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Speech Perception in Mandarin- and Cantonese-Speaking Children with Cochlear Implants: A Systematic Review

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SPEECH PERCEPTION IN MANDARIN- AND CANTONESE-SPEAKING CHILDREN WITH COCHLEAR IMPLANTS: A SYSTEMATIC REVIEW

by

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A capstone research project submitted to the Graduate Faculty in Audiology in partial fulfillment of the requirements for the degree of Doctor of Audiology, The City University of New York

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ABSTRACT

SPEECH PERCEPTION IN MANDARIN- AND CANTONESE-SPEAKING CHILDREN
WITH COCHLEAR IMPLANTS: A SYSTEMATIC REVIEW

by

SUM YEE FONG

Advisor: Carol A. Silverman, Ph. D., M. P. H.

Background: Current cochlear implants are limited in their ability to convey pitch and tone information. Poor representation of pitch and tone information in cochlear implants hinders lexical tone perception for cochlear-implant users who speak tonal languages such as Mandarin and Cantonese. As the demand for cochlear implants in China is increasing, it is necessary to understand the speech perception abilities of Mandarin and Cantonese-speaking cochlear-implant users and the factors that contribute to improved speech perception for these users.

Objective: The purpose of this investigation is to perform a systematic review on the speech perception abilities in children with cochlear implants who speak Mandarin or Cantonese, in light of poor encoding of pitch and tone information in current cochlear implants.

Methods: A comprehensive search was conducted utilizing the databases PubMed, Medline Complete, Web of Science, and China Academic Journals. The keywords used to identify relevant studies included "cochlear implant", "Chinese", "speech perception", "人工耳蝸" (cochlear implant), "兒童" (children), and "言語" (speech).

Results: 21 articles examining the speech perception abilities in Mandarin- or Cantonese-speaking children with cochlear implants were identified. The results revealed that speech perception abilities in Mandarin- or Cantonese-speaking children with cochlear implants significantly improve following cochlear implantation.

Discussion: Speech perception abilities in prelingually deafened Mandarin- or Cantonese-speaking children significantly improve post cochlear implantation, although performance still remains poorer when compared to that of their age-matched peers with normal-hearing sensitivity. Age at implantation and duration of cochlear-implant use are two strong predictors for speech perception abilities in Mandarin- or Cantonese-speaking children with cochlear implants. More research is needed to examine whether the use of novel cochlear-implant devices and speech coding strategies would improve speech perception abilities in Mandarin- or Cantonese-speaking children with cochlear implants.

Conclusions: Despite poor encoding of pitch and tone information in current cochlear implants, early implantation remains critical for speech development in prelingually deafened Mandarin- or Cantonese-speaking children and should be encouraged.

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INTRODUCTION

Cochlear implants have been shown to provide individuals with profound hearing loss with successful speech perception. The findings of a large body of research has demonstrated that prelingually deafened children implanted at an early age acquire speech and language skills not only more rapidly than unimplanted deaf children, but at a rate comparable to that of their age-matched peers with normal-hearing sensitivity (Svirsky et al., 2000; Geers et al., 2003). These prelingually deafened children, who then had no choice but to enroll in special education classes prior to the development of cochlear-implant technology, now are able to enroll in mainstream classrooms if implanted at an early age (Geers, 1990; Geers & Brenner, 2003).

Despite this degree of success, cochlear implants are severely lacking in other areas. One area in need of major improvement is the encoding of pitch information. Current cochlear implants are limited in their ability to convey pitch and tone information. Poor representation of pitch and tone information in cochlear implants hinders not only music perception and speech perception in noise for all cochlear-implant users (McDermott, 2004; Caroll, Tiaden, & Zeng, 2011), but also lexical tone perception for cochlear-implant users who speak tonal languages (Ciocca et al., 2002; Lee et al., 2002; Peng et al., 2004; Wei et al., 2000).

In non-tonal languages, pitch variation conveys emotion, expresses attitudes, and distinguishes statements from questions. In tonal languages such as Mandarin and Cantonese, pitch variation at the monosyllabic level conveys lexical meaning. For example, in Mandarin Chinese in which there are four contrastive tones, the syllable /ma/ means "mother" when produced with the flat tone, "hemp" when produced with the rising tone, "horse" when produced with the dipping tone, or "scold" when produced with the falling tone (Chao, 1976). Cantonese Chinese has six contrastive tones, so the syllable /si/ may mean "poetry", "history", "try", "time", "market", or "be" depending on which of the six tones it carries (Chao, 1947).

Marked deficits and large individual variability in lexical tone perception have been observed in prelingually deafened children with cochlear implants. Peng et al. (2004) examined tone perception and production in 38 prelingually deafened Mandarin-speaking children who were implanted at an average age of 5.8 years. They reported an average score of approximately 73% correct for tone perception and 53% correct for tone production. Xu et al. (2009) found an average score of 67% correct for tone perception in a group of 107 Mandarin-speaking children with cochlear implants aging from 2.5 to 16.2 years old. Similar findings have also been reported in Cantonese-speaking children with cochlear implants, with Ciocca et al. (2002), Lee et al. (2002), and Wei et al (2002) all noting an average score in the 60% range. Such performance was significantly poorer compared with that for Mandarin- or Cantonese speaking children with normal-hearing sensitivity, who had an average score in the 90% range (Xu et al., 2009; Lee et al., 2002).

Lexical tone perception relies on a number of acoustic cues. The most important of all is the fundamental frequency (F0) contour, or the variations in fundamental frequency over the temporal domain. In the absence of F0 information, above-chance performance in lexical tone perception can still be achieved by the use of secondary cues such as duration, temporal information including temporal envelope and fine structure, and spectral information (Liu & Samuel, 2004; Kuo et al., 2008; Wang et al., 2011). Most of these cues, however, are poorly represented in current cochlear implants (Xu & Zhou, 2011). Because of frequency-place mismatch and limited insertion depth of the electrodes, F0 information is not explicitly encoded. Rather, F0 information is carried in the temporal envelope presented on the electrodes. Spectral resolution is compromised by the limited number of electrodes and current spread, and temporal fine structure information is lost with the use of constant pulse rate stimulation (Caroll, Tiaden, & Zeng, 2011).

Several new speech coding strategies have been developed to improve the encoding of temporal and spectral information in cochlear implants. For example, the HiResolution 120 strategy from Advanced Bionics is designed to enhance spectral resolution by creating additional virtual channels through manipulation of the proportion of current delivered to adjacent electrode pairs (Choi & Lee, 2012). The fine structure processing strategy from Med El attempts to provide temporal fine structure information by modifying the timing of stimulation in the most apical electrodes (Hochmair et al., 2016). Nonetheless, significant improvement in lexical tone perception has not been observed with the use of these new coding strategies (Chang et al., 2009; Schatzer et al., 2010).

With a huge population of tonal language speakers worldwide, the demand for cochlear implants in tonal language speakers will continue to grow. The Chinese language alone has more than 1.3 billion speakers (Lewis, Simons & Fennig, 2016). To better serve this population, it is necessary to understand the speech perception abilities of Mandarin and Cantonese-speaking cochlear-implant users and the factors that contribute to improved speech perception for these users. Such investigation is particularly important for children with cochlear implants. Unlike adults, children are more susceptible to the negative effects of poor encoding of pitch and tone information in cochlear implants, as they do not have the language foundation that allows them to use linguistic contextual cues. Therefore, the aim of this systematic review is to summarize the literature on the speech perception abilities in children with cochlear implants who speak Mandarin or Cantonese, in light of poor encoding of pitch and tone information in current cochlear implants. Specifically, this review seeks to answer the following questions:

1. How are speech perception abilities in Mandarin- or Cantonese-speaking children, both before and after cochlear implantation, compared to their peers with normal hearing?

2. What are the different factors that contribute to speech perception abilities in Mandarin- or Cantonese-speaking children with cochlear implants?

3. What are the effects of different cochlear implant systems and speech coding strategies on speech perception abilities in Mandarin- or Cantonese-speaking children with cochlear implants?

Given that the lexical meaning of a word in Mandarin and Cantonese depends on pitch variation at the monosyllabic level, this review will focus on studies using speech materials involving words, phrases, or sentences.

METHODS

A comprehensive review was performed utilizing the databases via the Mina Rees Library of the Graduate Center of The City University of New York. The keywords "cochlear implant", "Chinese", and "speech perception" were used when searching in English databases including PubMed, Medline Complete, and Web of Science, and the keywords "人工耳蝸" (cochlear implant), "兒童" (children) , and "言語" (speech) were used when searching in China Academic Journals, a Chinese database. These searches resulted in a total of 436 references. Articles were reviewed if participants were Mandarin- or Cantonese-speaking cochlear implant users below the age of 18 and the speech materials used in the studies included words, phrases, or sentences. Studies involving bimodal or hybrid users, users with Auditory Neuropathy Spectrum Disorder (ANSD), and composite score results were excluded. After excluding duplicates and articles with irrelevant titles, 58 articles were selected for abstract review, followed by full article review if the articles were judged to have met the inclusion criteria indicated above. Based on the abstract review, 12 articles were excluded as they included bimodal or hybrid users, users with ANSD, or predominantly adult users. Full article review of the remaining 46 articles resulted in the exclusion of an additional 25 articles due to the following reasons: no examination of speech perception on words, phrases, or sentences; unreported or missing results; small sample sizes ($n < 6$). Ultimately, 21 articles were chosen for this systematic review.

RESULTS

To investigate the speech perception abilities in children with cochlear implants who speak Mandarin or Cantonese, data from 21 studies were reviewed.

Study Characteristics

The study characteristics are summarized in Table 1. All studies were prospective in design except for the two retrospective studies by Cui, Wang, Zeng, and Li (2005a, 2005b). Of the 21 studies, 10 (47.6%) were descriptive observational involving only one single group of participants; and out of these 10 studies, 6 were longitudinal in which the group was followed over time. Of the 21 studies, 8 (38%) were descriptive comparative involving two groups, with two studies also being longitudinal. Of the 21 studies, 3 were cross-sectional and involved more than two groups (Hao et al., 2015; Lee & van Hasselt, 2005; Xiong, Chen, Liu, & Su, 2003). Of the 21 studies, 10 (48%) were written in English, and eleven (52%) were written in Chinese.

Table 1.

