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Lexical tone recognition in noise in normal-hearing children and prelingually deafened children with cochlear implants

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Abstract

Objective: The purpose of the present study was to investigate Mandarin tone recognition in background noise in children with cochlear implants (CIs), and to examine the potential factors contributing to their performance. *Design:* Tone recognition was tested using a two-alternative forced-choice paradigm in various signal-to-noise ratio (SNR) conditions (i.e. quiet, +12, +6, 0, and −6 dB). Linear correlation analysis was performed to examine possible relationships between the tone-recognition performance of the CI children and the demographic factors. *Study sample:* Sixty-six prelingually deafened children with CIs and 52 normal-hearing (NH) children as controls participated in the study. *Results:* Children with CIs showed an overall poorer tone-recognition performance and were more susceptible to noise than their NH peers. Tone confusions between Mandarin tone 2 and tone 3 were most prominent in both CI and NH children except for in the poorest SNR conditions. Age at implantation was significantly correlated with tone-recognition performance of the CI children in noise. *Conclusions:* There is a marked deficit in tone recognition in prelingually deafened children with CIs, particularly in noise listening conditions. While factors that contribute to the large individual differences are still elusive, early implantation could be beneficial to tone development in pediatric CI users.

Key Words: Cochlear implants; noise; pediatric; speech perception

Introduction

In tone languages, such as Mandarin Chinese, the tone carries lexical meanings. At monosyllabic levels, the tones distinguish lexical meanings among otherwise identical phonemes. For example, the four tones in Mandarin, namely, the high level tone (tone 1), the rising tone (tone 2), the falling-rising tone (tone 3), and the high-falling tone (tone 4) of a monosyllable ‘‘shi’’ can mean ‘‘lion’’, ‘‘ten’’, ‘‘arrow’’, and ‘‘view’’, respectively. The primary acoustical cue for tone recognition is the fundamental frequency (F0) or the F0 contour of the syllables (see Xu & Zhou, 2011 for a review). When the F0 information is obscure in speech signals, listeners can resort to secondary cues, such as temporal envelope cues, to obtain certain levels of tone recognition (Fu et al, 1998; Fu & Zeng, 2000; Xu et al, 2002; Luo & Fu, 2004; Kong & Zeng, 2006). In current multichannel cochlear implant (CI) systems, F0 information is not explicitly encoded in the electrical pulsatile stimulations. As a result, CI users experience various degrees of difficulty in perceiving lexical tones (Ciocca et al, 2002; Lee et al, 2002; Peng et al, 2004; Han et al, 2009; Wang et al, 2011; Xu et al, 2011; Zhou et al, 2013; Chen et al, 2014b; Li et al, 2014). Whereas, the exact link between perception and production, at least in the pitch-related tasks, and the neural mechanisms underlying each type of ability are still a matter of debate (see Hutchins and Moreno, 2013 for a review), marked deficits in tone production have been shown in prelingually deafened children with CIs (Peng et al, 2004; Xu et al, 2004; Han et al, 2007; Zhou & Xu, 2008). Furthermore, a positive correlation between tone perception and tone production in prelingually deafened children with CIs has been demonstrated in Xu et al (2011) and Zhou et al (2013).

An important question is whether or not lexical tone information is indispensable in daily conversation of a tone language. In a previous study, we presented the sine-wave replicas of Mandarin Chinese monosyllables and sentences to native-Chinese-speaking listeners for recognition. In the sine-wave replicas, the speech signals were reduced to only three sinusoids that follow the contours of the first three formants of the speech (Remez et al, 1981). While the tone recognition scores of the sine-wave replicas of Chinese monosyllables were just slightly above chance, sentence recognition of the sine-wave replicas was nearly perfect (Feng et al, 2012). Thus, it seems that lexical tone is not important for sentence

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Abbreviations

CI	cochlear implant
NH	normal hearing
F0	fundamental frequency
SNR	signal-to-noise ratio
SSN	speech-shaped noise

recognition in Mandarin Chinese. A recent functional imaging study using Chinese sentences with flattened pitch contours confirmed that the details of F0 contours are not essential for adequate lexical-semantic processing during sentence comprehension in tone languages (Xu et al, 2013). However, this view has been further examined in noise listening conditions. It has long been known that F0 contours, even in non-tonal languages, such as English, play a significant role in reducing the deleterious effects of noise, especially those of competing speech (Laures & Weismer, 1999; Binns & Culling, 2007; Miller et al, 2010). A couple of recent reports have demonstrated that tone information can help circumvent the deleterious effects of noise in Mandarin Chinese sentence recognition (Wang et al, 2013; Chen et al, 2014a). With appropriate tone information, sentence recognition in speech-shaped noise at 0 dB signal-to-noise ratio (SNR) was nearly perfect, but was reduced to ~70% correct when the tone information was removed or disrupted (Chen et al, 2014a). Therefore, tone information seems to be particularly important for tone-language speech recognition in noise.

Tone recognition in noise is fairly robust in normal-hearing (NH), native-Mandarin-speaking adult listeners. At an SNR of −5 dB, adult NH listeners can achieve nearly perfect tone recognition (Kong & Zeng, 2006; Krenmayr et al, 2011; Lee et al, 2013). Data on tone recognition in noise by native-Mandarin-speaking children are relatively sparse. Zhu et al (2014a) found that 7-year-old NH children could achieve ~90% correct at an SNR of −10 dB. In a recent study on tone recognition in children with profound hearing impairment fitted with hearing aids, tone-recognition performance was only ~50% correct at an SNR of −5dB (Zhu et al, 2014b). The questions that still remain are whether or not NH young children can perceive tones in noise conditions as accurately as adults do and how children with CIs perceive tones in noise conditions. The present study was designed to specifically address such research questions.

