Neuronal Mechanism of Speech Hearing: An fMRI Study

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Abstract. It is well known that bilateral superior temporal gyrus (STG) specialize in speech perception. However, there is no study to explicitly represent the interaction between the bilateral STG depending on hearing condition (*i.e.* binaural or monaural hearing) based on neuroimaging findings. To this end, speech sentences containing numerical sound(s) were provided in binaural, monaural left and monaural right hearing condition. Participants were asked to correctly identify the presented numerical sound and speech hearing performance was calculated based on the number of correctly identified sounds. From the results, neuronal activations of the right STG were shown significantly different levels of neuronal activations across the three hearing conditions. In addition, the neuronal networks that are functionally connected with this right STG and associated with the speech hearing were iteratively identified in the bilateral STG. The reported findings support the importance of the right STG toward the enhancement of the speech hearing performance.

Keywords: Speech perception, superior temporal gyrus, hearing performance, binaural hearing, monaural hearing, functional magnetic resonance imaging, functional connectivity.

1 Introduction

Recent functional magnetic resonance imaging (fMRI) studies have reported that the neuronal activations in the right superior temporal gyrus (STG) as well as the left STG are crucial in speech perception including speech hearing [1, 2, 3, 4]. It has also been found that functional (correlated activations between brain regions) and effective (causal activations between distinct brain regions) connectivity patterns between bilateral STG associated with speech perception [5, 6, 7]. However, there have been limited studies that explicitly examined the neuronal responses in the STG and interactions between the bilateral STG, which are associated with speech perception performance depending on each type of hearing conditions (i.e. binaural or monaural hearing). We hypothesized that there would be distinct (1) neuronal activations in the STG depending on hearing conditions in association with speech hearing and (2) functional connectivity (FC) patterns between bilateral STG that are tightly associated with speech hearing performance.

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2 Methods

2.1 Study Participants and Experimental Design

Healthy right-handed male native Korean volunteers (*n*=12; age=25.3±1.7; Edinburg's handedness score=89.8±10.7 [8]) participated in this study. The English ability of the participants to perform task paradigm was evaluated using Wide Range Achievement Test (Blue version; score=60.4±5.2; [9]). In the experiment, the participants performed a task run which lasted 486 seconds. As shown in Fig. 1, the task run was consisted of 18 trials. Each trial was divided into speech hearing block and response block. In speech hearing block, auditory stimuli were pseudo-randomly presented either in binaural hearing (BH), monaural hearing in the left ear (MH_L), or right ear (MH_R) condition for 6 times in each condition via a MR-compatible auditory headset (NordicNeuroLab; www.nordicneurolab.com). The auditory stimuli consisted of eighteen English sentences containing numerical words (*i.e.*, "Two dollars and fifty cents."). In the response block, the participants were instructed to select a target numerical word accurately (*i.e.*, '15' vs. '50'), which was presented in the speech hearing block, using by a button response box (Current Design; www.curdes.com). A speech hearing (SH) score was defined as the correctly identified number of trials. Thus, the maximum SH score in each hearing condition is 6.

