and Dialect (Kyungsang vs. *Seoul*) were included as fixed factors in the models, and for each of the fixed factors the level in italics was set as the reference by sum-coding the discrete variables (as ±1). The model included random intercepts for Subject and Repetition and random slope of Accent for the subjects. Measurements were averaged across the three laryngeal types and three places of articulation for each subject

After verifying the previous observations (Lee & Jongman, 2015; Lee et al., 2016) regarding age variation in the realization of F0 as a function of Accent among the Kyungsang speakers, the second phase of this statistical analysis estimated the F0 and VOT variables based on the mixed-effects regression models including the three variables Laryngeal (fortis vs. aspirated vs. *lenis*), Accent (HL vs. HH vs. *LH*), and Age (younger vs. *older*) with the reference level in italics (see sections 3.1 and 3.2). Considering the different tonal nature of the two dialects, the regression models were run and reported separately for each dialect. The separate regressions enabled us to interpret the regression results more explicitly, and to understand the changing role of F0 as a function of Laryngeal for each of the two dialects in detail. The model also included random intercepts for Subject and Repetition and random slope of Laryngeal and Accent for the subjects. Measurements were averaged across the three places of articulation for each subject. For each statistical analysis, the final regression model excluding non-significant main and interaction effects was reported by a backward selection. The model selection was automatically done by using the *step* function in the *lmerTest* package (Kuznetsova, Brockhoff, & Christensen, 2015) in R, which also provided the statistical significance for each predictor with *p*-values using Satterthwaite's approximation for degrees of freedom.

3 Results

3.1 Verification of the lexical pitch change in Kyungsang Korean

Pooled across the three stop categories, this study tested if the previously reported (Lee & Jongman, 2015, Lee et al., 2016) age difference in F0 across the three accent types, HL, HH, and LH, was also present in these speech materials. Figure 2 illustrates the measured mean midpoint F0 values between older and younger speakers in Seoul and Kyungsang Korean as a function of Accent (i.e., HL, HH, and LH). Table 2 summarizes the parameter estimation for the fixed effects and interaction terms from the selected final model, which maximally includes all possible fixed effect predictors and interaction terms among the factors.

Significant main effects were found for Accent, Dialect, and Age. As seen in Figure 2, the regression model predicted higher mean F0 values for both HL ($\beta = 0.43$, $t = 5.76$) and HH ($\beta = 0.30$, $t = 4.37$) words than for LH words, lower F0 values for Seoul speakers than for Kyungsang ($\beta = -0.86$, $t = -3.75$), and higher F0 values for younger than for older speakers ($\beta = 1.75$, $t = 7.59$). The significant two-way interaction of Accent × Dialect showed that the estimated mean F0 difference between HL and LH ($\beta = 0.55$, $t = 7.32$) and that between HH and LH ($\beta = 0.15$, $t = 2.29$) were greater for Kyungsang speakers compared to those for Seoul speakers. The significant interaction term of Accent × Age also indicated that the F0 differences across Accent patterned differently between the two age groups; the higher F0 for HL ($\beta = -0.22$, $t = -2.94$) and HH ($\beta = -0.17$,

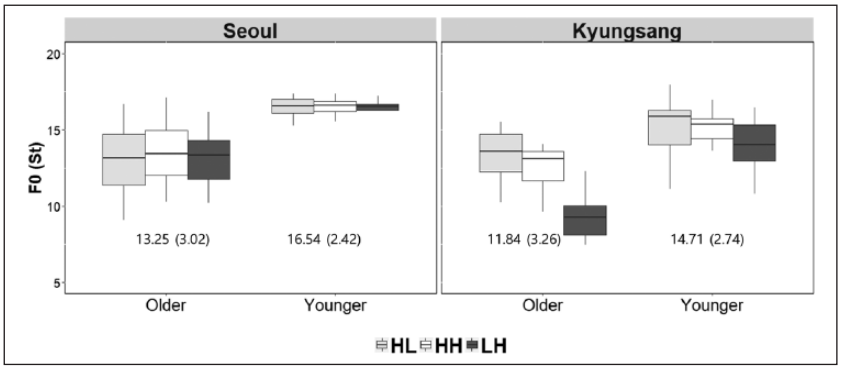

Figure 2. F0 distribution for Seoul and Kyungsang Korean as a function of ACCENT (HL, HH, and LH) between older and younger speakers. Measured mean F0 (St) values are indicated below the boxplots with the SD in parentheses.

Table 2. Estimates for predictors of the mixed-effects models in the analysis of the F0 parameter by ACCENT, DIALECT, and AGE.

	Coefficient β	SE(β)	t value
(Intercept)	14.02	0.23	**60.81**
$\text{ACCENT}_{\text{HL}}$	0.43	0.07	**5.76**
$\text{ACCENT}_{\text{HH}}$	0.30	0.06	**4.37**
$\text{DIALECT}_{\text{kyungsang}}$	−0.86	0.23	**–3.75**
$\text{AGE}_{\text{young}}$	1.75	0.23	**7.59**
$\text{ACCENT}_{\text{HL}} \times \text{DIALECT}_{\text{kyungsang}}$	0.55	0.07	**7.32**
$\text{ACCENT}_{\text{HH}} \times \text{DIALECT}_{\text{kyungsang}}$	0.15	0.06	**2.29**
$\text{ACCENT}_{\text{HL}} \times \text{AGE}_{\text{young}}$	−0.22	0.07	**–2.94**
$\text{ACCENT}_{\text{HH}} \times \text{AGE}_{\text{young}}$	−0.17	0.06	**–2.57**
$\text{DIALECT}_{\text{kyungsang}} \times \text{AGE}_{\text{young}}$	−0.04	0.23	−0.18
$\text{ACCENT}_{\text{HL}} \times \text{DIALECT}_{\text{kyungsang}} \times \text{AGE}_{\text{young}}$	−0.28	0.07	**–3.79**
$\text{ACCENT}_{\text{HH}} \times \text{DIALECT}_{\text{kyungsang}} \times \text{AGE}_{\text{young}}$	−0.07	0.06	−1.15

Bold indicates $p < 0.05$.

