

Age-related differences in the perception of Korean laryngeal contrasts: fMRI evidence*

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Park, Haeil. 2010. Age-related differences in the perception of Korean laryngeal contrasts: fMRI evidence. *Studies in Phonetics, Phonology and Morphology* 16.1. 91-106. This study aims to investigate whether there is any difference in the neural correlate of the comprehension of Korean laryngeal contrasts between younger and older Korean adults, and more specifically, to test if the increasingly popular “tonogenesis” hypothesis that Koreans may be undergoing a shift in Korean stop system can be supported by the neural findings of the present study. Five younger and five older Koreans were scanned while performing the auditory identification task of word-initial stops. The fMRI results revealed that there is a significant difference in activation between younger and older subjects. Specific activities unique to younger speakers were observed in the right Superior Temporal Gyrus, an area of the brain associated with pitch perception, while those unique to older speakers in the left Superior Temporal Gyrus, an area responsible for Voice Onset Time (VOT) perception. The results of this study uphold the claim that the laryngeal contrasts of Korean are increasingly distinguished less by VOT differences than by their effect on pitch in the following vowel. (**Kyung Hee University**)

Keywords: Korean laryngeal contrasts, VOT, fundamental frequency (f_0), pitch, fMRI

1. Introduction

Korean is famous for its unique three-way laryngeal contrast of tense /p' t' k'/ vs. lax /p t k/ vs. aspirated /p^h t^h k^h/ in word- or phrase-initial position. Since Lisker and Abramson's (1964) cross-linguistic study, differences in Voice Onset Time (VOT), an important speech parameter denoting the time interval between the release of a stop consonant and the onset of voicing, have been seen as the primary distinguisher of Korean stops (e.g., Kim 1970; Kagaya 1974; Cho et al. 2002). At the same time, fundamental frequency (f_0) in the following vowel has been considered to play an important role in distinguishing lax from aspirated and tense stops (e.g., Han & Weitzman 1970; Hardcastle 1973; Cho et al. 2002). Recently, however, Silva (2006) reported that the VOT values for lax and aspirated stops overlap for younger speakers, arguing that contemporary Korean is

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changing in such way that phonemic distinctions once marked primarily by VOT differences are now coded by differences in f_0 distinctions. Although Silva's findings have been confirmed in other acoustic studies (e.g., Kang and Guion 2006, Wright 2007), they call for a further investigation through recently developed neuroimaging technologies such as functional Magnetic Resonance Imaging (fMRI) and electroencephalography (EEG), given that various linguistic hypotheses can be successfully tested using such neuroimaging tools (e.g. Ben-Shachar et al. 2004; Eulitz and Lahiri 2004; Park et al. 2010).

The aim of this paper is to investigate age-based differences in the neural correlate of Korean laryngeal contrast perception using a "sparse" sampling method of functional Magnetic Resonance Imaging (fMRI)¹. In particular, we explore whether there is any difference between younger and older Koreans in a way that the perception of word-initial Korean laryngeal stops is represented in VOT- and pitch-related brain regions. The current fMRI results (cf. Park and Iverson 2008²) can be expected to illuminate whether support for Silva's claim on Korean "tonogenesis" consists not only in the acoustic signal but also in the neural representation of the perception of these sounds.

1.1 Emergent pitch sensitivity in Seoul Korean

In this section we briefly review Silva's (2006) acoustic study as to Korean "tonogenesis" defined as the origin of lexical tonal contrasts which bear crucially on the current study. In his breakthrough report on the change in progress of VOT patterns, Silva (2006) argued that modern Seoul Korean is developing a tonal system arising as a result of a VOT change in Korean's three-way laryngeal contrast as illustrated in Figure 1. More specifically, younger speakers were found to code the contrast between lax and aspirated stops in phrase-initial position with differences not in VOT but in f_0 , which suggests that they are phonologizing f_0 differences while dephonologizing VOT differences, and that f_0 as opposed to VOT has assumed the primary role in marking the lax vs. aspirated distinction.

