An fMRI Study of How Deaf Children Process the Two Tones (Second Tone and Third Tone) in Mandarin Chinese

Mengrui Shi* and Qiang Li

Tianjin University of Technology, Tianjin, China
Email: smr789@foxmail.com (M.S.)
*Corresponding author

Manuscript received December 12, 2023; revised January 15, 2024; accepted February 20, 2024; published May 24, 2024

***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 (second 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, superior parietal lobe, and interior frontal gyrus, among others. Through comparisons, the brains of deaf and mute children, although they exhibit relatively reduced activation in certain areas of the auditory cortex, may show enhanced activation in additional regions such as the middle occipital gyrus. This suggests that the brain of deaf children may undergo a reorganization of its functional networks, allowing for improved spatial perception, visual abilities, and other skills. This adaptation enables them to better process tonal information despite the absence of auditory input. These findings contribute to the understanding of the neural basis of tone processing and may help in refining intervention strategies.**

***Keywords*—brain activity, functional Magnetic Resonance Imaging (fMRI), deaf children, tones**

I. Introduction

Tonal variation in Chinese refers to the changes in pitch and tone of syllables within Chinese words [1]. Chinese has four basic tones: the first tone (flat tone), the second tone (rising tone), the third tone (falling-rising tone), and the fourth tone (falling tone). The first tone is generally flat, the second tone rises, the third tone falls and then rises, and the fourth tone falls sharply. Tones play a crucial role in distinguishing word meanings in Chinese, as different tones can alter the meanings of words [2]. For example, "yí" and "yǐ" have different meanings. Accurate use of tones is essential for understanding and effective communication in spoken Chinese and is a key aspect of learning the language.

Functional Magnetic Resonance Imaging (fMRI) is a non-invasive imaging technique that measures neural activity by detecting changes in brain oxygenation levels [3]. It provides insights into brain function and connectivity and is used to investigate various neural processes such as cognition, perception, and emotion. fMRI has widespread applications in neuroscience research, disease diagnosis, and treatment evaluation, revealing the relationships between behavior, cognition, and diseases by monitoring brain activity.

There is a noticeable contrast between deaf children and children with normal hearing in acquiring language tones. Children with normal hearing receive language input through auditory means, allowing them to directly perceive and imitate pitch and tonal variations in tones [4]. In the early stages of language development, they learn tones through imitation and perception of the linguistic input in their environment. In contrast, deaf children, due to hearing limitations, cannot receive tone information through auditory means and need to rely on other sensory channels to access language information. Deaf children typically rely on sign language, lip-reading, or visual aids to understand and express tone information, learning and using tones through visual cues and gestures [5]. 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.

Studying tone recognition in deaf children is significant in helping them overcome barriers in language communication and improving their language comprehension and expression abilities. By studying the cognitive processes and application of tones in deaf children, more effective educational and assistive tools can be developed to facilitate their language development. A deeper understanding of the role of tone recognition in the language learning of deaf children can create more opportunities and an equal environment for them, enhancing their quality of life and integration into society.

Furthermore, gaining a deeper understanding of tone processing in hearing children also provides insights into the research on language acquisition and development. Tones are an essential component of language and play a crucial role in phonetic discrimination and semantic comprehension. By studying the brain activity of hearing children during tone processing, we can uncover the developmental trajectory and neural basis of tone processing, which can guide language education and speech therapy interventions.

II. Materials And Methods

A. 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.

B. 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 100ms, generated using E-prime software [6]. 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.

C. 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 1000ms 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.

D. Data Analysis

MRI data were preprocessed using SPM12 [7]. 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). The slice-time correction was implemented based on intermediate times. The high-resolution T1 image was then co-registered with the mean functional image (i.e., reference image) using the Normalized Mutual Information algorithm. The co-registered T1 image was processed with the unified segmentation procedure. 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).

III. RESULTS

Due to the limited sample size, representative features can be selected from these few data points for the analysis of tone processing (Tone 2 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, Tables I–IV were obtained, along with corresponding brain activation maps.

A. Data on tone processing in deaf children

From Table I, we can observe that in Tone 2, the activation areas in the brains of deaf children are mainly located in the right supplementary motor area, and bilateral pre-central gyrus. The corresponding Fig. 1 for Table 1 is shown below.

