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# Age-sensitive associations of segmental and suprasegmental perception with sentence-level language skills in Mandarin-speaking children with cochlear implants

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ABSTRACT

*Background and aim:* It remains unclear how recognition of segmental and suprasegmental phonemes contributes to sentence-level language processing skills in Mandarin-speaking children with cochlear implants (CIs). Our study examined the influence of implantation age on the recognition of consonants, lexical tones and sentences respectively, and more importantly, the contribution of phonological skills to sentence repetition accuracy in Mandarin-speaking children with CIs.

*Methods:* The participants were three groups of prelingually deaf children who received cochlear implants at various ages and their age-matched controls with normal hearing. Three tasks were administered to assess their consonant perception, lexical tone recognition and language skills in open-set sentence repetition.

*Results:* Children with CIs lagged behind NH peers in all the three tests, and performances on segmental, suprasegmental and sentence-level processing were differentially modulated by implantation age. Furthermore, performances on recognition of consonants and lexical tones were significant predictors of sentence repetition accuracy in the children with CIs.

*Conclusion:* Overall, segmental and suprasegmental perception as well as sentence-level processing is impaired in Mandarin-speaking children with CIs compared with age-matched children with NH. In children with CIs recognition of segmental and suprasegmental phonemes at the lower level predicts sentence repetition accuracy at the higher level. More importantly, implantation age plays an important role in the development of phonological skills and higher-order language skills, suggesting that age-appropriate aural rehabilitation and speech intervention programs need to be developed in order to better help CI users who receive CIs at different ages.

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**What this paper adds?**

Findings of this study contribute to better understanding of speech perception and language processing in Mandarin-speaking children with cochlear implants (CIs). Specifically, our results demonstrate that performances of Mandarin-speaking children with CIs on segmental, suprasegmental, and sentence-level processing were differentially modulated by implantation age. Furthermore, recognition of both consonants and lexical tones contributes to sentence repetition accuracy in children with CIs. These findings have prognostic implications for developing post-implant rehabilitation and intervention programs.

## 1. Introduction

In Mainland China, the number of profoundly deaf children who have received multichannel cochlear implants (CIs) is dramatically increasing as a result of economic growth and philanthropic efforts. However, different from the developed countries where most of the deaf children are now implanted prior to two years of age, implantation in Mandarin-speaking children occurs across a wide range of ages. It remains unclear how language processing skills including speech perception vary as a function of implantation age in Mandarin-speaking children. A better understanding of the age factor is an important step towards the development and optimization of age-appropriate aural rehabilitation and speech intervention programs.

While speech perception in children with CIs has been examined extensively (Eisenberg et al., 2006; Robbins, Koch, Osberger, Zimmerman-Phillips, & Kishon-Rabin, 2004; Moog & Geers, 1990; Osberger, Fisher, Zimmerman-Phillips, Geier, & Barker, 1998; Sarant, Blamey, Dowell, Clark, & Gibson, 2001; Zwolan et al., 2004), most of the studies have been conducted with English-speaking children. Although some studies have investigated speech perception of Mandarin-speaking children, they generally focused on the perception of lexical tones. This focus is probably due to (a) the critical role that lexical tones play in a tonal language, such as Chinese (Xi, Zhang, Shu, Zhang, & Li, 2010; Yu et al., 2015; Zhang et al., 2012) and (b) the limitations that current CI devices have in presenting vocal pitch information (Han et al., 2009; Peng, Tomblin, Cheung, Lin, & Wang, 2004; Wang, Zhou, & Xu, 2011; Xu et al., 2011). For example, Peng et al. (2004) found that the overall average accuracy of lexical tone identification in prelingually deafened pediatric CI users was only about 73%, which is apparently much lower than the age-matched peers with normal hearing (NH). Similarly, Zhou, Huang, Chen, and Xu (2013)) showed that implanted children scored about 67% correct on a lexical tone identification task. These results together with those of other studies (Han et al., 2009; Wang et al., 2011; Xu et al., 2011) consistently suggest that prelingually deafened children with CIs have difficulty in perceiving lexical tone contrasts.

