Speech Prosody 2024
2-5 July 2024, Leiden, The Netherlands

Tonal Processing in Mandarin-speaking Children with Extensive Cochlear Implant Experiences Using an Oddball Paradigm

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Abstract

Tones are essential in differentiating word meanings in Mandarin and are predominantly realized through manipulation of fundamental frequency (F0). However, for children with cochlear implants (CIs), acquiring tones can be a challenge due to the limitation of CI devices in processing F0. Fortunately, research has shown that substantial CI experiences can potentially counteract the disadvantages CI children face in tonal acquisition, and help them achieve a production level similar to their normal-hearing counterparts. This study thus intends to investigate whether CI children could also perform equally well in tonal processing. Six CI children were recruited five years after implantation, along with 12 chronological-age- and hearing-age-matched children with normal hearing. The passive oddball paradigm was used in an event-related potential (ERP) experiment, including a Tone 1/Tone 4 contrast and a Tone 2/Tone 3 contrast. Results showed that CI children had p-MMR and LDN in the Tone 1/Tone 4 contrast, and only p-MMR in the Tone 2/Tone 3 contrast. On the other hand, both groups of matched children with normal-hearing displayed LDN in Tone 1/Tone 4 and Tone 2/Tone 3 contrasts. This implies that lexical tonal processing in CI children might be less mature than that in their normal-hearing counterparts despite their near-normal performance in tonal production.

Index Terms: tonal processing, cochlear implants, mismatch responses (MMRs), Mandarin tones, oddball paradigm

1. Introduction

Mandarin is a widely-spoken language in which lexical tones are used to differentiate word meanings. There are four lexical tones in Mandarin, including a high-level Tone 1, a mid-rising Tone 2, a mid-dipping Tone 3, and a high-falling Tone 4 [1]. Children tend to acquire Tones 1 and 4 earlier than Tones 2 and 3, and can usually master all four tones before three years of age [2]. Unfortunately, for children with cochlear implants, they do not have this luxury, as their hearing device has limited capacity in processing low frequencies due to insufficient electrode arrays attached to the cochlear apex, where F0 is mainly processed [3]. As a result, children with CIs tend to receive degraded cues of lexical tones and thus have a lower performance in tone perception and flatter contours in tonal production [3], [4].

However, tonal production of hearing-impaired children has been found to improve with longer CI experiences. Children wearing CI for at least five years are capable of producing tones comparable to those of their normal-hearing peers [5]–[7]. This makes us wonder whether the tonal processing ability of CI children would also be up to par. As their auditory input is more impoverished than that of normal-hearing children, it is likely that CI children are not capable of the level of tonal processing in normal-hearing children. On the other hand, it is equally likely that CI children could develop an alternative strategy in tonal processing, much like what they have done with tonal production, in order to achieve a normal-level proficiency. This is what we plan to find out in this study.

An oddball paradigm was adopted to elicit event-related potentials (ERPs), which could reflect the neural responses of tonal processing in the brain. ERPs are especially suitable for children with CIs since they do not tamper or interfere with the metallic and magnetic components of the CI [8]. The oddball paradigm presents listeners with repetitions of two stimuli, one of which is far more frequent than the other. Detection of the oddball (i.e., the less frequent stimulus) is thought to be an unconscious process and listeners are not required to pay conscious attention to the stimulus stream. Several ERP components are believed to reflect the detection of the oddball at different developmental stages. The oddball effects are typically calculated by subtracting the ERP to the frequent standard stimuli from that to the infrequent deviant stimuli [9]. For adults, the effect is typically manifested as the Mismatch Negativity (MMN), which peaks at 100 to 250 ms from the onset of a stimulus change. For infants[10], [11] and younger children [12], [13], especially when the deviant stimuli are less discriminative from the standard stimuli [13], a positive mismatch response (p-MMR) is usually observed at 100 to 500 ms after the onset of stimulus switch over frontal central electrode sites. In addition, for school-aged children and adolescents, a subsequent frontal-central negativity known as the late discriminate negativity (LDN) [14] that tends to peak at 300 to 700 ms after the onset of stimulus change [15] [16] is also observed. The polarity and latency of these mismatch responses could serve as objective indices reflecting

10.21437/SpeechProsody.2024-18

the automaticity and maturity of speech feature processing in children [13], [17].

