An fMRI study of the neural mechanisms of third and fourth tone recognition in deaf children

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Abstract. Vocal tone is an important component of language and it plays a key role in language comprehension and communication. However, children with hearing loss face challenges in vocal tone recognition due to hearing impairment. In this study, five deaf children and two children with normal hearing were recruited to compare the differences in third and fourth tone recognition tasks between deaf and normal children. The results revealed that (1) some of the deaf children's brain regions that process vocal tones did not work properly due to hearing loss; (2) deaf children may rely on different neural networks when processing vocal tone information. (3) Deaf children process vocal tone information with hemispheric characteristics.

Keywords: deaf children; vocal tones; fMRI; brain regions; computer technology.

1. Introduction

In human languages, tone is a phonological feature that has different expressions and meanings in tonal languages. In Chinese language, vocal tones are widely used and have an important role in semantic expressions[1] . However, the recognition and comprehension of vocal tones can be challenging for deaf children, as they may not be able to access vocal tone information through the auditory system. Therefore, studying and understanding the differences in vocal tone recognition between deaf and normal children is important to improve language development and provide better educational approaches for deaf children.

In recent years, with the development of computer science and neuroscience, researchers have started to apply computer technology to study the brain mechanisms of language and cognition. fMRI is a non-invasive neuroimaging technique that can measure changes in blood oxygen levels in the brain, thus reflecting how active various brain regions are under different tasks, providing us with a powerful tool to study the neural mechanisms of speech perception[2] . Computer science provides powerful tools and methods to process MRI images in order to process and analyze large amounts of fMRI data[3] . The use of computer technology allows us to study in depth the perceptual and cognitive processes of vocal tones in deaf and normal children and to reveal their neural mechanisms.

The purpose of this study was to use computer technology to analyze fMRI data to explore the differences in the recognition of third and fourth tones between deaf and normal children. A computer-assisted approach was used to analyze and compare the brain imaging data of the two groups of subjects to reveal the neurological functional differences in vocal tone processing between deaf and normal children. Through this study, we hope to gain more insight into the neural mechanism differences in vocal tone recognition between deaf and normal children, and provide a scientific basis for language rehabilitation and education of deaf children. This study will help promote interdisciplinary collaboration between the fields of computer science and neuroscience, and contribute to the intersection of research in the fields of language cognition and computer science.

2. Materials and methods

2.1 Subjects

Native Mandarin-speaking children (N=7.00 male; right-handed; age=11±0.4 [mean ± SD] years) were recruited from Tianjin to participate in this study. Five of them were deaf children (DC),and two were hearing children (HC). All participants underwent a physical examination prior to the start of the study to ensure that they were physically healthy and fit to participate in this experiment. Participants with HC reported no neurological or hearing-related impairment and had normal or corrected real vision.

2.2 Stimulation

The stimuli used for the experiments consisted of 96 pairs of vocal tones, each pair consisting of two tones at a frequency of 500 Hz and a duration of 100ms. The tones were generated using E-prime (Psychology Software Tools, Inc., version 2.0). The voice pairs consisted of four tones: "one", "two", "three" and "four", each with Each tone has four different combinations, and the tones are presented in a random order within two blocks.

2.3 Experimental steps

We performed functional magnetic resonance imaging (fMRI) while the participants performed a tone recognition task. First, four identical hanyu pinyin characters appeared on the screen simultaneously, each with the vocal tones of "一", "二", "三", and "四". Next, the participants were instructed to listen to the sounds and to place them according to the pitch pattern by pressing the "1", "2", "3", or "4" buttons to classify them into one of four categories based on pitch patterns.

2.4 fMRI data acquisition

All MRI data were acquired using a Siemens 3-Tesla PRISMA MRI system and a 32-channel head coil at the General Hospital of Tianjin Medical University. Resting-state fMRI images were acquired by gradient-echo (GRE) multiband multi-excitation echo-planar imaging (multiband-EPI) sequence: TR/TE=800/30ms, flip angle=56°, field of view (FOV)=104 * 104mm, layer thickness 1.5mm. Finally, T1-weighted high-resolution structural images were acquired using magnetization-prepared rapid gradient-echo (MP-RAGE) with the following parameters: 188slices, TR=2000ms, TE=2000ms, flip angle=8°.