¹ The "sparse" sampling method developed by Hall et al. (1999) has been increasingly used in many auditory functional Magnetic Resonance Imaging (fMRI) studies. The new method is referred to as a method in which the acquisition of brain images occurs in between stimuli, thereby minimizing the effect of scanner noise and hence enabling greater detection of brain activation.

² Preliminary individual-based fMRI results of 3 older Koreans using a non-"sparse" imaging method were reported in Park and Iverson (2008). Its slightly different results from the ones reported here might have been due to differences in methods (non-sparse vs. sparse) as well as statistical contrasts ($\{(\text{lax}+\text{tense}+\text{aspirated})-3*\text{V}\}$ vs. $\{\text{lax}+\text{tense}+\text{aspirated}\}$) that were employed in each study, even though the overall results of the two studies were not different from each other in that subjects with overlapping VOT difference tend to activate pitch-related areas in the right hemisphere to a greater degree than subjects with clear differences do.

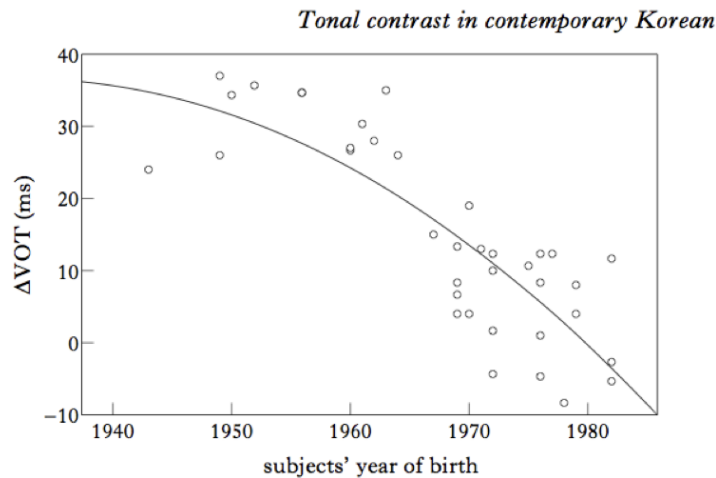


Figure 1. ΔVOT ($VOT_{asp} - VOT_{lax}$) as a function of subjects' year of birth (from Silva 2006)

Consistent with Silva's finding, Kang and Guion (2006) observed that there is no significant difference in VOT values between the lax and aspirated stops for younger speakers. In addition, Wright (2007) found the acoustic results in support of a shift in Korean's three-way stop distinctions, reporting a trend in which mean VOT differences between lax and aspirated stops are decreasing.

1.2. fMRI techniques

fMRI, one of the most recent neuroimaging techniques, is a method of measuring haemodynamic response (or change in blood flow) related to neural activity. Since 1990s, fMRI has been widely used in neuroscience studies due to its non-invasiveness and non-exposure to radiation. Change in blood flow and blood oxygenation is closely correlated with brain activity. Since oxygenated hemoglobin is diamagnetic, meaning it is repelled by a magnetic field, the signal intensity that is obtained by an MRI scanner gets higher when the level of blood oxygenation is increased. For this reason, most fMRI researches are based on Blood Oxygenation Level-Dependent (BOLD) signal to acquire MR images. The BOLD response or haemodynamic response, caused by a brief neural activity, normally reaches the peak after 4-5 seconds, and returns to the baseline.

One of the advantages with this fMRI method is that it enables us to localize the brain areas responsible for specific aspects of language. As previously mentioned, the present study aims to compare the brain

activation patterns in perception of Korean laryngeal distinctions between young and old adults. Thus, comparing the brain areas of younger and older subjects sensitive to the identification of Korean laryngeal contrasts via an fMRI technique will permit us to confirm which cue, VOT or f_0 , is the main contributor in distinguishing three-way Korean stops for each group.

2. Methodology

2.1 Subjects

The participants were ten native speakers of Seoul Korean, 5 male younger speakers and 5 older speakers, with neither history of neurological/psychiatric illness nor speech/hearing impairments. The age of the younger speakers ranged from 20 to 35 (mean age = 28.4, Standard Deviation (SD) = 3.79), while that of their older counterparts from 45 to 57 (mean age = 47.4, SD = 6.22). All participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971). They were paid for their participation and gave written informed consent prior to the experiment, in accordance with the Declaration of Helsinki.

