The frontal and temporal lobe in the identification of laryngeal contrasts

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To investigate neuroanatomical correlates of the categorization of laryngeally contrastive phonemes, an event-related functional magnetic resonance imaging was performed during an auditory identification task in which 10 participants were distinguished among the three types of word-initial stop phonemes, either lax, tense, or aspirated. Perception of the aspirated consonant series elicited significantly higher activation in the inferior frontal gyrus as compared with both the lax and tense series, and the tense series showed significantly higher activation in the left superior temporal gyrus in comparison with either the lax or the aspirated series. The results show differential involvement of frontal and temporal lobe language areas for distinct phonemic contrasts, supporting a linguistic feature formulation model that posits variably specified phonological representations for the three-way distinctions. *NeuroReport* **21:474–478 © 2010 Wolters Kluwer Health | Lippincott Williams & Wilkins.**

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Introduction

Among the brain networks involved in language modules, speech perception is regarded to be the result of interplay between the temporal lobe and the left inferior frontal lobe [1,2]. As an auditory cortex, the superior temporal gyrus (STG) is largely responsible for phonemic or phonological perception [3,4]. It is further understood that the left STG is sensitive to temporal processing whereas the right STG is specialized for spectral processing [5]. Similarly, the left STG is critical for extracting information from a short temporal integration window, as opposed to the right STG processing a longer time frame [6].

The inferior frontal gyrus (IFG), generally understood as a key area for speech production is now also known to play a critical role in speech comprehension and phonological identification, or discrimination [7], which was traditionally attributed to areas in the temporal lobe. Broca's area located in the IFG, particularly Brodmann area (BA) 44, which has close anatomical connections with the motor and somatosensory cortices responsible for tongue and larynx movement, seems to be closely associated with motor-related language production [8,9]. It is also understood that the motor-related speech area of IFG takes part even in language perception, especially with respect to complex laryngeal configurations. Watkins and Paus [10] proposed that this area modulates the motor system in perceiving speech, consistent with the motor theory of speech perception positing a close link between speech perception and motor production systems [11].

We can therefore hypothesize that both the temporal and frontal lobes may play a cooperative or exclusive role in identifying distinct laryngeal categories. Therefore, in this study, we examined the neural correlates of the categorization of word-initial phonological contrasts by exploring how the categorization of laryngeally and temporally contrastive distinctions is processed in the left IFG and the left STG, given that the importance of interaction between the left IFG and left STG in phonological categorization has already been proved [12]. For this purpose, we used a phonemic categorization task involving Korean's unique three-way contrast of tense versus lax versus aspirated plosives.

Korean plosives are distinguished by a special three-way laryngeal contrast, which, at the beginning of the word (phrase-initially), does not involve the feature (voice). Thus, unlike the three-way laryngeal system of Thai and other languages contrasting voiceless unaspirated (/t/) with voiceless aspirated (/t^h/) with voiced (/d/) stops, the plosive system of Korean distinguishes a (lightly aspirated) 'lax' series from a (heavily) 'aspirated' series from an (unaspirated, glottally constricted) 'tense' series. For example, *pul* (gloss: 'fire') is Lax-initial, *p'ul* ('horn') is Tense-initial, and *phul* ('grass') is Aspirated-initial.

The aspirated stops have arguably the most 'marked' or complex laryngeal representation, whereas the tense

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stops have the shortest formant transition. Therefore, we hypothesized that the perception of the laryngeally most complex sounds, aspirated stops, may recruit IFG to a greater extent than less complex representations like lax stops, and that the identification of the tense stops with a short formant transition may elicit the left STG more than the aspirated stops and lax stops with their longer formant transitions.

Methods

Participants

Ten right-handed native Korean speakers (six men and four women), with neither history of neurological/psychiatric illness nor speech/hearing impairments, participated in this study. The age range of the participants was 20–35 (mean, 28)-years old. They gave a written informed consent before the experiment. This study was carried out under the guidelines established by the Institutional Review Board.

Stimuli and procedure

As contrasting stimuli, we used three types of monosyllabic words (56 words for each type) beginning with one of the three-way laryngeally contrastive Korean stops (Lax /k, t, p, c/: ㄱ, ㄷ, ㅂ, ㅈ; Tense /k', t', p', c'/: ㄲ, ㄸ, ㅃ, ㅉ; Aspirated /k^h, t^h, p^h, c^h/: ㅋ, ㅌ, ㅍ, ㅊ) followed by one of five different vowels: 아 (/a/), 에 (/e/), 이 (/i/), 오 (/o/), 우 (/u/).