Study and Participant Characteristics

Authors	Year	Study Design	Article Language	Subjects' Language	Sample Size (n)	Prelingual or Postlingual Deaf	Mean (SD) Age	Age Range
Chen, Feng, & He	2007	Descriptive comparative Prospective	Chinese	Mandarin	Total: 58 (CI users < 2 years of use: 10 CI users > 2 years of use: 8 HA users < 2 years of use: 18 HA users > 2 years of use: 22)	Prelingual	CI users: 76.7 months HA users: 77.6 months	CI users: 50-124 months HA users: 46-130 months
Chen, Han, & Sun	2014	Descriptive comparative Prospective	Chinese	Mandarin	Total: 42 (< 6 months of CI use: 20 > 6 months of CI use: 22)	Prelingual	N/A	N/A

Authors	Year	Study Design	Article Language	Subjects' Language	Sample Size (n)	Prelingual or Postlingual Deaf	Mean (SD) Age	Age Range
Chen et al.	2014	Descriptive observational Prospective	English	Mandarin	96	N/A	4.5 years (1.0)	2.4-7.0 years
Chen et al.	2016	Descriptive comparative, longitudinal Prospective	English	Mandarin	80	N/A	N/A	N/A
Cui et al.	2005a	Descriptive comparative Retrospective	Chinese	Mandarin	Total: 32 (1 year of CI use: 18 2 years of CI use: 14)	Prelingual	1 year of CI use: 2.9 (1.5) 2 years of CI use: 3.0 (1.3)	N/A
Cui et al.	2005b	Descriptive comparative Retrospective	Chinese	Mandarin	Total: 23 (Implanted < age 3: 14 Implanted > age 3: 9)	Prelingual	3.0 years	N/A
Fu et al.	2015	Descriptive observational, longitudinal Prospective	Chinese	Mandarin	83	Prelingual	N/A	N/A
Hao et al.	2015	Cross-sectional Prospective	Chinese	Mandarin	46	Prelingual	N/A	3.3-7.2 years

Authors	Year	Study Design	Article Language	Subjects' Language	Sample Size (n)	Prelingual or Postlingual Deaf	Mean (SD) Age	Age Range
Lee & van Hasselt	2005	Cross-sectional, longitudinal Prospective	English	Cantonese	Total: 64 (Implanted < age 3: 15 Implanted between age 3-6: 18 Implanted > age 6: 31)	Prelingual	6.0 years	N/A
Liu et al.	2013	Descriptive observational Prospective	English	Mandarin	230	Prelingual	8.0 years (3.4)	2.8-17.5 years
Liu et al.	2015	Descriptive observational, longitudinal Prospective	English	Mandarin	105	Prelingual	N/A	N/A
Wang et al.	2007	Descriptive comparative Prospective	English	Mandarin	Total: 29 (Implanted < age 3: 15 Implanted > age 3: 14)	N/A	Implanted < or at age 3: Mean=7.0 years SD=1.8 Implanted > age 3: Mean=10.3 years SD=2.5	Implanted < or at age 3: 4-11 years Implanted > age 3: 7.2-15.1 years
Wei et al.	2000	Descriptive observational, longitudinal Prospective	English	Cantonese	28	Prelingual	N/A	N/A

Authors	Year	Study Design	Article Language	Subjects' Language	Sample Size (n)	Prelingual or Postlingual Deaf	Mean (SD) Age	Age Range
Wu et al.	2006	Descriptive comparative, longitudinal Prospective	English	Mandarin	Total: 28 (Implanted < age 3: 15 Implanted > age 3: 13)	Prelingual	N/A	N/A
Wu & Yang	2003	Descriptive observational, longitudinal Prospective	English	Mandarin	16	Prelingual	5.8 years	4.2-8.8 years
Xiong et al.	2003	Cross-sectional Prospective	Chinese	Mandarin	Total: 16 (duration of CI use < 1 year: 7 duration of CI use = 1-3 years: 5 duration of CI use > 3 years: 4)	Prelingual	N/A	N/A
Yu et al.	2015	Descriptive observational, longitudinal Prospective	Chinese	Mandarin	60	N/A	N/A	N/A

Authors	Year	Study Design	Article Language	Subjects' Language	Sample Size (n)	Prelingual or Postlingual Deaf	Mean (SD) Age	Age Range
Zhang et al.	2010	Descriptive observational Prospective	Chinese	Mandarin	27	Prelingual	8.9 years (3.2)	4.2-15.6 years
Zhao & Xing	2002	Descriptive observational, longitudinal Prospective	Chinese	Mandarin	6	Prelingual	6 years	4-14 years
Zhou et al.	2007	Descriptive observational, longitudinal Prospective	Chinese	Mandarin	92	Prelingual	N/A	2-7 years
Zhu et al.	2011	Descriptive comparative Prospective	English	Mandarin	Total: 37 (Prelingual: 27 Postlingual: 10)	Prelingual & Postlingual	Prelingual: 8 years Postlingual: 10.1 years	Prelingual: 6-14.5 years Postlingual: 6.4-17.9 years

Participant Characteristics

Table 1 and Table 2 detail characteristics of the participants. Only two studies (10%) (Lee & van Hasselt, 2005; Wei et al., 2000) targeted Cantonese-speaking participants, the rest (90%) involved Mandarin-speaking participants. The sample sizes ranged from 6 to 230, with 38% of the studies comprising more than 50 users of cochlear implant. In the 11 of the 21 studies (52%) that involved 2 or more groups, the total sample sizes ranged from 16 to 58; and the participants were grouped according to the duration of cochlear-implant use in 5 of these 11 studies and according to the age of implantation in 5 of these 11 studies. Of the 21 studies, 17 (81%) indicated the onset of hearing loss, and all but one study (Zhu et al., 2011) included only participants who were prelingually deaf. Of the 21 studies, 10 (48%) indicated the age range of the participants (2-17.9 years) at the beginning of the study. In the 19 of the 21 studies (90%) that specified the age at implantation, the youngest implanted age was 0.7 year and the oldest implanted age was 17.5 years. Duration of cochlear-implant use was identified in 11 of the 21 studies (50%) and ranged from as few as 3 months of use to more than 11 years of use. Etiologies of hearing loss included congenital, meningitis, ototoxicity, perinatal infection, anoxia at birth, enlarged vestibular aqueduct syndrome, and idiopathic. Maternal education level was specified in the two studies by Chen, Wong, Chen, and Xi (2014, 2016) and ranged from 0 to 19 years, with a mean of 10.6 years in the 2014 study and a mean of 9.7 years in the 2016 study.

Implant Information

Table 2 also shows the type of cochlear implant and speech coding strategy used in the studies. Of the 21 studies, 15 (71%) identified the cochlear-implant manufacturers: 14 of these studies included devices from Cochlear Corporation; 4 included devices from Advanced Bionics, and 2 included devices from Med-EL. The investigators of one study (Yu et al., 2015) examined participants implanted with the Venus device from Nurotron Biotechnology, a cochlear-implant manufacturer based in China. Of the 7 studies that specified the type of speech coding strategy, almost all (i.e., 6) studies utilized the advanced combinational encoder (ACE) strategy. Wang, Huang, Wu, and Kirk (2007) were the only investigators who utilized the spectral-peak (SPEAK) strategy, and Zhu et al. (2011) included two participants who utilized the Advanced Bionics' Fidelity 120 strategy.

Table 2.

Participant Characteristics (cont.) and Implant Information

Authors	Year	Age at Implantation	Duration of CI Use	Etiology of Hearing Loss	Maternal Education Level (years)	CI Manufacturer	Type of Speech Coding Strategy
Chen, Feng, & He	2007	Mean (SD) < 2 years of CI use: 51.2 months (12.9) > 2 years of CI use: 50.7 months (11.2)	< 2 years of CI use: Mean=18.3 months SD=6.7 > 2 years of CI use: Mean=32.8 months SD=9.2	N/A	N/A	Cochlear Nucleus Sprint	ACE
Chen, Han, & Sun	2014	Mean: 4.5 years Range: 1.9-8.8 years Implanted under age of 3: 8 Implanted at age of 3-5: 20 Implanted at age of 5-8: 14	20: < 6 months of use 10: 6-12 months of use 12: 1-2 years of use	N/A	N/A	N/A	N/A
Chen et al.	2014	Mean: 2.7 years SD: 1.0 Range: 0.7-5.0	Mean: 1.6 years SD: 0.7 Range: 0.8-4.4	N/A	Mean: 10.6 years SD: 3.6 Range: 0-19	Advanced Bionics (HiRes 90K) Cochlear (Nucleus system) Med-EL (Sonata and Pulsar)	N/A

Authors	Year	Age at Implantation	Duration of CI Use	Etiology of Hearing Loss	Maternal Education Level (years)	CI Manufacturer	Type of Speech Coding Strategy
Chen et al.	2016	Mean: 2.6 years SD: 1.0 Range: 0.9-5.0	N/A	N/A	Mean: 9.7 years SD: 3.6 Range: 0-19	N/A	N/A
Cui et al.	2005a	Range (in years) 1 year of CI use: 1.3-5.7 2 years of CI use: 1.3-5.1	1 year of CI use: 18 2 years of CI use: 14	1 year of CI use Congenital: 16 Meningitis: 2 2 years of CI use Congenital: 11 Ototoxicity: 2 Meningitis: 1	N/A	Cochlear Nucleus 24	ACE
Cui et al.	2005b	14 implanted under age of 3 9 implanted after age of 3 Range: 1.1-5.8 years	N/A	Congenital: 21 Meningitis: 2	N/A	Cochlear Nucleus 24	ACE
Fu et al.	2015	Mean: 2.9 years Range: 1-4.1 18 implanted at age 1-2 30 implanted at age 2-3 24 implanted at age 3-4 11 implanted at age 4-5	N/A	N/A	N/A	N/A	N/A
Hao et al.	2015	Range: 1-6 years	Range: 3-36 months	N/A	N/A	N/A	N/A

Authors	Year	Age at Implantation	Duration of CI Use	Etiology of Hearing Loss	Maternal Education Level (years)	CI Manufacturer	Type of Speech Coding Strategy
Lee & van Hasselt	2005	Range: 1.0 to 14.1 years 15 implanted < age of 3 Mean: 23.9 months SD: 7.6 18 implanted at age 3-6 Mean: 53.5 months SD: 9.9 31 implanted > age of 6 Mean: 109.3 months SD: 31.0	N/A	N/A	N/A	Cochlear Nucleus CI 22M, CI24M, CI24(CS), CI24(RST)	N/A
Liu et al.	2013	Mean: 3.9 years SD: 3.0 Range: 0.9-16.0	Mean: 4.1 years SD: 2.7 Range: 1.1-11.8	N/A	N/A	N/A	N/A
Liu et al.	2015	Mean: 3.1 years SD: 2.3 years Range: 0.9-15.5 years	N/A	N/A	N/A	Cochlear, Advanced Bionics, Med-EL	N/A
Wang et al.	2007	15 implanted < or at age 3 Mean: 2.2 years, SD: 0.8 14 implanted > age 3 Mean: 6.5 years, SD: 2.1	Implanted < or at age 3 Mean: 4.5 years SD: 0.1 Implanted > age 3 Mean: 4.1 years SD: 1.6	N/A	N/A	Cochlear Nucleus 24	SPEAK