Studies on consonant perception of Mandarin-speaking CI users have also been conducted although much fewer in number than those on lexical tone perception. For example, Lin and Peng (2003) found that the average scores for the initial consonant discrimination in Mandarin-speaking children with CIs were about 77% and the performance on consonant production correlated negatively with the age of implantation. More recently, Liu, Zhou, Berger, Huang, and Xu (2013)) showed that CI children scored, on average, 8% below the mean performance of NH group on recognition of consonant contrasts, suggesting that CI children lag behind their NH peers in consonant perception. Studies on the phonological acquisition of Mandarin-speaking NH children have revealed complex acquisition trajectories of suprasegmental (lexical tones) and segmental (consonants and vowels) phonemes (Hua & Dodd, 2000; Li & Thompson, 1977; To, Cheung, & McLeod, 2013; Wong, 2013). For example, Singh and colleges investigated the effects of variation in tones, vowels and consonants on spoken word recognition in Mandarin-learning children (Singh, Goh, & Wewalaarachchi, 2015; Wewalaarachchi, Wong, & Singh, 2017). The results showed that children aged 2.5–3.5 years old were highly sensitive to tone mispronunciations and less sensitive to vowel and consonant mispronunciations. However, children aged 4–5 years old demonstrated a decreased sensitivity to lexical tones and an increased sensitivity to vowels and consonants. These studies indicate that phonological acquisition does not have a single sensitive/critical period or linear developmental trajectory associated with the acquisition of various aspects of phonological features (see Werker & Hensch, 2015 and Singh & Fu, 2016 for reviews). Therefore, it is possible that prelingually deafened Mandarin-speaking children who receive CIs at different ages may undergo different developmental trajectories in the acquisition of lexical tones and consonants. The literature suggests that there is a sensitive period of about 7-years-old for cochlear-implanted children, during which the central auditory system remains plastic to some extent (Sharma, Dorman, & Spahr, 2002). Thus children with CIs implanted within the sensitive period are more likely to develop close-to-normal speech perception abilities (Percy-Smith et al., 2013; Zheng et al., 2011). However, whether and how the perception of consonants and lexical tones is differentially affected by implantation age has rarely been explored in previous studies.

Apart from the perception of individual consonants and lexical tones, sentence-level linguistic processing is essential to the communication of daily life, which is loaded with varying amounts of challenge for a CI user depending on factors such as implantation age and linguistic knowledge. Sentence recognition by Mandarin-speaking children with CIs has been examined with a sentence repetition task in several previous studies. Zhu et al. (2011) found that at 5.4 years after implantation, the mean performance of children age ranged 6–14.5 years was about 82% correct for the open-set recognition of multi-talker sentences. In two follow-up tests carried out 6 and 12 months after implantation, Zheng et al. (2011) showed that children age ranged 3–6 years scored 33% and 66%, respectively, for the recognition of closed-set sentences in quiet. These studies, however, did not clarify whether and how the ages of implantation that are critical for the acquisition of consonants and lexical tones affect the recognition of open-set sentences. Furthermore, recognizing spoken sentences and repeating the words involves more high-level cognitive processes than recognition of individual phonemes or tones, including access and integration of word meanings, and syntactic and pragmatic processing (Patel, Xu, & Wang, 2010; Wang, Shu, Zhang, Liu, & Zhang, 2013; Xu, Zhang, Shu, Wang, & Li, 2013). More recent studies have called into question the underlying mechanisms of the sentence repetition task and their clinical informativeness (Klem et al., 2015; Polišenská, Chiat, & Roy, 2015). The results indicate that immediate verbal repetition scores should not simply be viewed as an indicator of receptive skills or speech intelligibility; rather, it is a composite measure of language skills and a reliable clinical marker of language impairment, which collectively reflect speech perception, speech production, lexical phonology and morpho-syntactic knowledge. It remains unclear to what extent perceptual performance of the lower-level phonological units such as consonants and lexical tones may contribute to higher-order language skills with sentence repetition in children, especially those with CIs.

Given the knowledge gaps in previous studies, the aim of the present study is to investigate speech perception and language processing in Mandarin-speaking children who received cochlear implants at various ages. Specifically, we aimed to clarify (1) how Mandarin-speaking children who received CIs at different ages may perform differently from the NH controls in the three tasks of consonant recognition, lexical tone recognition and sentence repetition; (2) to what extent segmental and suprasegmental perception may contribute to sentence-level language skills in the children with CIs.