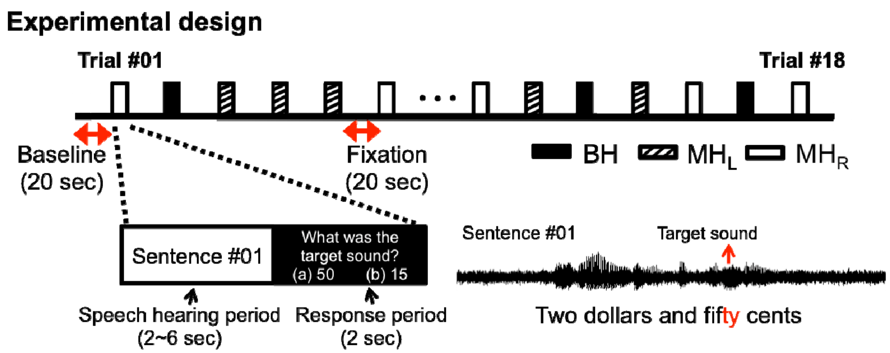

Fig. 1. Experimental design of speech hearing of numerical target sound

2.2 fMRI Data Acquisition and Preprocessing

The blood-oxygen-level-dependent (BOLD) fMRI data were acquired via a 3-T scanner (Tim Trio, Siemens, Erlangen, Germany). A gradient-echo echo-planar-imaging (EPI) pulse sequence was used to measure the neuronal activations based on BOLD mechanism (248 volumes; TE/TR=30/2000 ms; FA=90°; FOV=24×24 cm^2; in-plane voxel=64×64; number of slices=36 without a gap between slices). Five volumes at the beginning were excluded and the remaining EPI volumes were preprocessed using SPM8 software toolbox (www.fil.ion.ucl.ac.uk/spm) using default parameters with an order of slice timing correction, head motion correction, normalization to the Montreal Neurological Institute (MNI) coordinates with a 3 mm isotropic voxel size, and spatial smoothing using an 8 mm isotropic full-width at half-maximum Gaussian kernel.

2.3 Definition of Regions-of-Interest (ROIs)

A general linear model (GLM) method was applied to estimate the degree of neuronal activation using the preprocessed BOLD signal [12]. Each of the three hearing conditions with 6 hearing blocks was modeled as separate regressor in a design matrix using onset timings and durations of the each of the blocks. The coefficients (β-values) of the three regressors for each of the three hearing conditions were estimated from the GLM approach based on least-squares algorithm [12]. The neuronal activation was estimated using averaged β-values within 19 voxels around foci with maximum β-value from spatial patterns for each hearing condition. To define the regions of interest (ROIs) that showed a main effect of hearing condition on neuronal activation, one-way repeated measures analysis of variance (ANOVA: uncorrected $p<0.001$ with minimum of 20 connected voxels) was administered. Then, the ROIs that are tightly linked with the speech hearing were identified using a regression analysis with neuronal activation of ROIs and average speech hearing scores in each of the three hearing conditions.

2.4 Identification of Neuronal Networks Associated with Speech Hearing

To estimate the FC patterns associated with each hearing condition (*i.e.,* BH, MH_L and MH_R), the preprocessed BOLD time-series (TS) was voxel-wisely separated into each trial. Subsequently, the separated BOLD TS were temporally concatenated as a single BOLD TS for each of the three hearing conditions. The partial FC analysis was applied to remove potential confounding artifacts included in the BOLD signals due to non-neuronal origins such as head movements and physiological artifacts. In detail, three principal components (PCs) of the BOLD signals in each of the white matter and cerebrospinal fluid were extracted via principal component analysis. Then, the 6 PCs, global mean BOLD signal, and 6 head motion parameters were regressed out from the BOLD signal in voxel wise across a whole brain area. The ROIs tightly linked with the speech hearing score were used as seed regions of the FC analysis. More specifically, the average BOLD signal in proximity of the ROI (i.e. 19 neighboring voxels) was obtained and subsequently used as a reference BOLD signal for the FC analysis. The FC level in each voxel was calculated from Pearson's correlation coefficient (CC) between averaged BOLD signal of the seed ROI and the BOLD signal of the corresponding voxel. The resulting CC values were converted into normally distributed z-scores using Fisher's r-to-z transform to normalize the FC levels across a whole brain for each participant and to proceed group-level analysis.

In the group-level, One-way ANOVA test was conducted using the FC patterns with z-scores and the speech hearing scores across subjects as covariate. This procedure was carried out to identify the brain regions whose the FC level from the seed ROI was tightly linked with speech hearing score (uncorrected $p<0.005$ with minimum of 20 connected voxels). If identified brain regions were not in proximity with seed regions of the FC analysis (i.e. > 8mm in distance), these regions were considered as a new seed ROI. Then, the newly identified seed ROI was used for the subsequent FC analysis. This repeated FC analysis with speech hearing scores as covariate in the one-way ANOVA framework was continued until there is no seed region was identified.

