

Speech perception in Mandarin-speaking children with cochlear implants: a systematic review

Yuan Chen* and Lena L.-N. Wong

Clinical Hearing Sciences (CHearS) Laboratory, Division of speech and Hearing Sciences, The University of Hong Kong, 7th Floor, Meng Wah Complex, Pokfulam, Hong Kong, China.

**Corresponding author. Tel.: +85259871023*

E-mail address: chenyan@connect.hku.hk

Abstract

Objective: This paper reviewed the literature on the trajectories and the factors significantly affecting post-implantation speech perception development in Mandarin-speaking children with cochlear implants (CIs). *Design:* A systematic literature search of textbooks and peer-reviewed published journal articles in online bibliographic databases was conducted. *Study sample:* PubMed, Scopus, and Wiley online library were searched for eligible studies based on predefined inclusion and exclusion criteria. *Results:* A total of 14 journal articles were selected for this review. A number of consistent results were found. That is, children with CIs, as a group, exhibited steep improvement in early speech perception, from exhibiting few prelingual auditory behaviors before implantation to identifying sentences in noise after one year of CI use. After one to three years of CI use, children are expected to identify tones above chance and recognition of words in noise. In addition, early age at implantation, longer duration of CI use and higher maternal education level contributed to greater improvements in speech perception. *Conclusions:* Findings from this review will contribute to the establishment of appropriate short-term

24 developmental goals for Mandarin-speaking children with CIs in mainland China
 25 and clinicians could use them to determine whether children have made appropriate
 26 progress with CIs.

27 **Key words:** Behavioral measures, cochlear implant, pediatric, speech
 28 perception

29 **Abbreviations:**

CI	Cochlear implant
HI	Hearing impairment
IT-MAIS	Infant-toddler Meaningful Auditory Integration Scale
MAIS	Meaningful Auditory Integration Scale
MESP	Mandarin Early Speech Perception
MPSI	Mandarin Pediatric Speech Intelligibility
LNT	Monosyllabic Lexical Neighborhood Test
MLNT	Multisyllabic Lexical Neighborhood Test
S/Ns	Signal-to-noise ratios
HAT	Hearing aid trial
MEL	Maternal education level
CDaCI	Childhood Development after Cochlear Implantation
PBK	Phonetically Balanced word Lists-Kindergarten
HINT	Hearing In Noise Test

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37 **Introduction**

38 It is estimated that there are 27.8 million people with some levels of hearing
39 impairment (HI) in mainland China. According to the Ministry of Health (2001),
40 115,000 children under age 7 were identified with severe to profound HI. In
41 addition, 30,000 infants are born with significant HI annually. Cochlear
42 implantation is becoming a more common intervention for these children in
43 Mainland China. About 7,000 people were expected to receive cochlear
44 implantations in Mainland China each year and 85% of them were under 7 years of
45 age (Liang & Mason, 2013). As of 2015, the Chinese government alone had funded
46 implants for 18,600 children (Y. Chen, Wong, Zhu, & Xi, 2016). However, this
47 number does not quite address the incumbent hearing needs. Tong and Lee (2009)
48 estimated that 36,000-192,000 implantations should be performed each year if we
49 were to reach the level of expecting intervention of developed countries.

50 **Test materials for assessing speech perception outcomes with cochlear** 51 **implants**

52 Successful case management and intervention of children with cochlear implants
53 (CIs) require reference to appropriately defined developmental goals established
54 via studies of outcome measurement in pediatric CI recipients. Because a single
55 measure is subject to ceiling or floor effects, a battery of hierarchical tests is often
56 used to track the development of speech perception. Such a test battery has been
57 used in the Childhood Development after Cochlear Implant (CDaCI) study and has
58 been proved to be a practical strategy for tracking emergent skills in pediatric
59 implantees (Eisenberg et al., 2006)

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61 Outcome measurement in Mainland China is limited by the availability of
62 measurement tools. At present, the only test battery available for evaluating
63 preschool children were those developed following the CDaCI protocol. This
64 battery includes Mandarin versions of the Infant-toddler Meaningful Auditory
65 Integration Scale (IT-MAIS) (Zheng, Soli, et al., 2009b); the Meaningful Auditory
66 Integration Scale (MAIS) (Zheng, Soli, et al., 2009b); the Mandarin Early Speech
67 Perception (MESP) test (Zheng, Meng, et al., 2009); the Mandarin Pediatric Speech
68 Intelligibility (MPSI) test (Zheng, Soli, et al., 2009a); the Mandarin versions of the
69 Monosyllabic Lexical Neighborhood Test (LNT) and the Multisyllabic Lexical
70 Neighborhood Test (MLNT) (Liu et al., 2013).

71 The Mandarin versions of the IT-MAIS and the MAIS are parent questionnaires of
72 early prelingual auditory development for very young children. While the IT-MAIS
73 targets infants under age three, the MAIS evaluates auditory behavior in children
74 aged from 3 to 6 years of age. Both the MAIS and the IT-MAIS contain a total of
75 10 questions, with the first two being different to suit the expected auditory behavior
76 of children at different ages and the remaining eight being identical. Results from
77 the IT-MAIS and the MAIS are often combined for ease of analysis (Zheng, Soli,
78 et al., 2009b).