The present study employed a tone contrast recognition test designed for young children (Han et al, 2009; Zhou et al, 2013). The test allowed us to compare recognition scores of different tone contrast pairs and to construct the confusion matrices. The understanding of the nature of the recognition errors in children of CIs is useful for guiding the habilitation efforts. In Mandarin Chinese, the onsets of F0 contours for tone 1 and tone 4 are high. Tone 1 stays high in the course of the contour and tone 4 drops precipitately (see Xu and Zhou, 2011). On the contrary, the onsets of F0 contours of tone 2 and tone 3 are low and show more complex and yet similar patterns (see Xu and Zhou, 2011; Chen et al, 2014b). Previous studies of tone recognition of CI users in quiet have confirmed the high confusability of tone 2 and tone 3 (Peng et al, 2004; Han et al, 2009; Wang et al, 2011; Zhou et al, 2013, Chen et al, 2014b). In the present study, the confusion patterns of Mandarin tone recognition in noise were examined. We hypothesized that recognition of tone 2 and tone 3 would show more errors in both NH and CI children in noise conditions.

Materials and methods

Subjects

Sixty-six Mandarin-speaking, prelingually deafened children with unilateral CI, 39 boys and 27 girls, between the ages of 2.13 and 17.20 years (Mean ± SD, 5.33 ± 3.41 years) participated in the present study. While a majority of the children were diagnosed with congenital hearing loss, the etiology of most children was unknown. The inclusion criteria were as follows: (1) hearing loss diagnosed before 1 year of age, (2) chronological age ≥2 years old, (3) age at implantation ≤18 years old, (4) Mandarin as the native language, and (5) no other disabilities such as mental retardation, autism, attention deficient disorder, visual disorders, etc. All CI children had bilateral severe to profound hearing loss (≥ 85 dB HL) and limited or no hearing aid use experience before implantation. During the time of the study, hearing aid use on the opposite ear was not encouraged after implantation in China. Therefore, none of the 66 children with CIs used hearing aids after implantation. The age at implantation was between 0.60 and 16.50 years (Mean ± SD, 2.97 ± 3.05 years) and the duration of CI use was between 0.17 and 8.49 years (Mean ± SD, 2.36 ± 1.98 years). All CI children received post-operative aural rehabilitations in rehabilitation centers.

Fifty-two typically-developing, Mandarin-speaking NH children (25 boys and 27 girls) between the ages of 3.41 and 6.60 years (Mean ± SD, 4.89 ± 0.90) were also recruited from the local kindergartens and elementary schools in the Beijing area to participate as controls. Student's *t*-test revealed no statistical differences in the mean chronological ages between the two groups of subjects (CI versus NH) ($p > 0.05$). Therefore, these two groups were comparable in terms of chronological age so that they were matched at least in one aspect of subject characteristics.

Test materials

Eighteen monosyllables (i.e. bei, bi, chi, chuang, deng, hu, jian, mao, mi, qiang, san, shu, tang, tu, wa, wu, ye, and yu) in Mandarin Chinese were selected. For each of these monosyllables, two tones were assigned to produce a tone contrast. The two words in each tone contrast were distinguished from each other only by the tone type. Therefore, a total of 36 Chinese words were selected as the test material (see Han et al, 2009 for a complete list of the 36 words). The selection of these 18 monosyllables (36 words) was based on the vocabulary level of young children. The test materials were implemented in previous studies (Han et al, 2009). Also, the appropriateness of the words was confirmed with 113 normal-hearing, native Mandarin-speaking children between 3 and 9 years old (Zhou et al, 2013). For each of the tone contrasts (i.e. tone 1 versus 2, tone 1 versus 3, tone 1 versus 4, tone 2 versus 3, tone 2 versus 4, and tone 3 versus 4), there were three pairs of monosyllabic words.

The recording of the monosyllabic words was carried out in a double-wall sound-treated booth (Acoustic Systems) from one male and one female native Mandarin-speaking adult. The distance between the speaker's mouth and the microphone (Model RE50B) was kept at ~10 cm. The sampling rate and the resolution were set at 44.1 kHz and 16 bits, respectively. Each test word was recorded multiple times so that it was possible to select the pair of tone contrasts with equal duration (within a precision of 1 ms). Duration cue has been shown to assist in classifying Mandarin tones (Xu et al, 2002). Since the purpose of the present study was to examine the effects of noise on the pitch-related aspect of lexical tone recognition, not on token duration discrimination, we used tone tokens of equal durations so as to remove the confounding effects of syllable duration on tone recognition.

The speech-shaped noise (SSN) from the Mandarin Hearing in Noise Test (Wong et al, 2007) was used as the masker. The SSN has a long-term spectrum similar to those of the Mandarin sentences spoken by a male voice. In the present study, the speech tokens and the SSN were mixed digitally to form signal-to-noise ratios (SNRs) of +12, +6, 0, and −6 dB. First, all tone tokens were equalized in root-mean-square values. Then, an appropriate amount of noise was added to the speech tokens to yield the desired SNRs.