Authors	Year	Age at Implantation	Duration of CI Use	Etiology of Hearing Loss	Maternal Education Level (years)	CI Manufacturer	Type of Speech Coding Strategy
Wei et al.	2000	Range: 2-12 years	N/A	N/A	N/A	Cochlear Nucleus 22: 14 Cochlear Nucleus 24: 12 Advanced Bionics Clarion: 2	N/A
Wu et al.	2006	Mean: 3.8 years Range: 1.1-8.2 years 15 implanted < age 3 13 implanted > age 3	Implanted < age 3: Mean=4.9 years SD=0.7 Implanted > age 3: Mean=4.6 years SD=1.0	N/A	N/A	Cochlear Nucleus CI24M	ACE
Wu & Yang	2003	Mean: 3.1 years, SD: 1.4	N/A	N/A	N/A	Cochlear Nucleus CI24M	ACE
Xiong et al.	2003	Mean / Range: 6.1 years / 2.8-8.7 years 3 implanted < age 3 5 implanted at age 3-5 8 implanted > age 5	7 with < 1 year of use 5 with 1-3 years of use 4 with > 3 years of use	Perinatal infection: 2 Ototoxicity: 3 Anoxia at birth: 1 Idiopathic: 10	N/A	Cochlear Nucleus 22 & 24	N/A

Authors	Year	Age at Implantation	Duration of CI Use	Etiology of Hearing Loss	Maternal Education Level (years)	CI Manufacturer	Type of Speech Coding Strategy
Yu et al.	2015	Mean: 39.6 months SD: 18.9 months Range: 12-71 months 30 implanted < 36 months 30 implanted > 36 months	N/A	N/A	N/A	Nurotron Venus	N/A
Zhang et al.	2010	Mean: 3.8 years SD: 2.5 Range: 1.1-10.9 years	Mean: 4.9 years SD: 2.2 Range: 1.5-9.2 years	EVAS: 2 Idiopathic: 25	N/A	N/A	N/A
Zhao & Xing	2002	N/A	N/A	Ototoxicity: 2 Congenital: 3 Idiopathic: 1	N/A	Cochlear Nucleus 24	N/A
Zhou et al.	2007	N/A	N/A	N/A	N/A	Cochlear Nucleus 24CS	N/A
Zhu et al.	2011	Prelingual: Mean=2.6 years Range=1.1-7.7 years Postlingual: Mean=8.4 years Range=4.5-17.5 years	Prelingual: Mean=5.4 years Range=1.5-11.1 years Postlingual: Mean=1.8 years Range=0.3-3.9 years	Prelingual: All congenital Postlingual: 5 EVAS, 5 idiopathic	N/A	Cochlear Nucleus 24: 35 Advanced Bionics HiRes 90K: 2	ACE: 35 Fidelity 120: 2

Speech-Recognition Measures and Materials

Table 3 lists the speech-recognition materials used in the studies. More than 50% of the studies used monosyllabic or disyllabic words for at least one measure of speech recognition. Of the 21 studies, 9 (43%) assessed sentence recognition; 4 of these 9 studies (44%) included a noise condition. Of the 21 studies, 3 (14%) also employed digits as one measure of speech recognition.

Speech-recognition materials developed by the China Rehabilitation Research Centre for Deaf Children (CRRCDC) were most commonly used in studies with Mandarin-speaking participants, followed by the Mandarin Lexical Neighborhood Test (M-LNT), Mandarin Multisyllabic Lexical Neighborhood Test (M-MLNT), and the Mandarin Pediatric Speech Intelligibility Test (MPSI). The CRRCDC materials include linguistic stimuli from vowels and consonants to open sentences, although most studies that used the CRRCDC materials focused on monosyllabic and disyllabic words. The M-LNT and M-MLNT contain monosyllabic and disyllabic word lists that are further divided into easy and hard word lists based on word frequency. Of the 19 Mandarin studies, 3 (16%) employed MPSI, a Mandarin closed-set sentence recognition test based on the English Pediatric Speech Intelligibility test. This test was developed to evaluate children from three to six years old and includes a quiet condition and a noise condition using a competing sentence at signal-to-noise ratios at +10, +5, 0, -5, and -10 dB. Besides the CRRCDC materials and MPSI, other tests that assess sentence recognition are Mandarin Hearing in Noise Test for Children (MHINT-C), Mandarin Auditory Perception Test Battery (MAPTB), and Mandarin Speech Test Materials (MSTM). Utilized by Zhang et al. (2010), the MHINT-C measures the speech response threshold in dB S/N, or the lowest signal-to-noise ratio to achieve a 50% correct response rate, with noise presented in three different conditions: noise in front, noise to the implanted ear, and noise to the non-implanted ear. The MAPTB is a test battery with eleven sub-tests designed to evaluate the recognition of tones, vowels, consonants, words, phrases, and sentences, and the MSTM assesses recognition of disyllabic words and sentences that are phonemically balanced in vowels, consonants, and tones. One study (Hao et al., 2015) used Mandarin Pediatric Lexical Tone and Disyllabic-word Picture Identification Test in Noise (MAPPID-N), a computerized test developed by The Institute of Acoustics of the Chinese Academy of Sciences and People's Liberation Army General Hospital to measure the speech-recognition abilities in noise of Mandarin-speaking children using disyllabic words and digits. The remaining studies either did not specify the materials used (Wang et al., 2007), or used materials devised by the study authors (Cui et al., 2005a; 2005b).

Of the two studies with Cantonese-speaking participants, Wei et al. (2000) did not specify the name of the test used, whereas Lee & van Hasselt (2005) devised their own word lists. All but one study (Yu et al., 2015) indicated if the tests were closed- or open-set, with 9 of the 21 (43%) studies using closed-set, 7 of the 21 (33%) studies using open-set, and 4 of the 21 (19%) studies using both open and closed sets.

Statistical Analyses

The statistical analyses used in the studies are shown in the last column of Table 3. Only descriptive statistics were utilized in 5 the 21 (24%) studies. Of the remaining 16 studies (76%) in which inferential statistics were employed, 11 (69%) used parametric analyses, 3 (19%) used nonparametric analyses, and 2 (12%) used both nonparametric and parametric analyses. The parametric analyses employed in the studies include independent *t*-test, dependent *t*-test, analysis of covariance (ANCOVA), analysis of variance (ANOVA), repeated measures ANOVA, two way ANOVA, two-way repeated ANOVA, Pearson's correlation coefficient, linear regression, and multiple regression. The nonparametric analyses employed in the studies include Wilcoxon rank-sum test, Kruskal–Wallis H test, Fisher's exact test, and Spearman's rank correlation coefficient. One study (Wei et al., 2000) did not identify the specific nonparametric tests used.

Table 3.

Speech-Recognition Materials and Statistical Analyses

Authors	Year	Speech Recognition Materials used	Types of Linguistic Stimuli	Closed or Open Set	Statistical Analysis
Chen, Feng, & He	2007	CRRCDC[1]	Vowels, consonants, **monosyllabic words**	Closed	Wilcoxon rank-sum test Kruskal–Wallis H test (Compared scores among: CI users with < 2 years use and CI users with > 2 years use HA users with < 2 years use and HA users with > 2 years use CI users with < 2 years use and HA users with < 2 years use CI users with > 2 years use and HA users with > 2 years use)
Chen, Han, & Sun	2014	CRRCDC	Disyllabic words	Closed	Fisher's exact test (Compared scores between: group with < 6 months of use and group with > 6 months of use)

Authors	Year	Speech Recognition Materials used	Types of Linguistic Stimuli	Closed or Open Set	Statistical Analysis
Chen et al.	2014	MPSI[2]	Sentences in quiet and noise	Closed	Stepwise multiple regression Spearman's rank correlation coefficient
Chen et al.	2016	MPSI	Sentences in quiet and noise	Closed	Independent t-test (Compared scores between group without previous hearing-aid trial and group with previous hearing-aid trial at baseline, 3 , 6, & 12 months post CI activation)
Cui et al.	2005a	Word lists devised by Eye & ENT Hospital of Fudan University	Monosyllabic words	Closed	ANCOVA (age as covariate; compared scores between group with 1 year of CI use and group with 2 years of CI use)

Authors	Year	Speech Recognition Materials used	Types of Linguistic Stimuli	Closed or Open Set	Statistical Analysis
Cui et al.	2005b	Word lists devised by Eye & ENT Hospital of Fudan University	Monosyllabic words	Closed	Independent t-test (age as covariate; compared scores between group implanted < age 3 and group implanted > age 3)
Fu et al.	2015	MPSI	Sentences in quiet and noise	Closed	Descriptive only (for sentences in quiet and noise tasks of single CI group at pre-op, 3, 6, & 12 months post activation)
Hao et al.	2015	MAPPIDN[3]	Disyllabic words and digits	Closed	ANOVA (factors: age at implantation and duration of CI use; compared scores among children implanted ranging 22 to 85 months and children with duration of CI use of 3-6 months, 7-12 months, and 13-24 months)

Authors	Year	Speech Recognition Materials used	Types of Linguistic Stimuli	Closed or Open Set	Statistical Analysis
Lee & van Hasselt	2005	Word lists devised by authors	Monosyllabic, disyllabic, multisyllabic words	Open	Repeated Measures ANOVA (factors: age at implantation and duration of CI use; compared scores among children implanted < age 3, at age 3-6, > age 6 at 7 intervals: pre-op, 6 months, 1, 2, 3, 4, & 5 years post CI activation)
Liu et al.	2013	M-LNT[4] and M-MLNT[5]	Monosyllabic and disyllabic words	Open	Two-way ANOVA (factors: word difficulty and syllable length; compared scores of single CI group on disyllabic easy, disyllabic hard, monosyllabic easy, and monosyllabic hard words) Linear and stepwise multiple regression analyses