79 The MESP consists of two versions, the standard version (SV-MESP) and low-
80 verbal version (LV-MESP), and both are closed-set speech identification tests.
81 There are six categories in the SV-MESP and four categories in the LV-MESP. The
82 first three categories in the two versions are the same. They are Category 1 - Speech

83 Detection, Category 2 - Pattern Perception, and Category 3 - Spondee Perception.
84 However, Category 4 on the LV-MESP refers to Simple Word Perception while
85 Category 4 on the SV-MESP examines Vowel Perception. The SV-MESP has two
86 more categories: Category 5 - Consonant Perception, and Category 6 - Tone
87 Perception. Unlike the SV-MESP, which uses pictures and recorded test materials,
88 the LV-MESP uses actual objects, live-voice materials and a small response set (i.e.,
89 four items). Therefore, the LV-MESP is more appropriate for younger children with
90 limited vocabulary. Both versions are hierarchical in that a child progresses to the
91 next category if his/her score on the current category is significantly above chance.
92 The LV-MESP is used when children could not be evaluated using the SV-MESP.
93 Both versions are scored to report the highest category that a child is able to achieve
94 scores above chance level (Zheng, Meng, et al., 2009).

95 The MPSI evaluates closed-set sentence identification in quiet and in noise. It is
96 introduced when category 3 or 4 on the MESP is achieved. Children are expected
97 to select the target from a picture plate depicting six sentences. Testing with the
98 MPSI is attempted in quiet, and then in the presence of a competing sentence at
99 signal-to-noise ratios (S/Ns) of +10, +5, 0, -5 and -10 dB. The MPSI is scored to
100 report the most challenging test condition that a child is able to achieve scores
101 significantly above chance level.

102 The Mandarin versions of the LNT and the MLNT examine open-set word
103 recognition. The LNT consists of three monosyllabic easy word lists and three
104 monosyllabic hard words lists, with 20 items in each list. Similarly, the MLNT
105 consists of three disyllabic easy word lists and three disyllabic hard word lists. The

106 “easy” words are spoken frequently and have low neighborhood density (i.e., there
107 are few phonemically similar words around the target word). On the contrary, the
108 “hard” words exhibit low word frequency and high neighborhood density (Liu et
109 al., 2015).

110 Even with this CDaCI protocol in place, no single study has used all measures to
111 track speech perception in Mandarin-speaking children with CIs. Most importantly,
112 there is no systematic documentation of the development of speech perception in
113 Mandarin-speaking children using CIs. One aim of this review is then to synthesize
114 evidence from studies using these measures as an attempt to establish
115 developmental goals for this population.

116 **Factors affecting speech perception**

117 Studies have always shown a wide range of speech perception skills among English-
118 speaking implant recipients. Many factors have been identified to affect the
119 development of speech perception of children with CIs. Individual characteristics
120 such as late age at implantation, presence of other disabilities, abnormal inner ear
121 structure, poor preoperative hearing level and central processing problems are
122 related to poorer speech perception with CI, whereas longer duration of CI use
123 correlates with better outcomes. Educational variables such as more training and
124 the use of oral mode of communication would promote speech understanding
125 ability. CI device characteristics such as a well-fitted map, as evidenced by a wide
126 dynamic range and optimal growth of loudness characteristic, are expected to yield
127 good speech perception performance. In terms of family characteristics, higher
128 family income, smaller family size, and higher parental/family involvement

129 contribute to better speech perception skills (Geers, Brenner, & Davidson, 2003).

130 However, factors contributing to speech perception in Mandarin-speaking children
131 with CIs are not necessarily identical to those reported among their English-
132 speaking peers because of differences in linguistic, cultural and socioeconomic
133 factors (Y. Chen, Wong, Zhu, & Xi, 2015).

134 Linguistically, Chinese is a tonal language where tones are used to convey lexical
135 meaning within syllables, in contrast to changes in pitch to express emotions in
136 English. Tone information is particularly important for tonal language and speech
137 recognition in noise (Mao & Xu, 2016). Thus, poor pitch information conveyed by
138 CIs poses a special challenge for Mandarin speakers. In addition, vowels may
139 contribute more in perceiving Mandarin sentences than in perceiving English
140 sentences. F. Chen, Wong, and Wong (2013) reported a 3:1 advantage for vowel-
141 only sentences over consonant-only sentences while a 2:1 advantage has been
142 reported in English (Cole, Yan, Mak, & Fanty, 1996). Thus, the acoustic
143 information carried by these two languages is dissimilar.

144 Culturally, the stigma associated with deafness and the fragmentation of hearing
145 healthcare services have prevented the formation of a deaf culture which use sign
146 languages as the main means of communication. This has resulted in an exclusive
147 use of oral mode of communication in mainland China (Liang & Mason, 2013). In
148 addition, there has been a long Chinese tradition of families, including those with
149 limited financial resources, investing in the education of their children. This
150 tradition is further enhanced by the one-child policy dated back in 1979. This
151 guarantees a high level of family involvement (Liang & Mason, 2013), which plays

152 a crucial role in enhancing speech perception development in a country with weak
153 hearing service infrastructure (Y. Chen et al., 2015). Geers et al. (2003) also found
154 that children from smaller families tend to achieve better speech perception
155 outcomes than those from bigger families (Geers et al., 2003). However, it is not
156 uncommon for many children living in rural China to be left under the care of their
157 grandparents when their parents work in the cities. The grandparents have little
158 education and often do not understand the implications of providing a rich language
159 environment.