As for children with CIs, previous studies indicated that they tend to show longer latencies and lower amplitudes of MMN in response to lexical tones [18]–[20]. However, there was not much control over age of implantation [18], [19] and duration of CI experiences [20], [21]. As previous studies showed that extensive CI experiences could actually help hearing-impaired children to achieve a normal-hearing level of tonal production [6], we would like to study how lexical tones are processed in CI children by controlling for their length of implantation.

2. Method

2.1. Participants

Eight children with CIs were recruited five years after implantation (mean age = 9.09 yrs, ranging from 6.30 to 12.23 yrs). We also recruited 16 normal-hearing children to act as controls. Eight of them were hearing-age-matched (mean age = 5.45 yrs, ranging from 4.82 to 5.89 yrs), and the other eight were chronological-age-matched (mean age = 9.09 yrs, ranging from 6.34 to 12.30 yrs). Two independent *t* tests showed that the hearing age of the CI children was not significantly different from that of the hearing-age-matched control group [$t(14) = -0.26$, $p = .80$], and the chronological age of the CI children did not differ significantly from the chronological-age-matched group [$t(14) = 0$, $p = 1$].

2.2. Stimuli

Based on the order of acquisition and ease of discrimination [2], two sets of Mandarin tonal contrasts (/ba1/-/ba4/ and /ba2/-/ba3/) were used. The /ba1/-/ba4/ contrast was easy to discriminate auditorily and was acquired earlier in children, whereas the /ba2/-/ba3/ contrast was difficult to discriminate and was acquired later [2]. The stimuli were recorded by the first author, who is a female native speaker of Mandarin, in a sound-treated room using a KORG MR-1000 recorder and a SHURE SM10A head-mounted microphone. The sampling rate was set at 44.1-kHz and a 16-bit quantization. All four tones were adjusted to 300 ms in duration and 70 dB in root-mean-square (RMS) intensity by Praat (ver. 6.1.52) [22].

2.3. Procedure

Since the prerequisite of MMN elicitation is that the central auditory system has to form a representation of the repeated standard stimuli in the short-term memory trace before the presentation of a deviant stimulus [23], [24], we asked subjects to perform two working memory tests, digit span and nonword repetition, to examine their short-term memory capacity and phonological working memory, respectively. The digit span test was designed to include two to nine digits based on the Wechsler Intelligence Scale for Children (WISC) forward digit span test [25]. Participants were asked to repeat the digits they heard until they responded incorrectly in two consecutive trials that had the same digit span. The nonword repetition test [26] consisted of Mandarin gap word and nonword phrases of two-, four-, and six-syllables. Participants were asked to repeat the phrases they heard as accurately as possible.

After the two memory tests, subjects were engaged in an ERP oddball paradigm. Two oddball sessions, one for the Tone1/Tone4 contrast, and the other for the Tone2/Tone3 contrast, were presented to each participant in a counterbalanced fashion, and each session was further divided into three equal blocks to allow breaks. For the /ba1/-/ba4/ contrast, /ba1/ was chosen as the standard, and /ba4/ the deviant, while for the /ba2/-/ba3/ contrast, /ba2/ served as the standard and /ba3/ the deviant. There were 810 stimuli in each session, and the ratio of standard to deviant was 8:1, consisting of 720 standard stimuli and 90 deviant stimuli. The interstimulus interval (ISI) was set at 430 ms, following [17]. The stimuli were pseudo-randomized with at least two consecutive standard stimuli between two deviant stimuli. The stimuli were displayed via a desktop computer using PsychoPy v2023.2.3 [27]. Each child was seated in front of a screen at a distance of 80 cm, and was asked to watch a silent cartoon displayed on the screen during each session. The whole experiment lasted about an hour.