## 2. Methods

### *2.1. Participants*

Fifty-three prelingually deafened children (30 boys and 23 girls) with CIs and sixty chronological age-matched NH children (24 boys and 36 girls) participated in the experiment. Children with CIs were recruited from rehabilitation centers and schools for deaf children in Beijing. They were all profoundly deaf (unaided pure-tone threshold average ≥ 90 dB HL) and forty-one of them used hearing aids prior to cochlear implantation. As age-matched controls, NH children were recruited from normal kindergarten, primary and middle schools in Beijing. None of the children with NH or CIs had a history of neurological, psychiatric, or neuropsychological disorders. The current study was approved by the Institutional Review Board (IRB) of the National Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University. A written informed consent was obtained from the participants or their legal guardians.

All of the CI participants were users of Cochlear's Nucleus 22 or 24 devices (Cochlear Beijing Limited, Beijing, China), with no less than half a year of implant experience. They all wore CIs during waking hours. The primary mode of communication after receiving implantation was oral language for the kindergarten children, while CI children from primary and high schools used both oral and sign languages. The fifty-three CI participants were categorized into three groups: the kindergarten group consisted of 25 children with 11 children implanted in the right ear and 14 implanted in the left ear; the primary school group consisted of 12 children with 6 children implanted in the right and another 6 in the left ear; the high school group consisted of 16 children with 4 children implanted in the right ear and 12 implanted in the left ear. The sixty NH children were also divided into three groups, i.e., the kindergarten group (N = 25), primary school group (N = 15) and high school group (N = 20). The demographic information of the NH children and children with CIs is summarized in Table 1.

## 3. Speech perception tests

Three speech perception tests were administered to measure Mandarin consonant recognition, lexical tone recognition and immediate repetition of open-set sentences, respectively (please refer to Appendixes A–C for all the stimuli). The consonant/lexical tone recognition subtests adopted a 3-alternative forced-choice paradigm. Children need to choose from 3 pictures (representing familiar words) the target that matched the aurally presented word. In the consonant recognition task, distracters that shared the same rimes and lexical tones but had different consonants were included. Similarly, in the lexical tone task, distracters that shared the same consonants and rimes but had different lexical tones were included. In each subtest, there were also unrelated distracters that had different consonants, vowels and lexical tones from the target and consonant/lexical tone distracters. Each subtest consisted of 10 items, and was scored in term of percentage of correct recognition. The paradigm of sentence repetition subtest followed Zhang et al. (2005) and Zhu et al. (2011)., Participants were required to repeat 10 declarative sentences with each sentence comprised of 3 to 5 words, generally easy and familiar in daily life. This task is self-paced and children were encouraged to guess which words they heard. Repetition accuracy was scored in terms of percent correct keywords in sentences. A word was considered as a correct response only when it was reported without any error in consonant, vowel or lexical tone. All the 3 subtests were carried out in a sound-treated room. Children were seated midway between two loudspeakers with the height of the loudspeakers adjusted to be at each child's ear level. Auditory stimuli were presented at 65 dB SPL calibrated at the listener's head. Familiarization of the testing procedures was provided for each child before the tests.

**Table 1**
Subjects information.

| | Children with CIs | | | | | | | Children with NH | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Age | | Age of implantation | | CI duration | | Number (M/F) | Age | | Number (M/F) |
| | M (S.D.) | range | M (S.D.) | range | M (S.D.) | range | | M (S.D.) | range | |
| kindergarten | 5.1 (0.9) | 4–7.3 | 2.7 (1.2) | 0.8–5 | 2.4 (1.2) | 0.6–4.3 | 25 (12/13) | 5.7 (0.8) | 4.2–7.1 | 25 (10/15) |
| primary | 11.9 (1.7) | 9.4–14 | 4.9 (2.0) | 2.2–9 | 7.0 (1.5) | 4.3–9 | 12 (9/3) | 10.3 (1.0) | 9–11.8 | 15 (5/10) |
| middle school | 18.5 (2.1) | 14.8–21.7 | 8.4 (2.5) | 4–16 | 10.1 (3.3) | 0.7–14.7 | 16 (9/7) | 16.5 (2.6) | 13.3–21.4 | 20 (9/11) |

*Note*: CI, Cochlear Implant; NH, Normal Hearings; M (S.D.): Mean (Standard Deviation); M/F: Male/Female.