For example, *tal* (gloss: 'moon') is Lax-initial, *t'al* ('daughter') is Tense-initial, and *thal* ('mask') is Aspirated-initial. For these three coronal stops, the voice onset time values were: tense 12 ms, lax 65 ms, and aspirated 92 ms. All words, pronounced by a 30-year-old woman native speaker of Seoul Korean, were carefully controlled with respect to the number of phonemes and syllables, word frequency, and imageability.

As an event-related design, all three contrasting types of words and baseline null stimuli (no speech sound) were pseudo-randomly presented every 2.5 s based on the temporal sequence calculated using the Optseq2 (*http://surfer.nmr.mgh.harvard.edu/optseq/*). For each stimulus, the participants were instructed to indicate which they heard among the three consonant types, or a vowel, by pressing one of four buttons.

Data acquisition, processing, and statistical analysis

Brain activity was measured using a Philips 3T magnetic resonance imaging (MRI) system (Achieva, Phillips Medical Systems, Best, The Netherlands) for the acquisition of a T_2*-weighted gradient echo planar imaging sequence sensitive to the blood oxygenation level dependent contrast (repetition time = 2500 ms, echo time = 35 ms, flip angle 90°, slice thickness = 4.5 mm, scan image matrix of 80 × 80 and field-of-view of 220 mm, voxel unit of $2.75 \times 2.78 \times 3\,mm^3$). A high-resolution T_1-weighted structural MRI volume data set was also obtained from each participant.

Functional imaging data were preprocessed using the SPM5 software (Wellcome Department of Cognitive Neurology, London, UK). All images underwent preprocessing steps before statistical analysis: correction for variability in slice acquisition timing, realignment, coregistration to the T1-weighted image, spatial normalization to an echo planar imaging template in the Montreal Neurological Institute space, and smoothing with 8 mm full-width half-maximum Gaussian kernel. The preprocessed data were statistically analyzed using the general linear model at every voxel with respect to the canonical hemodynamic response function. Both correct and incorrect responses were included in the analysis. One-sample *t* tests for the Lax, Tense, and Aspirated conditions with random participant effects were used to locate activations common to all participants ($n = 10$). A voxel-level threshold with an uncorrected P value of less than 0.001 ($T = 4.3$, d.f. = 9) with cluster size greater than 40 was used to detect statistical difference at the voxel level. We compared percentage signal changes in the left STG and left IFG defined in the statistical maps of the aspirated condition and the tense condition, respectively.

Results

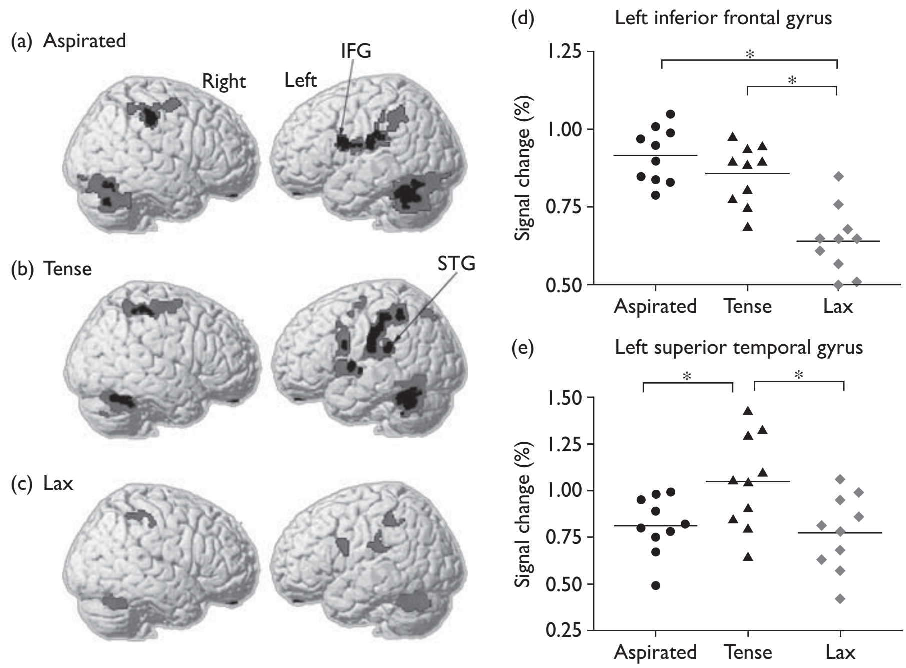
Behavioral results

The average response times and standard deviations (SD) for Lax, Tense, and Aspirated tasks were 1001 (SD 203) ms, 1057 (210) ms, and 1053 (201) ms, whereas the mean accuracies for these conditions were 94 (SD 3.9), 91 (5.3), and 93% (4.8), respectively. One-way repeated measures of analysis of variances showed no significant difference in mean response time and accuracy across the three laryngeal types ($P > 0.05$). The accuracy scores for each participant's responses to the given stimuli inside the scanner were measured by calculating the portion of correct responses among all responses, while excluding no responses.

