

The brains of speech experts and non-experts compared: An fMRI investigation of phonological processing*

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Park, Haeil. 2016. The brains of speech experts and non-experts compared: An fMRI investigation of phonological processing. *Linguistic Research* 33(3), 519-533. The present study aims to investigate whether there are distinctions in language-related brain function between speech experts and control subjects, and if so, how the functional reorganization or plasticity of the brain plays out in learning speech skills. Here, we used functional Magnetic Resonance Imaging (fMRI) to compare cerebral activity patterns associated with phonological perception in announcers and non-announcers during the task of identifying three-way Korean laryngeal contrasts. The results show that there are significant differences in neural activity pattern between the two groups. In particular, the announcer group, as compared to the control group, showed less activation in the regions associated with phonological perception: the left superior temporal gyrus, the primary sensorimotor cortex including pre- and post-central gyrus and the supramarginal gyrus (SMG). These findings provide evidence for neuroplasticity after learning language skills in a way that a continuing verbal training results in a greater language processing efficiency, thereby inducing less amount of activation in language-related regions. (Kyung Hee University)

Keywords functional Magnetic Resonance Imaging, phonological processing, announcers, brain plasticity, laryngeal contrasts

1. Introduction

Studies on neural markers of special skills have fascinated researchers for several decades in that they can debunk the brain mechanisms of plasticity, i.e., the ability of the brain structure and function to continually change after learning new skills.

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Among them are music skills which have long been studied with respect to their motor, audition, space-temporal sensory capacities. In particular, functional neuroimaging studies have revealed significant differences in brain activation between musicians and non-musicians during the performance of auditory, motor, and somatosensory tasks (Elbert *et al.* 1995; Pantev *et al.* 1998; Schlaug 2001). For example, professional musicians showed a lesser degree of neural activation in motor and premotor cortices responsible for movement than non-musicians during the finger tapping tasks (Jäncke *et al.* 2000; Krings *et al.* 2000).

It remains unclear, however, whether there is such functional disparity between speech experts and their non-professional counterparts. Speaking is known as one of the most complex, innate motor skills since speech involves an activity that produces approximately fourteen sounds per second by moving one hundred or so muscles in a coordinated way. Among experts of this skill are announcers or voice actors, who tend to receive at least 10 years of extensive speech-related training since their childhood. Understanding the brain plasticity of speech experts, namely, the way their brain structure or function changes after their extensive verbal training is crucial for grasping neural mechanisms underpinning speech processing.

Thus, we aimed to investigate the nature of brain plasticity related to speech learning by comparing activation regions modulated by the identification/perception of Korean laryngeal contrasts in both groups. It is hypothesized that there will be a significant difference in activation pattern between the two groups, and that announcers will engage phoneme perceptual brain areas to a lesser degree than the control subjects during the laryngeal contrast identification task. The rationale behind these hypotheses is that the continuous verbal training of the announcers greatly increases language processing efficiency, which will lead to a fewer number of active neurons during the relevant task. Alternative hypothesis is that the announcer group will activate more of the task-related areas or there will be no activational differences between the two groups.

2. Methodology

2.1 Subjects

Two groups, consisting of subjects without history of neurological and

psychiatric disorders participated in the present study. The first group (n=5) was composed of announcers (n=5, females, 25-37 years old, mean=31, s.d.=3.7) with more than 10 years of 5-8 hours of training per day and the age- and gender-matched control group (n=5, females, 25-37 years old, mean=32, s.d.=3.1) consisted of undergraduate and graduate students who had no formal speech training. All subjects were right-handed according to the Edinburgh Handedness Inventory (Oldfield 1971). Written informed consent was obtained from all subjects in accordance with the guidelines of the Internal Review Board.

2.2 Task and stimuli

All subjects participated in the task of Korean laryngeal contrast perception. Korean words were sequentially presented on the screen positioned above the eyes. Three types of monosyllabic words were used, each word starting with three-way laryngeally contrastive Korean stops (Lax: /k, t, p, ts/: Tense: /k',t', p', ts'/; Aspirated: /kh, th, ph, tsh/) followed by one of five different vowels: /a/, /e/, /i/, /o/, /u/.