2.4. EEG recording, pre-processing, and data analysis

The continuous electroencephalography (EEG) was recorded from 32 Ag/AgCl electrodes mounted in an elastic cap (EASYCAP GmbH, Germany) distributed according to the extended 10-20 system and amplified with a bandpass from 0.05 to 100 Hz by using the actiCHamp amplifier (BrainProducts, Gilching, Germany) and digitized at a sampling rate of 500 Hz. Six frontocentral electrodes (F3, Fz, F4, C3, Cz, C4) were selected to cover the typical scalp distribution of the MMN. The electrodes were referenced online to FCz, and an electrode was placed on the tip of the nose as offline reference to mitigate potential artifacts from CIs [28]. The vertical electrooculogram (EOG) (VEOG) was monitored using two electrodes placed above and below the left eye. The horizontal EOG (HEOG) was recorded using two electrodes placed on the right and left external canthus. Impedances were kept below 10 kΩ.

The EEG data was processed using EEGLAB v2022.1 [29] and ERPLAB v9.00 [30] in MATLAB R2018b (The Mathworks, Natick, MA). The continuous EEG data were epoched with a 200-ms pre-stimulus interval and a 700-ms post-stimulus interval, and the pre-interval (-200 to 0 ms) was used for baseline correction. The epoched EEG data were filtered with a band-pass filter of 0.1 to 30 Hz (12 dB/octave), and then re-referenced to the nose. The epochs with voltage variations larger than ±100 µV at VEOG, HEOG, or any other electrodes were rejected. Only participant data with an acceptance rate of the deviant stimuli of more than 50% were included for further ERP averages (cf. [11], [13]).

In both the Tone 1/Tone 4 contrast and the Tone 2/Tone 3 contrast, the grand averaged ERPs for standard and deviant stimuli for each participant and each electrode were calculated, and the difference waves were generated from subtracting the standard waveforms from the deviant waveforms. The mean amplitudes of the standard and deviant stimuli were calculated in three time windows: 100 to 300 ms, 300 to 500 ms, and 500 to 700 ms. Based on prior findings, we expect to observe the pMMR effects in earlier time windows such as the time windows of 100 to 300 ms as well as the 300 to 500 ms [13], [17]. LDN effects following the pMMR effects if the processing of speech reaches automaticity and maturity [31].

3. Results

3.1. Working memory tests

The results of the digit span test of the three subject groups are shown in Figure 1. No significant difference was found between children with CIs and the two groups of matched children with normal-hearing [*F*(2,21) = 2.14, *p* = .14].

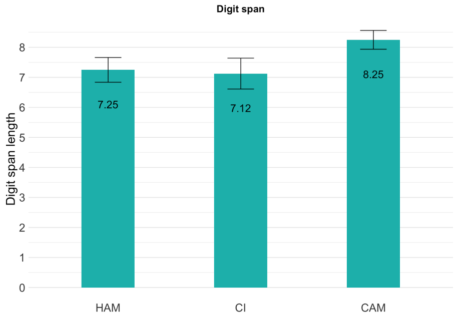

Figure 1: *Results of the digit span test*
(HAM: hearing-aged-matched children; CI: children with CIs; CAM: chronological-aged-matched)

Figure 2 shows the nonword repetition results of the three groups. The effect of group was significant in the two-syllable trials [*F*(2,21) = 6.169, *p* <.01]. Post-hoc tests showed that children with CIs were significantly less accurate than the chronological-age-matched children (*p* <.01) and the hearing-age-matched children (*p* <.05). However, for the four-syllable and six-syllable trials, there was no significant difference among the three speaker groups.

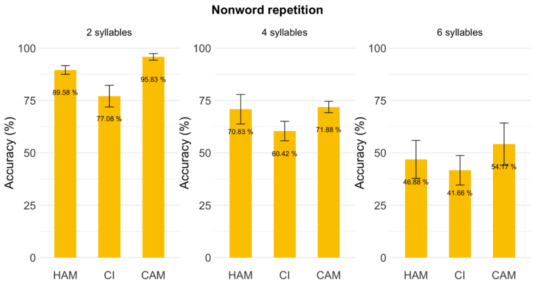

Figure 2: *Results of nonword repetition*
(HAM: hearing-aged-matched children; CI: children with CIs; CAM: chronological-aged-matched)

3.2. ERP results

Figures 3 & 4 show the averaged ERP waveforms of the standard and deviant stimuli in Tone 1/Tone 4 and Tone 2/Tone 3 contrasts, respectively. The average of the frontal and central electrodes (F3/Fz/F4/C3/Cz/C4) was used for illustration. A four-way ANOVA was conducted for Tone 1/Tone 4 and Tone 2/Tone 3 contrasts. The group (CI, hearing-age-matched, chronological-age-matched) was a between-subjects factor. The condition (standard/deviant) and time window (100 to 300 ms, 300 to 500 ms, and 500 to 700 ms) were within-subjects factors. If significant main effects or interactions associated with the group factor were found, further analyses were conducted for each group. For each group, a paired *t*-test was conducted to further evaluate whether standard and deviant stimuli differed in each time window.