Table 1. Table for Tone 2 processing data in deaf children

Area	H	Cluster size	MNI coordinates			Peak
			x	y	z	
Supplementary motor area	R	537	4	14	66	T = 8.14
Pre-central gyrus	L	259	−48	−6	50	T = 8.95
	R	274	50	−4	52	T = 9.01

Note: Area represents the name of the activated region; H 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.

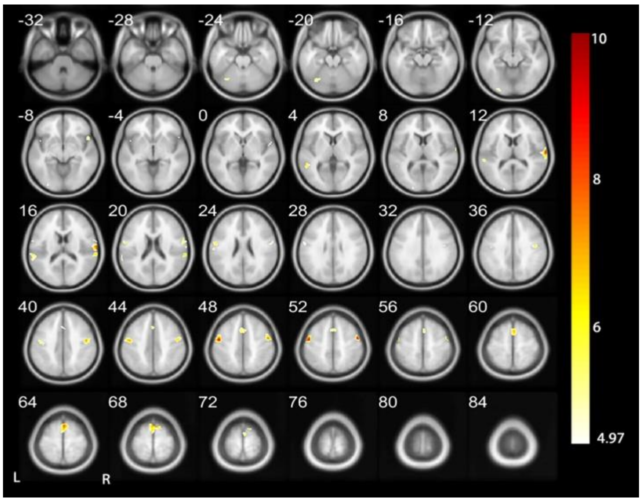

Fig. 1. Brain activation map for Tone 2 in deaf children.

From Table II, we can observe that 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 corresponding Fig. 2 for Table 2 is shown below.

Table 2. Table for Tone 3 processing data in deaf children

Area	H	Cluster size	MNI coordinates			Peak
			x	y	z	
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

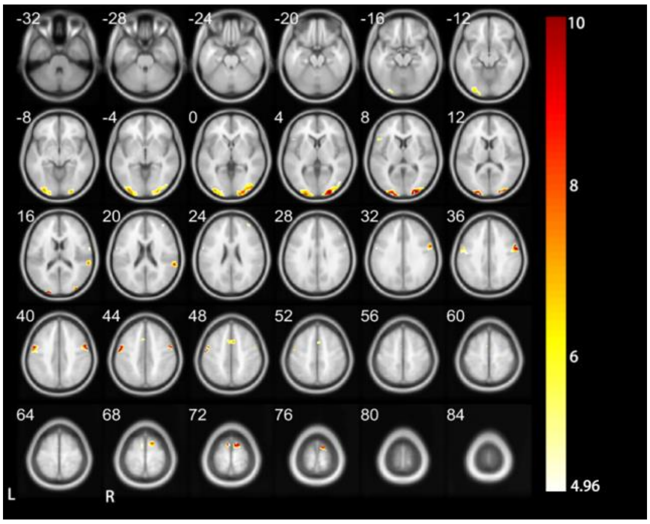

Fig. 2. Brain activation map for Tone 3 in deaf children.

B. Data on Tone Processing in Hearing Children

From Table 3, it is evident that in Tone 2, the brain activation regions for hearing children are mainly located in the bilateral middle occipital gyrus, left superior parietal lobe, and right superior temporal gyrus. The corresponding Fig. 3 for Table III is shown below.

Table 3. Table for Tone 2 processing data in hearing children

Area	H	Cluster size	MNI coordinates			Peak
			x	y	z	
Middle occipital gyrus	L	82	−30	−92	−10	T = 5.79
	R	179	30	−94	0	T = 6.51
Superior parietal lobe	L	212	−30	−48	58	T = 6.73
Superior temporal gyrus	R	314	66	−14	14	T = 8.93

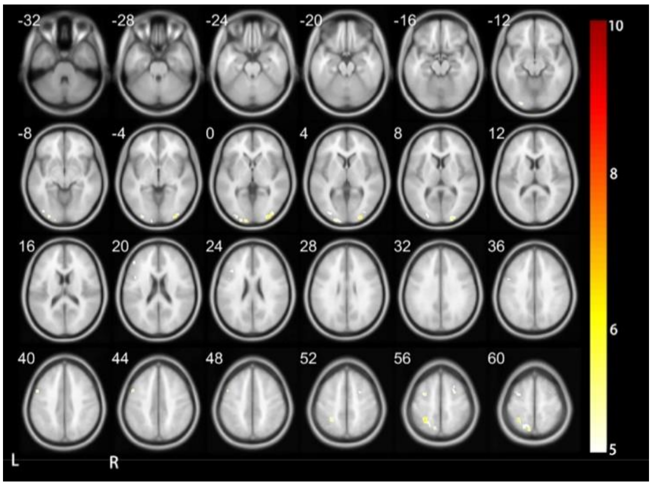

Fig. 3. Brain activation map for Tone 2 in hearing children.