160 Socioeconomically, although developing at a fast rate, mainland China is still a
161 developing country. The infrastructure in Mainland China is often nascent (Liang
162 & Mason, 2013). Universal hearing screening has yet to cover all provinces and
163 municipalities and many implantees have not undergone a hearing aid trial (HAT)
164 before implantation (Y. Chen et al., 2015). Mandarin-speaking children may thus
165 receive CIs at a later age and pre-implant auditory stimulation may be limited.

166 Therefore, as the second aim of this paper, existing evidence was therefore
167 reviewed to identify factors affecting speech perception in the context of mainland

168 China. **Methods**

169 **Search Methods**

170 The main inclusion criterion was studies that evaluated children with prelingual HI
171 and who used Mandarin as their first language. PubMed, Scopus, and Wiley online
172 library were searched for eligible studies. The keywords used included [(Chinese)
173 OR (Mandarin) OR (Putonghua)] AND [(cochlear implantation) OR (cochlear

174 implants) OR (cochlear implant)] AND [(perception) OR (identification) OR
175 (detection) OR (recognition) OR (comprehension)]. The search was limited to
176 journal papers published in English and conducted in mainland China. Studies on
177 children with other disabilities and (or) abnormal inner ear structures and/or nerve
178 deficiency were excluded.

179 **Results**

180 **Paper selection**

181 The search initially yielded 468 titles (253 from PubMed, 132 from Scopus, 83 from
182 Wiley online library) that were potentially relevant to the topics of concern. Two
183 hundred and one papers appeared more than once in these databases, resulting in
184 299 duplicates that were discarded, and 169 non-duplicated records to retrieve.

185 After a review of the abstracts and full papers, 155 articles were further excluded
186 as they contained information that is not relevant to the topic of concern (i.e., reports
187 on NH children or adults, reports on post-lingual children or adults, and irrelevant
188 study objectives). Finally, 14 articles remained for the review.

189 **Findings**

190 Across the 14 studies, participant demographics varied substantially and none
191 reported effect size. Thus, the data could not be pooled for meta-analyses. These
192 results are therefore being presented descriptively.

193 **The trajectories in speech perception development in Mandarin-speaking** 194 **children with CIs**

195 Four out of the 14 studies tracked the development of speech recognition over time
196 using a time-series design (X. Q. Chen et al., 2010; Y. Chen et al., 2016; Liu et al.,
197 2015; Zheng et al., 2011). Table 1 shows detailed information and the most
198 important reasons for biases. Outcomes were assessed in terms of (1) prelingual
199 auditory behavior, (2) early speech identification, (3) closed-set sentence
200 identification, and (4) open-set word recognition.

201 The IT-MAIS/MAIS, the MESP, and the MPSI were used in Zheng et al. (2011) and
202 Y. Chen et al. (2016) at baseline and 3, 6, and 12 months after implantation while
203 only the IT-MAIS and MAIS were used in X. Q. Chen et al. (2010) at the same test
204 intervals. The LNT and MLNT were administered in Liu et al. (2015) at 6, 12, 24,
205 36, 48, 60, 72, and 84 months after implantation. All but Liu et al. (2015) reported
206 outcomes in children implanted not later than 6 years of age; those in Liu et al.
207 (2015) were implanted between 0.5 and 15.5 years of age. Not all studies provided
208 detailed reports on subject demographics, thus it was difficult to ascertain how
209 homogeneous the subjects were within a study and compare results across studies.

210 Eight out of the 14 reported on tone perception performance (see Table 4). Seven
211 studies were cross-sectional (Y. Chen, Wong, Chen, & Xi, 2014; Han et al., 2009;
212 A. Li, Wang, Li, Zhang, & Liu, 2014; Mao & Xu, 2016; Tao et al., 2015; Xu et al.,
213 2011; Zhou, Huang, Chen, & Xu, 2013) and one is a review (Tan, Dowell, & Vogel,
214 2016). None of the tone perception tests used in these studies had been standardized,
215 which was the major source of bias. Other sources of bias include small sample size
216 of not more than 30 (Han et al., 2009; A. Li et al., 2014; Tao et al., 2015; Xu et al.,
217 2011) and omitted information such as maternal education level, hearing aid use

218 before and after implantation and interventions obtained (Zhou et al., 2013).

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220 1. Prelingual auditory behavior

221 Three studies evaluated early prelingual auditory behavior during the first 12
222 months of CI use using the IT-MAIS/MAIS (X. Q. Chen et al., 2010; Y. Chen et al.,
223 2016; Zheng et al., 2011).

224 These studies all generated similar results (see Table 2). That is, the mean scores at
225 3, 6, and 12 months were around 50%, 65%, and 82%, respectively. Y. Chen et al.
226 (2016) and Zheng et al. (2011) both compared their IT-MAIS/MAIS results with
227 those obtained in English-speaking children in Eisenberg et al. (2006); no
228 significant differences were found. This suggested that implant recipients were able
229 to attain similar prelingual auditory skills reaching about 80% on the IT-
230 MAIS/MAIS by 12 months after implantation, regardless of language exposure
231 (English versus Mandarin).

232 2. Early speech identification

233 Two studies (Y. Chen et al., 2016; Zheng et al., 2011) evaluated early speech
234 perception within the first 12 months of CI use using the MESP (see Table 2).