2.5 fMRI data preprocessing

The fMRI data were preprocessed using SPM12 software to ensure the quality and reliability of the data. In the preprocessing, a series of steps were used to optimize the functional images as follows: (1) The temporal order between different slices was corrected by temporal layer correction[4] , which eliminated the temporal bias due to the different acquisition order, which is important for the subsequent data analysis because it can ensure the data consistency in time. (2) Head motion correction was performed on the original functional images using least squares and a six-parameter rigid-body spatial transformation[5] . The accuracy of the data was improved by calculating the spatial offset of each voxel and correcting the image artifacts caused by head motion. (3) After head movement correction, two procedures were used to spatially align all images to the mean value of the images[6] . First, all functional images were aligned to the mean functional image to further eliminate the effect of head motion. This step resulted in more accurate functional images and reduced errors due to head motion. Second, the high-resolution T1 structural images are co-aligned with the average functional images (reference images) with the aim of aligning anatomical structural information with functional data to provide anatomical references for subsequent analysis. (4) The co-aligned T1 structural images are segmented using a unified segmentation procedure[7] . By segmenting the T1 structural images into different tissue categories, such as gray matter, white matter and cerebrospinal fluid, more accurate tissue localization information can be obtained to provide accurate anatomical information for the subsequent spatial alignment and analysis. (5) To convert functional images to standard space, we converted the functional images realigned in local space to Montreal Neurological Institute (MNI) space with the aim of comparing data between subjects and aligning with most standard spatial templates.(6) The normalized functional images were resampled with a 3x3mm voxel size and smoothed using a Gaussian kernel with a full half-peak width of 4mm. The smoothing process can effectively reduce the noise and enhance the spatial distribution of the signal, improving the signal-to-noise ratio and statistical efficacy of the data.

2.6 fMRI data analysis

After data preprocessing, the fMRI data were analyzed using the SPM package[8] , a voxel-based statistical method, and the brain was divided into 90 brain regions according to the AAL template[9] , and the activation intensity and clump size were accurately calculated for each brain region, and the results were presented as a trilinear table. The results were visualized using MRIcron, BrainNet to visualize the brain activation regions and the size of the activated regions more visually.

3. Results

3.1 Results of DF and HC when performing the tone three task

Table 1 Results of Executing Vocal TRIPLE-TIME DF

Brain region	Hemisphere	Cluster	Peak	Peak MNI coordinates(mm)		
				x	y	z
Supplementary motor area	R	650	9.29	0	12	58
Pre-central gyrus	L	213	7.68	-50	6	44
Triangle - Interior frontal gyrus	R	38	5.83	50	28	28
Operc- Interior frontal gyrus	R	17	5.34	46	10	26
Middle frontal gyrus	R	21	5.58	36	52	22
Superior temporal gyrus	L	140	7.07	-64	-24	10
	R	43	6.63	64	-6	0
Insula	L	53	6.48	-32	28	0
Middle occipital gyrus	L	72	7.12	-28	-100	8
Superior part of temporal pole	L	24	6.35	-54	10	-6

Note: Brain region represents the name of the activated region; Hemisphere represents the hemisphere where the activated region is located; x, y and z are Montreal Neurological Institute (MNI) brain map coordinates.

Table 2 Results of Executing Vocal TRIPLE-TIME HC

Brain region	Hemisphere	Cluster	Peak	Peak MNI coordinates(mm)		
				x	y	z
Middle occipital gyrus	L	458	7.29	-24	-102	2
	R	376	7.60	24	-94	4
Interior occipital gyrus	R	77	6.02	50	-72	-2
Triangle - Interior frontal gyrus	L	781	8.09	-46	10	48
Medial part of superior frontal gyrus	L	77	6.73	-2	26	40
Supplementary motor area	L	44	6.50	-8	16	68
Interior parietal lobe	L	44	5.81	-26	-48	40

Note: Brain region represents the name of the activated region; Hemisphere represents the hemisphere where the activated region is located; x, y and z are Montreal Neurological Institute (MNI) brain map coordinates.

As seen in the results, during the execution of the vocal tone triad task, the right supplementary motor area, left precentral gyrus, right triangular inferior frontal gyrus, right insula inferior frontal gyrus, right middle frontal gyrus, bilateral superior temporal gyrus, left insula, left middle occipital gyrus, and left temporopolar superior temporal gyrus regions were activated in children with DF, and the bilateral middle occipital gyrus, right medial occipital gyrus, left triangular inferior frontal gyrus, left superior medial frontal gyrus, left supplementary motor area, and the left medial parietal lobe were activated.

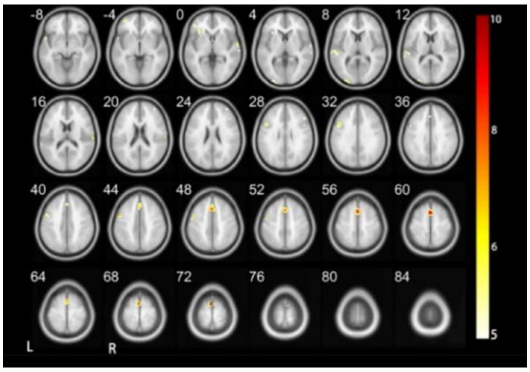

Fig. 1 Results of executing the vocal triple-time DF

3.2 Results of DF and HC when performing the tone four task

Table 3 Results of The Execution of The Vocal TONES FOUR-TIME DF

Brain region	Hemisphere	Cluster	Peak	Peak MNI coordinates(mm)		
				x	y	z
Superior part of temporal pole	L	22	6.04	-54	8	-6
Middle occipital gyrus	L	33	6.61	-28	-100	8
Supplementary motor area	L	29	6.23	-4	2	72

Note: Brain region represents the name of the activated region; Hemisphere represents the hemisphere where the activated region is located; x, y and z are Montreal Neurological Institute (MNI) brain map coordinates.