Table 1. Conditions and example stimulus

Condition	Example
Lax	<i>tal</i> 'moon'
Tense	<i>t'al</i> 'daughter'
Aspirated	<i>thal</i> 'mask'
Null	silence

A 30-year-old female speaking Seoul Korean dialect produced all the stimuli, which were meticulously controlled for the number of phoneme and syllable, lexical frequency, and imageability. Before scanning, the participants were provided with the practice session to become familiarized with the experimental procedure. They were asked to identify whether the words that they see on the screen start with lax, aspirated, or tense consonants. They were presented in an event-related design with 40 words per condition (total 160)¹. E-prime software package (Psychology Software Tools, Inc. 2002) was used for the presentation of the stimuli and measurement of their response times. Each

¹ Within this design, stimuli within each condition are presented not in a fixed order, but in a random sequence on a trial-by-trial basis. This design has been the most frequently used in psycho- or neuro-linguistic experiments, due to the capability to deal with numerous cognitive psychology questions through a higher degree of inferential/statistical power.

stimulus was presented every 2 seconds in a pseudo-random sequence which was calculated by the Optseq 2 mechanism (<http://surfer.nmr.mgh.harvard.edu/optseq/>).

2.3 Data acquisition, pre-processing and statistical analysis

Brain activity was measured using a Philips 3T MRI system (Achieva, Phillips Medical Systems, Best, the Netherlands) for the acquisition of a T2*-weighted gradient echoplanar imaging (EPI) sequence sensitive to the BOLD contrast (TR=2500ms, TE=35ms, flip angle 90°, slice thickness=4.5mm, scan image matrix of 80×80 and field of view of 220mm, voxel unit of 2.75×2.78×3mm³). To facilitate later spatial normalization, a high-resolution T1-weighted structural MRI volume dataset was also obtained from all subjects.

Functional imaging data were preprocessed with the SPM12 software (Wellcome Department of Cognitive Neurology, London, UK). All images underwent five preprocessing steps before they were statistically analyzed: 1) variability correction in slice acquisition timing, 2) realignment, 3) coregistration to the T1-weighted image, 4) spatial normalization to an EPI template in the MNI space, and 5) smoothing with 8 mm FWHM Gaussian kernel. The preprocessed data were statistically analyzed using the general linear model (GLM) with the canonical hemodynamic response function modeled as a boxcar function. Both correct and incorrect responses were included in the analysis. One-way within-subjects ANOVAs for the $\{((\text{Lax}/+/\text{Tense}/+/\text{Aspirated}) - 3 \times \text{baseline})\}$ with random subject effects were used to locate areas that are commonly activated in all subjects ($n=5$). The results of the one-sample within-subjects ANOVAs for the control group are shown in Figure 1 and Table 1. A voxel-level threshold with an uncorrected $p < 0.001$ ($t = 4.3$, $df = 9$) with cluster size > 150 was used to detect statistical difference at the voxel-level. Two-sample t -tests of the $\{((\text{Lax}/+/\text{Tense}/+/\text{Aspirated}) - 3 \times \text{baseline})\}$ contrast for the control group as compared to the announcer group were used to identify activation regions uniquely involved with control subjects' perception of laryngeal contrasts. The two-sample t -test results are shown in Figure 3 and Table 2.

3. Results

3.1 Behavioral results

One-way repeated measures ANOVAs for accuracy and reaction time were applied to test for task-specific differences. The average response times and standard deviations (s.d.) for Lax, Tense and Aspirated tasks in non-announcers were 980 (s.d. 201) ms, 1011 (s.d. 230) ms, and 1023 (s.d. 198) ms, while the mean accuracies for these conditions were 90 (s.d. 4.3), 89 (s.d. 5.1), and 91 (s.d. 4.2) percent, respectively. The average response times and standard deviations for Lax, Tense and Aspirated tasks in announcers were 970 (s.d. 190) ms, 990 (s.d. 185) ms, and 1005 (s.d. 205) ms, whereas the mean accuracies for these conditions were 92 (s.d. 4.5), 94 (s.d. 5.0), and 95 (s.d. 4.8) percent, respectively. There was no significant difference in mean response time across the three laryngeal types ($p > 0.05$) in both announcers and non-announcers. The accuracy scores (as measured by percent correct) did not differ significantly across conditions in the two groups ($p > 0.05$).