Test procedure

The test was conducted in a sound-treated room. A custom MATLAB (MathWorks, Natick, MA) graphical user interface was programmed to display the pictures, to present the acoustical stimuli, and to record the subject's responses. Before the test, the program displayed three possible pairs of monosyllabic words with pictures for each tone contrast. Each subject was required to choose one pair that he or she was most familiar with to be used for the test. Therefore, 12 monosyllabic words for the six tone contrasts were used for a tone test. It turned out that a majority of the children, despite their age, chose the same six pairs of words for the test. During the test, the program displayed the two pictures of a pair of tone contrasts on a laptop computer screen. The speech stimulus corresponding to one of the pictures was presented through a pair of loudspeakers (Logitech V20) located in front of the subject. The subjects were required to point to the picture corresponding to the word they heard and the experimenter would click with a computer mouse on the picture to record the response. Before the formal testing, all children practiced for a few minutes to familiarize themselves with the task and to make sure that they understood the procedures. Feedback was provided in the practice session.

In the formal test, there were five SNR conditions (i.e. quiet, +12, +6, 0, and −6 dB) for the NH children and four SNR conditions (i.e. quiet, +12, +6, and 0 dB) for the CI children. The CI children were not tested at the −6 dB SNR because our pilot experiment indicated that most of the CI children could not perform above chance at such an SNR. Therefore, there were a total of 240 tokens (6 tone pairs ×2 tones ×2 speakers ×5 SNR conditions ×2 repetitions) for the NH children and 192 tokens (6 tone pairs ×2 tones ×2 speakers ×4 SNR conditions ×2 repetitions) for the children with CIs. The four or five SNR conditions were randomized and within each SNR condition the test tokens were randomly presented. The subjects were asked to point at the one of the two pictures shown on the computer screen to indicate which word they had just heard. The subjects were encouraged to take as many short rests as necessary so that they were engaged during the test. The level of presentation was adjusted for each subject to his or her most comfortable level in the quiet condition. Typically, those levels were between 65 and 70 dB (A), as measured with a sound level meter positioned at where the center of the interaural axis would be. Adding noise to the speech signals, even at the lowest SNR condition, resulted in an increase of sound intensity by only a few dB.

Data analyses

The percent-correct data of the tone-recognition test was arcsine transformed and then statistically analyzed. The purpose of arcsine transformation was to homogenize the variance of the percent-correct data and thus to make them more suitable for ANOVA and other statistical analysis (Studebaker 1985). A two-way ANOVA was implemented to investigate the effects of hearing status (NH and CI) and SNR conditions (i.e. quiet, +12, +6, 0, and −6 dB) on tone-recognition performance as well as the possible interactions between the main factors. A one-way repeated-measures ANOVA was adopted to evaluate the possible effects of tone type (i.e. tone 1, tone 2, tone 3, and tone 4) or tone contrast (i.e. tone 1 versus tone 2, tone 1 versus tone 3, tone 1 versus tone 4, tone 2 versus tone 3, tone 2 versus tone 4, and tone 3 versus tone 4) on the recognition performance. The p value indicating a statistical significance was set at 0.05. Linear correlation analyses were also performed to determine whether the tone-recognition performance of the pediatric CI users was related to any of the demographic factors including age of implantation, chronological age, and duration of CI use.

Results

Since no differences were found in the tone-recognition scores derived from the male and female voices, recognition data were pooled across the two talkers. Figure 1 shows the group mean tone-recognition performances of the two groups of children. The overall tone-recognition performance of the NH children did not change much whenever the SNR was higher than −6 dB. The average

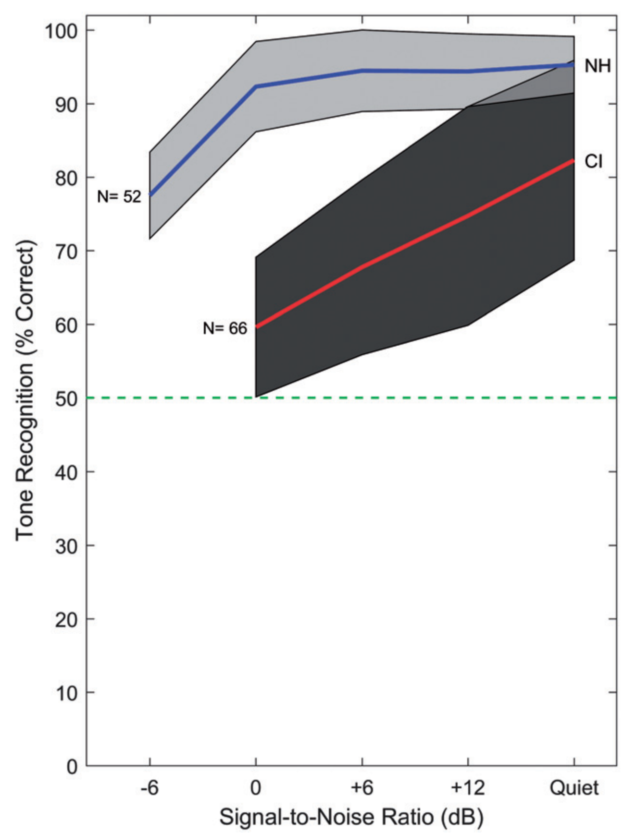

Figure 1. The group mean tone-recognition performances at various signal-to-noise ratios. Light and dark gray color represent the NH and CI group, respectively. The thick line represents the group mean performance and the shadowed area represents ±1 SD. The dashed line represents the chance level (50% correct).

