Characteristics of Mandarin Open-set Word Recognition Development among Chinese Children with Cochlear Implants

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Abstract

Background: Cochlear implants (CIs) can improve speech recognition for children with severe congenital hearing loss, and open-set word recognition is an important efficacy measure. This study examined Mandarin open-set word recognition development among Chinese children with CIs and normal hearing (NH).

Methods: This study included 457 children with CIs and 131 children with NH, who completed the Mandarin lexical neighborhood test. The results for children at 1–8 years after receiving their CIs were compared to those from the children with NH using linear regression analysis and analysis of variance.

Results: Recognition of disyllabic easy words, disyllabic hard words, monosyllabic easy words, and monosyllabic hard words increased with time after CI implantation. Scores for cases with implantation before 3 years old were significantly better than those for implantation after 3 years old. There were significant differences in open-set word recognition between the CI and NH groups. For implantation before 2 years, there was no significant difference in recognition at the ages of 6–7 years, compared to 3-year-old children with NH, or at the age of 10 years, compared to 6-year-old children with NH. For implantation before 3 years, there was no significant difference in recognition at the ages of 8–9 years, compared to 3-year-old children with NH, or at the age of 10 years, compared to 6-year-old children with NH. For implantation after 3 years, there was a significant difference in recognition at the age of 13 years, compared to 3-year-old children with NH.

Conclusions: Mandarin open-set word recognition increased with time after CI implantation, and the age at implantation had a significant effect on long-term speech recognition. Chinese children with CIs had delayed but similar development of recognition, compared to normal children. Early CI implantation can shorten the gap between children with CIs and normal children.

Key words: Children; Cochlear Implantation; Open-set Word Recognition

INTRODUCTION

Clinical trials of cochlear implants (CIs) for children with severe hearing impairment were started during the 1980s under the management of the US Food and Drug Administration. Advances in CI technology and medical science have provided large improvements in the speech recognition of children with severe and profound congenital hearing loss.[1-4] Eisenberg et al. have proposed postoperative testing for children who receive CIs, which includes open-set word recognition assessment.[5,6] In this context, speech recognition is a comprehensive expression of sensory, language, and cognitive processes, which reflects the ability to identify auditory speech and obtain vocabulary from long-term memory. Thus, assessing children's speech recognition can help clinicians monitor the child's speech development, as well as provide reference data for postoperative CI mapping and auditory speech rehabilitation.

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The lexical neighborhood test (LNT) is an important speech recognition testing tool that involves an open-set speech perception assessment based on the neighborhood activation model (NAM), which aims to explain the phases of sound perception and word recognition.[7] The initial activation phase involves a stimulus triggering a set of similar words in the memory, which are activated in multidimensions and at a magnitude that is related to its similarity to the target word. The second stage is the lexical selection phase, and the word's frequency adjusts the activation of similar vocabularies as a biasing factor. Easy and difficult word lists are created based on vocabulary frequency, adjacent vocabulary, and the frequency of the adjacent vocabulary. In those lists, easy words have relatively high frequencies (above the median) and relatively low neighborhood densities, while difficult words have relatively low frequencies and relatively high neighborhood densities. The test vocabulary for the LNT is selected from the language database of younger normal children and is suitable for assessing early open word recognition among normal children and children with CIs.

This study aimed to explore the characteristics of open-set word recognition development among Chinese children with CIs, based on the Mandarin LNT (M-LNT). Furthermore, we compared the results from children with CIs and normal children, to provide a theoretical and clinical reference for predicting postoperative outcomes for CI implantation at various ages.

METHODS

Ethical approval
The study was approved by the Ethics Committee of the Beijing Tongren Hospital. Informed consent forms were signed by the participants' parents.