Authors	Year	Speech Recognition Materials used	Types of Linguistic Stimuli	Closed or Open Set	Statistical Analysis
Liu et al.	2015	M-LNT and M-MLNT	Monosyllabic and disyllabic words	Open	Two-way ANOVA (factors: age at implantation and duration of CI use; compared scores of single CI group at 6, 12, 24, 36, 48, 60, 72, and 84 months post CI activation)
Wang et al.	2007	Name of speech material not specified	Closed-set phonemes, mono-/di-/tri-syllabic word patterns, vowels, consonants, tones, **open-set disyllabic words**	Open and closed	Independent *t*-test (compared scores between children implanted < age 3 and children implanted > age 3) Pearson's correlation coefficient
Wei et al.	2000	Name of speech material not specified	Ling's 7, vowels, diphthongs, consonants, tones, **sentences**, story comprehension	Open	Non-parametric tests (Specific tests not indicated; compared scores at pre-op, 6 months, 1 & 2 years post CI activation)

Authors	Year	Speech Recognition Materials used	Types of Linguistic Stimuli	Closed or Open Set	Statistical Analysis
Wu et al.	2006	M-MLNT	Easy and hard monosyllabic words	Open	Independent *t*-test (Compared scores between children implanted < age 3 and children implanted > age 3 on easy and hard monosyllabic words)
Wu & Yang	2003	MAPTB[6]	**Open monosyllabic/trochee/spondee words**, closed spondee words, vowels, consonants, tones, **closed phrases, closed sentences**	Open and closed	Dependent *t*-test (compared scores of single CI group at 6, 12, 18, 24, 30, and 36 months post activation) Pearson's correlation coefficient
Xiong et al.	2003	CRRCDC	Vowels, consonants, **digits**, tones, **mono-/di-/tri-syllabic words** (closed), open phrases, **open and closed sentences**	Open and closed	Descriptive only (scores of groups with CI use < 1 year, 1-3 years, and > 3 years and groups implanted < age 5 and > age 5)

Authors	Year	Speech Recognition Materials used	Types of Linguistic Stimuli	Closed or Open Set	Statistical Analysis
Yu et al.	2015	CRRCDC	Vowels, consonants, **mono- and di-syllabic words**	N/A	Descriptive only (Scores on monosyllabic and disyllabic words of single CI group at pre-op, 3 months, 1, 2, & 3 years post activation)
Zhang et al.	2010	M-MLNT & MHINT-C[7]	Easy and hard mono- and di-syllabic words, sentences in quiet and noise	Open	Dependent t-test (compared scores of single CI group on easy and hard monosyllabic and disyllabic words) Wilcoxon rank-sum test (compared scores of single CI group under different noise conditions)
Zhao & Xing	2002	CRRCDC	Disyllabic words (Auditory only vs. auditory + lipreading	Closed	Descriptive only (Scores of single CI group with and without lipreading at pre-op, 6, & 12 months post-op)

Authors	Year	Speech Recognition Materials used	Types of Linguistic Stimuli	Closed or Open Set	Statistical Analysis
Zhou et al.	2007	CRRCDC	Vowels, consonants, **digits**, tones, **mono-, di-, trisyllabic words, short sentences**	Open and closed	Descriptive only (Scores of single CI group at 3, 6, 9, & 12 months post activation)
Zhu et al.	2011	MSTM[8]	Disyllabic words and sentences	Open	Two-way repeated ANOVA (factors: talker gender and test type; compared scores between prelingually deafened and postlingually deafened children with different talkers presenting stimuli) Single and multiple linear regression

[1]CRRCDC: Speech recognition materials developed by the China Rehabilitation Research Centre for Deaf Children; [2]MPSI: Mandarin Pediatric Speech Intelligibility; [3]MAPPID-N: Mandarin Pediatric Lexical Tone and Disyllabic-word Picture Identification Test in Noise; [4]M-LNT: Mandarin Lexical Neighborhood Test; [5]M-MLNT: Mandarin Multisyllabic Lexical Neighborhood Test; [6]MAPTB: Mandarin Auditory Perception Test Battery; [7]MHINT-C: Mandarin Hearing in Noise Test for Children; [8]MSTM: The Mandarin Speech Test Materials

Speech-Recognition Outcomes

Tables 4 and 5 detail the speech recognition outcomes and statistical findings from each study.

Table 4.

Speech-Recognition Outcomes – Digit and Word Recognition

Authors	Year	Digits	Statistical Significance	Words	Statistical Significance
Chen, Feng, & He	2007	N/A	N/A	Mean (SD) < 2 years of CI use: 49.5% (12.3%) > 2 years of CI use: 62.7% (9.6%) < 2 years of HA use: 38.1% (11.1%) > 2 years of HA use: 44.9% (12.1%)	Significant differences between... < 2 years of CI use and > 2 years of CI use groups: $\|Z\|$ = 2.268, p= .023 < 2 years of CI use and < 2 years of HA use groups: H = 9.554, p= .023 > 2 years of CI use and > 2 years of HA use groups: H = 17.899, p= .000
Chen, Han, & Sun	2014	N/A	N/A	# of children scoring... < 80% with < 6 months of CI use: 10 > 80% with < 6 months of CI use: 10 < 80% with > 6 months of CI use: 1 > 80% with > 6 months of CI use: 21	Significant difference between... < 6 months of CI use and > 6 months of CI use: p< .01
Chen et al.	2014	N/A	N/A	N/A	N/A
Chen et al.	2016	N/A	N/A	N/A	N/A
Cui et al.	2005a	N/A	N/A	Mean (SD) 1 year of CI use: 75% (9.7%) 2 years of CI use: 87.1% (10.3%)	Significant difference between... 1 year and 2 years of CI use groups: F = 17.19, p= .00

Authors	Year	Digits	Statistical Significance	Words	Statistical Significance
Fu et al.	2015	N/A	N/A	N/A	N/A
Hao et al.	2015	Mean: Age at implantation between 48-60 months and duration of CI use between... 3-6 months: 78.6% 7-12 months: 97.8% 13-24 months: 99.9% Age at implantation > 61 months, specific scores were not indicated but lower scores were noted compared to those implanted between 48-60 months	Significantly better scores with increased CI use, F = 14.709, df = 2, p= 0.0021 Significantly differences in scores among different ages at implantation, with significantly better scores for those implanted between 48-60 months, F = 3.989, df = 2, p= .0456	Mean: Age at implantation between 48-60 months and duration of CI use between... 3-6 months: 66.5% 7-12 months: 89.4% 13-24 months: 99.8% Age at implantation > 61 months, specific scores were not indicated but lower scores were noted compared to those implanted between 48-60 months	Significantly better scores with increased CI use, F = 32.192, df = 2, p = .0001 Significantly differences in scores at different age at implantation, with significantly better scores for those implanted between 48-60 months, F = 6.112, df = 2, p= .0148

Authors	Year	Digits	Statistical Significance	Words	Statistical Significance
Lee & van Hasselt	2005	N/A	N/A	Mean (SD) Preop Implanted < age 3: 0% (0%) at age 3-6: 3.7% (15.8%) > age 6: 4.6% (13.3) 6 months post CI activation Implanted < age 3: 10.3% (27.3%) at age 3-6: 16.5% (34.9%) > age 6: 37.2% (40.7%) 1 year post CI activation Implanted < age 3: 38.9% (42.2%) at age 3-6: 37.4% (43.6%) > age 6: 41.7% (42.4%) 2 years post CI activation Implanted < age 3: 76.6% (28.7%) at age 3-6: 51.5% (41.0%) > age 6: 42.5% (40.0%) 3 years post CI activation Implanted < age 3: 88.8% (14.0%) at age 3-6: 67.6% (29.3%) > age 6: 49.0% (32.8%) 4 years post CI activation Implanted < age 3: 83% (15.4%) at age 3-6: 67.6% (34.1%) > age 6: 66.1% (26.2%) 5 years post CI activation Implanted < age 3: 85% (11.9%) at age 3-6: 77.0% (24.3%) > age 6: 57.8% (33.3%)	Significant differences between implanted at < age 3 and implanted at > age 6 groups when tested at 2 and 3 years post CI activation intervals. (Statistical values not indicated)

Authors	Year	Digits	Statistical Significance	Words	Statistical Significance
Liu et al.	2013	N/A	N/A	Mean Disyllabic easy: 65.0% Disyllabic hard: 51.3% Monosyllabic easy: 38.9% Monosyllabic hard: 46.2%	Significantly better performances with... Easy lists than hard lists, $F[1, 229] = 76.455$, $p < .0001$ Disyllabic lists than monosyllabic lists, $F[1, 229] = 15.190$, $p < .0001$ When comparing scores from 96 age-matched children having normal-hearing sensitivity (data obtained from a previous study) to 83 subjects with 4-6 years of CI use and 78 subjects with same chronological age, CI groups scored: 26.3%, 31.3%, and 18.8% lower at 4, 5, 6 years of CI use, respectively, $p = .0001$ 47.6%, 49.6%, and 42.4% lower at 4, 5, 6 years of chronological age, respectively, $p < .0001$

Authors	Year	Digits	Statistical Significance	Words	Statistical Significance
Liu et al.	2015	N/A	N/A	Mean At 6 months post CI activation: 30.9% At 36 months: 66.3% After 72 months: 81.7% (Specific scores for easy & hard mono-/di-syllabic word tests at different test intervals not indicated; Refer to graph)	Significantly better performance with increased duration of CI use $F[7, 97] = 59.03$, $p < .00001$ Trend for continuous improved scores among 48, 60, 72, and 84 months post CI activation but no significant differences (pvalue not indicated) Significantly poorer scores on monosyllabic hard list than monosyllabic easy list and disyllabic easy/hard lists, with greatest improvement noted at 24 to 36 months post CI activation, $p = .005$
Wang et al.	2007	N/A	N/A	Mean Implanted < age 3 group: 80% Implanted > age 3 group: 60.4%	Implanted < age 3 group performed significantly better than > age 3 group, $p < .05$
Wei et al.	2000	N/A	N/A	N/A	N/A

Authors	Year	Digits	Statistical Significance	Words	Statistical Significance
Wu et al.	2006	N/A	N/A	Mean (SD) Easy version Implanted < age 3 group: 80.0% (8.8%) Implanted > age 3 group: 62.5% (19.9%) Hard version Implanted < age 3 group: 70.5% (9.2%) Implanted > age 3 group: 59.1% (15.2%) Across both groups 71.9% (17.2%) for easy version 65.2% (13.4%) for hard version	Implanted < age 3 group performed significantly better than implanted > age 3 group, regardless of test difficulty *p*= .005 for easy version, *p*= .022 for hard version Implanted < age 3 group performed significantly better on easy than hard version *p*= .007 for implanted < age 3 group, *p*= .629 > for age 3 group
Wu & Yang	2003	N/A	N/A	Mean (SD) Monosyllabic words/trochee/spondee: Scores not indicated, but most scored 100% at 12 months post CI activation Phrases: 75% (6.3%) at 12 months, 90.1% (7.3%) at 24 months	Trend of improved scores for closed phrases with increased CI use but no significant differences, *p*= .066