$t = -2.57$) compared to LH became lower for younger speakers, indicating that the F0 differences across the accent classes were smaller for younger than older speakers. Notably, the age variation was modulated by DIALECT as indicated by the three-way interaction of $\text{ACCENT}_{\text{HL}} \times \text{DIALECT}_{\text{kyungsang}} \times \text{AGE}_{\text{young}}$. The F0 difference between HL and LH words was smaller for younger speakers relative to older speakers, and the difference became even smaller for younger Kyungsang speakers compared to younger Seoul speakers ($\beta = -0.28$, $t = -3.79$). However, the estimated mean F0 difference between HH and LH lacked the statistical significance regarding the age and dialect variations, indicating that the younger speakers of both dialects produced HH words with a higher F0 compared to LH words. The observed interactions among the three factors might be expected based on the fact that Kyungsang Korean, but not Seoul Korean, is a pitch accent language where F0 values characterize the contrastive accent words, and that the F0 distinction across accent words is reduced for younger Kyungsang generations compared to older generations under the sound change.

Overall, older Kyungsang speakers exhibited the most distinct F0 differences across the accent contrasts compared to the other three groups. This observation confirmed that older and younger Kyungsang speakers differ in their use of F0 to distinguish lexical pitch accent words. This justifies our present approach using diachronic comparisons to test the effect of sound change in the lexical pitch accent on the use of F0 and VOT as cues to the three-way laryngeal stop contrast.

3.2 Interaction of F0 as a function of laryngeal type with pitch accent and age

Figure 3 shows the mean midpoint F0 values for older (top panels) and younger (bottom panels) speakers as a function of LARYNGEAL and ACCENT between Seoul (left panels) and Kyungsang Korean (right panels). Table 3 summarizes the parameter estimate β for each of the fixed effects as well as the interaction terms in the model selected for each dialect. While the regression model maximally including all two-way and three-way interaction terms was selected for Kyungsang Korean, the model selected for Seoul Korean included only the two-way interaction terms.

For Seoul Korean, the F0 parameter was significantly predicted by LARYNGEAL, ACCENT, and AGE. In Figure 3 (two left panels), the estimated mean F0 was significantly higher for the fortis ($\beta = 0.44$, $t = 6.14$) and aspirated ($\beta = 2.18$, $t = 22.93$) stops than for the lenis stop. The mean F0 also significantly differed by ACCENT for Seoul speakers; the HL ($\beta = -0.12$, $t = -2.24$) and HH ($\beta = 0.14$, $t = 4.14$) words (categorized according to Kyungsang's accent words) estimated lower and higher mean F0 values relative to LH words, respectively. Regarding the AGE effect, the mean F0 was higher for younger than older speakers ($\beta = 1.77$, $t = 5.95$), indicating an intrinsic pitch difference across age (Benjamin, 1981). The unexpected effect of ACCENT in non-tonal Seoul Korean might be due to inherent pitch differences across following vowels. Given that F0 tends to negatively correlate with F_1 (Lehiste, 1967), the acoustic parameter for vowel height, we compared F0 values in St across vowel qualities (i.e., /a/, /ɨ/, and /o/) after the target stop consonants between the non-tonal Seoul and tonal Kyungsang dialects of Korean. In Seoul Korean, the mean F0 was higher for the non-low vowels /ɨ/ (mean F0 = 18.36 (St), *SD* = 2.35) and /o/ (mean F0 = 17.84 (St), *SD* = 2.72) included in HH and LH words compared to the low vowel /a/ (mean F0 = 14.84 (St), *SD* = 3.07). The pattern seemed comparable to the pattern found for Kyungsang Korean with higher F0 for the non-low vowels /ɨ/ (mean F0 = 16.61 (St), *SD* = 2.52) and /o/ (mean F0 = 14.75 (St), *SD* = 3.24) than /a/ (mean F0 = 14.84 (St), *SD* = 3.07), although the F0 differences between the low and non-low vowels in Kyungsang Korean were smaller than in Seoul Korean.

Regarding LARYNGEAL × ACCENT, the significant interactions of $\text{LARYNGEAL}_{\text{fortis}} \times \text{ACCENT}_{\text{HL}}$ and $\text{LARYNGEAL}_{\text{fortis}} \times \text{ACCENT}_{\text{HH}}$ for Seoul Korean indicated that the estimated higher F0 for the fortis than for the lenis stop became even higher for HL words ($\beta = 0.14$, $t = 2.86$), but lower for HH words compared to LH words ($\beta = -0.08$, $t = -1.77$). That is, the F0 difference in the fortis–lenis contrast was greatest for the HL words and smallest for the HH words, patterning "$\text{HH}_{\text{fortis-lenis}} < \text{LH}_{\text{fortis-lenis}} < \text{HL}_{\text{fortis-lenis}}$." The comparison with the aspirated stop showed that the estimated higher F0 for the aspirated stop than the lenis stop was lowered for HL than LH ($\text{LARYNGEAL}_{\text{asp}} \times \text{ACCENT}_{\text{HL}}$, $\beta = -0.20$, $t = -4.20$), but it became even higher for HH than LH ($\text{LARYNGEAL}_{\text{asp}} \times \text{ACCENT}_{\text{HH}}$, $\beta = 0.14$, $t = 3.08$), indicating that the F0 difference in the lenis-aspirated pair was greatest for the HH words and smallest for the HL words, revealing the pattern of "$\text{HL}_{\text{asp.-lenis}} < \text{LH}_{\text{asp.-lenis}} < \text{HH}_{\text{asp.-lenis}}$." Overall, the LARYNGEAL × ACCENT interaction indicated that the F0 differences across the three stops are not the same across Kyungsang's accent words.