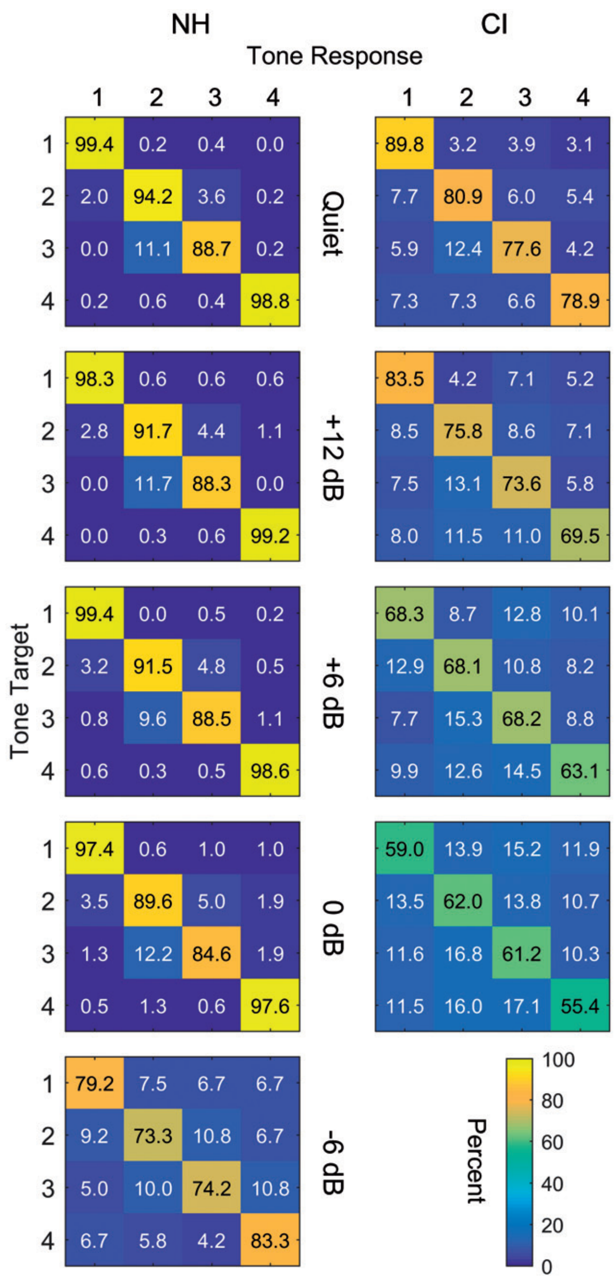

Figure 2. Tone-recognition confusion matrices of the two groups under various SNRs. Data were pooled from all subjects in each group. For each panel of 4 × 4 cells, the rows indicate the target tone types, while the columns indicate the response tone types. The color (gray) scale in each cell and the value in it represent percent of responses.

scores of the NH group were 95.3, 94.4, 94.5, and 92.3% correct in quiet, +12 dB, +6 dB, and 0 dB SNR, respectively. However, there was a remarkable decrease in performance at −6 dB SNR, with an average score of 77.5% correct. In contrast to the NH group, the tone-recognition performance of the CI group declined steadily along with the decrease of SNR. The average scores of the CI children in quiet, +12 dB, +6 dB, and 0 dB SNR were 82.3, 74.7, 67.7, and 59.6% correct, respectively. A two-way ANOVA revealed significant main effects of both hearing status ($F = 564.83$, $p < 0.001$) and SNR ($F = 29.21$, $p < 0.001$). Additionally, the interaction of these two factors was also significant ($F = 12.64$, $p < 0.001$).

A one-way repeated-measures ANOVA was performed to further evaluate the effects of SNR on tone recognition. For the NH group, the one-way repeated-measures ANOVA showed significant differences among the five SNR conditions ($F(4,48) = 15.52$, $p < 0.001$). The Tukey–Kramer *post-hoc* multiple comparisons revealed that the performance of the NH children in the −6 dB SNR condition was significantly poorer than that in any of the other SNR conditions (all $p < 0.001$). No significant difference was found between any two of the other four SNR conditions (i.e. quiet, +12, +6, and 0 dB SNRs, all $p > 0.05$). For the CI group, there was a significant difference among the four SNR conditions in tone recognition ($F(3,63) = 40.05$, $p < 0.001$). Not surprisingly, the Tukey–Kramer *post-hoc* multiple comparisons indicated that the tone-recognition performance of the CI children was significantly different between any two of the SNR conditions (all $p < 0.001$).

Figure 2 displays the tone-recognition confusion matrices for the two groups. In the NH group (Figure 2, left panels), the most prominent confusions were found between tone 2 and tone 3 in all SNR conditions except for the −6 dB SNR condition. In particular, tone 3 was frequently recognized as tone 2 in those SNR conditions. In the −6 dB SNR condition for the NH group, the confusions were more or less evenly distributed among the four tones. In the CI group (Figure 2, right panels), similar confusions between tone 2 and tone 3 existed in the quiet, +12 dB, and +6 dB SNR conditions. However, the tone confusions were distributed evenly among the four tones in the 0 dB SNR condition for the CI group.

The effects of noise on recognition of different tone types can be visualized by examining the values on the diagonals of the tone confusion matrices (Figure 2). For the NH group, a one-way repeated-measures ANOVA showed that there were significant differences in recognition scores of the four different tones in quiet, +12 dB, +6 dB, and 0 dB SNR conditions (all $p < 0.001$), but not in the −6 dB SNR condition ($p = 0.137$). Further paired *t*-tests with Bonferroni correction showed that the differences resided in the relatively lower scores for tone 2 and tone 3 and relatively higher scores for tone 1 and tone 4.