Table 4 Results of The Execution of The Vocal TONES FOUR-TIME HC

Brain region	Hemisphere	Cluster	Peak	Peak MNI coordinates(mm)		
				x	y	z
Cerebelum_Crus1	R	169	6.88	6	-82	-26
Interior occipital gyrus	L	838	8.16	-24	-102	2
Middle occipital gyrus	R	358	7.98	26	-96	2
Middle temporal gyrus	R	105	7.11	50	-72	-2
Middle frontal gyrus	R	56	6.14	32	4	56
Triangle - Interior frontal gyrus	L	1065	9.14	-42	20	24
Interior parietal lobe	L	242	8.36	-30	-46	54

Note: Brain region represents the name of the activated region; Hemisphere represents the hemisphere where the activated region is located; x, y and z are Montreal Neurological Institute (MNI) brain map coordinates.

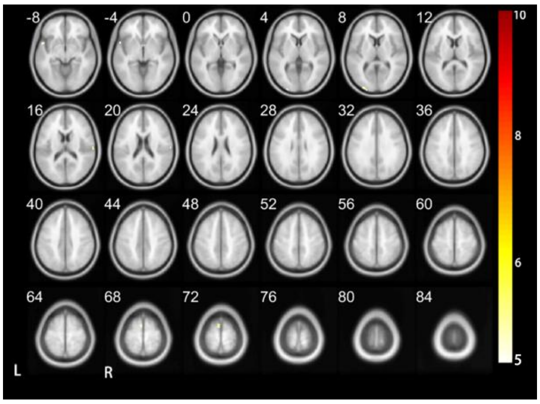

Fig. 2 Results of executing the vocal tones four-time DF

As seen in the results, the left superior temporal pole, left middle occipital gyrus and left supplementary motor area were activated in children with DF and the right Cerebelum_Crus1, left medial occipital gyrus, right middle occipital gyrus, right middle temporal gyrus, right middle frontal gyrus, left triangular inferior frontal gyrus and medial parietal area were activated in children with HC during the execution of the vocal tones IV task.

4. Discussion

4.1 Due to hearing loss, part of the deaf child's brain area that processes vocal tones does not work properly

Related studies have shown[10] that the left inferior frontal gyrus, right middle temporal gyrus and bilateral superior temporal gyrus are key regions in the neural correlates of tone perception. However, in the comparison of tone IV, no activation was found in the middle temporal gyrus, middle frontal gyrus, inferior frontal gyrus and parietal regions in DF children compared to HC children. The inferior frontal gyrus, middle frontal gyrus and parietal regions have important roles in human behavior and cognition, including emotion, memory, cognitive control and auditory perception. [11,12] suggesting that these brain regions fail to function properly in deaf children compared to normal children. Deaf children usually rely on gestures such as sign language or oral language to communicate, unlike normal children who receive speech information directly through auditory input to learn and recognize vocal tones.[13]

4.2 Deaf children may rely on different neural networks when processing vocal tone information

In the vocal tone III comparison, the left precentral gyrus, right insula inferior frontal gyrus, right middle frontal gyrus, bilateral superior temporal gyrus, left insula, and left temporal pole superior temporal gyrus were activated in children with hearing loss, and these regions did not show activation in children with HC. Because speech information cannot be received directly through auditory input, deaf children may require additional cognitive resources and attentional inputs for processing vocal tones, resulting in additional brain area activation. In contrast, normal children have already formed corresponding neural networks and cognitive patterns during speech learning and perception, and thus would show more efficient brain activity patterns in the vocal tone discrimination task. The above results, in which the activation clump size was significantly larger in normal children than in children with hearing impairment, also validate our conjecture. Moreover, a previous study found,[14] that auditory centers of deaf patients showed significant activation in response to visual stimuli. After our comparison, we found that deaf children had stronger activity in regions such as the superior temporal gyrus in the third tone recognition task, suggesting that deaf children may use visual information instead of auditory information to process tones, [15] requiring more brain regions to process this task.

4.3 Children with hearing impairment process vocal tone information with hemispheric characteristics

A previous study showed that tones and segments can be processed in parallel in the left and right hemispheres, but the product of their integration or integration is located in the left hemisphere.[16] In addition, our study found that children with hearing loss exhibit hemispheric characteristics when processing vocal tone information. That is, unlike normal children, the corresponding brain hemisphere is activated when processing specific vocal tones. Specifically, in the Tone III results, hearing-impaired children showed an inverse difference from normal children in the activation patterns of the middle occipital gyrus and the subfrontal gyrus of the triangle. In addition, in Tone IV, hearing impaired children showed more activation in the left middle occipital gyrus, while normal children showed stronger activation in the right hemisphere.

Summary

Overall, our study discusses the neural mechanisms of vocal tone recognition in deaf children. Our results suggest that the main activation differences between deaf and hearing children in vocal tone processing tasks are found in the middle occipital gyrus, inferior frontal gyrus and middle frontal gyrus regions. Deaf children may rely on different neural networks to process vocal tone information compared to hearing children. In contrast to previous studies, we found that deaf children may rely on visual information for processing and processing of vocal tone information. The study only discussed the neural mechanisms of vocal tone recognition in deaf children for the third and fourth, and further studies are needed to confirm the results.

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