Participants
The present study was a prospective study, which included 457 children who received CIs at our center, including 289 boys and 168 girls. The children underwent CI implantation at the ages of 1.0–6.9 years, had a mean age of 2.96 ± 1.44 years, had undergone unilateral implantation, had a closed-set word recognition test score of ≥70%, and could attend open-set word recognition testing with no auditory neuropathy spectrum disorders or cognitive disabilities. The children had used their CIs for 4.15 ± 2.16 years (range: 1.0–8.9 years) and had been tested at the age of 7.12 ± 2.37 years (range: 3.1–13.9 years). The CIs included a Nucleus (Cochlear, Australian) device (243 children), a Maestro (Medel, Austria) device (121 children), and a HiResolution Bionic Ear System (Advanced Bionics, USA) device (93 children). Before the implantation, 224 children had used hearing aids, with average aided hearing thresholds of 32.49 ± 6.69 dB HL at 250–4000 Hz.

The 131 children with normal hearing (NH; 3.0–6.9 years old) were recruited from a kindergarten in Beijing. At 250–4000 Hz, the average pure tone hearing threshold of the NH group was ≤20 dB HL. All of these children had A-type tympanograms, no ear disease history, had Mandarin as their first language, and had passed the intelligence tests for kindergarten admission. In the NH group, testing was performed at the ages of 3.0–3.9 years (34 children), 4.0–4.9 years (40 children), 5.0–5.9 years (33 children), and 6.0–6.9 years (24 children).

Test environment and equipment
The children with CIs were tested in a standard sound-proof room with background noise of <20 dB. The testing was administered using a pure tone audiometer and external loudspeakers, with a sound intensity of 70 dB sound pressure level (SPL). All children directly faced the loudspeakers (0°) at a distance of 1 m.

The children with NH were tested in a quiet classroom with background noise of <35 dB. The testing was administered using a laptop and external loudspeakers, with real-time monitoring of the sound field and a sound intensity of 70 dB SPL. All children directly faced the loudspeakers (0°) at a distance of 1 m.

Test material and methods
The M-LNT[8] includes four lists of disyllabic easy words (DE), disyllabic hard words (DH), monosyllabic easy words (ME), and monosyllabic hard words (MD). Each list has an exercise with 10 target words and three formal tests with 20 target words. The testing was recorded by a professional broadcaster using a professional device, and the words were played randomly. All subjects received a detailed explanation of the test requirements and were asked to repeat the word that they heard. The repeated word was only considered correct only if the initial word, final word, and tone were correct. The correct recognition rate was calculated as the correct number of words repeated divided by the number of questions in the test (20) and then multiplied by 100%.

Statistical methods
Data were processed using SPSS version 17.0 (SPSS Inc., Chicago, IL, USA). Numerical data were reported as the mean ± standard deviation (SD). The unitary linear regression analysis was used to create regression equations using time and the M-LNT scores of children with CIs. And, analysis of variance (ANOVA) was used to analyze the M-LNT scores among children with CIs in three groups and NH children. The statistical significance level was set at $P < 0.05$.

RESULTS

The effects of cochlear implants on open-set word recognition over time
The development of open-set word recognition was examined over time after the CI implantation, and the children were categorized according to whether the implantation was performed before the age of 3 years (281 children) or after 3 years (176 children). The times of CI usage are shown in Table 1. Tables 2 and 3 show the correct recognition rates for the four M-LNT wordlists according to time after the CI

Table 1: Number of patients with different time since cochlear implantation

Time (years)	Implanted before 3 years old (n = 281)	Implanted after 3 years old (n = 176)	Total (n = 457)
1	23	51	74
2	57	39	96
3	47	28	75
4	44	19	63
5	36	7	43
6	31	11	42
7	24	8	32
8–9	19	13	32

Table 2: The mandarin lexical neighborhood test recognition rates at 1–8 years after implantation before the age of 3 years, n=281

Test age (years)	DE (%)	DH (%)	ME (%)	MH (%)
1	48.91 ± 18.89	38.04 ± 17.37	46.09 ± 15.59	36.52 ± 12.65
2	63.66 ± 17.57	48.75 ± 17.06	56.70 ± 16.90	42.05 ± 13.97
3	72.02 ± 17.87	59.26 ± 16.08	63.83 ± 15.82	48.19 ± 16.20
4	77.79 ± 14.32	62.61 ± 15.68	69.89 ± 13.58	52.50 ± 15.50
5	85.29 ± 11.50	70.69 ± 13.05	72.22 ± 11.86	58.06 ± 15.23
6	86.67 ± 12.04	70.13 ± 11.53	77.48 ± 11.28	59.84 ± 16.15
7	87.32 ± 10.50	71.65 ± 13.08	79.17 ± 13.88	64.17 ± 13.65
8–9	90.00 ± 9.07	78.95 ± 12.20	81.84 ± 12.38	69.44 ± 11.62

DE: Disyllabic easy words; DH: Disyllabic hard words; ME: Monosyllabic easy words; MD: Monosyllabic hard words.