3.2.1. Tone 1/Tone 4 contrast

The results of ANOVA showed that there were significant interactions of latency × group [*F*(6, 63) = 2.33, *p* <.05] and condition × latency [*F*(3, 63) = 5.76, *p* <.01]. A near-significant interaction of condition × latency × group [*F*(6, 63) = 2.01, *p* =.08] was also found. Further analyses of MMRs for each tonal contrast and each subject group are as follows.

Children with CIs demonstrated marginally more positive responses to deviant stimuli than standard stimuli in the time window of 300 to 500 ms [*t*(47) = -1.93, *p* =.06], and significantly more negative responses to deviant stimuli than standard stimuli in the time window of 500 to 700 ms [*t*(47) = 5.59, *p* < .001]. Additionally, no significantly different responses between deviant and standard stimuli in the time window of 100 to 300 ms. Regarding the two groups of normal-hearing children, no significantly different responses between deviant and standard stimuli in the time window of 100 to 300 ms. The hearing-age-matched children showed near-significantly more negative responses to deviant stimuli in the time window of 300 to 500 ms [*t*(47) = 1.80, *p* =.08], and significantly more negative responses to deviant stimuli in the time window of 500 to 700 ms [*t*(47) = 2.64, *p* <.05]. Chronological-age-matched children displayed marginally more negative responses to deviant stimuli in the time window of 300 to 500 ms [*t*(47) = 1.70, *p* =.10], and significantly more negative responses to deviant stimuli in the time window of 500 to 700 ms [*t*(47) = 2.20, *p* <.05]. In other words, for the Tone 1/Tone 4 contrast, children with CIs demonstrated p-MMR-like and LDN responses, while hearing- and chronological-age-matched children showed LDN responses.

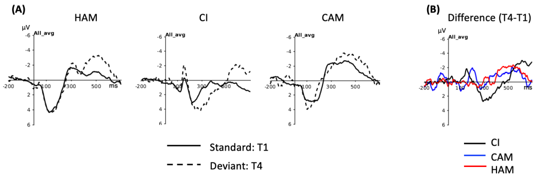

Figure 3: *(A) Average waveforms of standard and deviant stimuli, and (B) difference waveforms across the three subject groups in the Tone 1/Tone 4 contrast*
(HAM: hearing-aged-matched children; CI: children with CIs; CAM: chronological-aged-matched)

3.2.2. Tone 2/Tone 3 contrast

The results of ANOVA showed that there were significant interactions of condition × group [*F*(2, 21) = 3.54, *p* <.05], latency × group [*F*(6, 63) = 4.58, *p* <.001], condition × latency [*F*(3, 63) = 3.32, *p* <.05], condition × latency × group [*F*(6, 63) = 2.33, *p* <.05], and condition × group × electrode [*F*(15, 315) = 2.71, *p* <.001]. Further analyses of MMRs for each tonal contrast and each subject group are as follows.

Children with CIs demonstrated significantly more positive responses to deviant stimuli than standard stimuli in the time window of 100 to 300 ms [*t*(47) = -4.07, *p* < .001], 300 to 500 ms [*t*(47) = -5.03, *p* < .001], and 500 to 700 ms [*t*(47) = -4.60, *p* < .001]. Hearing-age-matched children showed marginally more negative responses to deviant stimuli in the time window of 100 to 300 ms [$t(47) = 1.71$, $p = .09$], and significantly more negative responses to deviant stimuli in the time window of 300 to 500 ms [$t(47) = 2.78$, $p < .01$] and 500 to 700 ms [$t(47) = 5.68$, $p < .001$]. Chronological-age-matched children displayed significantly more positive responses to deviant stimuli in the time window of 100 to 300 ms [$t(47) = -5.31$, $p < .001$], and near-significantly more negative responses in the time window of 500 to 700 ms [$t(47) = 1.97$, $p = .05$]. In other words, for the Tone 2/Tone 3 contrast, children with CIs demonstrated p-MMR responses, while hearing-age-matched children showed LDN responses, and chronological-age-matched children showed p-MMR and LDN responses.