235 Results from the two studies suggest that by six months of CI use, about 50% of
236 children were able to achieve pattern perception (Category 2) on the LV-MESP.
237 After six months of CI use, a small proportion of children were able to achieve
238 spondee perception (Category 3) on the SV-MESP. After 12 months of CI use, the
239 expectation was that more than 50% of children were able to achieve vowel and

240 consonant perception (Category 4 and 5 respectively on the SV-MESP). Because of
241 differences between the MESP and the English version of the Early Speech
242 Perception test (ESP) (i.e., there were six categories in the MESP and four
243 categories in the ESP), comparison of performance in Mandarin-speaking and
244 English-speaking children could not be made.

245 3. Closed-set sentence identification

246 Two studies (Y. Chen et al., 2016; Zheng et al., 2011) evaluated closed-set sentence
247 identification in quiet and in noise using the MPSI during the first year of CI use
248 (see Table 2). Both studies showed that only a small proportion of children (10% to
249 20%) started to demonstrate very limited closed-set sentence identification in quiet
250 (33% to 42%, chance=16.7%) after six months of CI use, suggesting this ability is
251 only emerging. By 12 months of CI use, more than half of the children were able to
252 identify on average about half of the MPSI sentences in quiet. Furthermore, closed-
253 set sentence identification in noise emerged after 12 months of CIs. That is, about
254 30% to 50% of children were able to identify closed-set sentences on +10 dB S/N
255 test condition.

256 4. Open-set word recognition

257 Only one study (Liu et al., 2015) examined open-set word recognition
258 longitudinally using the LNT and the MLNT. Results displayed in Figure 1 show
259 significant improvement in the first 36 months of CI use, and performance
260 plateaued after 48 months of CI use.

261 5. Tone perception

262 Five studies used different two-alternative forced-choice tone contrast tests to
263 evaluate tone identification (Y. Chen et al., 2014; Han et al., 2009; A. Li et al., 2014;
264 Xu et al., 2011; Zhou et al., 2013). The demographics varied greatly across studies
265 which included mean age at testing ranging from 2.41 to 16.5 years of age, mean
266 age at implantation ranging from 3.1 to 6.4 years of age, and mean duration of CI
267 use ranging from 1.3 to 4.4 years. Despite variations in these demographics and test
268 materials, mean tone identification scores ranged from 67% to 82% in quiet were
269 reported, which is significantly above chance level (i.e., 50%).

270 Only one study (Tao et al., 2015) investigated tone recognition skills in children
271 with relatively long duration of CI use (mean=6.5 years) using a four-alternative
272 forced-choice tone recognition test and found good performance in quiet (overall
273 mean=81% correct, chance level=25%). Only one study (Mao & Xu, 2016)
274 investigated Mandarin tone identification in the presence of speech-shaped noise
275 and found a marked deficit in tone perception performance in noise; and
276 performance was more susceptible to noise than their normal hearing peers. Tan et
277 al. (2016) synthesized results from four studies (Han et al., 2007; Peng, Tomblin,
278 Cheung, Lin, & Wang, 2004; Xu et al., 2004; Zhou et al., 2013) on Mandarin tone
279 identification and production and concluded that lexical tone perception was
280 possible by children with CIs. However, no conclusion regarding the age of
281 implantation and duration of CI use required to achieve such a level of tone
282 perception skills was given.

283 Four studies evaluated variations in perceptual abilities across the four lexical tones.
284 A. Li et al. (2014) found tone contrasts containing Tone 4 was the easiest to identify

285 while Zhou et al. (2013) did not find statistical differences in perception among the
286 six tone contrasts. On the other hand, Y. Chen et al. (2014) and Mao and Xu (2016)
287 reported that Tone 2 / Tone 3 contrast was the most difficult.

288 **Summary**

289 Before implantation and 3 months after implantation, most children with CIs could
290 only be evaluated using the IT-MAIS/MAIS. After six months of CI use, about half
291 of the children were achieving Pattern perception (i.e., Category 2 on the LV-
292 MESP). After 12 months of implantation, around half of the children could be
293 evaluated using the SV-MESP and the MPSI, achieving Vowel or Consonant
294 perception (i.e, Category 4 and 5 on the SV-MESP) and +10 dB S/N test condition
295 of the MPSI-N, suggesting substantial progress in closed-set word and sentence
296 identification during the first year of CI use. Open-set word recognition ability
297 evaluated using the MLNT/LNT showed steep improvement between 12 to 36
298 months, and performance plateaued after 48 months of CI use. However, outcomes
299 of the MLNT/LNT were from one study; further investigations are required to
300 verify these findings.

301 Although all studies about tone perception were cross-sectional and differs in
302 participant demographic characteristics and test materials, the studies all concluded
303 that perception of lexical tone was possible in Mandarin-speaking children with
304 CIs. That is, children are expected to identify tones above chance level after one to
305 three years of CI use. Overall, mean tone identification scores ranged from 67% to
306 82% in quiet (chance level=50%), but there are mixed findings in terms of which
307 tone contrasts are easier to identify. Further research is required to examine tone

308 perception in noise and long-term development of tone perception in quiet.

309 Table 3 summarizes speech perception developmental expectations/goals, defined
310 as speech perception skills that at least 50% children with CIs in the previous studies
311 were able to demonstrate at each test interval.