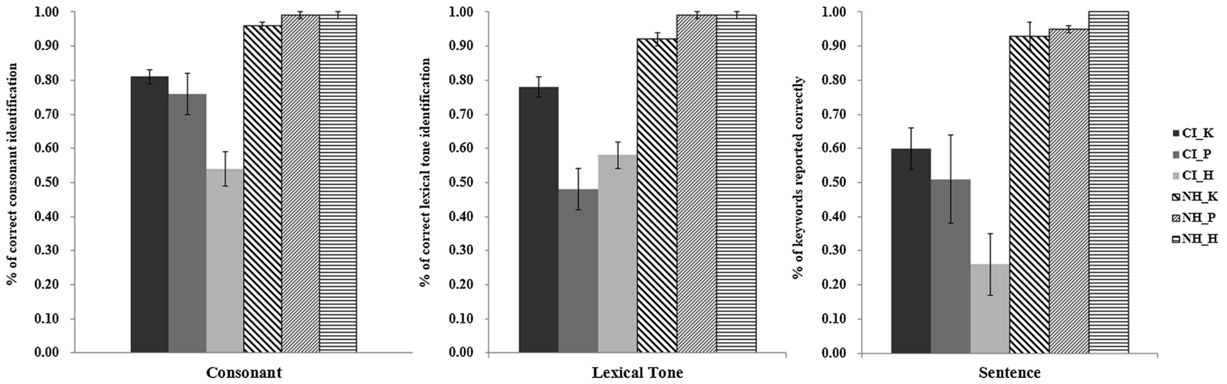


**Fig. 1.** Performances of the children with CIs and NH peers on the three speech perception tests. Error bars represent standard error of the mean across subjects. CI, cochlear implant; NH, normal hearing; K, kindergarten; P, primary school; H, high school.

## 4. Results

Fig. 1 presents a summary of the results of all the three tests across the NH and CI groups. Separate two-way analyses of variance (ANOVAs), with hearing status (CI and NH) and age (kindergarten, primary school and high school) as the two between-subject factors, were carried out for each task. For all the three tests, the results revealed significant main effects of hearing status [consonant, $F(1, 107) = 161.09$, partial $\eta^2 = 0.60$; lexical tone, $F(1, 107) = 188.25$, partial $\eta^2 = 0.64$; sentence, $F(1,92$[2]$) = 80.88$, partial $\eta^2 = 0.54$. All $p$ values $< .001$] and age [consonant, $F(2,107) = 13.585$, $p < .001$, partial $\eta^2 = 0.20$; lexical tone, $F(2,107) = 7.112$, $p = .001$, partial $\eta^2 = 0.12$; sentence, $F(2,92) = 3.22$, $p = .044$, partial $\eta^2 = 0.07$]. The interactions between hearing status and age were also significant [consonant, $F(2,107) = 18.91$, $p < .001$, partial $\eta^2 = 0.26$; lexical tone, $F(2,107) = 22.189$, $p < .001$, partial $\eta^2 = 0.29$; sentence, $F(2,92) = 7.06$, $p = .001$, partial $\eta^2 = 0.133$]. Simple effect tests revealed similar results for the three test, i.e., NH groups did not differ in the performance [consonant, $F(2,108) = 0.23$, $p = .796$, partial $\eta^2 = 0.02$; lexical tone, $F(2,108) = 0.29$, $p = .751$, partial $\eta^2 = 0.08$; sentence, $F(2,92) = 0.28$, $p = .755$, partial $\eta^2 = 0.15$], while the CI groups showed significant difference [consonant, $F(2,108) = 10.16$, $p < .001$, partial $\eta^2 = 0.50$; lexical tone $F(2,108) = 3.45$, $p = .035$, partial $\eta^2 = 0.48$; sentence, $F(2,92) = 3.36$, $p = .039$, partial $\eta^2 = 0.45$].