2.1.1 VOT and f_0 values of 10 participants

Table 1 illustrates the VOT data of lax and aspirated stops for five younger (speakers 1-5) and five older Korean participants (speakers 6-10) and independent samples *t*-test results. The age of each subject is also specified in the table. Following Silva (2006)'s methodology, nine 3-syllable tokens (3 tokens from 3 places of articulation) beginning with a consonant in the sentence frame, *i ken _____ i-la-ko ha-ci-yo* 'this is called _____' were averaged for each mean VOT of the three manners of articulation (see Appendix A for the list of target words). All of the younger subjects turned out to belong to the "innovator" category in terms of their phonological systems to the extent that they no longer use VOT differences as the primary distinguisher of Korean stop categories. As for older subjects, they showed substantial VOT differences between lax and aspirated plosives.

Table 1. VOT data and *t*-test results³ (* indicates a significant difference)

Speaker	Age	Mean VOT and range (ms): lax	Mean VOT and range (ms): aspirated	<i>t</i> -test results
1 (male)	34	85.67 (72, 94)	92.78 (82, 104)	P > .05
2 (male)	25	78.67 (54, 86)	87.89 (56, 104)	P > .05
3 (male)	28	63.89 (55, 72)	66.22 (41, 103)	P > .05
4 (male)	30	87.00 (76, 99)	78.22 (68, 90)	P > .05
5 (male)	25	58.44 (47, 80)	66.56 (54, 78)	P > .05
Speaker	Age	Mean VOT and range (ms): lax	Mean VOT and range (ms): aspirated	<i>t</i> -test results
6 (male)	43	46.7 (31, 77)	89.3 (70, 110)	*P < .05
7 (male)	51	58.3 (38, 75)	105.6 (70, 120)	*P < .05
8 (male)	57	61.5 (26, 88)	107.6 (87, 136)	*P < .05
9 (male)	44	54.5 (35, 70)	92.3 (75, 119))	*P < .05
10 (male)	43	64.2 (38, 82)	100.7 (81, 121)	*P < .05

On the other hand, Table 2 shows the f_0 data in the following vowel after lax and aspirated stops for 5 younger (speakers 1-5) and those after tense and aspirated stops for 5 older subjects (speakers 6-10)⁴ and their individual statistical results.

³ Speaker 4 exhibits a distribution where the average VOT value of the lax stop series is longer than that of the aspirated stop series, as also reported in Silva (2006) and Wright (2007).

⁴ One older subject aged 43 has VOT and f_0 patterns similar to younger Koreans. We did not include him in our investigation of activation areas to common to older subjects in order to rule out the possibility of the subject's using different perceptual strategies than other older subjects, thereby reducing statistical power.

Table 2. f_0 data and t -test results (* indicates a significant difference)

Speaker	Age	Mean f_0 and range (Hz): lax	Mean f_0 and range (Hz): aspirated	t -test results
1 (male) ⁵	34	128 (116, 139)	181 (171, 192)	*P < .05
2 (male)	25	127.33 (121, 136)	175.67 (175, 196)	*P < .05
3 (male)	28	131.33 (124, 136)	194.33 (171, 206)	*P < .05
4 (male)	30	111.00 (103, 127)	145.44 (121, 159)	*P < .05
5 (male)	25	109.00 (101, 120)	135.33 (118, 152)	*P < .05
Speaker	Age	Mean f_0 and range (Hz): tense ⁶	Mean f_0 and range (Hz): aspirated	t -test results
6 (male)	43	160.5 (150, 164)	171.2 (155, 182)	P > .05
7 (male)	51	170.6 (148, 178)	178.6 (166, 193)	P > .05
8 (male)	57	130.7 (111, 157)	125.2 (117, 144)	P > .05
9 (male)	44	161.7 (145, 173)	167.5 (156, 177)	P > .05
10 (male)	43	145.8 (126, 154)	154.2 (138, 159)	P > .05

