An fMRI study of how deaf children process the two tones (first tone and third tone) in Mandarin Chinese

Mengrui Shi[1, a], Qiang Li[1, b]

[1]Engineering College for the Deaf, Tianjin University of Technology, Tianjin, China.

[a] smr789@foxmail.com, [b] lylq@tjut.edu.cn

Abstract. The objective of this study is to investigate the brain activity patterns of deaf children and hearing children during the processing of two different tones (first tone and third tone) using resting-state functional magnetic resonance imaging (fMRI). Furthermore, the study aims to identify the differences in brain activation regions between deaf children and hearing children during the tone processing task. Five deaf children and two hearing children were selected as participants. Resting-state functional magnetic resonance imaging (fMRI) scans were conducted on the subjects using an fMRI scanner. The acquired fMRI data were then preprocessed and analyzed to examine the patterns of brain activity. Deaf children and hearing children exhibit differences in brain activation regions during the execution of tone recognition tasks. These differences can be observed in various areas such as the pre-central gyrus, superior temporal gyrus, middle occipital gyrus, supplementary motor area and interior frontal gyrus, among others. The results suggest that deaf children may rely on different neural networks to process tone information compared to hearing children, possibly exhibiting stronger neural plasticity and compensatory mechanisms. These findings contribute to the understanding of the neural basis of tone processing and may help in refining intervention strategies.

Keywords: Deaf children; tones; fMRI; brain activity.

1. Introduction

Tones are an essential component of language and represent the pitch variations of syllables [1]. Mandarin Chinese, as a tonal language, is the most widely spoken language in the world, and its most significant distinction from non-tonal languages like English lies in its tonal characteristics [2]. Mandarin Chinese has four tones: yīnpíng (first tone), yángpíng (second tone), shǎngshēng (third tone), and qùshēng (fourth tone) [3]. These tones result in different spatial and temporal patterns of neural fiber firing in the auditory system [4]. Different tones can distinguish different meanings of words [5]. For example, in Mandarin Chinese, " gū" and " gǔ" are two distinct words with different meanings.

Functional magnetic resonance imaging (fMRI) is a non-invasive brain imaging technique [6] that provides spatial and temporal information about brain activity during specific tasks. fMRI utilizes magnetic fields and harmless radio waves to generate high spatial resolution images of brain activity [7]. By using fMRI, we can investigate the patterns of brain activation in deaf children and hearing children during tone processing tasks, thereby gaining insights into the neural mechanisms of tone processing in language comprehension.

The critical period for language development in children is from 0 to 3 years of age [8]. Hearing children can acquire Mandarin Chinese phonology fully during this stage. However, deaf children, due to their auditory system impairments, still face significant challenges in language development compared to their hearing peers, even with interventions such as hearing aids or cochlear implants. They may experience delayed language development, reduced articulation clarity, and difficulties in everyday communication [9]. While producing the four tones in Mandarin Chinese is relatively effortless for hearing children who are native speakers, it is extremely challenging for deaf children, especially for tones one and three. The aim of this study is to compare the brain activity patterns of deaf children and hearing children during tone processing tasks using fMRI, in order to explore the differences in tone processing between the two groups of children.

These findings have significant implications for the language development and rehabilitation of deaf children. Deaf children may encounter challenges in tone recognition and production during the process of language acquisition. Understanding the neural mechanisms underlying tone processing in deaf children can contribute to the development of more effective rehabilitation strategies to enhance their perception and production of tones. For instance, training methods that incorporate visual and kinesthetic information can be designed to strengthen deaf children's understanding of tones.

2. Materials and Methods

2.1 Study Participants

Seven children were selected from Tianjin City to participate in this study, including five deaf children (DC) and two hearing children with normal hearing (HC). All participants underwent a medical examination prior to the study to ensure their physical well-being and suitability for the experiment. The HC participants reported no neurological or hearing-related impairments and had normal or corrected-to-normal vision. Informed consent forms were signed by the parents of all participants before the examinations, and the study was approved by the hospital's ethics committee.

2.2 Stimulus Collection

The stimuli used in the experiment consisted of 96 pairs of tones. Each pair was composed of two tones with frequencies of 500 Hz and durations of 100 ms, generated using E-prime software [10]. Each pair included four tones: "Tone 1," "Tone 2," "Tone 3," and "Tone 4". Each tone was presented in four different combinations to ensure stimulus diversity and comparability.