3.2 Activation results

When compared with the resting baseline for the control group, the laryngeal contrast perception (Table 1; Figure 1) produced significant activation in the bilateral precentral gyrus, superior frontal gyrus (Brodmann Area [BA] 6), cingulate gyrus, cerebellum, and the left postcentral gyrus, inferior parietal lobule or supramarginal gyrus ([BA 40]: SMG), insula (BA 13), inferior frontal gyrus (or Broca's area) (BA 9/44), middle frontal gyrus (BA 9/6) as well as the right superior temporal gyrus (BA 22), and medial frontal gyrus (BA 6).

Conversely, when compared with the resting baseline for the announcers, the laryngeal contrast perception elicited the left hemisphere dominance in the temporal cortical activation (BA 42) (Table 1; Figure 2); that is, more activation in the left temporal lobe than in its right counterpart. Furthermore, the significant activations were observed in the left superior parietal lobule (BA 7), inferior parietal lobule or SMG (BA 40), inferior frontal gyri or Broca's area (BA 44 and 9), middle frontal gyri (BA 9 and 6), medial frontal gyrus (BA 6), superior frontal gyrus (BA 6), lingual gyrus (BA 18), cerebellum and in the right cingulate gyrus, postcentral and precentral gyri (BA 2

and 4), inferior parietal lobule (BA 40). Overall, activation areas that were commonly found for both experimental groups constitute the well-established speech processing network of the brain, which includes Broca's area, the superior temporal gyrus (STG), the SMG and the cerebellum, as attested in the literature (Hickok and Poeppel 2007; Callan *et al.* 2004; Park *et al.* 2011; among others).

Table 1. Increased activation areas for {Control vs. Baseline} as well as {Announcer vs. Baseline}; $p < 0.001$ ($t = 4.30$, $df = 4$) and cluster size > 150 . BA: Brodmann Area. Zmax: maximum Z-value of the cluster. MNI: Montreal Neurological Institute coordinates. Csize: cluster size

Region	BA	Coordinate x,y,z (mm)	Zmax	Cluster size
<i>Control vs. Baseline</i>				
L Postcentral gyrus	2	-48, -28, 40	5.36	355
L Supramarginal gyrus, Inferior parietal lobule	40	-56, -34, 52	4.38	256
L Supramarginal gyrus, Inferior parietal lobule	40	-42, -38, 38	4.01	334
L Superior frontal gyrus	6	2, 10, 56	4.99	
L Cingulate gyrus	24	2, -2, 42	4.46	208
L Insula	13	-42, -2, 8	4.51	242
L Precentral gyrus	6	-58, 4, 24	4.87	385
L Precentral gyrus	6	-36, -8, 54	4.76	318
L Precentral gyrus	4/6	-44, -12, 54	4.41	354
L Precentral gyrus	6	-56, 2, 34	4.77	377/292
L Inferior frontal gyrus	6	-56, 2, 34	4.77	481
L Inferior frontal gyrus	9	-58, 4, 24	4.87	236
L Middle frontal gyrus	9/44	-36, -8, 54	4.76	227/201
L Middle frontal gyrus	6	-42, -2, 8	4.51	399
L Middle frontal gyrus	6	-34, 0, 60	3.80	204
L Cerebellum, nodule		0, -64, -34	4.51	
R Superior frontal gyrus	6	2, 10, 56	4.99	288
R Medial frontal gyrus	6	4, -6, 64	4.61	392
R Superior frontal gyrus		4, -6, 64	4.61	158
R Cingulate gyrus		2, -2, 42	4.46	404
R Precentral gyrus	6	36, -18, 66	4.59	396
R Precentral gyrus	24	46, -12, 58	4.58	315/294
R Precentral gyrus	6	26, -14, 70	4.54	242
R Superior temporal gyrus	6/4	66, -10, 6	4.49	314
R Superior temporal gyrus	6	-60, -32, 4	4.04	206
R Cerebellum, Declive	22	30, -68, -24	4.92	1227
R Cerebellum, Declive	22	20, -64, -24	4.85	1223
R Cerebellum, Declive		2, -78, -20	4.29	