For the interaction of LARYNGEAL × AGE, the significant interaction of $\text{LARYNGEAL}_{\text{fortis}} \times \text{AGE}_{\text{young}}$ indicated that the higher F0 for the fortis than the lenis stop was even higher for younger than for older Seoul speakers ($\beta = 0.52$, $t = 7.21$). But the absence of a significant $\text{LARYNGEAL}_{\text{asp}} \times \text{AGE}_{\text{young}}$ interaction indicated that the younger and older age groups showed a similar higher F0 for the

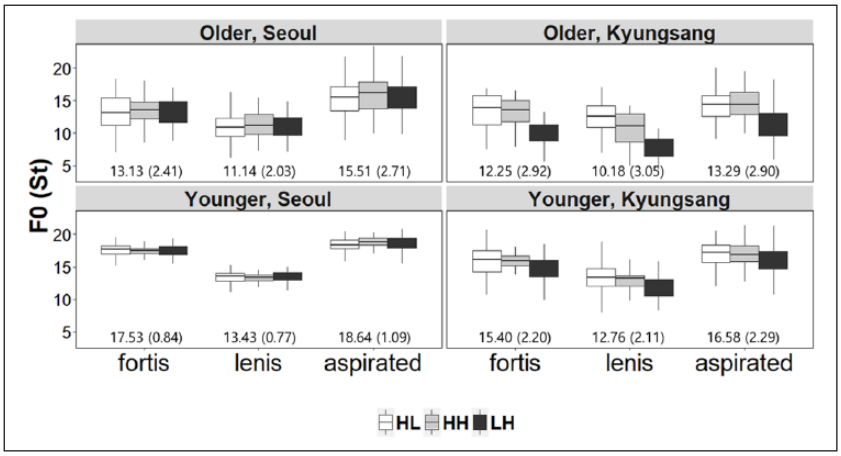

Figure 3. Mean midpoint F0 values for Seoul and Kyungsang Korean as a function of LARYNGEAL and ACCENT between older and younger speakers. Measured mean F0 (St) values are indicated below the boxplots with the SD in parentheses.

aspirated than for the lenis stop ($\beta = 0.01$, $t = 0.15$). Note that the age effect in Seoul Korean for only the fortis–lenis pair, and not for the aspirated–lenis pair, is consistent with Lee (2016a). In addition, the interaction of $\text{ACCENT}_{\text{HH}} \times \text{AGE}_{\text{young}}$ ($\beta = -0.08$, $t = -2.34$) indicated that the F0 difference between HH and LH words was smaller for younger than older speakers.

Finally, the absence of a significant three-way interaction term indicated that the F0 distinction across LARYNGEAL and ACCENT did not differ by AGE in Seoul Korean. That is, the effect of LARYNGEAL modulated by ACCENT patterned similarly between older and younger Seoul speakers, suggesting that the observed age variation by LARYNGEAL is not related to the accent words categorized by Kyungsang's accent classes.

For Kyungsang Korean, the mixed-effects regression model revealed significant effects for LARYNGEAL, ACCENT, and AGE, as seen in Figure 3 (two right panels). Similar to Seoul Korean, the estimated mean F0 was significantly higher for the fortis ($\beta = 0.46$, $t = 5.03$) and aspirated ($\beta = 1.61$, $t = 16.51$) stops than for the lenis stop. The mean F0 values were higher for younger Kyungsang speakers than older speakers ($\beta = 1.68$, $t = 4.99$). The significant effect of ACCENT revealed that the mean F0 was higher for HL ($\beta = 0.99$, $t = 11.36$) and HH ($\beta = 0.50$, $t = 6.17$) words compared to LH. The greater coefficients for the HL-LH comparison than for HH-LH in Kyungsang Korean also indicated an F0 pattern in the order of "LH < HH < HL," consistent with previous observations (Kenstowicz & Park, 2006; Lee & Jongman, 2015). The dialectal difference of F0 across ACCENT might suggest that the ACCENT effect in tonal Kyungsang Korean overlays the intrinsic F0 difference by vowel height, which is comparable to the observation where younger Seoul speakers showed less of an intrinsic F0 effect than older Seoul speakers due to the increased role of F0 for the laryngeal contrast (Bang, Sonderegger, Kang, Clayards, & Yoon, 2018).

Regarding LARYNGEAL × ACCENT, the lack of a significant interaction of $\text{LARYNGEAL}_{\text{fortis}} \times \text{ACCENT}_{\text{HL}}$ for Kyungsang Korean indicated that the estimated higher F0 for the fortis stop compared to the lenis stop was consistent between HL and LH words ($\beta = -0.00$, $t = -0.01$). But it became even higher for HH than LH words, given the near-significant interaction of $\text{LARYNGEAL}_{\text{fortis}} \times \text{ACCENT}_{\text{HH}}$ ($\beta = 0.21$, $t = 1.84$). The interaction patterns indicated that although the magnitude of the F0 difference in the fortis–lenis contrast is similar between HL and LH, it was greater for HH

Table 3. Estimates for predictors of the mixed-effects models in the analysis of the F0 parameter by LARYNGEAL, ACCENT, and AGE between Seoul and Kyungsang Korean.

	Seoul			Kyungsang		
	Coefficient β	SE(β)	*t* value	Coefficient β	SE(β)	*t* value
(Intercept)	14.87	0.29	**49.84**	13.23	0.37	**35.25**
$\text{LARYNGEAL}_{\text{fortis}}$	0.44	0.07	**6.14**	0.46	0.09	**5.03**
$\text{LARYNGEAL}_{\text{asp}}$	2.18	0.09	**22.93**	1.61	0.09	**16.51**
$\text{ACCENT}_{\text{HL}}$	−0.12	0.05	**–2.24**	0.99	0.08	**11.36**
$\text{ACCENT}_{\text{HH}}$	0.14	0.03	**4.14**	0.50	0.08	**6.17**
$\text{AGE}_{\text{young}}$	1.77	0.29	**5.95**	1.68	0.37	**4.99**
$\text{LARYNGEAL}_{\text{ortis}} \times \text{ACCENT}_{\text{HL}}$	0.14	0.04	**2.86**	−0.00	0.10	−0.01
$\text{LARYNGEAL}_{\text{fortis}} \times \text{ACCENT}_{\text{HH}}$	−0.08	0.04	*−1.77*	0.21	0.11	*1.84*
$\text{LARYNGEAL}_{\text{asp}} \times \text{ACCENT}_{\text{HL}}$	−0.20	0.04	**–4.20**	−0.52	0.08	**–5.85**
$\text{LARYNGEAL}_{\text{asp}} \times \text{ACCENT}_{\text{HH}}$	0.14	0.04	**3.08**	0.20	0.09	**2.13**
$\text{LARYNGEAL}_{\text{fortis}} \times \text{AGE}_{\text{young}}$	0.52	0.07	**7.21**	0.11	0.09	1.19
$\text{LARYNGEAL}_{\text{asp}} \times \text{AGE}_{\text{young}}$	0.01	0.09	0.15	0.13	0.09	1.47
$\text{ACCENT}_{\text{HL}} \times \text{Age}_{\text{young}}$	0.04	0.05	0.85	−0.52	0.08	**–5.97**
$\text{ACCENT}_{\text{HH}} \times \text{Age}_{\text{young}}$	−0.08	0.03	**–2.34**	−0.31	0.08	**–3.84**
$\text{LARYNGEAL}_{\text{fortis}} \times \text{ACCENT}_{\text{HL}} \times \text{AGE}_{\text{young}}$	—	—	—	0.02	0.10	0.28
$\text{LARYNGEAL}_{\text{asp}} \times \text{ACCENT}_{\text{HL}} \times \text{AGE}_{\text{young}}$	—	—	—	0.19	0.08	**2.21**
$\text{LARYNGEAL}_{\text{fortis}} \times \text{ACCENT}_{\text{HH}} \times \text{AGE}_{\text{young}}$	—	—	—	−0.15	0.11	−1.30
$\text{LARYNGEAL}_{\text{asp}} \times \text{ACCENT}_{\text{HH}} \times \text{AGE}_{\text{young}}$	—	—	—	−0.11	0.09	−1.21