312

313 **Factors influencing speech perception**

314 The second aim of this review was to identify factors influencing speech perception.
315 A total of seven studies were included (see Table 5). Three of them were
316 longitudinal studies (X. Q. Chen et al., 2010; Y. Chen et al., 2016; Liu et al., 2015)
317 while the rest were cross-sectional studies with sample size larger than 90 (Y. Chen
318 et al., 2014; Y. Chen et al., 2015; Liu et al., 2013; Zhou et al., 2013). The
319 demographics varied greatly across studies which included mean ages at testing
320 ranging from 4.16 to 8.00 years of age, mean ages at implantation ranging from
321 2.67 to 3.98 years of age, and mean duration of CI use ranging from 0.00 to 4.10
322 years. The outcomes evaluated included tone identification in quiet, early auditory
323 behavior, open-set word recognition in quiet, and sentence identification in quiet as
324 well as in noise.

325 All seven studies reported significant effects of age at implantation on speech
326 perception except Y. Chen et al. (2014). All seven studies found that longer duration
327 of CI use contributed to better speech perception except Y. Chen et al. (2014). Three
328 out of seven studies evaluated the effects of maternal education level (MEL) on
329 speech perception (Y. Chen et al., 2014; Y. Chen et al., 2015; Y. Chen et al., 2016).

330 Y. Chen et al. (2014) and Y. Chen et al. (2016) reported better MEL contributed to
331 better sentence perception in quiet and in noise. Y. Chen et al. (2015) found that
332 higher MEL contributed to speech perception via its effects on younger age at
333 implantation.

334 Four out of the seven studies (X. Q. Chen et al., 2010; Y. Chen et al., 2014; Y. Chen
335 et al., 2015; Y. Chen et al., 2016) evaluated the effects of a hearing aid trial (HAT)
336 before implantation on speech perception and mixed results were reported. While
337 X. Q. Chen et al. (2010) and Y. Chen et al. (2014) found this factor significantly
338 affected prelingual auditory skills and sentence identification in noise. Y. Chen et
339 al. (2014), Y. Chen et al. (2015), and Y. Chen et al. (2016) failed to find an effect of
340 this factor on tone identification in quiet, sentence identification in quiet and overall
341 speech perception as a composite score combining results from the IT-MAIS/MAIS,
342 the MESP, and the MPSI using principal component analysis, respectively.

343 Three out of the seven studies evaluated the effects of pre-implant hearing level on
344 speech perception (Y. Chen et al., 2014; Y. Chen et al., 2015; Y. Chen et al., 2016)
345 and mixed results were reported. Y. Chen et al. (2016) reported significant effects
346 on speech perception during the first year of CI use while Y. Chen et al. (2014) and
347 Y. Chen et al. (2015) did not find significant effects on speech perception in children
348 with one to three years of CI use.

349 Two out of the seven studies (Y. Chen et al., 2016; Zheng et al., 2011) measured the
350 effects of dialect exposure on prelingual auditory and early speech perception
351 development and both found that consistent language input via CI probably
352 enhances prelingual auditory and early speech perception development at least

353 during the first year of CI use. However, these studies are descriptive in nature and
354 many confounds such as age at implantation and whether the MEL have not been
355 controlled.

356

357 **Summary**

358 The findings that age at implantation, duration of CI use, and the MEL significantly
359 affected speech perception were consistently reported. Findings about the effects of
360 pre-implant hearing level and a HAT before implantation on speech perception were
361 rather inconsistent. The effect of dialect exposure on speech perception requires
362 research that controls confounds and employs statistical comparisons.

363

364 **Discussion**

365 **Tracking auditory and speech perception progress**

366 Clinicians may use the results provided in this review to determine whether children
367 make sufficient progress with a CI. In addition, speech perception developmental
368 goals listed in Table 3 could be used to identify children who are progressing at a
369 slower rate. However, Table 3 only provides general speech perception
370 developmental goals due to limited number of studies available. If a child exhibits
371 a delay of a particular skill at any test interval, greater attention should be devoted
372 to develop that skill. Besides using Table 3 to ensure that foundational skills have
373 been established before proceeding to more advanced ones, Robbin (2005) also
374 recommended other actions that clinicians can take for children who are progressing

375 at a slower-than-expected rate. These include confirming whether the device is
376 working, breaking down the training into smaller steps, communicating and
377 working with parents, considering the use of other devices that may enhance
378 sensory inputs, and ruling out additional disabilities.

379 However, it is important to remember that these developmental goals were derived
380 from a limited number of studies, ranging from one to four, and could only applied
381 to children in mainland China. Despite similarities in findings across studies, further
382 research is needed to account for possible idiosyncrasies and ensure trusted
383 conclusions, such as refining these speech perception goals for children implanted
384 at different ages. Furthermore, the studies reported in this review are limited to
385 demonstration of early speech perception skills and no research has examined more
386 advanced abilities such as open-set sentence recognition. Given that the CDaCI has
387 also incorporated the English version of the Hearing in Noise Test (HINT) and its
388 Mandarin version (MHINT, Wong, Soli, Liu, Han, & Huang, 2007) has been
389 standardized, it will not be long before reports of these abilities become available
390 as the children in mainland China gain experience with CI.

391 **Tone perception**

392 All reviewed studies reported certain levels of tone perception skills in spite of
393 sparse pitch information provided by a CI. However, as the mean duration of CI use
394 is fewer than 3 years in most studies and there is a lack of data on long-term tone
395 perception performance, the level of tone recognition ability that can be achieved
396 eventually is still unknown. Another concern is that tests used in these studies have
397 not been standardized. The Mandarin Tone Identification Test (MTIT) (Zhu, Wong,

398 & Chen, 2014), with good psychometric properties, has been made available
399 recently. Its application in CI users has yet to be reported.