Functional magnetic resonance imaging results

Figure 1a–c displays activation maps associated with each task. To confirm activations in the STG and IFG for all conditions, we displayed activation areas with a lower threshold P value of less than 0.005 with a cluster size greater than 100 voxels and areas with a threshold of P value of less than 0.001 and a cluster size greater than 40 voxels. A random-effects one-sample *t*-test of the Aspirated condition showed significant activation in the left IFG, whereas the Tense condition had significantly increased activation in both the left IFG and the left STG (Table 1 and Fig. 1b). Perception of the lax series also resulted in moderate, if not significant, activation in the IFG and STG (Fig. 1c).

Fig. 1



Activation maps for the Aspirated, Tense, and Lax conditions (a, b, and c) and percentage signal changes at the left inferior frontal gyrus [IFG, (d)] and the left superior temporal gyrus [STG, (e)]. The activated clusters with a threshold *P* value of less than 0.005 with cluster size greater than 100 are displayed in gray and clusters with a threshold *P* value of less than 0.001 and cluster size greater than 40 are in black. The percentage signal change for each stimulus condition was calculated at the left IFG and at the left STG defined in the activation maps of (a) and (b), respectively. *Indicates statistical significance with $P<0.05$.

Table 1 Activation areas for the identification of aspirated, tense, and lax series

Task	Region	BA	*x,y,z* (MNI)	Z_{max}	Csize
Aspirated	L inferior frontal gyrus/	44/6	−50, 2, 18	4.18	81
	L inferior frontal gyrus	44	−54, 8, 24	4.08	
	L inferior parietal lobule/	40	−58, −26, 28	3.89	62
	L inferior parietal lobule/	40	−64, −20, 24	3.71	
	L superior temporal gyrus	42	−52, −30, 24	3.43	
	L Inferior parietal lobule	40	−40, −44, 44	3.58	43
	L cerebellum		−28, −52, −42	3.9	512
	R inferior parietal lobule	40	48, −28, 42	4.37	91
	R cerebellum		6, −66, −40	3.80	68
Tense	L superior temporal gyrus	22	−64, −36, 22	3.67	57
	L insula	13	−48, 0, 2	4.38	69
	L superior temporal gyrus	22	−50, −8, −4	3.79	
	L inferior frontal gyrus	44	−54, 10, 4	3.59	46
	L inferior parietal lobule	40	−66, −20, 24	4.34	223
	L inferior parietal lobule	40	−42, −50, 48	3.51	74
	L superior parietal lobule	7	−34, −46, 54	3.67	74
	L Precentral gyrus	6	−56, 6, 28	3.65	34*
	L Fusiform gyrus	37	−50, −60, −12	3.71	42
	L cerebellum		−4, −48, −6	5.3	1986
	R inferior parietal lobule	40	44, −44, 56	3.62	72
	R Precentral gyrus	4	36, −22, 58	3.32	47
	R cerebellum		30, −62, −26	3.93	285
Lax	L cerebellum		−8, −50, −24	4.76	193
	L cerebellum		−4, −66, −28	4.62	115

BA, Brodmann area; Csize, cluster size; L, left; MNI, Montreal Neurological Institute coordinate; R, right; Z_{max}, *Z* maximum within a cluster.
*$P<0.001$ (uncorrected) and cluster size >40 (except for *).

As shown in Fig. 1d and e, we found significant differences in the percentage signal changes at the left IFG and the left STG among the three laryngeal conditions. The repeated measures of analysis of variance indicated that activity for the Aspirated and Tense tasks was statistically higher in the left IFG than the Lax task [F(2,27) = 16.21,

$P < 0.001$]. Brain activity for the Aspirated condition in the left IFG was higher, if not significant ($P = 0.19$), than the Tense condition. In contrast, the Tense condition produced substantially higher activity in the left STG than the other two conditions [$F(2,27) = 5.156$, $P = 0.013$]. There was no significant difference in the percentage signal changes between the Lax and Aspirated tasks at the left STG.

Discussion

In this study, we examined the role of language areas of the brain in the identification of Korean's three-way laryngeal contrasts during an auditory discrimination task specific to different phonological inputs. The perception of the aspirated and tense series produced significantly increased activation in the left IFG as compared with that of the lax series. Neural activity for the tense series was significantly higher than for the other two in the left STG.