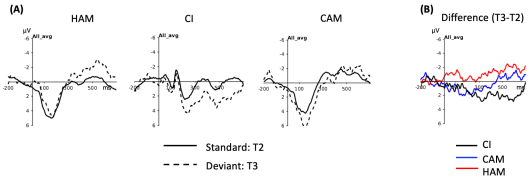

Figure 4: *(A) Average waveforms of standard and deviant stimuli, and (B) difference waveforms across the three subject groups in the Tone 2/Tone 3 contrast (HAM: hearing-aged-matched children; CI: children with CIs; CAM: chronological-aged-matched)*

4. Discussion

The purpose of this study is to observe whether children with longer CI experiences could perform tonal processing in a fashion similar to their normal-hearing counterparts using MMRs. Two sets of tone contrast differing in discriminative difficulty were used to investigate the automaticity and maturity of tonal processing in CI and normal-hearing children. Results showed that CI children demonstrated p-MMR and LDN in the Tone 1/Tone 4 contrast, and only p-MMR in the Tone 2/Tone 3 contrast. On the other hand, chronological- and hearing-age-matched children displayed LDN in both Tone 1/Tone 4 and Tone 2/Tone 3 contrasts. As p-MMR often appears in infants and younger children, it is deemed to be a representation of immature brain responses [13]. In other words, results of the current study suggested that lexical tonal processing in CI children might be less mature than that in their normal-hearing counterparts.

[17] claimed that the various mismatch components (p-MMR, LDN, MMN) can reflect the developmental process of the abilities for speech features from early to middle childhood. At the beginning stage of speech discrimination development, an enhancement in p-MMR might reflect involuntary attention orientation when children fail to analyze the acoustic difference between standard and deviant stimuli. Later, when entering an advanced level, children begin to process sound structures, as reflected by the emergence of LDN and its latency change. Finally, children develop automatic processing of subtle acoustic feature discrimination, similar to adults. In this study, children with CIs were observed to have LDN following p-MMR in the Tone 1/Tone 4 contrast, but only p-MMR in the Tone 2/Tone 3 contrast. This implies that the discrimination of the Tone 1/Tone 4 contrast is easier to process than that of the Tone 2/Tone 3 contrast, and is thus acquired earlier in children with CIs. This also suggests that the order of tone acquisition in CI children is similar to that in typical Mandarin-speaking children. However, the rate of acquisition might be slower, as reflected by the presence of LDN in Tone 1/Tone 4 and Tone 2/Tone 3 contrasts in the two groups of normal controls. This is consistent with previous behavioral studies [4], [32].

The less mature brain responses also suggest that CI children have difficulty in processing auditory tone stimuli, likely due to auditory deprivation [33], [34] and degraded auditory input in their early life [7]. However, the working memory and phonological working memory of the CI children were in general up to par with their normal-hearing counterparts. This implies that CI children might be using secondary cues, such as duration, amplitude, etc., for tones in order to achieve the level of tonal production proficiency [35]. As all stimuli In this study were of equal duration, this might be especially difficult for CI children to process. More studies would be needed in order to understand the function of secondary tonal cues to CI children.

5. Conclusion

This study suggests that children with extensive CI experiences may still have difficulty in processing lexical tones through only the auditory pathway, as they demonstrated less mature brain responses (p-MMR and later LDN response) in both of the two lexical tone contrasts compared to their normal-hearing counterparts. However, they tend to acquire tones in an order that is similar to that of their normal-hearing peers, even though the process might be more protracted.

6. Acknowledgements

This study is funded by the Department of Medical Research, National Taiwan University Hospital (No. 112-S0267). The authors also thank Yin-Ching Chang and Jing-Yi Huang for helping with data collection.

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