An fMRI study of how deaf children process the three tones 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. Objective: The objective of this study is to investigate the brain activity patterns of deaf children and hearing children during the processing of three different tones (first tone, 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. Methods: 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. Results: 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 comparison, it is possible that the brains of deaf children exhibit stronger plasticity and compensatory mechanisms. These findings contribute to the understanding of the neural basis of tone processing and may help in refining intervention strategies. Additionally, they provide a theoretical basis for the language development and rehabilitation of deaf children.

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, "mā" and "má" 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 two 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.

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.

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 (tones 1, 2, and 3) in deaf and normal-hearing children. (That is, the three different tone activation data are not the data of the same child).

The activation regions for the three different tones in deaf children correspond to Figures 1, 2, and 3. From Figures 1, 2, and 3, we can observe that in Tone 1, the activation areas in the brains of deaf children are mainly located in the middle occipital gyrus, supplementary motor area, and pre-central gyrus. In Tone 2, the activation areas in the brains of deaf children are mainly located in the supplementary motor area and pre-central gyrus. In Tone 3, the activation areas in the brains of deaf children are mainly located in the middle occipital gyrus and pre-central gyrus.

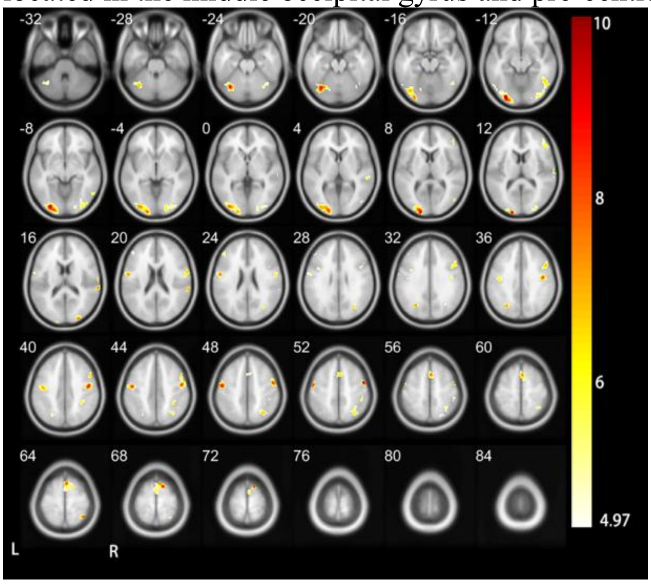

Fig. 1 Brain activation map for Tone 1 in deaf children

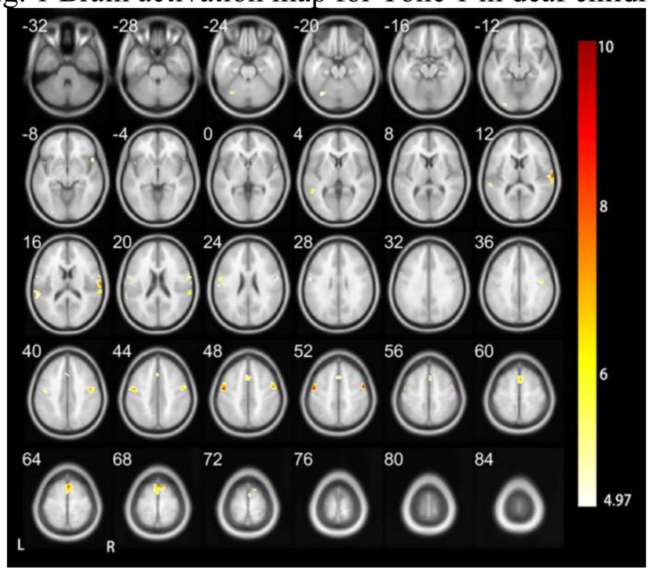

Fig. 2 Brain activation map for Tone 2 in deaf children

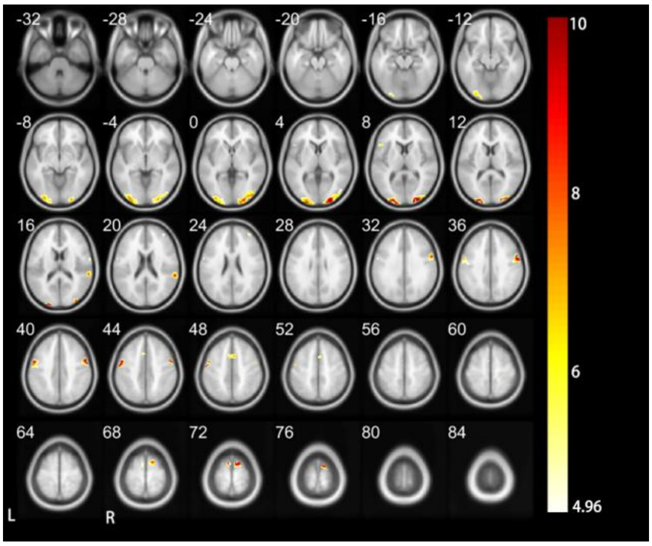

Fig. 3 Brain activation map for Tone 3 in deaf children

The activation regions for the three different tones in hearing children correspond to Figures 4, 5, and 6. From Figures 4, 5, and 6, it is evident that in tone 1, the brain activation regions for hearing children are mainly located in the middle occipital gyrus and superior temporal gyrus. In tone 2, the brain activation regions for hearing children are mainly located in the middle occipital gyrus, superior temporal gyrus, and superior parietal lobe. In tone 3, the brain activation regions for hearing children are mainly located in the pre-central gyrus and middle occipital gyrus.

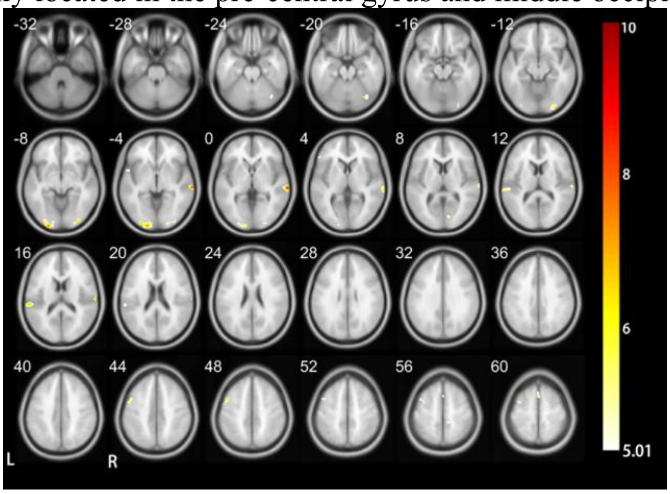

Fig. 4 Brain activation map for Tone 1 in hearing children

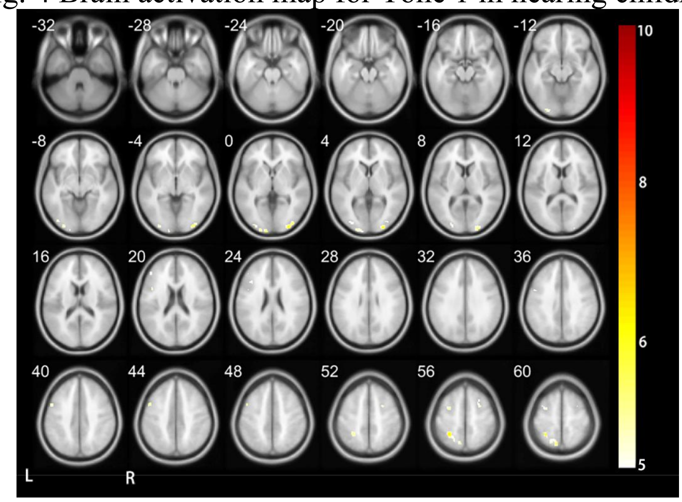

Fig. 5 Brain activation map for Tone 2 in hearing children

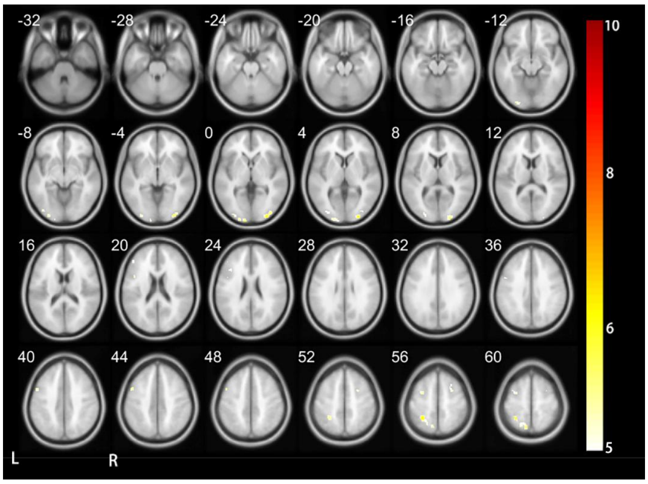

Fig. 6 Brain activation map for Tone 3 in hearing children

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 pre-central gyrus, while hearing children show activation mainly in the superior temporal gyrus. In tone 2, the brain activation patterns differ between deaf and hearing children. Deaf children show activation in the supplementary motor area, superior temporal gyrus, and pre-central gyrus, while hearing children show activation in the middle occipital 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 medial frontal gyrus.