Their f_0 values were distributed in quite an opposite pattern to their VOT values: for younger subjects, fundamental frequencies were significantly different among the lax, tense and aspirated stops, suggesting that attention to pitch distinctions, not VOT differences, play a primary role in distinguishing three laryngeal contrasts for these younger Korean speakers. On the contrary, for their older counterparts, there was no significant f_0 difference between the tense and aspirated series although a statistical difference was found between the lax and aspirated stops; this overlap

⁵ It was interesting to observe that speaker 1 had an unexpected f_0 pattern for the tense stops: 2 out of 3 tokens of bilabial tense stops exhibited a significant drop in pitch in a vowel following the stop sound. Because these cases were limited to only two tokens of eight tense stops and were not systematic, those values were not included in the calculation of mean f_0 for the tense stop series. It is not clear, however, why this f_0 drop appears only after a tense bilabial stop for the subject.

⁶ For older subjects we provide the f_0 data of the tense, not the lax, series since overlap was observed only between the tense and aspirated stops.

indicates that VOT distinctions are a primary distinguisher of Korean stop contrasts for these older Koreans.

2.2. Experimental design

An event-related design was employed to avoid the shortcomings of a blocked-design. Stimuli were pseudo-randomized using the OptSeq 2 mechanism (<http://surfer.nmr.mgh.harvard.edu/optseq/>). They were presented every 2.5 seconds through an MR-compatible headphone set. The task given to the subjects was to indicate which they heard among the three consonant types, or a vowel, by pressing one of four buttons. Inside the scanner, they were able to see four choices presented on the screen above their head in Korean ([1] ㄱ, ㅋ, ㆁ, ㆁ; [2] ㄷ, ㅌ, ㄴ, ㄴ; [3] ㅌ, ㅍ, ㅍ; [4] ㅇ). They familiarized themselves through instruction with which finger to use in correspondence to the numbers [1] through [4], as coded above.

2.3 Stimuli and procedure

The total number of stimuli was 168 monosyllabic words beginning with one of the three-way laryngeally contrastive Korean stops (lax, tense, aspirated) followed by one of five different vowels: ㅏ (/a/), ㅓ (/e/), ㅗ (/i/), ㅜ (/o/), ㅡ (/u/). All of the stimuli were pronounced by a 30-year old female native speaker of Seoul Korean⁷, and recorded in a silent room at the rate of 44,100 Hz. Presentation of the stimuli and registration of responses were done using E-Prime 1.1 (Psychology Software Tools Inc., PA, USA). Response accuracy and reaction time were recorded.

Table 3. Experiment design (five conditions and stimuli examples)

Condition	Description	Example	Gloss
1	Lax-initial	tal	‘moon’
2	Tense-initial	t’al	‘daughter’
3	Aspirated-initial	t ^h al	‘mask’
4	Vowel-initial	al	‘egg’
5	Baseline	<silence>	

⁷ Her speech exhibited a three-way voice onset time (VOT) contrast across the manner types. For the three coronal stops exemplified in Table 3, the VOT values were: tense 12ms, lax 65ms, aspirated 92ms. The existence of the three-way VOT distinction in her speech may be due to the fact that she pronounced the stimuli in isolated forms, not in a sentence frame.

There were five test conditions, as identified in Table 3, with 56 words in each except for the null condition. The first condition was made up of lax consonant-initial words, the second tense-initial words, and the third aspirated-initial words. The fourth condition was composed of vowel-initial words, and the fifth was the baseline condition (silence). During the baseline condition, the subjects listened passively to background scanner noise (which existed in the other conditions as well), and did not respond to that trial.

2.4 fMRI data collection and pre-processing

Brain activity was measured using a Philips 3T MRI system (IntraAchieva, Phillips Medical Systems, Best, the Netherlands) for the acquisition of a T_2^* -weighted gradient echo planar imaging (EPI) sequence sensitive to the BOLD contrast [TR⁸ = 2500ms, TE = 35ms, flip angle 90°, slice thickness = 4.5mm, scan image matrix⁹ of 80×80 and field of view¹⁰ of 220mm, voxel¹¹ unit of 2.75×2.78×3 mm³]. In order to facilitate later spatial normalization, a high-resolution T_1 -weighted structural MRI volume data set was also obtained from all subjects with a SENSE head coil configured with the following acquisition parameters: axial acquisition with a 256×256 matrix; 240 mm field of view; 0.9375×0.9375×1.5 mm³ voxels; TE 4.6 ms; TR 20 ms; flip angle 25°; slice gap 0 mm; 1 averaging¹² per slice.