400

401 **Factors influencing speech perception**

402 It was not surprising to find a younger age at implantation and a longer duration of
403 CI use contributed to better speech perception in Mandarin-speaking children with
404 CIs as the same effects were repeatedly reported in the English-speaking population
405 (Geers et al., 2003). The influence of age is related to “sensitive periods” in the
406 maturation of the auditory system (Sharma, Dorman, & Kral, 2005). Although the
407 sensitive cutoff point for central auditory system development is still debatable,
408 neural plasticity degrades with the increase in ages (Sharma et al., 2005; Sharma,
409 Dorman, & Spahr, 2002). Declining neural plasticity and lack of auditory
410 experience negatively affect central neural organization for audition and lead to
411 unsatisfactory hearing, speech and language performance after implantation
412 (Houston & Miyamoto, 2010; Sarant, Blamey, Dowell, Clark, & Gibson, 2000).
413 Considering the importance of early implantation on speech perception, Y. Chen et
414 al. (2015) and W. Li, Dai, Li, Chen, and Jiang (2016) examined variables that
415 contributed to early implantation. They found living in a rural community, financial
416 burden and communication barriers negatively affected the age at CI, while
417 universal newborn hearing screening and higher maternal education level positively
418 impacted the age at CI. Thus, to ensure early implantation, appropriate
419 infrastructure must be in place.

420

421 Better MEL significantly contributed to early speech perception over the first year
422 of CI use (Y. Chen et al., 2016). This highlighted the important role of mothers. Y.
423 Chen et al. (2015) speculated that the relationship between the MEL and speech
424 perception is not straightforward, probably being mediated by the socioeconomic
425 status of the family and mothers' interactions with their children. First, mothers
426 with higher MEL are more likely to have higher socioeconomic status which helps
427 to finance appropriate audiological and rehabilitative services. Second, mothers
428 with higher MEL tend to be less directive, talk more and use more varied vocabulary
429 when interacting with their children. Mothers with lower MEL, on the other hand,
430 may have difficulties applying techniques learned in aural rehabilitation sessions to
431 enhance speech perception development at home (Hoff & Tian, 2005). Therefore,
432 clinicians should assist these mothers to enhance verbal interactions with their
433 children.

434 Findings about the effects of pre-implant hearing level and a HAT before
435 implantation on speech perception were rather inconsistent. This may be explained
436 by two reasons. First, these factors may only affect some specific speech perception
437 skills. For example, Y. Chen et al. (2014) reported that a HAT significantly affected
438 sentence perception in noise but not tone perception in quiet or sentence perception
439 in quiet. Second, the effects of these factors may change with increased CI use. Y.
440 Chen et al. (2016) reported significant effects of pre-implant hearing level on speech
441 perception during the first year of CI use, but the effects of this factor seemed to
442 diminish as the same participants gained more experience with CIs (Y. Chen et al.,

443 2015). Longitudinal studies are needed to verify these speculations.
444 Other factors that have not been examined might also impact post-implantation
445 speech perception development in Mandarin-speaking children. First, as mentioned
446 above, it is not uncommon that grandparents act as main caregivers in mainland
447 China. These grandparents may be less educated and often are more directive and
448 interact less frequently with their grandchildren. Second, a large proportion of
449 children with CIs did not wear HA on the nonimplant ear perhaps because parents
450 and some clinicians have the misconceptions that HAs may interfere speech
451 perception especially during the first year use of CIs. However, Moberly,
452 Lowenstein, and Nittrouer (2016) found that early bimodal stimulation could
453 enhance language acquisition. Reference to evidence in English-speaking children
454 and localized research would clarify this concern and promote the use of a
455 contralateral HA in mainland China. Third, the exclusive use of oral mode of
456 communication after implantation in mainland China should be examined for
457 effectiveness among the late-implant population (i.e., those implanted after 5 years
458 of age) or children with slow progress. Last but not least, considering the diversity
459 of dialects in mainland China, the effects of dialect exposure on speech perception
460 is worth further research.

461

462 **Conclusions**

463 This review helps to establish developmental goals among Mandarin-speaking
464 children with CIs. Clinicians may use these goals to determine whether children

465 have made appropriate progress and whether increased attention should be given to
466 address particular speech perception issues. Tools for measuring more advanced
467 speech perception skills are needed.

468 After one to three years of CI use, children are expected to identify lexical tone
469 above chance level. Further studies are required to examine long-term tone
470 perception development and tone perception in noise.

471 Prevailing evidence suggests that a younger age at implantation, a longer duration
472 of CI use, and a higher MEL contribute to better speech perception skills. Studies
473 on the effects of pre-implant hearing level and a HAT generated mixed results.
474 Therefore, these effects need to be explored further with larger samples. In addition,
475 factors such as grandparent involvement, the use of HA on the nonimplant ear and
476 the exposure of dialects are worth considerations.