Authors	Year	Digits	Statistical Significance	Words	Statistical Significance
Xiong et al.	2003	Mean By duration of CI use < 1 year of use group: 75% 1-3 years of use group: 95% > 3 years of use group: 95% By age at implantation Implanted < age of 5 group: 95% Implanted > age of 5 group: 86%	N/A	Mean for monosyllabic words By duration of CI use < 1 year of use group: 55% 1-3 years of use group: 79% > 3 years of use group: 81% By age at implantation Implanted < age of 5 group: 75% Implanted > age of 5 group: 68% Mean for disyllabic words By duration of CI use < 1 year of use group: 64% 1-3 years of use group: 90% > 3 years of use group: 88% By age at implantation Implanted < age of 5 group: 82% Implanted > age of 5 group: 76% Mean for trisyllabic words By duration of CI use < 1 year of use group: 67% 1-3 years of use group: 87% > 3 years of use group: 89% By age at implantation Implanted < age of 5 group: 81% Implanted > age of 5 group: 81%	N/A

Authors	Year	Digits	Statistical Significance	Words	Statistical Significance
Yu et al.	2015	N/A	N/A	Pre-Op Median / Q1 / Q3: 0% for both mono and di-syllabic words 3 months post CI activation Median / Q1 / Q3 for mono-syllabic words: 4.3% / 0% / 84.3% Median / Q1 / Q3 for di-syllabic words: 3.3% / 0% / 88.3% 1 year post CI activation Mean (SD) for mono-syllabic words: 86.2% (19.7%) Mean (SD) for di-syllabic words: 87.4% (18.2%) 2 years post CI activation Mean (SD) for mono-syllabic words: 95.8% (9.0%) Mean (SD) for di-syllabic words: 95.9% (7.6%) 3 years post CI activation Mean (SD) for mono-syllabic words: 95.8% (12.4%) Mean (SD) for di-syllabic words: 94.1% (15.7%)	N/A

Authors	Year	Digits	Statistical Significance	Words	Statistical Significance
Zhang et al.	2010	N/A	N/A	Mean (SD) Easy monosyllabic: 68% (20%) Hard monosyllabic: 58% (18%) Easy Disyllabic: 77% (19%) Hard Disyllabic: 64% (22%)	Significantly better performances with... Easy lists than hard lists for both mono- and di-syllabic word lists, $p = .001$ When comparing scores to age-matched children having normal-hearing sensitivity (data extracted from a previous study), CI subjects performed significantly lower, $p = .001$
Zhao & Xing	2002	N/A	N/A	Mean / Range Pre-op (aided binaurally) Auditory only: 6.7% / 0-20% Auditory + lipreading: 41.7% / 20-50% 6 months post-op Auditory only: 28.3% / 20-50% Auditory + lipreading: 61.6% / 40-80% 12 months post-op Auditory only: 51% / 25-80% Auditory + lipreading: 73.8% / 65-98%	N/A

Authors	Year	Digits	Statistical Significance	Words	Statistical Significance
Zhou et al.	2007	Mean 3 months post CI activation: 55% 6 months: 84% 9 months: 94% 12 months: 96%	N/A	Mean for monosyllabic words 3 months post CI activation: 44% 6 months: 70% 9 months: 86% 12 months: 90% Mean for disyllabic words 3 months: 44.9% 6 months: 75% 9 months: 88% 12 months: 94% Mean for trisyllabic words 3 months: 43% 6 months: 70% 9 months: 86% 12 months: 91%	N/A
Zhu et al.	2011	N/A	N/A	Mean Prelingual: 82.3% Postlingual: 76.6%	Prelingual group: Performed significantly better... with Female 1 talker than with Male 1 or 2 talker (adjusted $p < .001$) with Female 2 talker than with Male 2 talker (adjusted $p = .024$) Postlingual group: Performed significantly better... with Female 1 talker than with Male 1 talker (adjusted $p = .033$) or Male 2 talker (adjusted $p < .001$) Across both groups: Performed significantly better with female than with male talkers (adjusted $p < .001$)

Digits

Xiong et al. (2003), Zhou et al. (2007), and Hao et al. (2015) utilized digits as one measure of speech recognition. Xiong et al. (2003) presented their results based on duration of cochlear-implant use and age at implantation. The mean scores were 75% for children with less than 1 year of use, and 95% for children with 1 to 3 years of use and children with longer than 3 years of use. The mean scores were 95% for children implanted younger than 5 years of age and 86% for children implanted older than 5 years of age. Similarly, Zhou et al. (2007) found better performance with increased duration of cochlear-implant use. The mean scores improved from 55% at 3 months post-activation to 96% at 12 months post-activation. Both Xiong et al. (2003) and Zhou et al. (2007) did not perform any statistical analyses. In contrast, Hao et al. (2015) examined performance using ANOVA with age at implantation and duration of cochlear-implant use as factors. The results revealed significantly better scores with increased duration of cochlear-implant use ($F = 14.709$, $df = 2$, $p < .01$) and for children implanted between 48 to 60 months of age ($F = 3.989$, $df = 2$, $p < .05$).

Monosyllabic/disyllabic/multisyllabic words

Chen, Feng, and He (2007) compared performance on monosyllabic words among four groups of Mandarin-speaking children with congenital severe to profound sensorineural hearing loss: children with less than two years of cochlear-implant use, children with more than two years of cochlear-implant use, children with less than two years of hearing-aid use, and children with more than two years of hearing-aid use. The mean scores for the groups were 49.5%, 62.9%, 38.1%, and 44.9%, respectively. The Wilcoxon rank-sum test was conducted to compare results based on duration of use and the Kruskal–Wallis H test was conducted to compare results based on types of devices. Significantly better performance was observed in children with more than 2 years of cochlear implant-use when compared to children with less than 2 years of cochlear-implant use ($|Z| = 2.268$, $p < .05$), in children with less than 2 years of cochlear-implant use when compared to children with less than 2 years of hearing-aid use ($H = 9.554$, $p < .05$), and in children with more than 2 years of cochlear-implant use when compared to children with more than 2 years of hearing-aid use ($H = 17.899$, $p = .00$).

Examining the performance of 42 Mandarin-speaking children with cochlear implant use ranging from less than 3 months to more than 24 months using disyllabic words, Chen, Han, and Sun (2014) observed the following: 10 children with less than 6 months of use but only 1 child with more than 6 months of use scored less than 80%, whereas 10 children with less than 6 months of use and 21 children with more than 6 months of use scored more than 80%. Based on nonparametric statistical analysis using the Fisher's exact test, a significant difference was found between children with less than 6 months of use and children with more than 6 months of use ($p < .01$).

Using monosyllabic words devised by the Eye & ENT Hospital of Fudan University, Cui et al. (2005a; 2005b) performed two studies to examine the influence of duration of cochlear-implant use (2005a) and age at implantation (2005b) on the speech perception abilities of Mandarin-speaking children with cochlear implants. In the 2005a study, the mean scores were 75% for children with 1 year of cochlear-implant use and 87.1% for children with 2 years of cochlear-implant use. The results of ANCOVA with age as covariate revealed significantly better performance for children with 2 years of use as compared to children with 1 year of use ($F = 17.19$, $p = .00$). In the 2005b study, performance of children implanted under the age of 3 was compared to performance of children implanted after the age of 3 years using the independent *t*-test. With a mean score of 78.9%, children implanted under the age of 3 years performed significantly better ($t = 2.22$, $p < .05$) than children implanted after age of 3 years, who as a group had a mean score of 70.6%.

Hao et al. (2015), who also measured speech perception with disyllabic words, reported the mean scores for Mandarin-speaking children implanted between 48 to 60 months of age as follows: 66.5% for children with 3 to 6 months of cochlear-implant use, 89.4% for children with 7 to 12 months of use, and 99.8% for children with 13 to 24 months of use. For children implanted after 61 months of age, specific scores were not indicated but lower scores were noted compared to those implanted between 48 to 60 months of age. Using ANOVA with age at implantation and duration of cochlear-implant use as factors, significantly better scores were observed with increased duration of cochlear-implant use ($F = 32.192$, $df = 2$, $p = .0001$) and for children implanted between 48 to 60 months of age ($F = 6.112$, $df = 2$, $p < .05$).

Lee and van Hasselt (2005) devised a word list composed of monosyllabic, disyllabic, and multisyllabic words to measure the speech perception abilities of 64 Cantonese-speaking children pre-operatively and at follow-up intervals of 6 months, 1 year, 2 years, 3 years, 4 years, and 5 years. The mean scores for children implanted under 3 years of age were 0% pre-operatively, 10.3% at 6 months, 38.9% at 1 year, 76.6% at 2 years, 88.8% at 3 years, 83% at 4 years, and 85% at 5 years. The mean scores for children implanted between 3 and 6 years of age were 3.7% pre-operatively, 16.5% at 6 months, 37.4% at 1 year, 51.5% at 2 years, 67.6% at 3 years, 67.6% at 4 years, and 76.9% at 5 years. The mean scores for children implanted after 6 years of age were 4.6% pre-operatively, 37.2% at 6 months, 41.7% at 1 year, 42.5% at 2 years, 49.0% at 3 years, 66.1% at 4 years, and 57.9% at 5 years. The results of repeated-measures ANOVA with age at implantation and duration of cochlear-implant use as factors revealed significant differences in performance between children implanted under 3 years of age and children implanted after 6 years of age at 2 and 3 years post-operatively. All other between-group comparisons were found to be insignificant.