2.3 Experimental Procedure

When participants performed the tone processing task, functional magnetic resonance imaging (fMRI) was conducted simultaneously. Firstly, four identical Chinese pinyin characters representing "Tone 1," "Tone 2," "Tone 3," and "Tone 4" were simultaneously displayed on the screen. Next, participants were instructed to listen to the sounds and categorize them into four groups based on the tone patterns by pressing the buttons labeled "1," "2," "3," or "4." Participants underwent practice sessions prior to the scanning to establish category response mappings. E-Prime was used, and a customized sparse sampling fMRI sequence was employed to minimize interference from scanner noise on auditory perception. Stimuli were presented during the 1000 ms silent interval between each imaging acquisition. Each participant completed a total of 96 trials. During each trial, the participant's categorization response and response time (RT) were recorded. All MRI data were acquired using a Siemens 3-Tesla PRISMA MRI system with a 32-channel head coil. Functional MRI images were obtained using a three-dimensional T2-weighted gradient echo planar imaging pulse sequence.

2.4 Data Analysis

MRI data were preprocessed using SPM12 [11]. For univariate activation analysis, raw functional images were corrected for head movement using a least-squares approach and a six-parameters (rigid body) spatial transformation. A two-pass procedure was used to spatially register all the images to the mean of the images after the first realignment (i.e., the register to mean approach). For multivariate model analysis, the prediction steps of the functional map included motion correction of the Baotou section, co-registration, normalization, and smoothing. The analyses were performed at two levels. At the first level, subject-specific delay effects of conditions were compared using linear contrasts, resulting in a t-statistic for each voxel. Main effects of load were calculated for the delay period of all three load levels and the control condition. Mixed effects group analysis was performed at the second level, entering the calculated delay-specific contrasts for the four conditions of each subject into a multi-group analysis of variance (ANOVA).

3. Results

Due to the limited sample size, representative features can be selected from these few data points for the analysis of tone processing (tone 1 and tone 3) in deaf and normal-hearing children. (That is, the two different tone activation data are not the data of the same child.) After data processing, Table 1 and Table 2 were obtained, along with corresponding brain activation maps.

Table 1. Activation result table of two tones discrimination tasks for deaf children

	Area	Hemisphere	Cluster size	MNI coordinates			Peak
				x	y	z	
Tone 1	Middle occipital gyrus	L	1688	-30	-88	-12	T=9.89
	Supplementary motor area	R	579	14	8	70	T=8.93
	Pre-central gyrus	L	323	-50	-8	48	T=9.25
		R	619	50	-4	52	T=9.66
Tone 3	Middle occipital gyrus	L	853	-24	-100	12	T=11.48
		R	812	24	-96	6	T=10.20
	Pre-central gyrus	L	251	-52	-6	48	T=11.47
		R	269	56	2	36	T=10.71

Note: Area represents the name of the activated region; Hemisphere represents the hemisphere where the activated region is located, with L representing the left hemisphere and R representing the right hemisphere; x, y, and z are Montreal Neurological Institute (MNI) brain map coordinates.

From Table 1, we can observe that in tone 1, the activation areas in the brains of deaf children are mainly located in the left middle occipital gyrus, right supplementary motor area, and bilateral pre-central gyrus. In tone 3, the activation areas in the brains of deaf children are mainly located in the bilateral middle occipital gyrus and bilateral pre-central gyrus. (The activation areas for the two different tones correspond to Fig. 1 and 2, respectively.)