Table 3: The Mandarin lexical neighborhood test recognition rates at 1–8 years after implantation after the age of 3 years, n=176

Time (years)	DE (%)	DH (%)	ME (%)	MH (%)
1	47.75 ± 25.03	35.20 ± 21.16	43.30 ± 21.90	30.21 ± 17.16
2	59.62 ± 22.31	43.59 ± 22.30	53.03 ± 21.13	35.26 ± 19.59
3	63.39 ± 25.36	51.32 ± 25.04	56.39 ± 22.85	40.36 ± 21.03
4	64.68 ± 22.96	51.84 ± 23.05	56.68 ± 20.40	41.89 ± 18.43
5	65.71 ± 16.69	52.11 ± 14.26	57.14 ± 18.45	42.67 ± 5.16
6	66.82 ± 16.47	52.36 ± 18.85	58.18 ± 16.17	43.18 ± 17.93
7	68.75 ± 24.60	52.75 ± 27.35	59.14 ± 18.45	46.05 ± 25.03
8–9	75.38 ± 15.47	53.46 ± 19.29	60.77 ± 17.30	46.77 ± 15.59

DE: Disyllabic easy words; DH: Disyllabic hard words; ME: Monosyllabic easy words; MD: Monosyllabic hard words.

implantation. The recognition rates for the DE, DH, ME, and MH wordlists gradually increased with CI usage time, with the highest score observed for the DE wordlist and the lowest score observed for the MH wordlist. Children who received their CI before the age of 3 years had better recognition rates, compared to children who received the CIs after the age of 3 years.

The linear regression model was used to create regression equations using time and the children's M-LNT scores.

Among children who received their CIs before the age of 3 years, the equations were Y = 50.096 + 5.545X for the DE wordlist, Y = 36.748 + 5.362X for the DH wordlist, Y = 45.180 + 4.910X for the ME wordlist, and Y = 31.186 + 4.602X for the MH wordlist. Among children who received their CIs after the age of 3 years, the equations were Y = 48.124 + 3.312X for the DE wordlist, Y = 36.189 + 2.651X for the DH wordlist, Y = 45.116 + 2.275X for the ME wordlist, and Y = 29.698 + 2.122X for the MH wordlist.

The regression coefficients were higher for cases with implantation before the age of 3 years, which indicates that the slope of the regression line was greater (i.e., faster development of word recognition), compared to the group with implantation after the age of 3 years.

Differences in open-set word recognition according to implantation age

The children with CIs were categorized into three groups according to their age at implantation (Group A: 1.0–1.9 years, Group B: 2.0–2.9 years, Group C: 3.0–6.9 years) [Table 4], and their word recognitions were compared to children with NH who underwent testing at the same ages. Table 5 shows the correct recognition rates for the four wordlists according to test age in the NH group, while Tables 6-8 show the results for Groups A–C.