Liu et al. (2013) evaluated speech perception of easy and hard monosyllabic and disyllabic words in 230 Mandarin-speaking children with cochlear implants using M-LNT and M-MLNT. Two-way ANOVA was employed to analyze the results statistically, with word difficulty and syllable length as factors. Significant higher scores were noted with easy words than with hard words ($F[1, 229] = 76.455$, $p < .0001$) and with disyllabic words than with monosyllabic words ($F[1, 229] = 15.190$, $p < .0001$). Compared with age-matched children having normal-hearing sensitivity, children with 4 to 6 years of cochlear-implant use scored 18.8% to 26.3% significantly lower ($p = .0001$) and children with cochlear implants aging 4 to 6 years old scored 42.4% to 47.6% significantly lower ($p < .0001$). To examine the effects of duration of cochlear-implant use and age at implantation on word-recognition scores, the investigators performed additional linear and stepwise multiple regression analyses and observed the following: duration of cochlear-implant use was significantly correlated with word-recognition scores ($r = 0.545$, $p < .0001$) and accounted for approximately 30% of the variance ($r^2 = 0.297$); age at implantation was significantly correlated with word-recognition scores ($r = -0.339$, $p < .0001$) and accounted for 11.5% of the variance ($r^2 = 0.115$); duration of cochlear-implant use and age at implantation together accounted for 32% of the variance in word recognition scores ($r^2 = 0.318$).

In a follow-up study, Liu et al. (2015) assessed word-recognition performance of 105 Mandarin-speaking children with cochlear implants at 6, 12, 24, 36, 48, 60, 72, and 84 months post-activation, again using easy and hard monosyllabic and disyllabic words from M-LNT and M-MLNT. The mean overall scores improved from 30.9% at 6 months post-activation to 81.7%

after 72 months post-activation. The results of two-way ANOVA, with age at implantation and duration of cochlear implant-use as factors, are shown in Table 3. There effects of age at implantation and duration of cochlear-implant use on performance were significant, regardless of word difficulty. Specifically, the investigators observed significantly better performance with increased duration of cochlear-implant use ($F[7, 97] = 59.03$, $p < .00001$) and a trend for continuous improved scores with increase in time over 48, 60, 72, and 84 months post-activation. They also found the scores to be significantly poorer with hard monosyllabic words than with easy monosyllabic words, easy disyllabic words, and hard disyllabic words. The greatest improvement for monosyllabic hard words was noted at 24 to 36 months post-activation ($p < .005$).

Wang et al. (2007) compared speech-recognition performance on open-set disyllabic words between children implanted under the age of three years and children implanted after the age of three years. Both groups of children were Mandarin-speaking and had used their implants for at least four years. Independent *t*-test showed that the mean score (80%) for children implanted under the age of 3 years was significantly better than the mean score (60.4%) for children implanted after the age of 3 years ($p < 0.05$). Pearson's correlation coefficient revealed a significant negative relation between age at implantation and word-recognition score ($r = -.527$, $p < .01$). That is, as age at implantation increased, word-recognition score decreased.

Similarly, Wu, Lin, Yang, and Lin (2006) (2006) measured performance for children implanted under the age of 3 years and children implanted after the age of 3 years using easy and hard monosyllabic words from M-MLNT. Both groups had been implanted for at least 3 years. The mean scores for children implanted under the age of 3 years were 80% with easy monosyllabic words and 62.5% with hard monosyllabic words. The mean scores for children implanted after the age of 3 years were 70.5% with easy monosyllabic words and 59.1% with hard monosyllabic words. Independent *t*-test analyses revealed children implanted under the age of 3 years performed significantly better than children implanted after the age of 3 years, regardless of word difficulty ($p < .01$ for easy words; $p = .05$ for hard words). Additionally, for children implanted under the age of 3 years, significantly better scores were observed with easy words than with hard words ($p < .01$).

In a different study, Wu and Yang (2003) examined speech perception performance in 16 Mandarin-speaking children at 6 month intervals from 6 to 36 months post-activation. Using subtests from MAPTB, participants were tested with open monosyllabic words, disyllabic and trisyllabic trochee and spondee words, and short phrases. The investigators reported that most children scored 100% on the monosyllable/trochee/spondee word subtest at 12 months post-activation. Performance on the closed phrase subtest improved from 75% at 12 months post-activation to 90.1% at 24 months post-activation, although the improvement was not statistically significant according to dependent *t*-test ($p > 0.05$). Pearson's correlation coefficient, utilized to examine the influence of age at implantation, revealed a moderate, inverse relation between scores at 12 and 24 months post-activation and age of implantation ($r = -0.6376$, $p < .05$). As age at implantation increased, scores on the closed phrase subtest decreased.

Xiong et al. (2003) used monosyllabic, disyllabic, and trisyllabic words to assess speech perception abilities in 16 Mandarin-speaking children with cochlear implants. The mean scores were reported according to duration of cochlear-implant use and age at implantation and are shown in Table 3. Regardless of word syllables, children with 1 to 3 years of cochlear-implant use and children with more than 3 years of use scored higher than children with less than 1 year of use. Likewise, children implanted under the age of 5 years scored higher than children implanted after the age of 5 years with monosyllabic and disyllabic words. It is unknown whether these differences were significant, as the investigators did not perform any statistical analyses.

Yu et al. (2015) measured speech perception with monosyllabic and disyllabic words in 60 Mandarin-speaking children pre-operatively and at follow-up intervals of 3 months, 1 year, 2 years, and 3 years post-activation. The first quartile, median, and third quartile were reported for results obtained pre-operatively and at 3 months post-activation, and the mean score was reported for results obtained at 1 year, 2 years, and 3 years post-activation. Pre-operatively, the first quartiles, medians, and third quartiles were all 0% for both monosyllabic and disyllabic words. At 3 months post-activation, the first quartiles were 0% for both monosyllabic and disyllabic words, the medians were 4.3% for monosyllabic words and 3.3% for disyllabic words, and the third quartiles were 84.3% for monosyllabic words and 88.3% for disyllabic words. The means improved from 86.2% for monosyllabic words and 87.4% for disyllabic words at 1 year post-activation to 95.8% for monosyllabic words and 94.1% for disyllabic words at 3 years post-activation. No statistical analyses were performed to examine the significance of these differences.

Using the M-MLNT, Zhang et al. (2010) evaluated speech perception of easy and hard monosyllabic and disyllabic words in 27 Mandarin-speaking children with cochlear implants. The investigators employed the dependent *t*-test to analyze the results statistically. They observed significantly better performance with easy words than with hard words for both monosyllabic and disyllabic words ($p = .001$). Compared with age-matched children with normal hearing, children with cochlear implants scored significantly lower ($p < .001$).

Zhao and Xing (2002) compared disyllabic word performance with and without lipreading in 6 Mandarin-speaking children with cochlear implants pre-operatively and at 6 and 12 months post-operatively. The pre-operative results were obtained with the children aided binaurally with hearing aids. The mean scores were 6.7% without lipreading and 41.7% with lipreading pre-operatively, 28.3% without lipreading and 61.6% with lipreading at 6 months postoperatively, and 51% without lipreading and 73.8% with lipreading at 12 months post-operatively. The investigators did not perform statistical analyses to examine the significance of these differences.

Zhou et al. (2007) utilized monosyllabic, disyllabic, and trisyllabic words for measurement of word recognition in 92 Mandarin-speaking children with cochlear implants at 3 months, 6 months, 9 months, and 12 months post-activation. The mean scores improved from 44% for monosyllabic words, 44.9% for disyllabic words, and 43% for trisyllabic words at 3 months post-activation to 90% for monosyllabic words, 94% for disyllabic words, and 91% for trisyllabic words at 12 months post-activation. The significance of these scores was unknown, as statistical analyses were not performed.

Zhu et al. (2011) assessed performance on Mandarin disyllabic words presented by male and female talkers in 27 prelingually deafened children and 10 postlingually deafened children. The mean age at implantation were 2.6 years for the prelingually deafened group and 5.4 years for the postlingually deafened group. The mean duration of cochlear-implant use was 5.4 years for the prelingually deafened group and 1.8 years for the postlingually deafened group. The mean scores were 82.3% for the prelingually deafened group and 76.6% for the postlingually deafened group. The investigators found that both groups performed significantly better when the words were presented by female talkers than by male talkers (adjusted $p < .001$). Additional single linear regression analyses revealed that age at implantation strongly predicted disyllabic recognition ($r^2 = 0.58$, $p < .001$) for the prelingually deafened group but neither age at testing nor age at implantation predicted disyllabic recognition for the postlingually deafened group. Across both groups, multiple linear regression analyses revealed a weak but significant correlation between age at implantation and disyllabic recognition ($r^2 = 0.17$, $p < 0.05$).

Table 5.

Speech-Recognition Outcomes – Sentence Recognition in Quiet and in Noise and Other Analyses

Authors	Year	Sentence in Quiet	Statistical Significance	Sentence in Noise	Statistical Significance	Other Analyses
Chen et al.	2014	Mean: ~90% % of participants able to be tested: 100% % of participants scoring above chance: 100% % of participants with scores comparable to age-matched NH controls: 51% (Specific scores not indicated; refer to graph)	N/A	Mean: at +10 dB S/N: ~70% at -10 dB S/N: 26% % of participants scoring above chance: at +10 dB S/N: > 50% at +5 dB S/N: > 50% at -5 dB S/N: 32% at -10 dB S/N: 4% % of participants with scores comparable to age-matched NH controls at -10 dB S/N: 6% (Specific scores not indicated; refer to graph)	N/A	Stepwise multile regression revealed... Duration of CI use ($\beta = .28$, $p < .005$) and maternal education level ($\beta = .35$, $p < .001$) together accounted for 21% of the variance in sentence perception scores in quiet with a medium effect size, Cohen's *f*2 = 0.27 Duration of CI use ($\beta = -0.41$, $p < .005$), maternal education level ($\beta = -0.21$, $p < .05$), previous hearing-aid trial ($\beta = -0.45$, $p < .001$), and pre-op hearing level ($\beta = 0.20$, $p < .05$) together accounted for 26% of the variance in speech perception scores in noise with a large effect size, Cohen's *f*2 = 0.35 Spearman's rho correlation analysis revealed... a moderate correlation between performance in tone perception in quiet and performance in sentence perception in quiet, $r_s = .47$, $p < .001$ a weak correlation between performance in tone perception in quiet and performance in sentencen perception in noise, $r_s = -0.28$, $p < .05$

Authors	Year	Sentence in Quiet	Statistical Significance	Sentence in Noise	Statistical Significance	Other Analyses
Chen et al.	2016	Proportion of participants able to be tested / Mean Group without previous hearing aid trial At baseline: 0 / -- 3 months post CI activation: 0 / -- 6 months: 7.9 / 25% 12 months: 48.8 / 70% Group with previous hearing aid trial At baseline: 0 / -- 3 months post CI activation: 8.3 / 61% 6 months: 20.6 / 42% 12 months: 56.7 / 60%	No significant difference between group with previous hearing-aid trial and group without previous hearing-aid trial at 12 months, $t(29) = 1.80$, $p > 0.05$	Proportion of participants able to be tested at 12 months / Mean Group without previous hearing aid trial +10 dB: 43.8 / 46% 5 dB: 31.3 / 41% 0 dB: 21.9 / 33% -5 dB: 15.6 / 13% -10 dB: 0 / -- Group with previous hearing aid trial: +10 dB: 56.7 / 50% 5 dB: 46.7 / 38% 0 dB: 36.7 / 29% -5 dB: 16.7 / 23% -10 dB: 13.3 / 12%	N/A	Not reported due to use of composite score which included scores from IT-MAIS/MAIS, LV-MESP, SV-MESP