Bold indicates $p < 0.05$, and italic indicates $p < 0.1$.

than for LH, meaning that F0 contrasting the fortis and the lenis category is more distinct for HH words than LH words, yielding the pattern of "$\text{LH}_{\text{fortis-lenis}} = \text{HL}_{\text{fortis-lenis}} < \text{HH}_{\text{fortis-lenis}}$." Regarding the F0 comparison of the aspirated–lenis stops, the higher mean F0 for the aspirated stop was lower for HL relative to LH words ($\beta = -0.52$, $t = -5.85$), but higher for HH than LH words ($\beta = 0.20$, $t = 2.13$). These results revealed that the F0 distinction of the aspirated–lenis contrast is in the order of "$\text{HL}_{\text{asp.-lenis}} < \text{LH}_{\text{asp.-lenis}} < \text{HH}_{\text{asp.-lenis}}$." Combining the results from the LARYNGEAL × ACCENT interactions in Kyungsang Korean, it is concluded that the laryngeal effect was boosted for HH words compared to other accent categories, and except for the fortis–lenis contrast which has a similar F0 difference between HL and LH tonal categories, the F0 difference for the other comparisons varied across tonal classes.

The lack of significant interactions of LARYNGEAL × AGE indicated that the F0 differences across the three stop categories were similar between older and younger Kyungsang speakers ($\text{LARYNGEAL}_{\text{fortis}} \times \text{AGE}_{\text{young}}$, $\beta = 0.11$, $t = 1.19$ and $\text{LARYNGEAL}_{\text{asp}} \times \text{AGE}_{\text{young}}$, $\beta = 0.13$, $t = 1.47$). These results are contrary to those from Seoul Korean where younger speakers had the greater F0 difference for the fortis–lenis contrast compared to older speakers. As seen in section 3.1, the interactions of ACCENT × AGE revealed that the effect of ACCENT was modulated by the AGE factor; the F0 differences across the contrastive accent words were smaller for younger compared to older Kyungsang speakers ($\text{ACCENT}_{\text{HL}} \times \text{AGE}_{\text{young}}$, $\beta = -0.52$, $t = -5.97$; $\text{ACCENT}_{\text{HH}} \times \text{AGE}_{\text{young}}$, $\beta = -0.31$, $t = -3.84$).

Importantly, the significant three-way interaction term indicated that the LARYNGEAL × ACCENT effect was also modulated by AGE ($\text{LARYNGEAL}_{\text{asp}} \times \text{ACCENT}_{\text{HL}} \times \text{AGE}_{\text{young}}$, $\beta = 0.19$, $t = 2.21$).

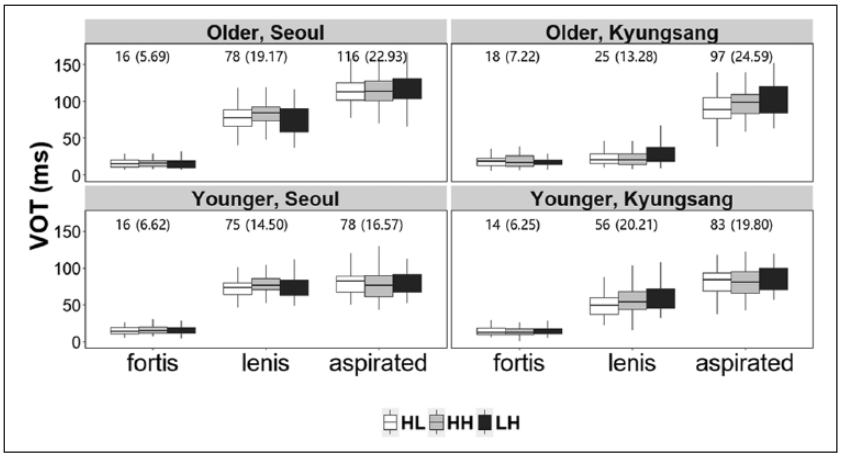

Figure 4. Mean VOT values for Seoul and Kyungsang Korean as a function of LARYNGEAL and ACCENT between older and younger speakers. Measured mean VOT (ms) values are indicated above the boxplots with the SD in parentheses.

Younger Kyungsang speakers produced the lenis and aspirated stops with a greater F0 difference than older speakers, and the younger speakers' use of the F0 cue for the contrastive stop pair was less affected by the lexical accent classes. This suggests that F0 as a cue to the laryngeal contrast is more robust for the younger than for the older speakers.

In sum, the results indicated that the estimated mean F0 difference was greater for younger speakers than for older speakers in both Seoul and Kyungsang Korean. For Seoul Korean, age-related variation in the use of F0 for the laryngeal contrast was observed for the fortis–lenis pair such that younger speakers distinguished the fortis from the lenis stop with a greater F0 difference compared to older speakers. For Kyungsang speakers, the age variation in distinguishing the stops interacted with the ACCENT predictor in a way that younger Kyungsang speakers' use of F0 for the laryngeal contrast was less affected by ACCENT.