We used the ANOVA to analyze the data, revealed that the four wordlists of M-LNT recognition scores between CI children in three groups and NH children had significant differences (Group A, DE: $F = 8.443$, $P \leq 0.001$, ME: $F = 9.249$, $P \leq 0.001$, DH: $F = 8.310$, $P \leq 0.001$, MH: $F = 9.435$, $P \leq 0.001$; Group B, DE: $F = 15.987$, $P \leq 0.001$, ME: $F = 14.945$, $P \leq 0.001$, DH: $F = 15.337$, $P \leq 0.001$, MH: $F = 15.393$, $P \leq 0.001$; Group C, DE: $F = 7.430$, $P \leq 0.001$, ME: $F = 8.500$, $P \leq 0.001$, DH: $F = 8.562$, $P \leq 0.001$, MH: $F = 10.454$, $P \leq 0.001$). We also used the Dunnett's t-test to compare the mean values of multiple groups. For Group A, there was no significant differences in DE ($P = 0.489$) and ME ($P = 0.168$) word recognition at the age of 6 years, or in DH ($P = 0.524$) and MH ($P = 0.150$) word recognition at 7 years, compared to children with NH at 3 years. Furthermore, there were no significant differences in recognition for the four wordlists in Group A at 10 years, compared to children with NH at 6 years (DE: $P = 0.321$, DH: $P = 0.394$, ME: $P = 0.185$, MH: $P = 0.170$). For Group B, there were no significant differences in DE ($P = 0.149$) word recognition at the age of 8 years, or the DH ($P = 0.052$), ME ($P = 0.277$), and MH ($P = 0.213$) recognition at 9 years, compared to children with NH at 3 years. Moreover, there was no significant difference in DE ($P = 0.170$) word recognition for group B at the age of 10 years, compared to children with NH at 6 years. For Group C, there was a significant difference in the word recognition scores at the age of 13 years, compared to children with NH at 3 years (DE: $P = 0.046$, DH: $P \leq 0.001$, ME: $P \leq 0.001$, MH: $P \leq 0.001$).

Table 4: Test age distributions in 457 cases according to their age at implantation

Test age (years)	Group A, n	Group B, n	Group C, n	Total, n
3	19	10	–	29
4	22	25	10	57
5	21	33	31	85
6	17	17	33	67
7	14	24	27	65
8	16	17	20	53
9	14	15	11	40
10	7	10	13	30
11	–	–	12	12
12	–	–	11	11
13–14	–	–	8	8

Group A: Implantation age at 1.0–1.9 years old; Group B: Implantation age at 2.0–2.9 years old; Group C: Implantation age at 3.0–6.9 years old; –: Not applicable.

Table 5: The Mandarin lexical neighborhood test recognition rates for the children with normal hearing, $n = 131$

Test age (years)	DE (%)	DH (%)	ME (%)	MH (%)
3	88.82 ± 17.62	78.38 ± 18.85	83.53 ± 14.90	72.21 ± 14.93
4	92.25 ± 10.86	85.25 ± 11.38	86.13 ± 12.06	76.25 ± 10.11
5	96.06 ± 5.12	88.48 ± 8.05	93.48 ± 7.34	86.06 ± 8.46
6	97.92 ± 5.09	92.92 ± 5.5	96.04 ± 5.31	88.13 ± 3.55

DE: Disyllabic easy words; DH: Disyllabic hard words; ME: Monosyllabic easy words; MD: Monosyllabic hard words.

Table 6: The Mandarin lexical neighborhood test recognition rates for implantation at 1.0–1.9 years old in according to test age, $n = 130$

Test age (years)	DE (%)	DH (%)	ME (%)	MH (%)
3	61.05 ± 17.84	50.79 ± 15.48	56.11 ± 13.56	41.67 ± 10.98
4	71.90 ± 14.53	58.18 ± 15.32	66.36 ± 14.57	50.45 ± 17.38
5	77.38 ± 14.88	64.76 ± 10.06	66.90 ± 13.18	53.57 ± 14.42
6	84.12 ± 16.41	66.76 ± 20.15	76.18 ± 10.54	58.24 ± 17.67
7	85.77 ± 11.15	72.50 ± 11.56	77.71 ± 12.54	60.79 ± 14.22
8	83.67 ± 12.60	74.67 ± 12.17	78.93 ± 10.77	61.00 ± 11.73
9	90.71 ± 7.81	75.77 ± 9.97	79.29 ± 16.27	68.93 ± 10.95
10	90.92 ± 13.42	84.28 ± 15.12	87.86 ± 9.06	72.14 ± 12.86

DE: Disyllabic easy words; DH: Disyllabic hard words; ME: Monosyllabic easy words; MD: Monosyllabic hard words.