Authors	Year	Sentence in Quiet	Statistical Significance	Sentence in Noise	Statistical Significance	Other Analyses
Fu et al.	2015	Proportion of participants able to be tested at... Pre-op: <5% 3 months post CI activation: <5% 6 months post CI activation: ~10% 12 months post CI activation: ~40% (Specific scores not indicated; refer to graph)	N/A	Proportion of participants able to be tested at... Pre-op, 3 and 6 months post CI activation +10 to -10 dB SNR: < 5% Proportion of participants able to be tested at 12 months post CI activation +10 dB SNR: ~30% +5 dB SNR: ~25% 0 dB SNR: ~15% -5 dB SNR: ~5% -10 dB SNR: 0% (Specific scores not indicated; refer to graph)	N/A	N/A
Liu et al.	2013	N/A	N/A	N/A	N/A	Regression analyses revealed… Duration of CI use was signficantly correlated with word recognition scores (r = 0.545, p< .0001) and accounted for about 30% of the variance ($r2$ = 0.297) Age at implantation was signficantly correlated with word recognition scores (r = -0.339, p< .0001) and accounted for 11.5% of the variance ($r2$ = 0.115) Stepwise multiple regression revealed that duration of CI use and age at implantation together accounted for 32% of the variance ($r2$ = 0.318)

Authors	Year	Sentence in Quiet	Statistical Significance	Sentence in Noise	Statistical Significance	Other Analyses
Liu et al.	2015	N/A	N/A	N/A	N/A	Two-way ANOVA revealed a significant effect of age at implantation and duration of CI use on performance, regardless of word difficulty Age at implantation / Duration of CI use Disyllabic-Easy: $F = 3.41$, $p = .0003$ / $F = 13.17$, $P < .001$ Disyllabic-Hard: $F = 6.62$, $p < .001$ / $F = 24.25$, $p < .001$ Monosyllabic-Easy: $F = 2.17$, $p = .044$ / $F = 14.21$, $p < 0.001$ Monosyllabic-Hard: $F = 4.13$, $p = .001$ / $F = 14.16$, $p < .001$
Wang et al.	2007	N/A	N/A	N/A	N/A	Correlation analyses revealed a significant negative relation between age at implantation and open-set word recognition $r = -.527$, $p < .01$ As age at implantation increased, open-set word recognition scores decreased

Authors	Year	Sentence in Quiet	Statistical Significance	Sentence in Noise	Statistical Significance	Other Analyses
Wei et al.	2000	Mean Pre-op: 12.2% At 6 months post CI activation: 37.8% At 1 year: 50.0% At 2 years: 52.1%	Significantly better performance post implantation, $p < 0.01$	N/A	N/A	N/A
Wu & Yang	2003	Mean (SD) 61% (6.6%) at 12 months 80.2% (5.2%) at 24 months	Trend of improved scores with increased CI use but no significant differences, $p = 0.067$	N/A	N/A	Regression analysis revealed a moderate relation between scores at 12-24 months post CI activation and age of implantation $r = -0.6376$, $p = .03$ for phrase recognition $r = -0.6756$, $p = .02$ for sentence recognition As age of implantation increased, phrase and sentence recognition scores decreased

Authors	Year	Sentence in Quiet	Statistical Significance	Sentence in Noise	Statistical Significance	Other Analyses
Xiong et al.	2003	Mean for closed-set sentences By duration of CI use < 1 year of use group: 45% 1-3 years of use group: 85% > 3 years of use group: 85% By age at implantation Implanted < age of 5 group: 81% Implanted > age of 5 group: 70% Mean for open-set sentences By duration of CI use < 1 year of use group: Not tested 1-3 years of use group: 80% > 3 years of use group: 84% By age at implantation Implanted < age of 5 group: 80% Implanted > age of 5 group: 70%	N/A	N/A	N/A	N/A

Authors	Year	Sentence in Quiet	Statistical Significance	Sentence in Noise	Statistical Significance	Other Analyses
Zhang et al.	2010	9 out of 27 participants able to be tested Scored by Speech Response Threshold in dB (A) (lowest hearing level to achieve a 50% correct response rate) Range: 46.3-71.7 dB(A)	When comparing to age-matched children having normal-hearing sensitivity from previous studies, CI children's SRTs were 31.5 dB(A) higher (Statistical values not indicated)	7 out of 27 participants were able to be tested Scored by Speech Response Threshold in dB S/N (lowest signal-to-noise ratio to achieve a 50% correct response rate) Mean (SD) / Range Noise in front: 9.2 / 5.7-16.3 Noise to implanted ear: 8.8 (4.2) / 6.5-17.7 Noise to non-implanted ear: 4.4 (3.4) / 2.3-8.7	Significantly better performance with noise directed to non-implanted ear than with noise directed to implanted ear, $p = .018$ No significant difference between noise in front and noise directed to implanted ear, $p = 1.0$ When comparing to age-matched children having normal hearing-sensitivity from previous studies, CI children's SRTs were: Noise in front: 13.4 dB S/N higher Noise to implanted ear: 19.7 dB S/N higher Noise to non-implanted ear: 15.2 dB S/N higher (Statistical values not indicated)	N/A

Authors	Year	Sentence in Quiet	Statistical Significance	Sentence in Noise	Statistical Significance	Other Analyses
Zhou et al.	2007	Mean 3 months post CI activation: 37% 6 months: 67% 9 months: 83% 12 months: 90%	N/A	N/A	N/A	N/A
Zhu et al.	2011	Mean Prelingual: 82.8% Postlingual: 84.4%	Prelingual group: No significant differences in sentence recognition with different talkers Postlingual group: No significant differences in sentence recognition with different talkers Across both groups: Performed significantly better in sentence recognition with female than with male talkers (adjusted $p < .001$)	N/A	N/A	Multiple linear regression analyses revealed... Prelingual group: Age at implantation strongly predicted disyllabic recognition ($r2 = 0.58$, $p < .001$) Age at testing and age at implantation strongly predicted sentence recognition ($r2 = 0.69$; $p < .01$ for age at testing and $p < .001$ for age at implantation) Postlingual group: Neither age at testing nor age at implantation predicted disyllabic or sentence recognition Across both groups: Weak but significant correlation between age at implantation and disyllabic recognition ($r2 = 0.17$, $p = .042$) No significant correlation between age at implantation and sentence recognition ($r2 = 0.12$, $p = 1.115$)

Sentences in quiet

Chen et al. (2014, 2016) utilized the MPSI to examine sentence recognition in quiet in Mandarin-speaking children with cochlear implants. In the 2014 study, all participants were able to be tested and they achieved a mean score of approximately 90%. About half of the participants achieved a score comparable to that of their age-matched normal hearing peers. Stepwise multiple regression revealed duration of cochlear-implant use ($\beta = .28$, $p < .01$) and maternal education level ($\beta = .35$, $p < .001$) together accounted for 21% of the variance in sentence-recognition scores in quiet with a medium effect size (Cohen's $f^2 = 0.27$). Spearman's rho correlation analysis revealed a moderate correlation between performance in tone perception in quiet and performance in sentence recognition in quiet ($rs = .47$, $p < .001$). In the 2016 study, 80 Mandarin-speaking children with cochlear implants with and without hearing-aid experience were tested pre-operatively and at 3 months, 6 months, and 12 months post-activation. None of the participants were able to be tested pre-operatively. At 3 months post-activation, none of the participants without previous hearing-aid experience could be tested; only 8.3% of the participants with previous hearing-aid experience could be tested and these achieved a mean score of 61%. The proportion of participants able to be tested improved to 7.9% at 6 months and to 48.8% at 12 months for those without previous hearing-aid experience; to 20.6% at 6 months and to 56.7% at 12 months for those with previous hearing-aid experience. Children with cochlear implants and with previous hearing-aid experience also obtained a higher mean score compared with children with cochlear implants without previous hearing-aid experience, although the results of the independent *t*-test revealed no significant difference in mean scores between the two groups at 12 months post activation ($t(29) = 1.80$, $p > 0.05$).

Fu et al. (2015), who also measured sentence recognition in quiet using MPSI, found that the number of children with cochlear implants who could be tested increased gradually with increased duration of cochlear-implant use. Fewer than 5% of the participants could be tested pre-operatively and at 3 months post-activation. At 6 months, approximately 10% of participants could be tested. At 12 months, approximately 40% of participants could be tested. Specific mean scores were not indicated, and statistical analyses were not performed.

Wei et al. (2000) analyzed the performance on open set sentence recognition in quiet in 28 Cantonese-speaking children with cochlear implants pre-operatively and at 6 months, 1 year, and 2 years post-activation. They noted that the mean scores improved from 12.2% pre-operatively to 52.1% at 2 years post-activation. The results of unspecified non-parametric tests revealed significantly better performance post-implantation ($p < .01$).

Assessing sentence recognition in quiet in Mandarin-speaking children with cochlear implants using closed set sentences from MAPTB, Wu and Yang (2003) observed a trend of improved performance with increased cochlear-implant use. The mean scores improved from 61% at 12 months post-activation to 80.2% at 24 months post-activation, although the improvement was not significant according to the results of the dependent *t*-test ($p > .05$). Pearson's correlation coefficient revealed a moderate, inverse relation between scores at 12 and 24 months post-activation and age of implantation ($r = -0.6756$, $p < .05$). As age at implantation increased, sentence recognition scores in quiet decreased.

Xiong et al. (2003) measured sentence recognition in quiet with both closed-set and open-set sentences in Mandarin-speaking children with cochlear implants. For both sets of sentences, children with 1 to 3 years of cochlear-implant use and children with more than 3 years of use scored higher than children with less than 1 year of use, and children implanted under the age of 5 years scored higher than children implanted after the age of 5 years. No statistical analyses were performed to investigate whether these differences were of any statistical significance.

Zhang et al. (2010) compared performance on MHINT-C in quiet between children with cochlear implants and age-matched normal hearing children. Of the 27 children with cochlear implants, 9 could be tested. Their SRTs in dB(A) ranged from 46.3 to 71.7 dB(A); the mean SRT for the group with cochlear implant was 31.5 dB(A) higher than that for the age-matched children with normal-hearing sensitivity.