For the CI group, a one-way repeated-measures ANOVA indicated that there were significant differences in recognition of different tones in the quiet and +12 dB SNR conditions (all $p < 0.001$), but not in the +6 dB and 0 dB SNR conditions (all $p > 0.05$). Further paired *t*-tests with Bonferroni correction showed that tone 1 received the higher recognition scores than other tones in the quiet and +12 dB SNR conditions.

Figure 3 shows the recognition scores for the six different tone contrasts in both NH and CI groups under various SNR conditions. A one-way repeated-measures ANOVA was adopted under each SNR condition. For both NH and CI groups, there were significant differences in recognition scores among the six tone contrasts in quiet, +12 dB, +6 dB, and 0 dB SNR conditions (all $p < 0.001$). *Post hoc* comparisons revealed that the differences were mainly due to significantly lower recognition scores of the tone contrast of tone 2 versus tone 3.

Linear correlation analyses were implemented to evaluate whether the tone recognition ability of the CI children was related to any of the demographic factors (i.e. chronological age, age at implantation, and duration of CI use). Only age at implantation had shown a weak, but significant correlation with the tone recognition

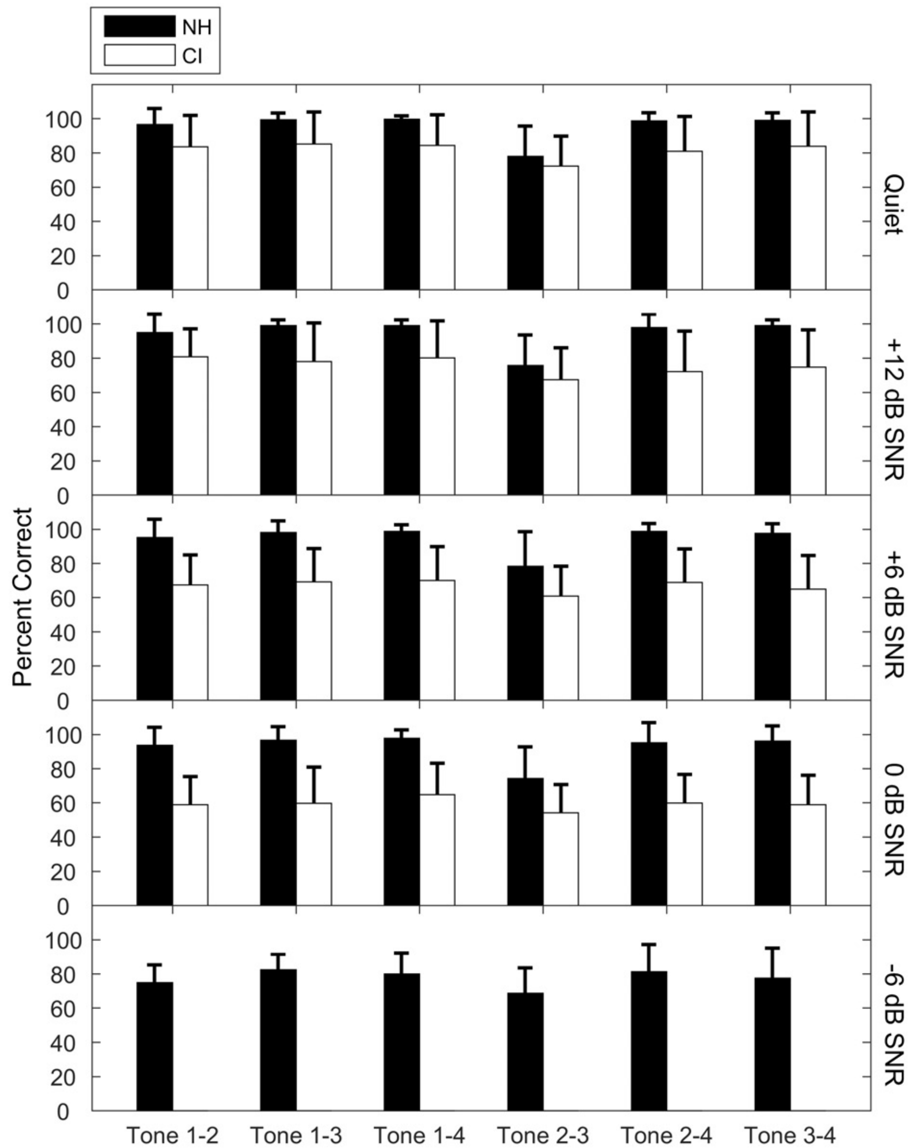

Figure 3. Tone-recognition performance of the six tone contrasts under various SNR conditions. Black and white bars represent the NH and CI groups, respectively. The error bars indicate 1 standard deviation.

performance in quiet ($r = -0.311$, $p = 0.022$), +12 dB SNR ($r = -0.281$, $p = 0.040$), and +6 dB SNR conditions ($r = -0.295$, $p = 0.031$). Note that the correlations were not corrected for multiple comparisons. Had we corrected for multiple comparisons, none of the correlations would be significant at $p < 0.05$. No significant correlation was found between tone-recognition performance and chronological age or duration of CI use.