3.3 Interaction of VOT as a function of laryngeal type with pitch accent and age

Figure 4 shows the mean VOT values produced by older (top panels) and younger (bottom panels) speakers as a function of LARYNGEAL and ACCENT between Seoul (left panels) and Kyungsang Korean (right panels). The regression models evaluated the effect of the fixed factors, LARYNGEAL, AGE and ACCENT and the interaction terms for the dependent variable of VOT separately for each dialect. Table 4 summarizes the parameter estimate β for each of the fixed effects and interaction terms in the final model. For both Seoul and Kyungsang Korean, the selected regression model included the three fixed effects, and the two-way interaction terms of LARYNGEAL × ACCENT and LARYNGEAL × AGE, but did not include ACCENT × AGE and the three-way interaction.

For Seoul Korean, the estimated mean VOT values were significantly predicted by LARYNGEAL, ACCENT, and AGE. As seen in Figure 4 (two left panels), the estimated mean VOT was significantly shorter for the fortis ($\beta = -47.17$, $t = -36.24$) and longer for the aspirated ($\beta = 33.61$, $t = 27.03$) stops relative to the lenis stop. The mean VOT also differed by ACCENT, showing longer VOT for the HH words (categorized according to Kyungsang's accent words) compared to LH words

Table 4. Estimates for predictors of the mixed-effects models in the analysis of the VOT parameter by LARYNGEAL, ACCENT, and AGE.

	Seoul			Kyungsang		
	Coefficient β	SE(β)	*t* value	Coefficient β	SE(β)	*t* value
(Intercept)	63.24	1.35	**46.76**	49.85	1.61	**30.86**
$\text{LARYNGEAL}_{\text{fortis}}$	−47.17	1.30	**–36.24**	−33.52	1.64	**–20.40**
$\text{LARYNGEAL}_{\text{asp}}$	33.61	1.24	**27.03**	41.15	1.58	**26.01**
$\text{ACCENT}_{\text{HL}}$	−0.73	0.60	−1.21	−2.62	0.65	**–4.02**
$\text{ACCENT}_{\text{HH}}$	1.15	0.56	**2.04**	−0.78	0.64	−1.22
$\text{AGE}_{\text{young}}$	−7.46	1.31	**–5.69**	1.88	1.61	1.16
$\text{LARYNGEAL}_{\text{fortis}} \times \text{ACCENT}_{\text{HL}}$	0.63	0.83	0.77	2.35	0.91	**2.57**
$\text{LARYNGEAL}_{\text{fortis}} \times \text{ACCENT}_{\text{HH}}$	−0.31	0.78	−0.40	0.49	0.90	0.54
$\text{LARYNGEAL}_{\text{asp}} \times \text{ACCENT}_{\text{HL}}$	0.40	0.79	0.50	−0.78	0.94	−0.83
$\text{LARYNGEAL}_{\text{asp}} \times \text{ACCENT}_{\text{HH}}$	−2.80	0.95	**–2.94**	−1.01	0.93	−1.08
$\text{LARYNGEAL}_{\text{fortis}} \times \text{AGE}_{\text{young}}$	7.39	1.26	**5.83**	−4.19	1.64	**–2.55**
$\text{LARYNGEAL}_{\text{asp}} \times \text{AGE}_{\text{young}}$	−12.68	1.22	**–10.32**	−9.35	1.58	**–5.91**
$\text{ACCENT}_{\text{HL}} \times \text{AGE}_{\text{young}}$	0.58	0.58	0.99	0.26	0.65	0.40
$\text{ACCENT}_{\text{HH}} \times \text{AGE}_{\text{young}}$	−1.10	0.56	*–1.96*	−0.20	0.64	−0.31

Bold indicates $p < 0.05$, and italic indicates $p < 0.1$.

($\beta = 1.15$, $t = 2.04$); the comparison of VOT between the HL and LH words was not significant ($\beta = -0.73$, $t = -1.21$). Regarding AGE, younger Seoul speakers produced the stop consonants with shorter VOT than older speakers did ($\beta = -7.46$, $t = -5.69$).

Significant two-way interactions were observed for LARYNGEAL × ACCENT and LARYNGEAL × AGE. For LARYNGEAL × ACCENT, the VOT distinction as a function of LARYNGEAL patterned consistently across the three contrastive accent words except for the VOT difference of the aspirated–lenis contrast between HH and LH words ($\beta = -2.80$, $t = -2.94$); the longer VOT for the aspirated stop compared to the lenis stop was shortened more for HH than for LH words, indicating a smaller VOT difference of the lenis-aspirated pair for LH than for HH words. The significant interaction of LARYNGEAL × AGE indicated that older and younger Seoul speakers had different VOT patterns across the three stop categories. The interaction of $\text{LARYNGEAL}_{\text{fortis}} \times \text{AGE}_{\text{young}}$ showed that the estimated shorter VOT duration for the fortis relative to the lenis stop was longer for younger Seoul speakers than for older speakers, indicating a reduced VOT difference in the fortis–lenis pair for younger as compared to older speakers ($\beta = 7.39$, $t = 5.83$). The interaction of $\text{LARYNGEAL}_{\text{asp}} \times \text{AGE}_{\text{young}}$ showed that the estimated longer VOT for the aspirated than for the lenis stop was reduced for younger speakers ($\beta = -12.68$, $t = -10.32$), indicating a smaller VOT difference in the lenis-aspirated contrast for younger speakers. Finally, a non-significant trend of $\text{ACCENT}_{\text{HH}} \times \text{AGE}_{\text{young}}$ ($\beta = -10.10$, $t = -1.96$) suggests that the longer VOT for the HH than LH words tends to be shortened for younger speakers.

For Kyungsang Korean, the mixed-effects regression model predicted significant effects of LARYNGEAL and ACCENT, but not for AGE. Similar to Seoul Korean, the estimated mean VOT value was shorter for the fortis ($\beta = -33.52$, $t = -20.40$) and longer for the aspirated stop ($\beta = 41.15$, $t = 26.01$) than for the lenis stop as seen in Figure 4 (two right panels). For the effect of ACCENT, the estimated mean VOT duration was shorter for the HL compared to LH words ($\beta = -2.62$, $t = -4.02$), but VOT was comparable between the HH and LH words ($\beta = -0.73$, $t = -1.21$). Contrary

to Seoul Korean where younger speakers exhibited shorter VOT than older speakers, the mean VOT was comparable between older and younger Kyungsang generations.