From Table IV, it is evident that in Tone 3, the brain activation regions for hearing children are mainly located in the left interior frontal gyrus and bilateral middle occipital gyrus. The corresponding Fig. 4 for Table IV is shown below.

Table 4. Table for Tone 3 processing data in hearing children

Area	H	Cluster size	MNI coordinates			Peak
			x	y	z	
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

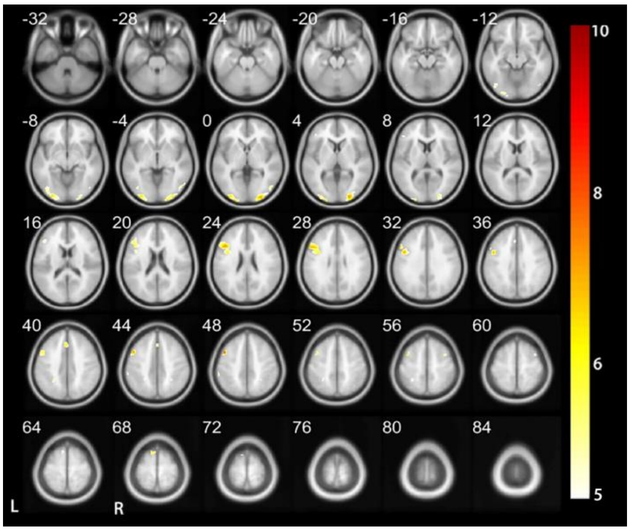

Fig. 4. Brain activation map for Tone 3 in hearing children.

By comparing the results, in Tone 2, the brain activation patterns differ between deaf and hearing children. Deaf children show activation in the supplementary motor area and pre-central gyrus, while hearing children show activation in the middle occipital gyrus, superior temporal gyrus and superior parietal lobe. 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 pre-central gyrus, while hearing children show activation in the interior frontal gyrus.

IV. Discussion

A. Due to Hearing Impairment, the Activation in Certain Areas of the Deaf Children's Brain is Smaller

There are differences in brain activation regions between deaf children and hearing children during the execution of tone recognition tasks. These differences can be observed in various regions such as the pre-central gyrus, superior temporal gyrus, middle occipital gyrus, supplementary motor area, superior parietal lobe, and interior frontal gyrus, among others.

The superior temporal gyrus is an important auditory hub, encompassing both primary and secondary auditory regions, as well as certain regions of the insula. Studies by Booth *et al.* [8] on brain areas involved in speech perception have shown that the bilateral superior temporal gyrus serves as a fundamental processing region for speech perception and initial comprehension. The prefrontal cortex plays multiple roles in tone recognition, including tone encoding, language perception, semantic comprehension, and emotional processing [9]. Hearing children exhibit stronger activation responses in auditory and language-related areas, such as the auditory cortex, prefrontal cortex, and temporal lobe, compared to deaf children. In contrast, deaf children show some specific patterns of brain activity during tone processing. They exhibit lower activation levels in the auditory cortex, which may be attributed to the absence of auditory input and the inability to receive the same auditory stimuli as hearing children [10]. This leads to insufficient stimulation of the auditory cortex in deaf children during sound processing, resulting in relatively lower activation levels in this region.

B. Deaf Children May Rely on Spatial Perception to Process Tones

The Supplementary Motor Area (SMA) is located near the precentral gyrus and is part of the motor cortex. It is primarily situated in the midline of the brain, between the two hemispheres, and is associated with spatial movement planning and coordination. The SMA plays a crucial role in motor control, participating in the coordination and regulation of voluntary movements, control of complex action sequences, and encoding of action planning and execution [11].

Studies suggest that compared to individuals with normal hearing, deaf children may exhibit enhanced spatial orientation abilities and heightened somatosensory perception. Due to the absence of auditory input, deaf children may rely more on spatial perception to gather sound-related information from their environment. Deaf children typically begin using sign language or other non-auditory forms of communication at an early age [12], which can have significant effects on their brain. Early language experiences and training may lead to the reorganization and reallocation of functional brain areas in deaf children to adapt to their communication needs. This brain plasticity can result in enhanced spatial perception abilities, thereby strengthening the utilization of spatial perception in tone recognition. As a result, in tone recognition tasks, deaf children may pay greater attention to the spatial location and direction of sound sources, utilizing their spatial perception abilities to infer the meaning of tones.