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References

- Chen, F., Wong, L. L., & Wong, E. Y. (2013). Assessing the perceptual contributions of vowels and consonants to Mandarin sentence intelligibility. *J Acoust Soc Am*, *134*(2), E1178-184. doi:10.1121/1.4812820
- Chen, X. Q., Liu, S., Liu, B., Mo, L. Y., Kong, Y., Liu, H. H., . . . Zhang, I. (2010). The effects of age at cochlear implantation and hearing aid trial on auditory performance of Chinese infants. *Acta Oto-Laryngologica*, *130*(2), 263-270.
- Chen, Y., Wong, L. L., Chen, F., & Xi, X. (2014). Tone and sentence perception in young Mandarin-speaking children with cochlear implants. *Int J Pediatr Otorhinolaryngol*, *78*(11), 1923-1930. doi:10.1016/j.ijporl.2014.08.025
- Chen, Y., Wong, L. L., Zhu, S. F., & Xi, X. (2015). A Structural Equation Modeling Approach to Examining Factors Influencing Outcomes with Cochlear Implant in Mandarin-Speaking Children. *PLoS ONE*, *10*(9), e0136576. doi:10.1371/journal.pone.0136576
- Chen, Y., Wong, L. N., Zhu, S. F., & Xi, X. (2016). Early speech perception in Mandarin-speaking children at one-year post cochlear implantation. *Res Dev Disabil*, *49-50*, 1-12. doi:<http://dx.doi.org/10.1016/j.ridd.2015.11.021>
- Cole, R., Yan, Y., Mak, B., & Fanty, M. (1996). The contribution of consonants versus vowels to word recognition in fluent speech. *The Journal of the Acoustical Society of America*, *100*(4), 2689-2689. doi:doi:<http://dx.doi.org/10.1121/1.417028>
- Eisenberg, L. S., Johnson, K. C., Martinez, A. S., Cokely, C. G., Tobey, E. A., Quittner, A. L., . . . Niparko, J. K. (2006). Speech Recognition at 1-Year Follow-Up in the Childhood Development after Cochlear Implantation Study: Methods and Preliminary Findings. *Audiology and Neurotology*, *11*(4), 259-268.
- Eisenberg, L. S., Johnson, K. C., Martinez, A. S., Desjardin, J. L., Stika, C. J., Dzubak, D. L., . . . Rector, E. P. (2008). Comprehensive Evaluation of a Child With an Auditory Brainstem Implant. *Otology & Neurotology*, *29*(2), 251-257. doi:10.1097/mao.0b013e31815a352d
- Geers, A., Brenner, C., & Davidson, L. (2003). Factors associated with development of speech perception skills in children implanted by age five. *Ear Hear*, *24*(1 Suppl), 24S-35S. doi:10.1097/01.aud.0000051687.99218.0f
- Geers, A., & Moog, J. S. (1989). *Evaluating speech perception skills: tools for measuring benefits of cochlear implants, tactile aids, and hearing aids*. . Boston College-Hill Press.
- Han, D., Liu, B., Zhou, N., Chen, X., Kong, Y., Liu, H., . . . Xu, L. (2009). Lexical tone perception with HiResolution and HiResolution 120 sound-processing strategies in pediatric Mandarin-speaking cochlear implant users. *Ear Hear*, *30*(2), 169-177. doi:10.1097/AUD.0b013e31819342cf
- Han, D., Zhou, N., Li, Y., Chen, X., Zhao, X., & Xu, L. (2007). Tone production of Mandarin Chinese speaking children with cochlear implants. *Int J Pediatr Otorhinolaryngol*, *71*(6), 875-880. doi:10.1016/j.ijporl.2007.02.008
- Health, T. M. o. (2001). *the Chinese disabled persons federatio, 2001 survey of Chinese disabled children (age 0-6)*. Beijing: Chinese Statistic Publication
- Hoff, E., & Tian, C. (2005). Socioeconomic status and cultural influences on language. *Journal of Communication Disorders*, *38*(4), 271-278.
- Kirk, K. I. (2000). In J. K. Niparko (Ed.), *Cochlear implants : principles & practices* (pp. 225-259). Philadelphia: Philadelphia : Wolters Kluwer Health/Lippincott Williams & Wilkins.
- Kirk, K. I. (2009). Cochlear implants : principles & practices. In J. K. Niparko (Ed.), *Clinical investigations of cochlear implant performance*. Philadelphia: Philadelphia : Wolters Kluwer Health/Lippincott Williams & Wilkins.