Zhou et al. (2007) examined sentence recognition in quiet in Mandarin-speaking children with cochlear implants at 3 months, 6 months, 9 months, and 12 months post-activation. The mean scores were 37% at 3 months, 67% at 6 months, 83% at 9 months, and 90% at 12 months. The investigators did not perform any statistical analyses to assess the significance of these differences.

Zhu et al. (2011) measured performance on MSTM sentences in quiet presented by male and female talkers in prelingually and postlingually deafened children with cochlear implants. The mean scores were 82.8% for the prelingually deafened group and 84.4% for the postlingually deafened group. The results of two-way repeated ANOVA revealed that across both groups, performance was significantly better when the sentences were presented by female talkers than by male talkers (adjusted $p < .001$). The results of additional single linear regression analyses revealed that age at testing and age at implantation strongly predicted sentence recognition ($r^2 = 0.69$, $p < 0.01$ for age at testing and $p < .001$ for age at implantation) for the prelingually deafened group. But neither age at testing nor age at implantation predicted sentence recognition for the postlingually deafened group. Across both groups, the results of multiple linear regression analyses revealed no significant correlation between age at implantation and sentence recognition ($r^2 = 0.12$, $p > .05$).

Sentences in noise

Chen et al. (2014) observed poorer performance on the MPSI sentences in noise as the signal-to-noise (S/N) ratio decreased. Although over 50% of children with cochlear implants in the study scored above chance at +10 and +5 dB S/N, only 32% and 4% scored above chance at -10 dB

S/N and -5 dB S/N, respectively. The mean scores decreased from approximately 70% at +10 dB S/N to 26% at -10 dB S/N, and only 6% of participants obtained a score comparable to that of their age-matched peers with normal-hearing sensitivity. Additional analyses were performed to examine the effects of different factors on sentence recognition in noise. Stepwise multiple regression revealed duration of cochlear-implant use ($\beta = -0.41$, $p < .005$), maternal education level ($\beta = -0.21$, $p < .05$), previous hearing-aid experience ($\beta = -0.45$, $p < .001$), and pre-operative hearing level ($\beta = 0.20$, $p < .05$) together accounted for 26% of the variance in speech perception scores in noise with a large effect size (Cohen's $f^2 = 0.35$). Spearman's rho correlation analysis revealed a weak correlation between performance in tone perception in quiet and performance in sentence recognition in noise ($rs = -0.28$, $p < 0.05$).

Chen et al. (2016) reported a similar decline in performance on MPSI sentences in noise with lower S/N ratios, regardless of previous hearing-aid experience. At 12 months post-activation, the proportion of participants able to be tested declined from 43.8% at +10 dB S/N to 15.6% at -5 dB S/N and 0% at -10 dB S/N for those without previous hearing-aid experience; the proportion declined from 56.7% at +10 dB S/N to 13.3% at -10 dB S/N for those with previous hearing-aid experience. The mean scores decreased from 46% at +10 dB S/N to 13% at -5 dB S/N for those without previous hearing-aid experience; and from 50% at +10 dB S/N to 12% at -10 dB S/N for those with previous hearing-aid experience. No statistical analyses were performed to examine whether the results were significantly different between the two groups.

Fu et al. (2015) found that the proportion of children with cochlear implants able to be tested with MPSI sentences in noise increased with increased duration of cochlear-implant use but decreased with lower signal-to-noise ratios. Less than 5% of participants could be tested preoperatively and at 3 and 6 months post-activation, even at +10 dB S/N. At 12 months post-activation, the proportions of participants able to be tested were approximately 30% at 10 dB S/N, 15% at 0 dB S/N, and 0% at -10 dB S/N. The mean scores were not indicated, and no statistical analyses were performed.

Zhang et al. (2010) compared performance on the MHINT-C sentences with noise presented in 3 conditions: noise in front, noise to the implanted ear, and noise to non-implanted ear. Of the 7 participants who were able to be tested, the mean SRTs in dB S/N were 9.2 with noise in front, 8.8 with noise to the implanted ear, and 4.4 with noise to the non-implanted ear. Based on the results of the Wilcoxon rank-sum test, performance with noise directed to the non-implanted ear was significantly better than that with noise directed to the implanted ear ($p < 0.05$). No significant difference was observed between performance with noise in front and with noise directed to the implanted ear ($p > .05$). Compared with age-matched peers having normal-hearing sensitivity, the mean SRTs (in dB S/N) for children with cochlear implants were 13.4, 19.7, and 15.2 higher with noise in front, noise to the implanted ear, and noise to the non-implanted ear, respectively.

DISCUSSION

The demand for cochlear implants in China is increasing, especially for prelingually deafened children. In light of poor encoding of pitch and tone in current cochlear implants, it is important to document speech perception outcomes in Mandarin- or Cantonese children with cochlear implants and investigate how these outcomes could be improved in this population. The primary purpose of this systematic review was to summarize the literature on the speech perception abilities in children with cochlear implants who speak Mandarin or Cantonese. A secondary purpose was to examine the different factors that contribute to speech perception abilities in Mandarin- or Cantonese-speaking children with cochlear implants.

Based on the findings of this systematic review, one can conclude that speech perception abilities in Mandarin- or Cantonese-speaking children with cochlear implants improve following cochlear implantation. For digit recognition tasks, excellent scores were observed at 12 months post-activation (Hao et al., 2015; Xiong et al., 2003; Zhou et al., 2007). Investigators who measured word recognition also showed better performance with increased duration of cochlear-implant use and younger age at implantation. Not all Mandarin- or Cantonese-speaking children with cochlear implants could be tested for sentence recognition in quiet or in noise even at 12 months post-activation, although a higher proportion of them were able to be tested and higher mean scores were obtained as duration of cochlear-implant use increased (Chen et al., 2014; Chen et al., 2016; Fu et al., 2015; Wei et al., 2000; Wu & Yang, 2003; Xiong et al., 2003; Zhang et al., 2010; Zhou et al., 2007; Zhu et al., 2011).

In the four studies that compared speech perception performance of children with cochlear implants and children without cochlear implants (Chen et al., 2007; Chen et al., 2014; Liu et al., 2013; Zhang et al., 2010), children with cochlear implants were found to perform significantly better than age-matched children with hearing aids (Chen et al., 2007) but significantly poorer than age-matched children with normal-hearing sensitivity (Chen et al., 2014; Liu et al., 2013; Zhang et al., 2010). Noted that none of the studies that compared performance to age-matched children with normal-hearing sensitivity actually recruited children with normal hearing as controls. Rather, the performance of children with normal-hearing sensitivity was extracted from previous studies, in which testing conditions might not correspond perfectly; this represents a historical comparison.

Duration of cochlear-implant use and age at implantation are strong predictors for speech perception abilities in Mandarin- or Cantonese-speaking children with cochlear implants (Chen et al., 2014; Liu et al., 2013; Liu et al., 2015; Wang et al., 2007; Wu & Yang, 2003; Zhu et al., 2011). Significantly better performance was observed for children implanted under the age of 3 and with increased duration of cochlear-implant use. Other minor factors such as maternal education level, previous hearing aid experience, preoperative hearing level, and performance in tone perception also may contribute to speech perception abilities in Mandarin-speaking children with cochlear implants, although only one study (Chen et al., 2014) included these factors for analyses. Interestingly, Chen et al. (2014) noted that performance in tone perception in quiet was moderately correlated with performance in sentence perception in quiet but weakly correlated with performance in sentence perception in noise. In light of such findings, one may question whether enhancement of tone information—a common goal in the design of novel cochlear implant devices and speech coding strategies—actually results in improvement of sentence perception in noise for tonal-language-speaking cochlear-implant users.

None of the investigators examined whether speech perception abilities in Mandarin- or Cantonese-speaking children with cochlear implants differed by the use of different cochlear-implant devices and speech coding strategies. Of the studies that specified the cochlear-implant devices and speech coding strategies, most participants were implanted with devices from the Cochlear Corporation and utilized the ACE strategy. As much emphasis has been placed on improving the encoding of pitch and tone in the design of novel cochlear implants and speech coding strategies, future studies are needed to further explore if novel cochlear implant devices and speech coding strategies actually contribute to better performance in speech perception of tonal languages.

Several limitations should be noted when interpreting the findings of these studies. First, a variety of speech recognition materials were used in the studies. The difficulty of these materials varied, thus limiting the generalizability of the findings. Second, statistical analyses were not performed in five studies (Fu et al., 2015; Xiong et al., 2003; Yu et al., 2015; Zhao & Xing, 2002; Zhou et al., 2007), resulting in findings of unknown significance. Furthermore, studies that utilized non-parametric analyses reported results in mean score instead of median (Chen et al., 2007; Chen et al, 2004; Chen et al., 2014; Wei et al., 2000; Zhang et al., 2010). A few studies also did not indicate the specific mean scores, and therefore results could only be inferred and approximated from graphs (Chen et al., 2014; Fu et al., 2015; Liu et al., 2015). Many of the long-term longitudinal studies suffered from mortality threat, which made it difficult to draw conclusions on long-term outcomes (Chen et al., 2016; Fu et al., 2015; Lee & van Hasselt, 2005; Liu et al., 2015; Wu et al., 2006; Wu & Yang, 2003; Yu et al., 2015). Finally, more studies involving Cantonese-speaking children with cochlear implants are needed, as only 2 of the 21 studies from this review included this population (Lee & van Hasselt, 2005; Wei et al., 2000).

CONCLUSIONS

The findings of this systematic review show that speech perception outcomes in Mandarin- or Cantonese-speaking children with cochlear implants follow a similar trend to that of their English-speaking counterparts: speech perception abilities in prelingually deafened Mandarin- or Cantonese-speaking children significantly improve post cochlear implantation, although performance still remains poorer when compared to that of their age-matched peers with normal-hearing sensitivity. Age at implantation and duration of cochlear-implant use are two strong predictors for speech perception abilities in Mandarin- or Cantonese-speaking children with cochlear implants. The younger the children are implanted and the longer the children wear their cochlear implants, the better their speech perception abilities. More research is needed to examine whether the use of novel cochlear-implant devices and speech coding strategies would improve speech perception abilities in Mandarin- or Cantonese-speaking children with cochlear implants. Despite poor encoding of pitch and tone information in current cochlear implants, early implantation remains critical for speech development in prelingually deafened Mandarin- or Cantonese-speaking children and should be encouraged.

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