DISCUSSION

Various researchers have examined postoperative speech recognition ability among children after CI implantation. Li et al.[9] evaluated the development of receptive and expressive vocabulary at 24 months after implantation, and found that children with implantation before the age of 3 years had a significantly faster development rate, compared to children with implantation after 3 years. Boons et al.[10] also directly compared open-set word recognition test results, and found that scores were higher for children with early childhood implantation, compared to late childhood implantation. Furthermore, Harrison et al.[11] demonstrated that speech comprehension was better in their early implantation group (vs. late implantation), which persisted after prolonged CI use. In the present study, children with CIs were evaluated for open-set word recognition at 1–8 years after surgery, and we found that implantation before the age of 3 years was associated with significantly better open-set word recognition ability, and that this difference persisted after long-term CI use. This difference may be related to early implantation providing effective sound stimulation during critical periods of language and speech development among children with severe or profound hearing loss. In this context, speech recognition is dependent on and closely related to the rapid and effective phonological coding of speech in real-time auditory memory, and early CI implantation can maximize the reshaping of central nervous system to improve speech recognition ability.

In the present study, we also observed that open-set word recognition increased with greater CI usage times, which is consistent with the findings of Montag et al.[12] Moreover, the present study revealed that recognition is better for easy words and disyllabic words, compared to difficult or monosyllabic words, which is consistent with the findings of Krull et al.[13] Therefore, the results indicate that children with CI experience the lexical effect, similar to children with NH, and that the NAM theory can reflect the same pattern among children with and without hearing impairment.[14,15]

Although we detected gaps between the open-set word recognition abilities of the CI groups and the NH group, the three CI groups exhibited increasing word recognition over time, with the greatest increase observed for Group A and the smallest increase observed for Group C. Group A's word recognition at the ages of 6–7 years were similar to that of 3-year-old children with NH, while their ability at 10 years was similar to that of 6-year-old children with NH. Group B's word recognition at the ages of 8–9 years was similar to that of 3-year-old children with NH, and their DE word recognition at 10 years was similar to that of 6-year-old children with NH. Group C had not achieved the word recognition of 3-year-old children with NH by the age of 13 years.

Although the speech recognition of children with CI increased over time, it still lagged that of children with NH. This may be related to the general development of language acquisition, as children with NH understand some simple words by 6 months, begin speaking at 1 year, and understand differences in various syntactic structures at 18 months. Thus, most children's vocabulary grows dramatically during their first 18 months, doubles during months 18–21, and subsequently doubles again during months 21–24. In contrast, children with severe or profound hearing loss have limited ability to detect sound and extract information, even when using hearing aids at an early age, and their cognitive and comprehensive development will lag that of

Table 7: The Mandarin lexical neighborhood test recognition rates for implantation at 2.0–2.9 years old in according to test age, *n*=151

Test age (years)	DE (%)	DH (%)	ME (%)	MH (%)
3	38.00 ± 10.85	32.50 ± 16.54	38.50 ± 13.13	33.50 ± 10.81
4	61.20 ± 20.98	42.50 ± 19.56	54.60 ± 19.57	39.20 ± 15.52
5	66.52 ± 18.73	51.82 ± 18.06	56.67 ± 16.52	43.64 ± 15.87
6	74.38 ± 17.40	62.06 ± 15.82	68.53 ± 16.08	48.82 ± 15.26
7	79.79 ± 12.80	63.54 ± 14.02	70.21 ± 16.05	50.83 ± 15.99
8	82.19 ± 11.69	66.06 ± 12.88	73.53 ± 10.57	55.88 ± 13.26
9	86.79 ± 10.67	67.67 ± 13.32	77.00 ± 7.27	62.33 ± 16.57
10	90.50 ± 10.39	75.00 ± 8.82	78.00 ± 12.74	67.78 ± 12.28

DE: Disyllabic easy words; DH: Disyllabic hard words; ME: Monosyllabic easy words; MD: Monosyllabic hard words.