Discussion

Our results showed that the tone recognition ability of the NH children maintained above 90% correct when the SNR was greater than −6 dB. However, at −6 dB SNR, tone recognition suffered remarkably with a group mean score being dropped to 77.5% correct. In contrast, tone recognition in NH adults is fairly robust in noise. Lee et al (2013) have shown that tone recognition in native Mandarin-speaking adults maintains around 90% correct at −10 dB SNR and decreases to ~80% at −15 dB SNR. Although the test format of the present study and that of Lee et al (2013) was not identical, it is evident that NH young children do not process lexical tone information as efficiently as NH adults in adverse noise conditions. Such a difference can be as large as 10 dB of SNR in favor of adults. In the literature, depending on the speech recognition task and masking noise used, the child-adult SNR difference has been reported in the range of 3–10 dB (Nittrouer & Boothroyd, 1990; Hall et al, 2002; Bonino et al, 2013; Corbin et al, 2016). A systematic investigation of the differential masking effects in adults and children on lexical tone recognition would be valuable to fill the gap of knowledge in this area.

A recent study by Zhu et al (2014a) showed that 7-year-old NH children achieved ~90% correct in tone recognition under the −10 dB SNR condition. This level of performance is similar to or better than that reported in NH adults (see Kong and Zeng, 2006; Krenmayr et al, 2011; Lee et al, 2013). It is possible that children by the age of 7 years have achieved adult-like tone recognition in noise. The tone test format in Zhu et al (2014a) is quite different from those used in the adult studies. In particular, the speech tokens were recorded from a single speaker in Zhu et al (2014a) whereas the other studies used multiple speakers. The tone-recognition performance in Zhu et al (2014a) is also much higher than the results of the NH children from the present study (Figure 1). One possible reason is that the mean chronological age of the children in the present study is younger than that in Zhu et al (2014a) study. The other reason might be that the present study used tone contrasts with equal durations. Therefore, our subjects were not able to rely on duration cues for tone recognition under adverse noise conditions. Note also that we mixed our signal and noise digitally before presentation. In Zhu et al (2014a) study, the speech signal was presented from a loudspeaker position in front of the listener and the noise was presented from a loudspeaker positioned behind the listener. Therefore, in addition to the potential spatial masking release, the SNRs in the ear canals of the listener might actually be higher than originally intended in their study.

For the children with CIs, however, the suboptimal tone-recognition performance in quiet was severely affected by even a moderate level of noise (0 dB SNR). The performance decreased from ~80% correct in the quiet condition to ~60% correct under the 0 dB SNR condition (Figure 1). This pattern was similar to the results reported by Zhu et al (2014b) who tested tone identification ability in noise in a group of profoundly hearing-impaired children fitted with hearing aids. Therefore, whereas tone information might provide resistance to noise in sentence recognition in NH adults (Wang et al, 2013; Chen et al, 2014a), children with profound hearing loss fitted with either hearing aids or CIs might not be able to rely on tones to help improve the recognition of continuous speech in a noisy listening environment.

Consistent with our hypotheses, results of present study showed that noise exerted different effects on the recognition of different tone types (Figure 2). For both the NH children and children with CIs, tone 1 and tone 4 were recognized with a higher accuracy than tone 2 and tone 3 at all SNR conditions except for the lowest SNR condition. This result was consistent with previous studies on tone acquisition of typically developing children (Li & Thompson, 1977; Peng et al, 2004) and tone recognition by CI children in quiet (Peng et al, 2004; Zhou et al, 2013). Given that tone 2 and tone 3 were most likely confused with each other (see Figure 2), it was not surprising that the tone 2 versus tone 3 contrast was the most difficult tone contrast (Figure 3) for both the NH and CI groups under various noise conditions. Zhu et al study (2014b) with hearing-impaired children who use hearing aids also revealed similar results. However, earlier studies in tone recognition in quiet in CI children produced somewhat mixed results with some showing significantly lower recognition scores for the tone contrast of tone 2 versus tone 3 (Han et al, 2009) and others showing no significant differences among the different tone contrasts (Zhou et al, 2013). In terms of acoustics, tone 2 and tone 3 are similar in that there are a low and a rising part in their F0 contours. Besides, tone 3 is the most complicated tone in Mandarin Chinese (Xu & Zhou, 2011). The acoustics and variations could explain why tone 2 and tone 3 were recognized with greater difficulties and that more confusions occurred between tone 2 and tone 3. However, in the lowest SNR conditions (i.e. −6 dB for the NH children and 0 dB for the CI children), no significant differences were observed among the recognition scores of the four tones or the six tone contrasts. Thus, the strong noise might have sufficiently blurred the acoustical distinctions of individual tones thus leading to a more or less evenly distributed error pattern.

Large individual variations of tone-recognition performance were found in the CI group in both quiet and noise conditions (Figure 1). Age at implantation and length of CI use were the two usual factors that have been identified as major contributors for the performance variations in tone recognition. In a study of tone recognition in quiet, Zhou et al (2013) determined that ~29% of the performance variance could be accounted for by the combination of these two factors. However, other studies indicated that only age at implantation was correlated with the tone-recognition performance (Han et al, 2009; Li et al, 2014). In the present study, our results showed a weak but significant correlation between the tone recognition ability in both quiet and noise conditions and the age at implantation. The benefit of early cochlear implantation has been demonstrated in numerous studies (Niparko et al, 2010; Liu et al, 2013; Dettman et al, 2016). The present study provided evidence to support early implantation for the Mandarin-speaking population.