Announcer vs. Baseline

L Superior parietal lobule	7	-28, -66, 42	5.22	230
L Superior temporal gyrus	42	-64, -20, 10	4.96	258
L Supramarginal gyrus, Inferior parietal lobule	40	-50, -40, 54	4.93	548
L Inferior frontal gyrus	44	-48, 8, 20	5.17	151
L Inferior frontal gyrus	9	-52, 14, 32	4.55	236
L Middle frontal gyrus	9	-52, 14, 32	4.55	268
L Middle frontal gyrus	6	-28, -4, 50	7.88	447
L Middle frontal gyrus	6	-26, -2, 60	4.04	219
L Medial frontal gyrus	6	-2, 0, 62	5.15	305
L Superior frontal gyrus	6	-6, 8, 52	4.73	295
L Lingual gyrus	18	-4, -66, -10	4.58	279
L Cerebellum, Declive		-48, -66, -32	4.38	484
L Cerebellum, Culmen		-4, -66, -10	4.58	726
R Cingulate gyrus	24	8, 2, 48	4.84	376
R Postcentral gyrus	2	50, -32, 58	5.10	221
R Precentral gyrus	4	38, -22, 64	4.54	348
R Inferior parietal lobule	40	58, -36, 42	4.27	657

Control subjects

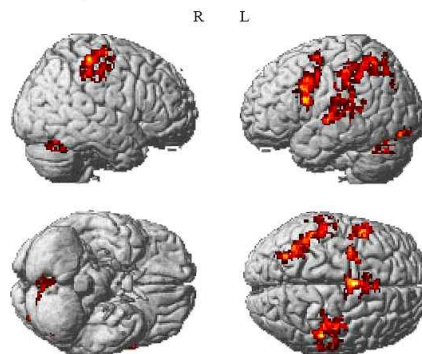


Figure 1. The control group activation maps for /Lax/, /Tense/, and /Aspirated/ perceptual identification relative to baseline (silence). Upper images are from a side surface view, lower images from a coronal view

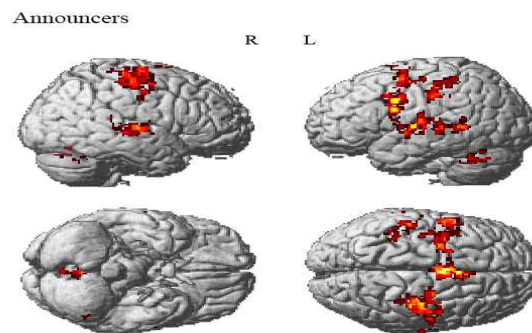


Figure 2. The announcer group activation maps for /Lax/, /Tense/, and /Aspirated/ perceptual identification relative to baseline (silence)

When comparing the control group with the announcer group for the identification of laryngeal contrasts, significant activations were found in the left lingual gyrus, putamen (area involved with controlling attention or selecting responses), superior temporal gyrus (BA 42: area of phonological network), transverse temporal gyrus (BA 42/41), pre- and post-central gyri (BA 2/3/4/5: area associated with subvocal rehearsal of phonological information), supramarginal gyrus (BA 40: area of phonological processing relevant to phonological decision) and superior parietal lobule (BA 5/7) as well as in the right precentral gyrus (BA 4/6). There was no activation areas in the reverse contrast, i.e., when contrasting the announcer group with the control group (Table 2 and Figure 3).

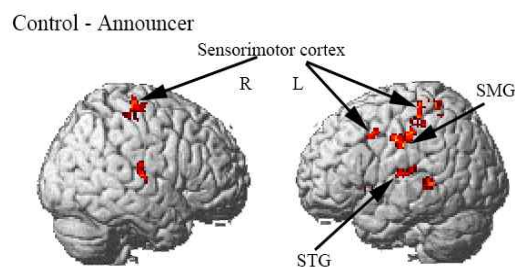


Figure 3. A group difference map of the activation between control subjects and announcers during laryngeal contrast perception shows stronger activation in the former than in the latter in the left superior temporal gyrus (STG), left supramarginal gyrus (SMG), and the bilateral sensorimotor cortex