Regarding the two-way interaction of LARYNGEAL × ACCENT, the VOT distinction as a function of LARYNGEAL was consistently present across the accent classes, except that the VOT difference in the fortis–lenis pair was greater for the LH than HL words ($\text{LARYNGEAL}_{\text{fortis}} \times \text{ACCENT}_{\text{HL}}$, $\beta = 2.35$, $t = 2.57$). The significant interaction of $\text{LARYNGEAL}_{\text{fortis}} \times \text{AGE}_{\text{young}}$ showed that the estimated shorter VOT for the fortis than for the lenis stop was even shorter for younger than for older speakers ($\beta = -4.19$, $t = -2.55$), indicating that the VOT difference in the fortis–lenis contrast was greater for younger than older speakers. The significant interaction of $\text{LARYNGEAL}_{\text{asp}} \times \text{AGE}_{\text{young}}$ showed that the estimated longer VOT for the aspirated than for the lenis stop was reduced for younger speakers ($\beta = -9.35$, $t = -5.91$), that is, the VOT difference in the lenis-aspirated contrast was smaller for younger Kyungsang speakers.

In both the Seoul and Kyungsang dialects of Korean, the absence of a significant ACCENT × AGE interaction indicated that VOT as a function of ACCENT patterned the same for the two age groups for both dialects. Finally, the absence of a significant three-way interaction of LARYNGEAL × ACCENT × AGE indicates that the age variation in VOT as a function of LARYNGEAL is not related to the accent classes. Overall, both Seoul and Kyungsang Korean showed age variation in the use of VOT as a cue to the three-way laryngeal contrast, although the pattern of age variation was not identical between the two dialects. Younger Seoul speakers produced the three stops with a less distinct VOT compared to the older Seoul speakers. For Kyungsang Korean, while the VOT distinction for the fortis–lenis pair was greater for younger than older speakers, that for the lenis-aspirated contrast was greater for older than younger speakers.

3.4 Discriminant analysis: Speaker-specific cue weightings

These mixed-effects regression analyses revealed age variation in the use of F0 and VOT as cues to the three-way laryngeal contrast for both the Seoul and Kyungsang dialects of Korean. To quantify the contribution of each cue, we further conducted discriminant function analysis to predict the fortis, lenis, and aspirated categories based on F0 and VOT. We examined how successfully each cue classified the three-way laryngeal contrast for each dialect and age group using the *lda* function with jacknifed prediction in the *MASS* package (Venables & Ripley, 2002) in R (R Core Team, 2015). The classification accuracy is presented separately for each dialect and age group in Table 5. Showing the decision boundaries of the stop categories, Figure 5 illustrates the quadratic discriminant classifications based on both F0 and VOT using the *partimat* function in the *klaR* package (Weihs, Ligges, Luebke & Raabe, 2005) in R.

The discriminant function analysis reported greater classification accuracy of the F0 predictor for younger than older speakers in both dialects, confirming the age variation in the use of F0 as a function of LARYNGEAL observed in the regression analyses. For older Seoul and Kyungsang speakers, F0 as a single predictor classified the three stop categories with 56% and 50% accuracy, respectively. For younger Seoul and Kyungsang speakers, the accuracy was 81% and 61%, respectively. This pattern indicates that younger speakers rely more on F0 than older speakers, which is true even for younger Kyungsang speakers who still preserve the lexical tonal properties. The discriminant analyses also indicated the dialectal variation in the use of F0 as a function of the laryngeal contrast, replicating Lee and Jongman (2012), where non-tonal (younger) Seoul speakers relied more on F0 than tonal (younger) Kyungsang speakers. Overall, F0 is used differently across age and dialect groups; F0 is the most reliable cue for younger Seoul speakers, whereas it is least reliable for older Kyungsang speakers.

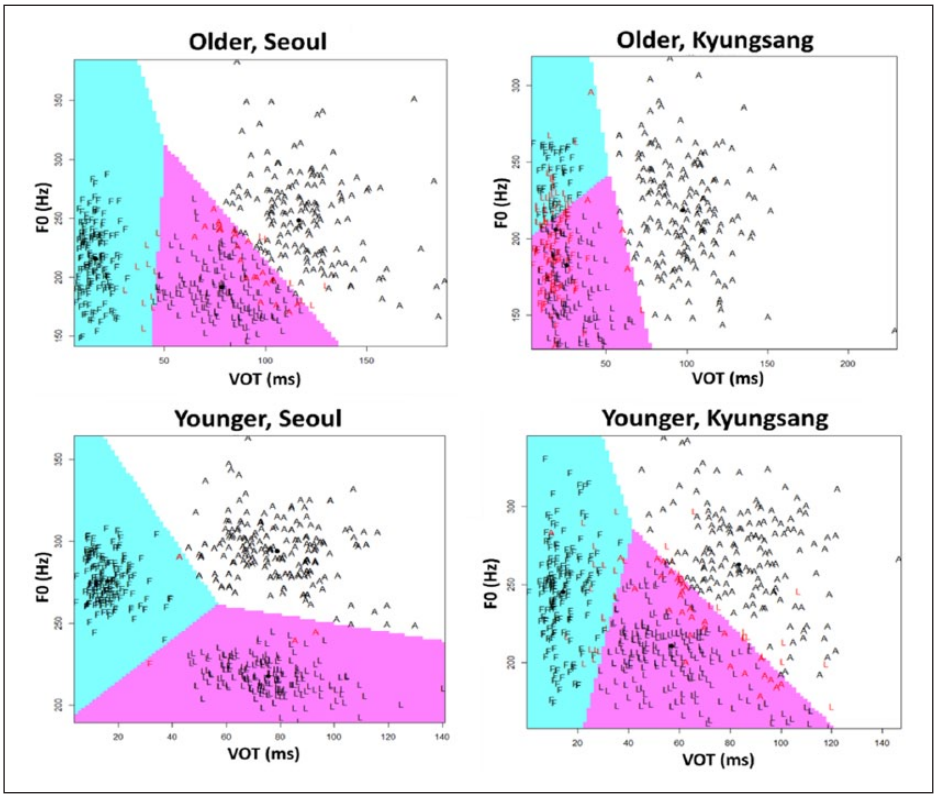

Figure 5. Decision boundaries in the distinction among the fortis (F), lenis (L), and aspirated (A) stops for Seoul and Kyungsang Korean between older and younger speakers. Blue, pink, and white shaded areas represent the prediction of the fortis, lenis, and aspirated stops, respectively. Black and red letters indicate correct and incorrect classification, respectively.