2.5 Statistical analysis

Functional imaging data were preprocessed using the SPM2 software (Wellcome Department of Cognitive Neurology, London, UK). All images were preprocessed in a number of steps before statistical analysis: correction for variability in slice acquisition timing, realignment, coregistration to the T_1 -weighted image, spatial normalization to an EPI

⁸ TR (repetition time) is the time interval between successive excitation pulses. TE (echo time) is the time interval between excitation and data acquisition. Excitation refers to the introduction of energy into the 'spinning' nuclei via radio frequency pulse, thereby inducing the nuclei into a higher energy state.

⁹ A matrix is an array of numbers in rows and columns. A matrix with m rows and n columns is an m × n matrix with m and n as its dimensions. The matrix used in MRI determines the resolution of the scan.

¹⁰ Field of View (FOV), usually defined in units of mm, is the size of the two- or three-dimensional spatial encoding area of the image. In other words, it is the square image area that contains the object of interest to be measured; thus, the smaller the FOV, the higher the resolution and the smaller the voxel size but the lower the measured signal.

¹¹ A voxel, often used for the visualization of medical data, is a volume element which represents a value in three-dimensional space, corresponding to a pixel for a given slice thickness.

¹² Averaging, often called signal averaging, is a signal-to-noise improvement method to suppress the effects of random variations or random artifacts.

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template in the MNI space, and smoothing with 8 mm FWHM Gaussian kernel. The data were analyzed using the general linear model framework at every voxel with respect to the canonical hemodynamic response function. Correct and incorrect as well as missing answers were included in the analysis. Two random-effects one-sample t tests of the {Lax + Tense + Aspirated} contrast for 5 younger and 5 older subjects were employed to locate activation common to all subjects in each group. Clusters with a minimum of 50 neighboring voxels and a voxel-level threshold uncorrected $p < 0.001$ ($T = 7.17$, $df = 4$) were considered to be significantly different.

3. Results

3.1 Behavioral results

There were significant differences in reaction time between younger and older subjects ($t = 6.25$; $p < 0.05$). The accuracy scores for each subject's responses to the given stimuli inside the scanner were measured by calculating how many responses were correct among all responses, while excluding several cases of no responses in the calculation. The accuracy did not differ significantly between the two groups ($t = 0.15$, $p > 0.05$).

3.2 fMRI results

Figure 2 (A)-(B) displays activation maps associated with each task. In order to confirm activations for laryngeal contrast perception, we displayed activation areas with a lower threshold $p < 0.001$ with cluster size > 50 voxels. Table 4 lists all the activation areas along with their specific coordinates and cluster sizes.

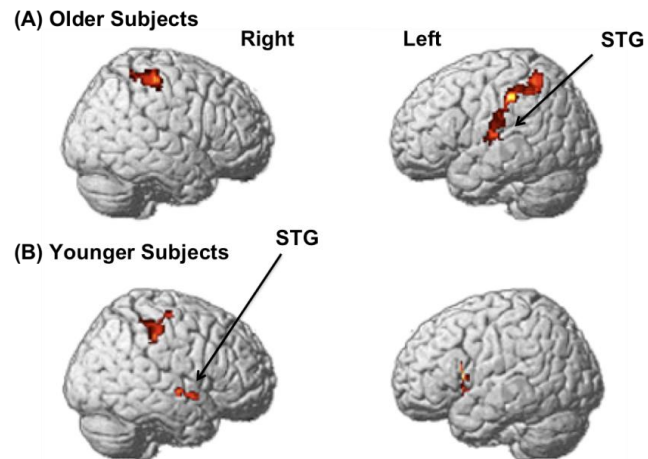


Figure 2. Activation maps for the older speakers (A) and younger speakers (B) in perception of laryngeal contrasts¹³.