3 Results

3.1 Behavioral Results

In the statistical analysis of speech hearing score across three conditions (*i.e.*, BH, MH_L, or MH_R), the main effect of hearing condition was estimated from one-way repeated measures ANOVA (p=1.6×10^{-3}). In addition, a paired *t*-test was conducted to compare hearing scores between binaural and monaural hearing condition. In detail, speech hearing score in BH condition (5.75±0.13) was significantly greater compared to MH_L (4.75±0.18) and MH_R (4.3±0.40) conditions with statistical significance values of p=1.29×10^{-4} and p=7.60×10^{-3}, respectively.

3.2 Language-Related Regions

Fig. 2 shows the main effect across the speech hearing conditions. The neuronal activations were found in right STG (peak *t*-score=13.75; 40 voxels; [45, -22, 1] mm), right superior frontal gyrus (SFG; peak *t*-score=17.75; 114 voxels; [24, 20, 49] mm), right angular gyrus (peak *t*-score=13.07; 25 voxels; [42, -73, 46] mm), left SFG (peak *t*-score=34.54; 87 voxels; [-24, 11, 64] mm), and left middle frontal gyrus (peak *t*-score=19.57; 26 voxels; [-36, 41, 37] mm). As shown in Fig. 3, the levels of neuronal activations in each of these brain regions were significantly greater from the BH condition compared to MH_L and MH_R conditions. From the regression analysis, the neuronal activations in the right STG showed significant correlation with speech hearing score (R^2=0.21, p=0.003), whereas the neuronal activations of the remaining regions were not significantly correlated with speech hearing score (Fig. 3).

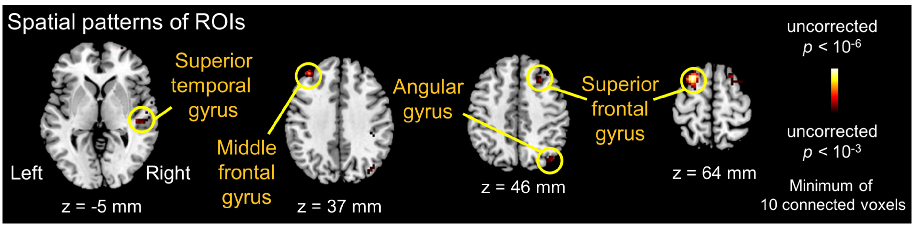

Fig. 2. Identified regions of interest (ROIs) that showed main effect of hearing conditions on neuronal activation

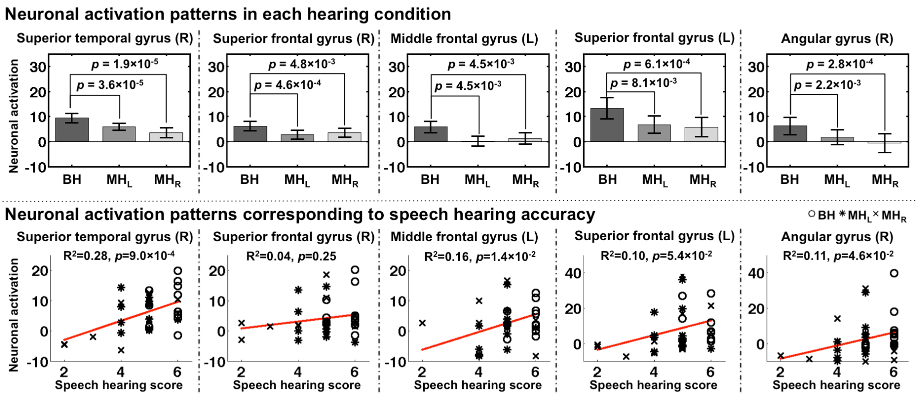

Fig. 3. Neuronal activation levels of ROIs and association with speech hearing accuracy

3.3 Language-Related Network

From the repeated FC analysis, language-related network was identified in the areas including left middle temporal gyrus (MTG; [-54, -40, -2] mm) which is in Wernicke's area. As shown in Fig. 4, the left MTG was functionally connected with right STG ([45, -22, 1] mm), right MTG ([63, -10, -17] mm), left MTG ([-66, -16, -2] mm), left STG ([-45, -19, 7] mm) and left STG ([-66, -40, 13] mm). The FC level between the brain regions of language-related network was significantly correlated with the speech hearing score (R^2>0.2, p<0.005). From a paired t-test between a pair of the hearing conditions, it was identified that the FC level was shown a marginal level of significance (p<0.05) from the BH condition than the MH_R condition except the FC level between left MTG ([-54, -40, -2] mm) and left STG ([-45, -19, 7] mm). The corresponding FC levels across all three hearing conditions were tightly correlated with the speech hearing scores (p<0.005).