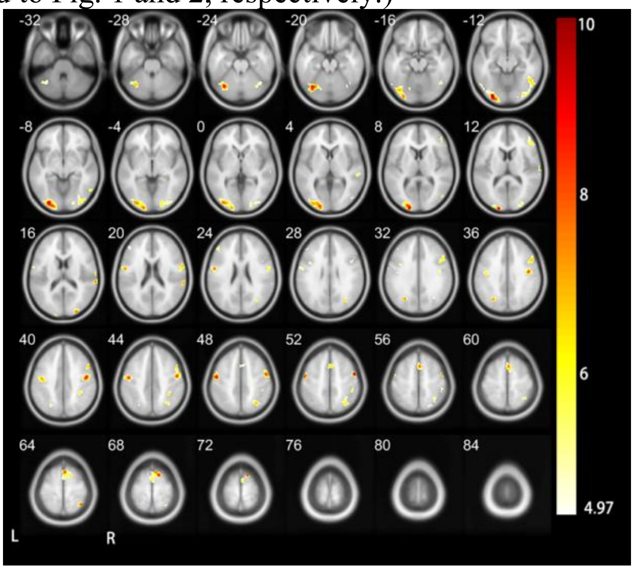

Fig. 1 Brain activation map for Tone 1 in deaf children

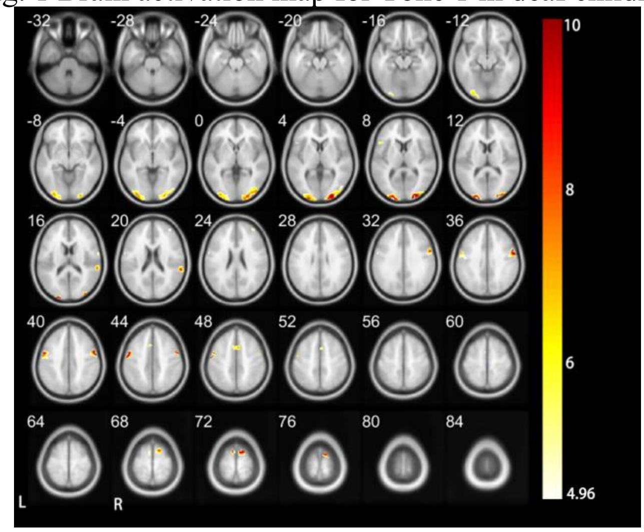

Fig. 2 Brain activation map for Tone 3 in deaf children

Table 2. Activation result table of two tones discrimination tasks in hearing children

	Area	Hemisphere	Cluster size	MNI coordinates			Peak
				x	y	z	
Tone 1	Middle occipital gyrus	L	272	-24	-98	-8	T=7.90
	Superior temporal gyru	L	116	-62	-30	16	T=7.08
		R	170	68	-26	-2	T=8.64
Tone 3	Interior frontal gyrus	L	781	-46	10	48	T=8.09
	Middle occipital gyrus	L	458	-24	-102	2	T=7.29
		R	376	24	-94	4	T=7.60

Note: Area represents the name of the activated region; Hemisphere represents the hemisphere where the activated region is located, with L representing the left hemisphere and R representing the right hemisphere; x, y, and z are Montreal Neurological Institute (MNI) brain map coordinates.

It is clear from Table 2 that for tone 1, the left middle occipital gyrus and the bilateral superior temporal gyrus are the predominant brain activity locations for hearing children. For tone 3, the left interior frontal gyrus and the bilateral middle occipital gyrus are where hearing children's brains are most active. (Figures 3 and 4 represent the activation zones for the two distinct tones, respectively.)