¹³ This activation result does not imply that older subjects do not rely on pitch to distinguish the stop types; in fact, when the threshold was raised to $P < 0.005$, we were able to observe activation in the right temporal lobe, i.e., a pitch-related area, which suggests that they might use f_0 as a secondary cue to Korean laryngeal contrasts.

Table 4. Activation areas for laryngeal contrast perception for 5 younger and 5 older speakers, $P < 0.001$ ($T = 7.17$) and cluster size > 50 . BA: Brodmann Area, MNI: Montreal Neurological Institute coordinate, Csize: cluster size.

Group	Region	BA	x,y,z (MNI)	Csize
Older Subjects	L Supramarginal Gyrus	40	-48, -28, 42	409
	L Superior Temporal Gyrus	42	-66, -18, 10	122
	R Postcentral Gyrus	40/2	44, -28, 58	186
Younger Subjects	L Inferior Frontal Gyrus	44	-42, 14, 18	63
	L Putamen		-26, 8, 4	151
	R Superior Temporal Gyrus	22/21	56, 0, -6	84
	R Postcentral Gyrus	2/40	48, -30, 44	144
	R Precentral Gyrus	6	26, -22, 56	78

A random-effects one-sample t test of the {lax+tense+aspirated} contrast produced significant activation in the right Superior Temporal Gyrus (STG) for younger speakers as shown in Table 4 and Figure 2(A), while the same contrast elicited significantly increased activation in the left STG for older speakers as seen in Table 4 and Figure 2(B).

The right hemisphere including the right STG and/or the right Middle Frontal Gyrus (MFG) is known to be responsible for pitch perception (e.g., Zatorre et al. 1992, 1997; Meyer et al. 2002, 2003). This suggests that younger speakers rely more on the perception of pitch to distinguish laryngeal contrasts. On the other hand, the left primary auditory cortex or left STG has been implicated in the perception of Voice Onset Time (e.g., Steinschneider et al. 1999; Fonseca et al. 2005). This observation indicates that older speakers rely on VOT cues to a greater extent than their younger counterparts.

4. Discussion

4.1 Pitch perception vs. VOT perception

The aim of this study was to identify age-related differences in the neural correlate of the laryngeal contrast discrimination. This study found that

there is a significant difference in brain firing pattern between younger and older Korean adults. In particular, younger speakers showed significant activation in the right STG. Zatorre et al. (1997), among others, argued that the right hemisphere including the right STG and/or right middle frontal gyrus is involved with the perception of pitch or tone regardless of its linguistic relevance. In addition, Meyer et al. (2002, 2003), based on their fMRI results, maintained that the right hemisphere was dominantly activated during the modulation of pitch contours. Given these observations, we conclude that the activation of the right STG for younger Korean speakers dovetails with Silva's (2006) claim that the laryngeal contrasts of Korean are increasingly distinguished via their effect on pitch in the following vowel rather than by VOT differences, at least among younger speakers.

On the other hand, the left auditory cortex or STG in the temporal lobe is known to be responsible for perceiving VOT differences. For one thing, Liegeois-Chauvel et al. (1999) revealed in their intracerebral evoked potential study that the coding of VOT takes place in the left auditory cortex (STG). Moreover, in their auditory evoked potential (AEP) study, Steinschneider et al. (1999) argued that VOT is represented in the left primary and secondary auditory cortex or left STG. As argued in section 2.1.1, the acoustic result of the older subjects entails that older Korean subjects use VOT as a primary cue for laryngeal contrasts. It can therefore be expected that the left temporal lobe, specifically, the left STG, will be activated to a greater degree by older subjects as opposed to younger ones, as found in the present study.

4.2 Implication

The current study showed that younger speakers of Seoul Korean for whom VOT is no longer the chief differentiator between lax and aspirated stops were found to be activating the pitch-related area of the brain (namely, the right hemisphere including the right STG). This result is consistent with Silva's conclusion that Korean may be undergoing a shift in the properties that distinguish its system of laryngeal contrasts. For younger speakers now overlapping the VOT values of initial lax stops and initial aspirates, this difference in f_0 is becoming phonologized, serving as the chief cue distinguishing lax from aspirated stops. As Silva suggests, for speakers who have reduced the substantial VOT difference between lax and aspirated stops, this may require a reinterpretation of the features coding the stop types phonologically.