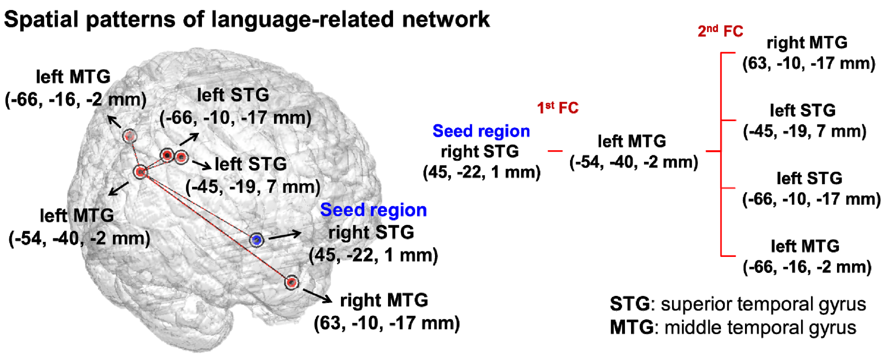

Fig. 4. Neuronal networks whose FC levels were significantly correlated with speech hearing score (uncorrected p<0.005 with minimum of 20 connected voxels)

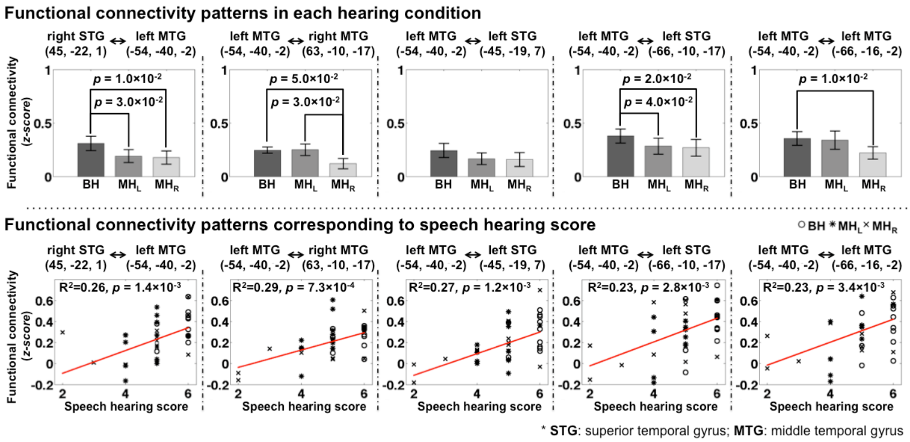

Fig. 5. Functional connectivity (FC) levels of the speech hearing related ROIs and a link between the FC levels across the ROIs and speech hearing scores

4 Discussion

In this study, we reported that there are distinct neuronal networks tightly linked with the speech hearing performance. More specifically, the neuronal activation level in the right STG was significantly correlated with the speech hearing score with greater level of from the BH and MH_L conditions than the MH_R condition. The language performance is known to be dominant in the left STG for the right-handed. Thus, this result may suggest that the right STG is crucial in speech hearing, whereas previous studies reported that contralateral STG was activated according to sound direction [10, 11].

From FC analysis, it was identified that FC level between right STG and left MTG was significantly correlated with speech hearing score. This result may indicate that the interaction between left STG and right MTG, reportedly the Wernicke's area, enhanced the speech hearing performance.

5 Conclusion

In this study, we present that the right STG is crucial in enhancement of the speech hearing performance. Moreover, it appears that the FC patterns from the right STG are tightly correlated with the speech hearing performance with much greater statistical significance compared to the correlation between the neuronal activity levels and speech hearing performance. Further investigation would be warranted to justify the reported findings via test-retest evaluation (1) applying supplementing analytical methods including various preprocessing algorithms to further reduce artifactual noises and (2) employing systematic experimental settings.

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