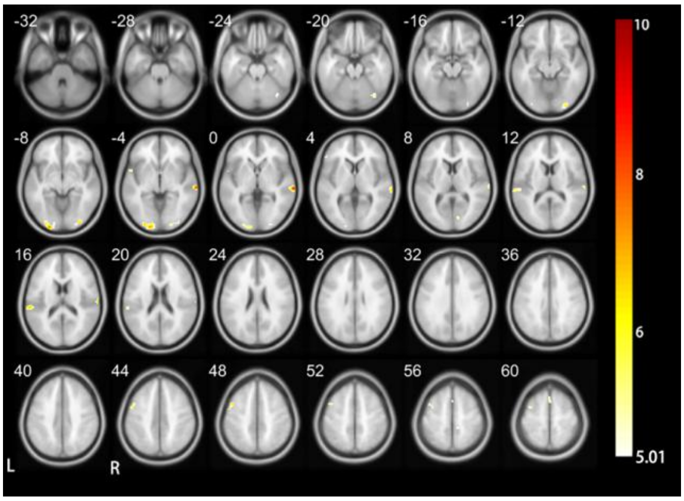

Fig. 3 Brain activation map for tone 1 in hearing children

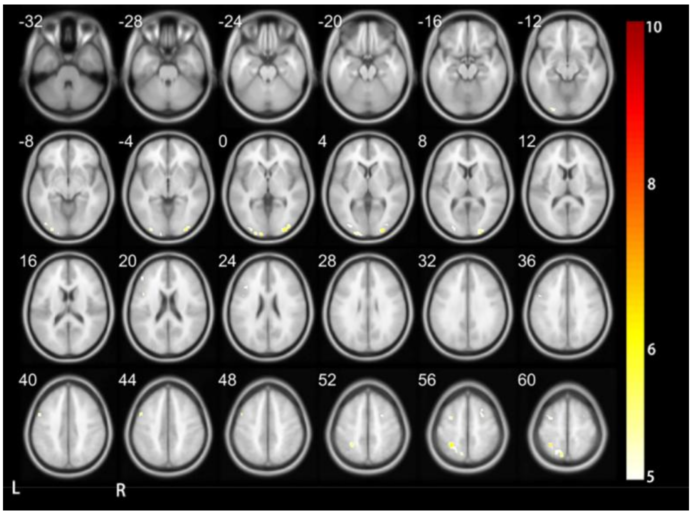

Fig. 4 Brain activation map for tone 3 in hearing children

By comparing the results, we can observe similarities and differences in the main brain activation areas between deaf and hearing children in each tone condition. Both groups show common brain activation in the middle occipital gyrus. However, the activation is more pronounced in deaf children. Additionally, deaf children show additional activation in the supplementary motor area and precentral gyrus, while hearing children show activation mainly in the superior temporal gyrus. In tone 3, both groups show activation in the middle occipital gyrus, but again, the activation is stronger in deaf children. Deaf children also show additional activation in the precentral gyrus, while hearing children show activation in the interior frontal gyrus.

4. Discussion

During tone identification tasks, differences in brain activity patterns between hearing and deaf children have been found, particularly in the pre-central gyrus, middle occipital gyrus, superior temporal gyrus, superior frontal gyrus, and middle occipital gyrus.

4.1 Due to hearing impairment, the activation in certain areas of the deaf children's brain is smaller

The superior temporal gyrus, which includes the primary and secondary auditory regions as well as some areas of the insula, is a crucial auditory hub. The bilateral superior temporal gyrus acts as a fundamental processing region for speech perception and early understanding, according to research on the brain regions involved in speech perception by Booth et al. [12]. Furthermore, Tan Li-Hai[13] proposes that processing of Chinese tone also involves the superior temporal gyrus. Tone encoding, linguistic perception, semantic comprehension, and emotional processing are all functions of the prefrontal cortex that are involved in tone recognition. Children who are deaf, on the other hand, have some distinctive patterns of brain activity when processing tones. Hearing children acquire language information by perceiving and imitating sounds in their surrounding environment through auditory perception. They are exposed to various tones and speech features in their linguistic environment, gradually learning to differentiate and recognize different tones. Due to the lack of auditory input and inability to receive the same auditory stimuli as hearing children, they show lower levels of activation in the auditory cortex. Due to insufficient stimulation of the auditory cortex during sound processing in deaf children, this causes comparatively lower levels of activation in this area.

4.2 Neuroplasticity in the brains of deaf children

Processing of visual information is mostly carried out by the temporal and occipital lobes of the brain. According to research, people who have hearing loss may also have better visual ability [14]. According to Zhu et al.'s research[15], patients with chronic hearing loss experience functional remodeling of the default mode network (DMN), which leads to a compensatory improvement in visual abilities after auditory deprivation. In the context of tone processing activities, deaf children demonstrate activity in multiple brain regions, including those related to visual and tactile processing (such as the middle occipital gyrus, among others), suggesting stronger plasticity and compensating mechanisms [16]. When the brain system integrates sensory processes, adaptive and compensating modifications called "cross-modal reorganization" take place. When one sensory modality is denied, other sensory modalities may operate better as a result. Deaf children rely more on visual information to learn more about their world since they lack auditory stimulus, which leads to improved visual functioning. This could be a coping technique to use different sensory pathways for tone processing in order to compensate for the lack of auditory input. Such compensatory activity suggests brain flexibility in deaf children's language development [17] and emphasizes the importance of numerous sensory pathways in tone perception. For some deaf children, they may obtain limited auditory input through auditory assistive devices such as hearing aids or cochlear implants. These devices are designed to simulate auditory signals and transmit them to the auditory cortex in the brain. Prolonged usage of these devices can facilitate brain readjustment and enhance the processing capabilities of auditory input. Children who are deaf become more sensitive to auditory stimuli due to this plasticity, which results in higher activation during tone processing. In contrast, hearing youngsters process tones more through the auditory pathway. This shows that functional network remodelling occurs in deaf people's brains to better accommodate the processing of tone information.

Neuronal plasticity serves as the foundation for the adaptability of the brain, enabling individuals with hearing impairments to develop language and communication skills despite the absence of normal auditory input. Through the alteration of neural connections, strengthening of alternative sensory pathways, or utilization of assistive devices, deaf children can adapt and enhance their abilities to communicate. Understanding this concept is crucial for the development and optimization of rehabilitation strategies for the deaf population, as well as for improving their overall quality of life.