Table 8: The Mandarin lexical neighborhood test recognition rates for implantation at 3.0–6.9 years old in according to test age, *n*=176

Test age (years)	DE (%)	DH (%)	ME (%)	MH (%)
4	46.50 ± 22.61	33.89 ± 23.02	38.89 ± 26.78	27.50 ± 19.64
5	54.39 ± 26.36	36.13 ± 22.16	48.93 ± 22.08	32.76 ± 18.59
6	54.68 ± 23.94	43.03 ± 21.90	49.84 ± 21.87	34.38 ± 16.30
7	60.29 ± 21.05	44.48 ± 19.89	56.22 ± 18.26	36.56 ± 19.23
8	61.00 ± 28.36	49.50 ± 26.10	56.75 ± 21.90	37.75 ± 22.56
9	64.82 ± 23.37	49.55 ± 20.79	57.11 ± 24.88	38.00 ± 16.43
10	65.85 ± 20.63	52.62 ± 26.73	57.38 ± 21.45	39.54 ± 21.45
11	66.75 ± 26.47	53.08 ± 22.71	57.87 ± 15.87	44.25 ± 19.67
12	67.91 ± 18.82	54.00 ± 17.12	58.50 ± 18.32	45.00 ± 16.96
13	70.00 ± 14.64	55.00 ± 14.49	59.38 ± 17.20	46.67 ± 14.72

DE: Disyllabic easy words; DH: Disyllabic hard words; ME: Monosyllabic easy words; MD: Monosyllabic hard words.

children with NH. The fact that brain has some degree of plasticity and repairability during early development might explain why Group A had the fastest development, as their early implantation would have facilitated the plasticity and repair (despite lagging behind that of children with NH). In contrast, Group C had the latest implantations, which might have missed the critical period for plasticity and repair, and subsequently generated the large gap in speech recognition between Group C and children with NH.

Svirsky *et al*.[16] found that children with severe hearing loss had delayed language and speech development, although receiving CIs before the age of 2 years was associated with superior speech recognition and language development, compared to implantation after the age of 2 years. Nittrouer *et al*.[17] also examined speech output among children who received CIs before the age of 3 years, and found that, despite the early intervention, these children still had delayed speech development, compared to children with NH. Clark *et al*.[18] assessed communication capacity among children who received CIs before the age of 5 years, and found that children with NH had peak capacity at the age of 3 years,

while the children with CIs had delayed communication. Moreover, Chilosi *et al*.[19] found that children who received CIs before the age of 2 years had delayed vocabulary development, compared to children with NH. Ambrose *et al*.[20] also indicated that 2.5–5-year-old children with CI implantation before 3 years had significantly lower speech awareness scores, compared to children with NH at the same age. Therefore, as we observed in the study, children with CIs tend to have delayed speech recognition and development, compared to children with NH, regardless of whether the implantation is performed at the ages of 2 or 3 years.

Children exhibited increasing speech recognition based on their implantation age and time of CI usage. For example, although children with CI had delayed speech recognition, the greatest increases were observed in Group A (implantation at the age of 1.0–1.9 years). Therefore, early implantation is recommended for eligible children. Nevertheless, it is important to be aware of the risk of CIs for very young infants, as Vlastarakos *et al*.[21] suggested that some factors may influence the assessment of infants' hearing and mask dysfunction that might influence surgery in this group. In addition, the risks of infant surgery and anesthesia are important considerations, as surgical anesthesia has a significantly higher risk among infants at <1 year old, compared to older children.[22] However, it was difficult to examine this risk in this study, based on the limited number of children who underwent CI implantation at the age of <1 year. Furthermore, we only followed up children who received CIs for 1–8 years after their implantation, and it would be useful to examine the changes in speech recognition ability (vs. children with NH) during even longer follow-up periods.

In conclusion, Chinese children with CIs exhibited similar but delayed trends in Mandarin open-set word recognition, compared to children with NH. However, speech development was faster in children who received their CIs at younger ages, which indicates that early CI implantation can shorten the gap in speech development between children with and without CIs. Therefore, we recommend early implantation for patients who are eligible to receive CIs, to achieve the greatest rehabilitation effect.

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Conflicts of interest

There are no conflicts of interest.

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