Table 5. Comparison of classification accuracy rates (%) from discriminant analyses for F0 and VOT as a function of the three-way laryngeal contrast across age and dialect groups.

	Seoul		Kyungsang	
	Older	Younger	Older	Younger
F0	56	81	50	61
VOT	86	70	71	79

VOT was a more effective predictor for older Seoul and younger Kyungsang speakers relative to the other two groups; VOT classified the three stops with 86% and 79% accuracy rates for older Seoul and younger Kyungsang speakers, respectively. But the accuracy rate was only 70% and 71% for younger Seoul and older Kyungsang speakers, respectively. In other words, although younger Kyungsang speakers have increased their use of F0 for the stop distinction, they still use VOT as much as the older Seoul speakers.

Figure 5 illustrates the age and dialectal variation in the efficacy of F0 and VOT as predictors of the three stop categories. Although F0 is not effective in predicting the three stops for older

Kyungsang speakers (i.e., the low F0 fails to separate the lenis stop from the other two categories), it reliably separates the lenis from the other two stops for the younger Seoul group. For the older Seoul and younger Kyungsang groups, while the fortis stop is classified based on the short VOT duration, the lenis-aspirated contrast is based on both VOT and F0, and the incorrect prediction is seen for the stimuli with ambiguous VOT and F0.

4 Summary and discussion

This study aimed to investigate the interaction between tone and segment under the ongoing sound change in Kyungsang Korean. We examined how younger and older Kyungsang speakers use VOT and F0 as cues to distinguish the three-way laryngeal stop contrast and found age-related variation in the weighting of these acoustic cues. In addition to the diachronic investigation, the acoustic comparisons with standard Seoul Korean not only confirmed the age variation in the Seoul Korean stops and the dialectal variation reported in previous studies, but also shed light on the changing role of the multiple acoustic cues in Korean. Lastly, quantifying the reliance on VOT and F0 across age and dialect groups elucidated the varying cue weighting strategies across different speaker groups.

To begin, we replicated previous findings on age variation in the production of Seoul Korean stops and on dialectal variation in the use of VOT and F0 as cues to the laryngeal distinction. We found that younger Seoul speakers relied more on F0 and less on VOT than older Seoul speakers, confirming previous observations (Kang, 2014; Kang & Guion, 2006; Lee, 2016a; Silva, 2006) that reported the increased importance of F0 in distinguishing the three stops in Seoul Korean. This result is in line with the phonetic trading relations (Repp, 1982) where the reduced effect of one cue (i.e., VOT) is compensated by the increased role of another cue (i.e., F0). We also replicated Lee and Jongman (2012) regarding the dialectal variation: tonal Kyungsang speakers relied less on F0 and more on VOT than non-tonal (younger) Seoul speakers. It should be pointed out that the dialectal variation is observed when comparing the stop production by Kyungsang speakers with that by younger, but not older, Seoul speakers whose reliance on F0 is as small as that of the Kyungsang speakers.

In addition to the replicated findings, the novel finding of this study is the age variation in Kyungsang speakers' use of the F0 and VOT cues in distinguishing the three stops.

Consistent with our previous observations (Lee & Jongman, 2015; Lee et al., 2016) of a sound change in the lexical pitch accent in Kyungsang Korean, this study found that the younger Kyungsang speakers' use of F0 was reduced for the accent contrast, but increased for the laryngeal contrast. Considering both the regression and discriminant analyses, it is noted that the way younger Kyungsang speakers utilize F0 as a function of the laryngeal contrast is similar to younger Seoul speakers rather than older Kyungsang speakers, supporting our hypothesis. Below, we offer two potential explanations for this changing role of the F0 cue.

The first explanation for this is the diachronic sound change in the lexical pitch accent in Kyungsang Korean. Previous studies examining the F0 perturbation due to consonant voicing (e.g., Kenstowicz & Park, 2006; Francis et al., 2006; Hombert, 1978) proposed that speakers of tonal languages need additional tonal representations relative to non-tonal speakers. For example, Kenstowicz and Park (2006) explained that while the stops of non-tonal Seoul Korean can be specified with only [± stiff vocal folds], those of tonal Kyungsang Korean additionally require [± upper] to specify the high and low tones of the initial syllables containing the stops. Previous experimental findings supported that sharing the F0 space for the purpose of both laryngeal and tonal contrasts accounted for the reduced use of F0 as a cue to the stop contrast among tonal speakers (e.g., Lee & Jongman, 2012). Given that the existence of lexical tone makes F0 a less reliable

cue to the segmental distinction, the reduced tonal property for these younger Kyungsang speakers might make F0 more available as a cue to the stop contrast. In fact, the significant three-way interaction of $\text{LARYNGEAL}_{\text{asp}} \times \text{ACCENT}_{\text{HL}} \times \text{AGE}_{\text{young}}$ in these Kyungsang data indicated that the F0 distinction for the laryngeal contrast is better maintained by younger than older speakers, due to their being less affected by the lexical pitch accent contrast. Therefore, given that younger speakers use F0 more for the stop distinction as they use F0 less for the accent contrast, the sound change in the lexical pitch accent in Kyungsang Korean is one of the most likely sources of the varying cue weighing between the two generations of Kyungsang speakers.

The second explanation is the influence of Seoul Korean. Younger Kyungsang speakers who have been under greater influence of Seoul Korean than older speakers might develop a cue weighting strategy similar to that of innovative Seoul Korean speakers who weight F0 more than conservative speakers. This is plausible because language experience or contact with another language is an important factor in explaining language-specific cue weighting strategies (e.g., Escudero & Boersma, 2004; Nittrouer & Burton, 2005). Given that short-term exposure to acoustic cues like VOT (Nielsen, 2011) and contact with different languages (Pearce, 2009) cause phonetic imitation and change in cue-weighting patterns, respectively, younger Kyungsang speakers who have been exposed to standard Seoul Korean since an early age would be more likely to change their speech toward Seoul speech than older Kyungsang speakers. We are not in a position to determine the direct source of the different cue weighting across Kyungsang generations, and therefore a closer examination will be needed.