Table 2. Increased activation areas for {Control vs. Announcer}; $p < 0.005$ ($t = 3.01$, $df = 4$) and cluster size > 50 . BA: Brodmann Area. Zmax: maximum Z-value of the cluster. MNI: Montreal Neurological Institute coordinates. Csize: cluster size

Region	BA	Coordinate x,y,z (mm)	Zmax	Cluster size
<i>Control vs. Announcer</i>				
L Putamen		-28, 4, 12	4.09	334
L Lingual gyrus		-24, -60, 0	3.48	98
L Caudate		-8, 10, 16	4.31	702
L Thalamus		-4 -10, 8	3.58	328
L Superior temporal gyrus	42/41	-62, -22, 10	3.25	186/56
L Transverse temporal gyrus	42	-62, -22, 10	3.25	100
L Postcentral(Supramarginal) gyrus	40	-62, -22, 10	3.25	80
L Postcentral gyrus	3/2	-46, -24, 40	4.35	158/125
L Postcentral gyrus	3	-36, -30, 54	4.52	408
L Precentral gyrus	4	-36, -30, 54	4.52	204
L Postcentral gyrus	5	36, -24, 70	3.79	109
L Superior parietal lobule	5/7	36, -24, 70	3.79	95/75
R Precentral gyrus	4/6	38, -22, 62	3.66	247/163

4. Discussion

We presented both announcers and control subjects with laryngeally contrastive words to compare the differences in brain activation pattern of the two groups during the identification of native phonemes, thereby testing how the cortical plasticity in announcers will play out.

We explored the hypothesis that announcers who practiced a verbal skill for over a decade will engage phoneme-perceptual brain regions to a lesser extent than control subjects, given the assumption that greater efficiency in a skill acquired through a long-term continuous training will be reflected in less activation of the brain regions associated with the skill (Jäncke *et al.* 2000; Krings *et al.* 2000).

As consistent with our hypotheses, there was not only a significant difference in brain activation between the announcers and the control group, but also greater brain activity for control subjects over announcers in brain regions for phoneme perceptual identification, i.e., the superior temporal gyrus (involved with phonological representation), the left primary sensorimotor cortex (involved with speech planning

and subvocal rehearsal) and the left SMG (involved with phonological decision or covert articulation)². Notably, significantly greater activity for the control group in response to laryngeal contrast perception condition compared to baseline was also found in the basal ganglia that consists of putamen and caudate, as well as the thalamus, all of which have been reported to be responsible for controlling attention and/or selecting responses (Desmond *et al.* 1998; McAlonan *et al.* 2006). This can be interpreted as due to the fact that non-announcers require greater attention during the task of selecting a perceived phonetic contrast, given their comparative lack of expertise in language.

Stronger activation in the bilateral STG (mostly, BA 42) was found in the controls than in the announcers. The bilateral STG is also associated with phonological network or representation of the speech signal (Hickok and Poeppel 2007; Callan *et al.* 2004). Thus, this STG activation suggests that the control subjects retrieved or accessed phonological representation of the laryngeal contrasts more than the announcers to facilitate their identification task.

Significantly greater activation for the control subjects was also found in the left primary sensorimotor cortex, especially the mouth-representational area along the pre- and post-central gyrus (BA 2/3/4).³ The left sensorimotor cortex is associated with subvocal rehearsal of phonological information (Porro *et al.* 1996). Thus, the greater involvement of the left primary sensorimotor cortex for the controls may be reflective of their internally articulating or “mouthing” the phonemes not only to facilitate their identification but to predict auditory or orosensory consequences of producing them.

Relatedly, activation in the primary sensorimotor cortex and the Broca’s area for both experimental groups (Table 1; Figures 1 and 2) is clearly in support of the

² This result is also compatible with the findings of previous literature in which the phoneme identification of second-language speakers showed significantly greater activity than that of native-language speakers in brain regions involved with phonological representation (the STG), orosensory-articulatory representation (the SMG), and speech planning or subvocal rehearsal (the primary sensorimotor cortex and the Broca’s area) (Callan *et al.* 2004; Park 2008). The second language learners seem to be tantamount to control subjects in terms of their comparative lack of expertise in a given language task, while the native language speakers are analogous to announcers with respect to their competence in language-related tasks.