4. Discussion

4.1 Auditory and language-related brain areas

Auditory brain areas include the primary auditory cortex (BA41), the secondary auditory cortex (BA42), and the auditory association cortex (BA22). Language-related brain areas include the bilateral middle frontal gyrus, Broca's area, and Wernicke's area. Broca's area, located in the posterior part of the left inferior frontal gyrus (BA44, BA45), serves multiple functions in language production, including phonological processing, higher-level semantic processing, and processing at the sentence and discourse levels. Wernicke's area, on the other hand, encompasses the left superior temporal gyrus, middle temporal gyrus, superior temporal sulcus, and angular gyrus.

4.2 Brain activation regions of deaf and hearing children compared

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, posterior cingulate gyrus, supplementary motor area, superior parietal lobe, and middle frontal gyrus, among others. 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. This leads to insufficient stimulation of the auditory cortex in deaf children during sound processing, resulting in relatively lower activation levels in this region.

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. [12] 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. Additionally, Tan Li-Hai [13] suggests that the superior temporal gyrus is also involved in the processing of Chinese tone. The prefrontal cortex plays multiple roles in tone recognition, including tone encoding, language perception, semantic comprehension, and emotional processing. The coordinated interaction of these functions allows us to perceive and understand tone variations and integrate them into language and emotional expression. These findings contribute to our understanding of how auditory abilities influence cognitive processes and may inform interventions aimed at optimizing auditory processing in deaf individuals.

4.3 Neuroplasticity in the brains of deaf children

In the context of tone processing tasks, deaf children show activation in additional brain areas (such as the Middle occipital gyrus, among others), including regions associated with visual and tactile processing, indicating stronger plasticity and compensatory mechanisms [14]. Cross-modal reorganization refers to adaptive and compensatory changes that occur when the neural system integrates sensory functions, whereby deprivation of one sensory modality can lead to enhanced functioning in other sensory modalities. Deprived of auditory stimulation, deaf children rely more on visual information to gather more information from the surrounding environment, resulting in enhanced visual functioning. This may be a compensatory mechanism to overcome the absence of auditory input and utilize alternative sensory pathways for tone processing. The presence of such compensatory activity implies neural plasticity in the language development of deaf children[15] and underscores the role of multiple sensory pathways in tone processing. This plasticity renders the visual and tactile regions of deaf children more sensitive to auditory stimuli, leading to stronger activation during tone processing. In contrast, hearing children rely more on the auditory pathway for tone processing. This suggests that the brains of deaf individuals undergo functional network reorganization to better adapt to the processing of tone information.

Additionally, in tone 2, the deaf group shows increased activity in the prefrontal and temporal lobes, which may be related to their specific needs in language learning and development. The supplementary motor area is also associated with spatial orientation. This suggests that compared to the normal hearing group, the deaf group exhibits enhanced spatial orientation abilities and proprioceptive senses. The posterior cingulate gyrus and inferior temporal gyrus are primarily responsible for visual information processing, indicating that visual abilities may be enhanced in the absence of hearing impairment [16]. Zhu et al. [17] found that the default mode network (DMN) in patients with chronic hearing loss undergoes functional reorganization, resulting in compensatory enhancement of visual abilities following auditory deprivation. Furthermore, in the absence of auditory stimulation, the visual cortex is more sensitive to reorganization or neural plasticity. Chen et al. [18] discovered that when cochlear implant recipients were solely exposed to visual stimulation, their visual cortex exhibited higher activity, which was associated with auditory speech recognition. Behavioral studies also suggest that deaf individuals have better visual abilities [19].

5. In conclusion

This study, by comparing the brain activity patterns of deaf and hearing children during three-tone processing tasks, revealed differences in tone processing between the two groups, providing insights into the underlying neural mechanisms of tone recognition in deaf and hearing children. 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. However, further research is needed to confirm these findings and investigate their implications for language development in deaf children, as well as to provide a theoretical basis for language development and rehabilitation in this population. This external study has certain limitations, such as relatively small sample size, etc. In future research, larger sample sizes will be expanded and grouped studies will be refined.

Funding

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

References

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

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

[16] 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.

[17] 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.

[18] CHEN L C, SANDMANN P, THORNE J D, et al. Cross-modal functional reorganization of visual and auditory cortex in adult cochlear implant users identified with fNIRS [J]. Neural Plasticity, 2016, 2016(9): 1-13.

[19] Horn DL, Davis RA, Pisoni DB, et al. Development of visual attention skills in prelingually deaf children who use cochlear implants. Ear Hearing, 2005, 26(4): 389-408.