Minimized linguistic feature formulation

The differential activation of lax, aspirated, and tense series in this study accords well with a minimalized linguistic feature formulation model [13], which is based on phonetic and phonological evidence, and was also supported in an event-related potential study [14], to distinguish three-way laryngeal categories in mental or underlying representation.

The model hypothesizes that the tense series of obstruents consists of geminate, or long, versions of the laryngeally simple lax series, which then, phonologically, are both without specified laryngeal content, whereas the aspirated series is marked by the feature (spread glottis). The laryngeal systems of all the world's languages can be represented phonemically by just three privative (singulary) features and their combinations: voice, constricted glottis, and spread glottis [15,16]. Therefore, this phonological model distinguishing Korean obstruents in terms of their laryngeal and temporal aspects may explain the current activation results in this study that shows differential recruitment of the inferior frontal and superior temporal lobes for each phonemic contrast.

Laryngeal processing and the left inferior frontal gyrus

The identification of aspirated or tense word-initial stops, but not of the lax stops, showed significant activation in the left IFG, especially at a cytoarchitectonic subdivision of Broca's area, BA44. The Pars Opercularis (BA44), which is embedded in a motor and somatosensory network [17], is relevant for generating complex articulatory movement of laryngeal muscles [18] and is involved in the production of the laryngeal component of speech sounds. As both aspirated and tense stops are known to involve an increase in isometric tension in the thyroarytenoids of the larynx as compared with lax stops [19], increased IFG activation during the perception of both aspirated and tense stops may be attributed to these motor-related properties of IFG, based on the motor theory of speech perception. The left IFG activation visible in perception of the aspirated and tense stops may also be explained by the increased articulatory rehearsal demanded in the task, in as much as the articulatory rehearsal component of verbal short-term working memory modulates activation in Broca's area (BA44) [20].

Higher, if not statistically significant, activation at the left IFG for the Aspirated than for the Tense condition (Fig. 1d) may be because of the representational marking of the aspirated stops (but not the lax and tense stops) with a specified laryngeal feature, for example, spread glottis, thus posing a higher demand on larynx-related phonological processing. Specifically, if representational complexity in the Korean aspirated series requires a greater degree of 'inner speech' in its perception than others, the elevated involvement of the left IFG in the Aspirated condition can be attributed to increased articulatory rehearsal corresponding to the specified or marked laryngeal feature (spread glottis). Therefore, the significantly greater activity in the left IFG for the Aspirated condition lends support to a laryngeally more complex representation of the Korean aspirated series vis-à-vis the other two, as proposed by Ahn and Iverson [13].

Note that an activation cluster corresponding to BA44 extended to or was found at the premotor cortex (BA6) in the Aspirated and Tense conditions, if not as strongly as BA44 (Table 1). This result is consistent with the earlier researches that BA6 together with BA44 was activated for the phonological processing [21,22]. Furthermore, the inferior parietal lobule (BA40), which has anatomic connections with BA6 [23] and is involved in the storage of phonemes that require more extensive phonological coding, was also activated in Aspirated and Tense conditions. Therefore, we can regard that BA6 along with BA40 may interplay with BA44 for complex phonological perception.

Temporal aspect and the left temporal lobe

The left temporal lobe is known to be responsible for extracting information from short temporal integration windows (approximately 20–40 ms), that is, encoding vowel formant transitions after stop consonants, as opposed to long temporal windows (approximately 150–250 ms), that is, encoding syllables [6]. Representation of the tense series as phonologically geminate, or long, entails that the period of closure and release for these is longer than for the lax or aspirated series [24], hence a greater portion of this more or less constant interval is consumed by closure with respect to the tense stops. As a consequence, the tense stops make less time available for formant transitions in the following vowel than the lax or aspirated stops, that is, closure duration is inversely reflected in the brevity of the temporal integration window opening into the following vowel. We measured the formant transitions after Korean tense stops to be around 30 ms, whereas those of the aspirated and lax series average 70 ms. It can therefore be expected that the left temporal lobe will be more sensitive to the tense series as opposed to the other two, thereby resulting in more activation of the left STG in the Tense condition, as found in this study.

In summary, the results of this study show a differential involvement of left IFG and left STG in the perception of different laryngeal contrasts, which is consistent with a minimalized linguistic feature formulation model.

Conclusion

This study investigated how the perception of the three-way Korean laryngeally (and temporally) contrastive distinctions in word-initial position is represented in the language areas of the brain. In an auditory discrimination task, we found more of left IFG involvement in the perception of the aspirated and tense consonants, but greater left STG activation for the tense consonant discrimination. This shows that the identification of each laryngeally and/or temporally contrastive segment distinctively activates both frontal and temporal language areas, and provides neurological support for a model hypothesizing variably specified phonological representations.

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