Next, VOT as a cue to the stop distinction was also used differently between the two Kyungsang generations. The VOT difference in the fortis–lenis contrast was greater, but the difference in the lenis-aspirated contrast was smaller for younger speakers. This age variation is due to the younger speakers' longer VOT duration for the lenis stop as compared to the older speakers, which is also exhibited in the higher classification accuracy of VOT for younger Kyungsang speakers (79%) than older speakers (71%) as seen in section 3.4. We further observed that only the fortis versus non-fortis pair showed a higher classification for younger (96%) than older Kyungsang speakers (75%). For the other pairs, the younger speakers showed a lower classification accuracy of VOT (lenis vs. non-lenis: 65% (older), 58% (younger); aspirated vs. non-aspirated: 97% (older), 82% (younger)), consistent with the notion of the phonetic trading relation. The fact that the higher classification accuracy is limited to the fortis versus non-fortis pair suggests that although the younger Kyungsang speakers' overall reliance on VOT (i.e., a conservative cue) revealed by the discriminant analysis is not reduced as much as it is for younger Seoul speakers, the similarly changing VOT for the lenis stop between Seoul and Kyungsang Korean can indeed be understood as a part of the process to develop the innovative F0 cue for Kyungsang speakers.

Notably, a comparison of the diachronic change in VOT in Seoul and Kyungsang Korean suggests that the stage of the sound change in the three-way laryngeal contrast is shared between the two dialects. A shared stage in the sound change is supported by our finding that the F0 and VOT pattern for the lenis-aspirated contrast is similar between the younger Kyungsang and older Seoul speakers. Recall that although previous studies (Kang, 2014; Kang & Guion, 2008) found an enhanced F0 distinction for the lenis-aspirated contrast in Seoul Korean, we observed it only for the fortis–lenis pair, indicating that the older Seoul speakers in this study use F0 as much as younger speakers to distinguish the lenis from the aspirated stop. Lee (2016a) also noted the same inconsistency across studies and accounted for it in terms of a more enhanced role of F0 as a cue to the lenis-aspirated pair in both older and younger Seoul speakers. Congruent with this discriminant analysis, the changing VOT pattern observed for younger Kyungsang speakers is similar to the VOT of older Seoul speakers who use VOT most effectively among the four speaker groups. That

is, younger Kyungsang speakers still use VOT effectively despite the increased use of F0, just as older Seoul speakers do. This observation indicates that the increased use of F0 for the stops does not necessarily mean a concurrent reduction in the contribution of VOT, contrary to our prediction of a diminished role of VOT (primary cue) because of the increased role of F0 (secondary cue) in the laryngeal contrast. A similar observation was also made by Kang (2014) based on the Seoul Korean stops, who argued that the redundant VOT cue loses its role once F0 becomes the primary cue (Kang, 2014: p. 88). Together, the findings in Kang (2014) and this study suggest that the sound change in the use of multiple acoustic cues to the three-way laryngeal stop contrast started by enhancing the role of F0 rather than diminishing the role of VOT first, and that there is a redundant stage before completely re-ordering the cue primacy between VOT and F0. This observation with Kyungsang data further implies that although the cue weighting pattern for each age and dialect group currently varies due to different stages of the sound change for each group, the change in cue weighting is in the same direction, presumably heading toward the same destination. In sum, these results suggest that the most innovative cue weighting pattern is found in younger Seoul speakers who rely primarily on the F0 cue, an intermediate pattern in older Seoul and younger Kyungsang speakers who use both F0 and VOT, and the most conservative pattern is found in older Kyungsang speakers who mainly rely on VOT.

The age and dialectal variation in the fortis–lenis contrast is also in line with the notion of a shared sound change stage across speaker groups, and supports our claim that Kyungsang Korean follows the diachronic change in Seoul Korean stops. Kang (2014) observed an enhanced F0 distinction for the fortis–lenis contrast, based on which she argued that the amplified role of F0 is a general tendency exhibited for both the fortis–lenis and the lenis-aspirated pair in Seoul Korean, although the degree of the F0 amplification varies across the stops. This regression analysis also shows that for Seoul Korean, the F0 difference in the fortis–lenis pair is greater for the younger than the older speakers. Younger Kyungsang Korean speakers, however, did not exhibit such enhanced F0 distinction for the fortis–lenis pair, which is opposite from their F0 pattern for the lenis-aspirated contrast. In other words, the most innovative group (younger Seoul) has the enhanced F0 distinction for both the fortis–lenis and lenis-aspirated contrasts, and the intermediate group (younger Kyungsang, older Seoul) has it only for the lenis-aspirated pair, suggesting that the fortis–lenis pair is not affected yet for the intermediate group as much as it is for the innovative group. Assuming that (younger) Seoul speakers are the leaders in the stop change, the enhanced F0 distinction among the younger Seoul speakers across all stop categories can be understood as the most innovative F0 pattern; the intermediate groups (younger Kyungsang and older Seoul speakers) would follow this innovative pattern and might be expected to exhibit this innovation later in the process of the stop change.

5 Conclusion

This study aimed to explore speaker-specific cue weighting by examining how speakers with varying linguistic experiences differed in their use of multiple acoustic cues to segment distinctions. For this purpose, we compared the weighting of VOT and F0 as acoustic cues to the three-way voiceless stop distinction in Korean between older and younger and between Seoul and Kyungsang speakers. Given the ongoing sound change in Kyungsang Korean marked by a shift toward standard Seoul Korean as well as the reduced lexical tonal property of the regional dialect, we hypothesized age-related variation in the use of VOT and F0 for the stops in Kyungsang Korean. This study elucidated the cue weighting pattern for each of the age and dialect groups. We found that younger Kyungsang speakers differed from older Kyungsang speakers in their use of VOT and F0,

and in fact resembled older Seoul speakers more closely. The shared cue weighting pattern across generations and dialects implies that although the stage of sound change currently varies across speaker groups—some are more innovative (or conservative) than others—the direction of the change is shared among speakers of the same language.

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Notes

1. Similar to the South Kyungsang dialect of Korean, the North Kyungsang dialect is also a tonal language that preserves the lexical pitch accent from Middle Korean (15th–16th centuries). Although the tonal property of the two regional varieties is quite similar, differences in the historical development between the two resulted in distinct tonal systems. This study focuses on South Kyungsang Korean; throughout the paper we refer to "South Kyungsang" by the term "Kyungsang Korean."
2. Although there are many phonological analyses, this study introduces the lexical pitch accent of South Kyungsang Korean, focusing on its phonetic properties, not introducing the phonological analyses that are beyond the scope of this study.

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