While several previous studies have shown that duration of implant use significantly predicts Mandarin tone recognition and sentence recognition in quiet in pediatric CI users (Zhou et al, 2013; Chen et al, 2014b), the present study showed no significant correlation between duration of implant use and tone recognition in noise. Duration of implant use and age of implantation interact in a complex way for speech and language development in prelingually deafened children (Niparko et al, 2010). Liu et al (2015) has recently shown that children implanted before 3 years of age steadily improved in open-set Mandarin word recognition in the 7-year long observation, whereas those implanted after 3 years of age showed some improvement in the first 3 years of implant use, but did not show any further improvement up to 7 years. Approximately half of the children in the present study were implanted after 3 years of age (group mean =2.97 years). Thus, the effects of duration of CI use on tone recognition in noise might be confounded by the heterogeneous age at implantation of our cohort of CI children.

It should be noted, though, that many research questions still remain to be answered. Chen et al (2014b) demonstrated that tone recognition in quiet was weakly correlated with sentence recognition in noise. It would be important to demonstrate how tone-recognition performance in noise translates into sentence recognition in noise for Mandarin-speaking CI users. Would a stronger correlation exist between lexical tone recognition in noise and sentence recognition in noise for Mandarin Chinese or other tone languages? A recent report has shown that better sentence recognition skills in noise predicts better spoken language skills in pediatric CI users (Eisenberg et al, 2016). Therefore, a further question that needs to be addressed would be how tone-recognition performance in noise affects language development in the rapidly-increasing population of tone-language-speaking pediatric CI users.

Conclusions

In the present study, we have found that normal-hearing children are fairly resilient to steady-state noise at moderate SNRs in tone recognition, although their performance at an SNR of −6 dB is poorer than that reported for adults. Prelingually-deafened children with CIs have shown a marked deficit in tone recognition. As a group, the tone-recognition performance of children with CI in quiet is equivalent to that of NH children at an SNR of −6 dB. The tone-recognition deficit in children with CI is further exacerbated with a moderate level of noise. Due to the acoustical similarities, Mandarin tone 2 and tone 3 are confused more frequently than any other tone contrasts in both CI and NH children. Age at implantation showed a weak correlation with tone-recognition performance of the CI children in noise. Thus, early implantation might be beneficial to tone development in the pediatric CI users.

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Declaration of interest: The authors report no conflict of interest. The authors alone are responsible for the content and writing of the paper.

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References

Binns C. & Culling J.F. 2007. The role of fundamental frequency contours in the perception of speech against interfering speech. *J Acoust Soc Am*, 122, 1765–1776.

Bonino A.Y., Leibold L.J. & Buss E. 2013. Release from perceptual masking for children and adults: Benefit of a carrier phrase. *Ear Hear*, 34, 3–14.

Chen F., Wong L.L. & Hu Y. 2014a. Effects of lexical tone contour on Mandarin sentence intelligibility. *J Speech Lang Hear Res*, 57, 338–345.

Chen Y., Wong L.L., Chen F. & Xi X. 2014b. Tone and sentence perception in young Mandarin-speaking children with cochlear implants. *Int J Pediatr Otorhinolaryngol*, 78, 1923–1930.

Ciocca V., Francis A.L., Aisha R. & Wong L. 2002. The perception of Cantonese lexical tones by early-deafened cochlear implantees. *J Acoust Soc Am*, 111, 2250–2256.

Corbin N.E., Bonino A.Y., Buss E. & Leibold L.J. 2016. Development of open-set word recognition in children: Speech-shaped noise and two-talker speech maskers. *Ear Hear*, 37, 55–63.

Dettman S.J., Dowell R.C., Choo D., Arnott W., Abrahams Y., et al. 2016. Long-term communication outcomes for children receiving cochlear implants younger than 12 months: A multicenter study. *Otol Neurotol*, 37, 82–95.

Eisenberg L.S., Fisher L.M., Johnson K.C., Ganguly D.H., Grace T., et al. 2016. Sentence recognition in quiet and noise by pediatric cochlear implant users: Relationships to spoken language. *Otol Neurotol*, 37, 75–81.

Feng Y.M., Xu L., Zhou N., Yang G. & Yin S.K. 2012. Sine-wave speech recognition in a tonal language. *J Acoust Soc Am*, 131, 133–138.

Fu Q.J. & Zeng F.G. 2000. Identification of temporal envelope cues in Chinese tone recognition. *Asia Pacific J Speech Lang Hear*, 5, 45–57.

Fu Q.J., Zeng F.G., Shannon R.V. & Soli S.D. 1998. Importance of tonal envelope cues in Chinese speech recognition. *J Acoust Soc Am*, 104, 505–510.

Hall J.W., Grose J.H., Buss E. & Dev M.B. 2002. Spondee recognition in a two-talker masker and a speech-shaped noise masker in adults and children. *Ear Hear*, 23, 159–165.

Han D., Liu B., Zhou N., Chen X., Kong Y., et al. 2009. Lexical tone perception with HiResolution and HiResolution 120 sound processing strategies in pediatric Mandarin-speaking cochlear implant users. *Ear Hear*, 30, 169–177.

Han D., Zhou N., Li Y., Chen X., Zhao X., et al. 2007. Tone production of Mandarin Chinese speaking children with cochlear implants. *Int J Pediatr Otorhinolaryngol*, 71, 875–880.

Hutchins S. & Moreno S. 2013. The Linked Dual Representation model of vocal perception and production. *Front Psychol*, 4, 825.

Kong Y.Y. & Zeng F.G. 2006. Temporal and spectral cues in Mandarin tone recognition. *J Acoust Soc Am*, 120, 2830–2840.