³ It should be noted that we also found significant effect in more dorsal motor and premotor cortical regions that may reflect button press response differences although we made an attempt to control for such activity by having them use the left hand.

motor theory of speech perception (Liberman and Mattingly 1985), whose main claim is that spoken words are perceived by identifying the gestures of the vocal tract. This implies that the motor system such as Broca's area and the primary sensorimotor cortex, which is involved in actual movement of speech articulators, is also recruited for speech perception. Indeed, there is ample Transcranial Magnetic Stimulation (TMS) and fMRI evidence showing that the neural activity of the motor system is involved in perceiving speech (Fadiga *et al.* 2002; Pulvermüller *et al.* 2006; among others). More direct and sensational evidence for the theory arises from the discovery of the mirror neurons that are activated not only when one performs a specific action or observes someone else's action, but also hears the sound that is caused by the specific action (Rizzolatti *et al.* 1996; Kohler *et al.* 2002). Thus, the finding of the present study that the sensorimotor cortex and the Broca's area have been activated while simply perceiving the speech sounds adds to evidence for the well-supported theory.

Finally, the greater activation of the left SMG was observed in the control group as compared to the announcer group (Figure 3 and Table 2). The left rather than right SMG has been known as an important part of phonological processing related to phonological decisions as well as covert articulation, based on lesion (Wilde 2010; Dewarrat *et al.* 2009) and neuroimaging studies (Shalom and Poeppel 2008; Hickok and Poeppel 2004, 2007). For instance, Wilde (2010) reported difficulties in phonological decisions after brain lesions in the left rather than right SMG, which led neurolinguists such as Hickok and Poeppel to include the left but not right SMG as their neural models of phonological processing. However, a TMS study revealed that both the right and the left SMG are important for accurate phonological decisions (Hartwigsen *et al.* 2010). The finding of our current study that more of the left but not right SMG activation was found for the control subjects as opposed to the announcers seems to be more in line with Hickok and Poeppel's model.

Overall, the finding of the present study contributes to the ongoing discussion of the brain plasticity which refers to an adjustment or adaptation of a sensory or motor system after learning new skills, and a compensation of lost function after the brain injury. Various electrophysiological or neuroimaging studies have provided evidence to the brain function and structure's capability to continually change throughout life in humans and animals after stimulation from the environment (Jenkins *et al.* 1994; Pascual-Leone *et al.* 1994; Wang *et al.* 2003).

Plastic changes, however, have mainly been discussed in terms of musicians' brains as compared to those of non-musicians. Schneider *et al.* (2002), for example, found that the gray matter volume of Heschle's gyrus was higher in professional musicians than in non-musicians, and Schlaug *et al.* (1995) revealed that the size of the corpus callosum was greater in musicians than their non-musician counterparts. Moreover, symphony orchestra musicians exhibited increased gray matter density in Broca's area than control subjects (Slumming *et al.* 2003).

The present study demonstrates that there exists a plasticity in brain function among speech experts. Given that the announcers activated less activation in sensorimotor areas, the result of the present study is supportive of one aspect of Jäncke *et al.*'s (2000) argument for plasticity that practicing for a long term has a dual effect: first, it provides a greater network of neurons that are involved in relevant motor control, and second, it permits greater efficiency in brain function within that increased neuronal network. That is, the announcers controlled the movement of speech organs more efficiently, which led to less activation in the sensorimotor areas. It still remains unclear whether the former effect of the long term practice can be observed in the case of announcers as well. Future research, therefore, remains to see whether a greater neural network in areas of speech motor control is found in announcers relative to non-announcers by comparing cortical density between the two groups in order to corroborate the neuroplasticity of speech experts.

5. Conclusion

The comparisons of activation patterns elicited by the perceptual identification of auditorily presented Korean words show that announcers as compared to control subjects engage fewer active neurons in the phonological speech processing areas including the STG, the left SMG, and the primary sensorimotor cortex. These results provide strong evidence for neuroplasticity related to learning language skills in a way that a long term extensive verbal training results in a higher efficiency in language processing, which will engage less amount of activation. Also, the sensorimotor and the Broca's area activation for the two groups is compatible with the motor theory of speech perception that emphasizes the role of the simulation and

embodiment in language perception.

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