Bonferroni adjusted post hoc pairwise comparisons were then carried out to examine the difference in all the subtests among the three NH groups and three groups with CIs, respectively. While there was no significant difference among the NH groups for each of the tests, [all $ps > 1.0$], the groups with CIs showed different patterns in the three tests. Specifically, for the consonant recognition test, there was no significant difference between the kindergarten and primary school groups, [$t(35) = 0.05$, $p = 1$, Cohen's $d = 0.35$], but both the kindergarten [$t(39) = 0.27$, $p < .001$, Cohen's $d = 1.75$) and primary school groups ($t(26) = 0.27$, $p < .001$, Cohen's $d = 1.13$) performed better than the high school group. For the lexical tone recognition test, the kindergarten group performed better than both the primary ($t(35) = 0.30$, $p < .001$, Cohen's $d = 1.67$) and high school groups ($t(39) = 0.19$, $p = .005$, Cohen's $d = 1.23$), while there was no significant difference between the primary school and high school groups ($t(26) = -0.10$, $p > 1$, Cohen's $d = -0.55$). For the sentence repetition test, the kindergarten group performed better than the high school group ($t(39) = 0.49$, $p = .007$, Cohen's $d = 1.19$), but there was no significant difference between the kindergarten and primary school groups ($t(35) = 0.17$, $p = .834$, Cohen's $d = 0.29$), and between the primary and high school groups ($t(26) = 0.32$, $p = .18$, Cohen's $d = 0.75$).

Using R (R Core Team, 2014) and the nlme package (Pinheiro, Bates, DebRoy, Sarkar, & R Core Team, 2016), a linear mixed-effects (LME) model was developed to examine whether the performances on consonants and lexical tones were predictive of sentence repetition accuracy in the children with CIs, with participants as a "by-subject" random effect, and CI age and CI duration as blocking variables. The advantages of the mixed effects model over the conventional correlation or multivariate regression analysis to incorporate categorical grouping factors, control for baseline differences across subjects, and deal with built-in correlational structure among the multiple variables have been demonstrated in recent speech perception studies (Koerner & Zhang, 2018, 2017). In the NH children, no LME regression analysis was carried out because of the ceiling-level performance on sentence repetition. The LME analysis revealed that performances on consonants ($F(1,41) = 11.33$, $p < 0.01$) and lexical tones ($F(1,41) = 13.42$, $p < 0.001$) were both significant predictors of sentence repetition in children with CIs (see Table 2).

## 5. Discussion and implications

The current study examined speech processing skills in Mandarin-speaking children who received CIs at different ages. Our results showed that children with CIs lagged behind their NH peers in both low-level (recognition of consonants and lexical tones) and high-order (sentence repetition) aspects of speech processing skills and that the performances of children with CIs on different tasks were differentially modulated by implantation age. Furthermore, recognition of consonants and lexical tones contributed to sentence repetition accuracy in children with CIs.

[2] Fifteen children with CIs did not finish the sentence comprehension test.

**Table 2**
*F*-statistics for fixed effects from the linear mixed-effects regression model.

| variable | *F*-value | *p*-value |
|---|---|---|
| Intercept | 152.20 | < .0001 |
| CI age | 8.73 | .0052 |
| CI duration | 6.07 | .018 |
| Consonant | 11.33 | .0017 |
| Lexical tone | 13.42 | .0007 |

*Note*. CI, Cochlear implant.