Whatever the particulars of the phonological reinterpretation, however, it now lies not just in the acoustic signal itself, but in the neural representation of the perception of these sounds as revealed by the present fMRI study. Thus, younger speakers who diminish the VOT difference between lax and aspirated stops show activation of the pitch-related

regions of the brain, indicating that for them the f_0 differences in the following vowel between the two stop types are phonological. On the contrary, older speakers who continue to retain a substantial VOT difference between lax and aspirated stops, and who also show similar pitch differentiation in the vowel following, do not activate the pitch-related area of the brain but the VOT-sensitive area, indicating that for them the f_0 difference is non-phonological. The fMRI results reported here furnish neurological support for a model hypothesizing that Koreans are undergoing a shift in Korean stop system. In addition, the present study shows that the acoustic findings for Korean subjects in terms of their VOT and f_0 patterns are consistent with what Silva (1992, 2006), Kang and Guion (2006), and Wright (2007) reported to the extent that as VOT ceases to be the primary distinguisher of lax vs. aspirated stops, f_0 patterns which once played a secondary role, are becoming more prominent.

Both the acoustic and the fMRI results of the present study point towards a change in how some Korean speakers produce and perceive differences in a Korean three-way laryngeal contrast. This is clearly indicated by age-based changes in VOT values. That is, older speakers are more likely to preserve clear VOT differences between lax and aspirated stops, whereas younger speakers are more likely to neutralize such distinctions. In spite of this change in progress in VOT patterns, younger speakers maintain the underlying contrast between lax and aspirated stops in Korean, which appears to be expressed in terms of the different f_0 patterns. In line with Silva (2006), the present study argues that this shift from the CV transition to the f_0 in the following vowels provides evidence that standard Korean is experiencing a sound change similar to that reported for other varieties of languages, including Mon-Khmer, in which historical distinctions between voiceless and voiced stops have been replaced by tonal distinctions in the modern Kammu dialect (cf. Svantesson and House 2006).

Future research, however, remains to be carried out on how the perception of Korean stops in word-medial position is represented in brain areas. This will allow us to have a more complete confirmation of the mental category distinctions implied by the acoustic observations of Korean laryngeal contrasts in both word-medial and word-initial positions extensively reported in the literature. Also, future study needs to investigate the nature of the similarities and differences in activation regions and magnitude between the perception of derived tense consonants (via post-obstruent tensing) and that of underlying tense consonants. It will be interesting to find out if activation of pitch-sensitive sites in the brain is modulated by the perception of the fundamental frequency of underlying tense or derived tense consonants or both. This will be crucial for shedding new light on neural support for the existence of two types of mental representations, underlying and surface.

5. Conclusion

This study investigated age-related neural differences in the perception of the three-way Korean laryngeal contrasts in word-initial position. During an auditory discrimination task, we found more of the right STG involvement in perception of the Korean stops for younger speakers with overlapping VOT distinctions, but greater left STG activation for older Korean speakers with clear VOT distinctions. Considering that the left STG is known to be sensitive to VOT perception, whereas its right hemisphere counterpart is responsible for pitch perception, the fMRI results reported here thus confirm the mental category distinctions implied by Silva's acoustic observations and support the emerging development of pitch sensitivity in the Korean stop system.

Appendix A. Target words used to measure VOT and f_0 (Silva 2006)

	Lax	Tense	Aspirated
Labial	pa.nu.cil 'sewing'	p'a.tu.tuk 'grinding sound'	p ^h a.na.mul 'scallion salad'
Alveolar	ta.mo.cak 'multiple cropping'	t'a.li.kun 'flatterer'	t ^h a.ko.cang 'foreign village'
Velar	ka.lo.dung 'street lamp'	k'a.ma.duk 'far away time'	k ^h a.ni.bal 'carnival'

Period (.) indicates a syllable boundary.

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