5. In Conclusion

This study demonstrated differences in tone processing between the two groups by comparing the brain activity patterns of hearing and deaf children during two-tone processing tasks. These findings offer insights into the underlying neurological mechanisms of tone identification in hearing and deaf children. The findings imply that deaf children may use distinct brain networks than hearing children to process tone information, possibly displaying greater neuronal plasticity and compensating mechanisms. Further study is required to verify these results, explore their implications for deaf children's language development, and establish a theoretical framework for language development and rehabilitation in this population. This independent study has some restrictions, including a small sample size, etc. Larger sample sizes will be expanded and pooled studies will be improved in upcoming study.

Funding

This work was supported by a research grant from CN: National Planning Office of Philosophy and Social Science[20BYY096].

Acknowledgements

We thank all the subjects for participating in and contributing to this research. We also thank Hao Ding and Wen Qin for her contribution to this research.

References

[1] Guo Chengyu, Chen Fei. Phonetic Realizations of Metrical Structure in Tone Languages: Evidence From Chinese Dialects [J]. Frontiers in Psychology, 2022, 13.

[2] Zhang Yixin, Schmidt Elaine, Post Brechtje. Perception of Intonation on Neutral Tone in Mandarin [J]. Frontiers in Communication, 2022.

[3] Wang Yuxia, Yang Xiaohu, Ding Hongwei, Xu Can, Liu Chang. Aging Effects on Categorical Perception of Mandarin Lexical Tones in Noise [J]. Journal of speech, language, and hearing research: JSLHR, 2021, 64(4).

[4] Sammler Daniela. Neural Bases of Intonation and Tone Perception in Mandarin Chinese [J]. International Journal of Psychophysiology, 2021, 168(S).

[5] Wenyi Ling, Theres Grüter. From sounds to words: The relation between phonological and lexical processing of tone in L2 Mandarin [J]. Second language Research, 2020, 38(2).

[6] Zou Yihuai, Kong Jian, Fang Jiliang, Bai Lijun. Editorial: Revealing neural plasticity in responding to non-invasive physical therapies via fMRI [J]. Frontiers in neurology, 2022, 13.

[7] De la PeñaArteaga Víctor, Morgado Pedro, Couto Beatriz, Ferreira Sónia, Castro Inês, Sousa Nuno, SorianoMas Carles, PicóPérez Maria. An fMRI study of frontal networks in obsessive-compulsive disorder during cognitive reappraisal [J]. European psychiatry: the journal of the Association of European Psychiatrists, 2022.

[8] Nourski Kirill V., Steinschneider Mitchell, Rhone Ariane E.. Intracranial electrophysiology of human auditory and auditory-related cortex during speech categorization tasks [J]. The Journal of the Acoustical Society of America, 2017, 141(5).

[9] Binos Paris, Nirgianaki Elina, Psillas George. How Effective Is Auditory–Verbal Therapy (AVT) for Building Language Development of Children with Cochlear Implants? A Systematic Review [J]. Life, 2021, 11(3).

[10] Laurence Richard, Dominic Charbonneau. An introduction to E-Prime [J]. Tutorials in Quantitative Methods for Psychology, 2009, 5(2).

[11] Han Hyemin, Park Joonsuk. Using SPM 12's Second-Level Bayesian Inference Procedure for fMRI Analysis: Practical Guidelines for End Users. [J]. Frontiers in neuro informatics, 2018, 12.

[12] Booth James R, Burman Douglas D, Meyer Joel R, et al.Functional anatomy of intra-and cross-modal lexical tasks [J]. Neuroimage, 2002, 16: 7-22.

[13] Tan Lihai. Human Brain Language Center and Language Ability Development, Protection and Remodeling [J]. Educator, 2019(24): 16-18.

[14] Hauser PC, Dye MW, Boutla M, et al. Deafness and visual enumeration: not all aspects of attention are modified by deafness. Brain Res, 2007, 1153(1): 178-187.

[15] ZHU X, HUAGN Z C, ZHAGN P P, et al. FMRI study of default mode network in patients with unilateral long-term sensorineural deafness [J]. Chinese Journal of Ear Science, 2015(3): 511-515.

[16] Sharma A,Glick H. Cross-modal re-organization in clinical populations with hearing loss [J]. Brain Sci, 2016, 6(1): 4.

[17] Cardin Velia, Orfanidou Eleni, Ronnberg Jerker, et al. Dissociating cognitive and sensory neural plasticity in human superior temporal cortex. Nat Commun, 2013; 4: 1473.