There is ample evidence for critical or sensitive period in speech and language acquisition, during which speech and language is learned efficiently (Bruer, 2001; Lenneberg, Chomsky, & Marx, 1967; Ruben, 1997; Scovel, 1988; Werker & Hensch, 2015). However, more and more empirical and theoretical investigators have opted to consider speech and language development not as a single unitary stage (Coene, Schauwers, Gillis, Rooryck, & Govaerts, 2011; Mills, Neville, & Lawson, 1992). It is likely that there are several sensitive periods associated with different aspects of speech and language. For example, neurophysiological data from Mills et al. (1992) show that semantic processing did not mature until the age of 4 years old, while the developmental trajectory of the syntactic system runs through the 15–16 years of age. There are also some studies related to NH children's phonological development. In English-speaking NH children, phonological acquisition and perceptual tuning in language development follow a progressive larger-unit-to-smaller-unit sequence with syllables developing first, then rhymes, and finally phonemes (Goswami & Bryant, 1990). Previous studies examining phonological acquisition in Mandarin-speaking NH children have showed that the age-related sensitivities to consonants and lexical tones in perception undergo subsequent refinement along an extended trajectory (Singh et al., 2015; Wewalaarachchi et al., 2017). Compared with children aged 2.5 to 3.5 years old, children aged 4 to 5 years demonstrated an increase in sensitivity to vowels and consonants but a decrease in sensitivity to lexical tones. In the current study, the youngest NH group, i.e., the kindergarten children at the average age of 5.7 years old performed equally well as the older groups on the recognition of consonants and lexical tones. Our results extended previous studies by indicating that typically developing NH children older than 5 years old reached relatively mature phonological competence. More importantly, the groups of children with CIs demonstrated different patterns. Specifically, the kindergarten and primary school children performed similarly on recognition of consonants, but the kindergarten group performed better than the primary school group on recognition of lexical tones. This result is remarkable given the fact that the duration of CI use was much shorter for the youngest group. Most of the kindergarten children received CIs at early ages, well within the sensitive period for lexical tone acquisition for a typically developing NH child. By contrast, most of the primary school children received CIs at older ages, and from the perspective of typical language development, the ages are far beyond the sensitive period for tone acquisition but still within the sensitive period of consonant acquisition. It is very likely that the different perception patterns of consonants and lexical tones are attributable to the different time courses of critical periods associated with acquisition of the segmental and suprasegmental phonological features (Werker & Hensch, 2015; Singh & Fu, 2016). Given that the Mandarin-speaking children are implanted with CI at various ages, this finding, therefore, points to the need for developing age-appropriate aural rehabilitation and speech intervention programs.

Sentence repetition reflects higher-order language skills involving cognitive processes beyond recognition of individual phonemes; for example, it requires lexical access, integration of word meanings, and syntactic and pragmatic encodings (Klem et al, 2014). For NH children who have the ability to discriminate and recognize segmental/suprasegmental phonemes without any difficulty, sentence repetition accuracy is more affected by their ability to utilize higher-level rather than lower-level information. However, for children with CIs, the better individual consonants/tones are identified, the better sentence repetition scores are. That is, compared with NH children, children with CIs may rely more on bottom-up processing strategies to extract consonantal and tonal information to recognize and understand sentences. This finding is consistent with the recent result of Smith, Pisoni, and Kronenberger (2018)) that the correlation between fast-automatic phonological coding and high-variability sentence recognition was greater in CI group than in NH group. However, it needs to be pointed out that the reliance of children with CIs on identification of individual segmental/suprasegmental phonemes during sentence recognition might at least in part stem from the deficiencies in use of higher-level information such as semantic context because their sentence-level performances deteriorate to a greater extent than those on phoneme recognition. That is, there exist interactions between lower-level and higher-level processes during CI users' sentence recognition. The current design of the study does not allow us to further address this issue, which needs to be explored by directly examining semantic, syntactic and pragmatic processing in future studies.

One interesting finding to note is that kindergarten children with CIs performed equally well on recognition of consonants and lexical tones, which suggests that the concern about the ability of current CI speech processors to provide acoustic cues for lexical tone perception may need to be reconsidered. It also needs to be pointed out that even the children with early CIs (i.e., the kindergarten group) performed worse than their NH peers on recognition of consonants and lexical tones, and especially on recognition of open-set sentences. The important difference is that the duration of hearing with CIs was only 2.4 years for the CI children, whereas the duration of hearing for the NH children was 5.7 years. In Zhu et al. (2011), the mean performance of children age ranged 6–14.5 years was about 82% correct for the open-set recognition of multi-talker sentences after 5.4 years of implantation. So it might be argued that the amount of hearing experience for the children with early CIs was too short to develop age-appropriate speech perception skills. A detailed discussion of this issue is beyond the scope of our study because the three groups of CI children differed in both age of implantation and duration of CI use. Specifically, younger children had earlier age of implantation but shorter duration of CI use, while older children had later age of implantation but longer duration of CI use. To address this issue, future studies need to have a longitudinal design in order to monitor whether the speech perception gap can be closed, when it would occur, and how other language skills such as vocabulary, grammar and reading comprehension grow as a function of both implantation age and duration of CI use.