Krenmayr A., Qi B., Liu B., Liu H., Chen X., et al. 2011. Development of a Mandarin tone identification test: Sensitivity index d' as a performance measure for individual tones. *Int J Audiol*, 50, 155–163.

Laures J.S. & Weismer G. 1999. The effects of a flattened fundamental frequency on intelligibility at the sentence level. *J Speech Lang Hear Res*, 42, 1148–1156.

Lee C.Y., Tao L. & Bond Z.S. 2013. Effects of speaker variability and noise on Mandarin tone identification by native and non-native listeners. *Speech Lang Hear*, 16, 46–54.

Lee K.Y., van Hasselt C.A., Chiu S.N. & Cheung D.M. 2002. Cantonese tone perception ability of cochlear implant children in comparison with normal-hearing children. *Int J Pediatr Otorhinolaryngol*, 63, 137–147.

Li A., Wang N., Li J., Zhang J. & Liu Z. 2014. Mandarin lexical tones identification among children with cochlear implants or hearing aids. *Int J Pediatr Otorhinolaryngol*, 78, 1945–1952.

Li C.N. & Thompson S.A. 1977. The acquisition of tone in Mandarin-speaking children. *J Child Lang*, 4, 185–199.

Liu H., Liu S., Wang S., Liu C., Kong Y., et al. 2013. Effects of lexical characteristics and demographic factors on Mandarin Chinese open-set word recognition in children with cochlear implants. *Ear Hear*, 34, 221–228.

Liu H., Liu S., Kirk K.I., Zhang J., Ge W., et al. 2015. Longitudinal performance of spoken word perception in Mandarin pediatric cochlear implant users. *Int J Pediatr Otorhinolaryngol*, 79, 1677–1682.

Luo X. & Fu Q.J. 2004. Enhancing Chinese tone recognition by manipulating amplitude envelope: Implications for cochlear implants. *J Acoust Soc Am*, 116, 3659–3667.

Miller S.E., Schlauch R.S. & Watson P.J. 2010. The effects of fundamental frequency contour manipulations on speech intelligibility in background noise. *J Acoust Soc Am*, 128, 435–443.

Niparko J.K., Tobey E.A., Thal D.J., Eisenberg L.S., Wang N.Y., et al. 2010. Spoken language development in children following cochlear implantation. *JAMA*, 303, 1498–1506.

Nittrouer S. & Boothroyd A. 1990. Context effects in phoneme and word recognition by young children and older adults. *J Acoust Soc Am*, 87, 2705–2715.

Peng S.C., Tomblin J.B., Cheung H., Lin Y.S. & Wang L.S. 2004. Perception and production of Mandarin tones in prelingually deaf children with cochlear implants. *Ear Hear*, 25, 251–264.

Remez R.E., Rubin P.E., Pisoni D.B. & Carrell T.D. 1981. Speech perception without traditional speech cues. *Science*, 212, 947–949.

Studebaker G.A. 1985. A rationalized arcsine transform. *J Speech Hear Res*, 28, 455–462.

Wang J., Shu H., Zhang L., Liu Z. & Zhang Y. 2013. The roles of fundamental frequency contours and sentence context in Mandarin Chinese speech intelligibility. *J Acoust Soc Am*, 134, 91–97.

Wang W., Zhou N. & Xu L. 2011. Musical pitch and lexical tone perception with cochlear implants. *Int J Audiol*, 50, 270–278.

Wong L.L., Soli S.D., Liu S., Han N. & Huang M.W. 2007. Development of the Mandarin Hearing in Noise Test (MHINT). *Ear Hear*, 28, 70–74.

Xu G., Zhang L., Shu H., Wang X. & Li P. 2013. Access to lexical meaning in pitch-flattened Chinese sentences: An fMRI study. *Neuropsychologia*, 51, 550–556.

Xu L., Chen X., Lu H., Zhou N., Wang S., et al. 2011. Tone perception and production in pediatric cochlear implants users. *Acta Otolaryngol*, 131, 395–398.

Xu L., Li Y., Hao J., Chen X., Xue S.A., et al. 2004. Tone production in Mandarin-speaking children with cochlear implants: A preliminary study. *Acta Otolaryngol*, 124, 363–367.

Xu L., Tsai Y. & Pfingst B.E. 2002. Features of stimulation affecting tonal-speech perception: Implications for cochlear prostheses. *J Acoust Soc Am*, 112, 247–258.

Xu L. & Zhou N. (2011). Tonal languages and cochlear implants. In: Zeng, F.G., Popper, A.N., Fay, R.R. (eds.) *Auditory Prostheses: New Horizons*. New York: Springer Science + Business Media, LLC, pp. 341–364.

Zhou N., Huang J., Chen X. & Xu L. 2013. Relationship between tone perception and production in prelingually-deafened children with cochlear implants. *Otol Neurotol*, 34, 499–506.

Zhou N. & Xu L. 2008. Development and evaluation of methods for assessing tone production skills in Mandarin-speaking children with cochlear implants. *J Acoust Soc Am*, 123, 1653–1664.

Zhu S., Wong L.L. & Chen F. 2014a. Development and validation of a new Mandarin tone identification test. *Int J Pediatr Otorhinolaryngol*, 78, 2174–2182.

Zhu S., Wong L.L. & Chen F. 2014b. Tone identification in Mandarin-speaking children with profound hearing impairment. *Int J Pediatr Otorhinolaryngol*, 78, 2292–2296.