C. The Brain of Deaf Children May Exhibit Plasticity

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 [13]. According to Zhu *et al.*'s research [14], 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 [15]. 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 [16] and emphasizes the importance of numerous sensory pathways in tone perception. 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 remodeling occurs in deaf people's brains to better accommodate the processing of tone information.

V. 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.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Mengrui Shi and Qiang Li conceived the presented idea. Mengrui Shi and Qiang Li developed the metrics and computational methods. Mengrui Shi implemented the computational methods, conducted the computational analysis with the support of Qiang Li, performed the empirical evaluation, and drafted the initial manuscript. The initial draft was further edited by Mengrui Shi and Qiang Li. All authors agreed on the final manuscript.

Funding

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

Acknowledgment

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] L. Zhang and S. Liu, "Acoustic analysis of Chinese tone production by Thai-speaking learners of L2 Chinese," *Journal of Second Language Studies*, vol. 3, no. 2, 2020.

[2] Y. Han, G. Martijn, M. Maria, and S. Marc, "Relative contribution of auditory and visual information to Mandarin Chinese tone identification by native and tone-naïve listeners," *Language and Speech*, 2019.

[3] R. Milena, P. K. Luan, G. Stephanie, and A. Olusola, "Altered threat-related effective connectivity in alcohol use disorder: An fMRI study," *Biological Psychiatry*, vol. 9, issue 9, pp. S101–S102, 2022.

[4] P. Wong and T.-T. L. Carrie, "Suprasegmental features are not acquired early: Perception and production of monosyllabic Cantonese lexical tones in 4- to 6-year-old preschool children," *Journal of Speech, Language, and Hearing Research: JSLHR*, vol. 61, no. 5, 2018.

[5] B. Naheed, "A review on linguistic neglect in deaf children," *Asian Journal of Research in Social Sciences and Humanities*, vol. 11, no. 11, 2021.

[6] H. L. Richard and D. Charbonneau, "An introduction to E-Prime," *Tutorials in Quantitative Methods for Psychology*, vol. 5, no. 2, 2009.

[7] H. Hyemin and P. Joonsuk, "Using SPM 12's second-level Bayesian inference procedure for fMRI analysis: Practical guidelines for end users," *Frontiers in Neuro Informatics*, vol. 12, 2018.
[8] J. R. Booth, D. D. Burman, J. R. Meyer *et al.*, "Functional anatomy of intra-and cross-modal lexical tasks," *Neuroimage*, vol. 16, pp. 7–22, 2002.
[9] V. V. Sharma, T. Michael, F. A. Russo, and A. Claude, "Absolute pitch: Neurophysiological evidence for early brain activity in prefrontal cortex," *Cerebral Cortex*, vol. 33, issue 10, pp. 6465–6473, 2023.
[10] S. Hassanzadeh, "The psychometric properties of the Persian version of categorization of auditory performance II and speech intelligibility rating scales in cochlear-implanted deaf children," *Audiology*, vol. 23, no. 6, 2015.
[11] T. Elinor, G. Leila, B. Laura, H. Gesa, and C. Joseph, "Coherent theta oscillations in the cerebellum and supplementary motor area mediate visuomotor adaptation," *NeuroImage*, vol. 251, 118985, 2022.
[12] T. Reagan, P. E. Matlins, and C. D. Pielick, "Deaf epistemology, sign language and the education of d/deaf children," *Educational Studies*, vol. 57, no. 1, 2021.
[13] P. C. Hauser, M. W. Dye, M. Boutla *et al.*, "Deafness and visual enumeration: Not all aspects of attention are modified by deafness," *Brain Res*., vol. 1153, no. 1, pp. 178–187, 2007.
[14] X. Zhu, Z. C. Huang, P. P. Zhang *et al.*, "FMRI study of default mode network in patients with unilateral long-term sensorineural deafness," *Chinese Journal of Ear Science*, no. 3, pp. 511–515, 2015.
[15] A. Sharma and H. Glick, "Cross-modal re-organization in clinical populations with hearing loss," *Brain Sci*., vol. 6, no. 1, 4, 2016.
[16] C. Velia, O. Eleni, R. Jerker *et al.*, "Dissociating cognitive and sensory neural plasticity in human superior temporal cortex," *Nat Commun.*, vol. 4, 1473, 2013.