It is important to note that the high school-aged children with CIs performed worse than the other two groups of CI children on all the three tasks despite having the longest duration of CI use. The results argue for the need of early implantation before the end of critical periods for the development of various speech perception abilities. This definitely pointed to implementing different treatment strategies with older implanted children to compensate for deficiencies in speech perception. For example, perceptual training programs with a multiple-talker identification task, which has been found to be useful for postlingually deafened adult CI users (Miller, Zhang, & Nelson, 2016), can be developed to investigate efficacy of this training method targeting at individual phonemes and its age-dependency. Thus our findings have prognostic importance for developing post-implant rehabilitation and intervention programs.

One limitation of this study is the small number of trials included in the consonant/lexical tone recognition subtests, which made it impossible for us to have a systematic comparison of the consonant/lexical tone confusion patterns. As some phonemic contrasts (e.g., tone2 and tone3) are prone to be perceptually confusing even in adults with NH (Shen & Lin, 1991), future studies are needed to test CI users of various ages using more consonant/lexical tone contrasts. Furthermore, as children were tested only in quiet listening conditions in our study, how background noise at various signal-to-noise ratios may affect the performances also merits further investigation.

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## Appendix A. Consonant recognition test

| Target | | Related distracter | | Unrelated distracter | |
|---|---|---|---|---|---|
| Chinese Pinyin | English Meaning | Chinese Pinyin | English Meaning | Chinese Pinyin | English Meaning |
| bao4 | leopard | pao4 | cannon | ji1 | chicken |
| pa1 | bending over | ba1 | eight | yu2 | fish |
| shan1 | mountain | san1 | three | tu4 | rabbit |
| du4 | stomach | tu4 | rabbit | shao2 | spoon |
| da3 | hit | ta3 | tower | shu1 | book |
| cha1 | fork | ca1 | wipe | sun3 | bamboo shoot |
| nan2 | male | lan2 | basket | xing1 | star |
| ti2 | lift | li2 | pear | shu3 | rat |
| bei1 | cup | fei1 | fly | gou3 | dog |
| tu4 | rabbit | lu4 | deer | bao1 | bag |

*Note*: Figures signify lexical tones.

## Appendix B. Lexical tone recognition test

| Target | | Related distracter | | Unrelated distracter | |
|---|---|---|---|---|---|
| Chinese Pinyin | English Meaning | Chinese Pinyin | English Meaning | Chinese Pinyin | English Meaning |
| chuang1 | window | chuang2 | bed | gou3 | dog |
| yan1 | smoke | yan3 | eye | xiong2 | bear |
| qi1 | seven | qi2 | flag | yue4 | moon |
| tu4 | rabbit | tu2 | drawing | ji1 | chicken |
| shu1 | book | shu4 | tree | xie2 | shoes |
| miao2 | seedling | miao4 | temple | bi4 | wall |
| bao1 | bag | bao4 | leopard | suo3 | lock |
| hu3 | tiger | hu2 | kettle | yan1 | smoke |
| shu1 | book | shu3 | rat | mao4 | hat |
| bi2 | nose | bi3 | pen | lu4 | deer |

*Note*: Figures signify lexical tones.

## Appendix C. Sentence repetition test

| Pinyin | English Meaning |
|---|---|
| Wo3/you3/hen3/duo1/peng2you3. | I have many friends. |
| Jin1tian1/shi4/nai3nai0/de1/sheng1ri4. | Today is my grandma's birthday. |
| Wo3/qu4/jiu4jiu0/jia1/chifan4. | I came to uncle's house for dinner. |
| A1yi2/zai4/jia1li3/zuo4fan4. | Aunt cooks at home. |
| Ba4ba0/qu4/shang4ban1/le0. | Daddy went to work. |
| Lao3shi1/chun1jie2/kuai4le4. | Teacher, happy Spring Festival. |
| Ma1ma0/dai4/wo3/qu4/you4er2yuan2. | Mom took me to the kindergarten. |
| Wo3men0/zai4/gong1yuan2/ kan4/hua1. | We are seeing flowers in the park. |
| Chi1/qing1cai4/dui4/shen1ti3/hao3. | Eating vegetables is good for health. |
| Da4jia1/yi1qi3/zuo4/you2xi4. | We all played games together. |

*Note*: Figures signify lexical tones; slashes mark word boundaries.

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