- Li, A., Wang, N., Li, J., Zhang, J., & Liu, Z. (2014). Mandarin lexical tones identification among children with cochlear implants or hearing aids. *Int J Pediatr Otorhinolaryngol*, *78*(11), 1945-1952. doi:10.1016/j.ijporl.2014.08.033
- Li, W., Dai, C., Li, H., Chen, B., & Jiang, Y. (2016). Factors impacting early cochlear implantation in Chinese children. *Eur Arch Otorhinolaryngol*, *273*(1), 87-92. doi:10.1007/s00405-015-3492-1
- Liang, Q., & Mason, B. (2013). Enter the dragon--China's journey to the hearing world. *Cochlear Implants Int*, *14 Suppl 1*, S26-31. doi:10.1179/1467010013z.00000000080
- Liu, H., Liu, S., Kirk, K. I., Zhang, J., Ge, W., Zheng, J., . . . Ni, X. (2015). Longitudinal performance of spoken word perception in Mandarin pediatric cochlear implant users. *International journal of pediatric otorhinolaryngology*, *79*(10), 1677-1682. doi:http://dx.doi.org/10.1016/j.ijporl.2015.07.023
- Liu, H., Liu, S., Wang, S., Liu, C., Kong, Y., Zhang, N., . . . Zhang, L. (2013). Effects of lexical characteristics and demographic factors on mandarin chinese open-set word recognition in children with cochlear implants. *Ear and Hearing*, *34*(2), 221-228. doi:10.1097/AUD.0b013e31826d0bc6
- Luo, X., Fu, Q. J., Wu, H. P., & Hsu, C. J. (2009). Concurrent-vowel and tone recognition by Mandarin-speaking cochlear implant users. *Hear Res*, *256*(1-2), 75-84. doi:10.1016/j.heares.2009.07.001
- Mao, Y., & Xu, L. (2016). Lexical tone recognition in noise in normal-hearing children and prelingually deafened children with cochlear implants. *Int J Audiol*, *1*-8. doi:10.1080/14992027.2016.1219073
- Moberly, A. C., Lowenstein, J. H., & Nittrouer, S. (2016). Early Bimodal Stimulation Benefits Language Acquisition for Children With Cochlear Implants. *Otol Neurotol*, *37*(1), 24-30. doi:10.1097/mao.0000000000000871
- Peng, S. C., Tomblin, J. B., Cheung, H., Lin, Y. S., & Wang, L. S. (2004). Perception and production of mandarin tones in prelingually deaf children with cochlear implants. *Ear Hear*, *25*(3), 251-264.
- Tan, J., Dowell, R., & Vogel, A. (2016). Mandarin Lexical Tone Acquisition in Cochlear Implant Users With Prelingual Deafness: A Review. *Am J Audiol*, *1*-11. doi:10.1044/2016_aja-15-0069
- Tao, D., Deng, R., Jiang, Y., Galvin, J. J., 3rd, Fu, Q. J., & Chen, B. (2015). Melodic pitch perception and lexical tone perception in Mandarin-speaking cochlear implant users. *Ear Hear*, *36*(1), 102-110. doi:10.1097/aud.0000000000000086
- Tong, M. C., & Lee, K. Y. (2009). Do Chinese speakers need a specialized cochlear implant system? *ORL J Otorhinolaryngol Relat Spec*, *71*(4), 184-186. doi:10.1159/000229295
- Wang, W., Zhou, N., & Xu, L. (2011). Musical pitch and lexical tone perception with cochlear implants. *Int J Audiol*, *50*(4), 270-278. doi:10.3109/14992027.2010.542490
- Xu, L., Chen, X., Lu, H., Zhou, N., Wang, S., Liu, Q., . . . Han, D. (2011). Tone perception and production in pediatric cochlear implants users. *Acta Otolaryngol*, *131*(4), 395-398. doi:10.3109/00016489.2010.536993
- Xu, L., Li, Y., Hao, J., Chen, X., Xue, S. A., & Han, D. (2004). Tone production in Mandarin-speaking children with cochlear implants: a preliminary study. *Acta Otolaryngol*, *124*(4), 363-367.
- Zheng, Y., Meng, Z. L., Wang, K., Tao, Y., Xu, K., & Soli, S. D. (2009). Development of the Mandarin Early Speech Perception Test: Children with Normal Hearing and the Effects of Dialect Exposure. *Ear and Hearing*, *30*(5), 600-612. doi:10.1097/AUD.1090b1013e3181b1094aba1098.
- Zheng, Y., Soli, S. D., Tao, Y., Xu, K., Meng, Z., Li, G., . . . Zheng, H. (2011). Early prelingual auditory development and speech perception at 1-year follow-up in Mandarin-speaking children after cochlear implantation. *International journal of pediatric otorhinolaryngology*, *75*(11), 1418-1426. doi:10.1016/j.ijporl.2011.08.005
- Zheng, Y., Soli, S. D., Wang, K., Meng, J., Meng, Z. L., Xu, K., & Tao, Y. (2009a). Development of the Mandarin pediatric speech intelligibility (MPSI) test. *Int J Audiol*, *48*(10), 718-728. doi:10.1080/14992020902902658

- Zheng, Y., Soli, S. D., Wang, K., Meng, J., Meng, Z. L., Xu, K., & Tao, Y. (2009b). A Normative Study of Early Prelingual Auditory Development. *Audiology and Neurotology*, *14*(4), 214-222.
doi:10.1159/000189264
- Zhou, N., Huang, J., Chen, X., & Xu, L. (2013). Relationship between tone perception and production in prelingually deafened children with cochlear implants. *Otol Neurotol*, *34*(3), 499-506.
doi:10.1097/MAO.0b013e318287ca86
- Zhu, S. F., Wong, L. L., & Chen, F. (2014). Development and validation of a new Mandarin tone identification test. *International journal of pediatric otorhinolaryngology*, *78*(12), 2174-2182.
doi:<http://dx.doi.org/10.1016/j.ijporl.2014.10.004>

Table 1. Summary of study characteristics and results on the trajectories of speech perception development in Mandarin-speaking children with CIs. M=mean, R=range, SD=standard deviation

Study	Participants demographics	Outcome measures	Overall results	Comments
X. Q. Chen et al. (2010)	N=259 Age at implantation (years): (M=1.8, R=0.7-3. 0). Test intervals: before CI, 1, 2, 3, 6, and 12 months after CI.	IT-MAIS/MAIS	The mean scores for the auditory skills improved significantly over time.	Omitted information (such as the presence of other impairments and dialect exposure)
Zheng et al. (2011)	N=39 Age at implantation: 1-2 years (n=4), 2-3 years (n=12), 3-4 years (n=12), 4-6 years (n=12) Test intervals: before CI, 3, 6, and 12 months after CI	IT-MAIS/MAIS MESP MPSI	Early speech perception results comparable to those of English-speaking counterparts Both Mandarin dialect exposure and the duration of pre-implant hearing aid use significantly impacted measures of early speech perception among children in Sichuan province.	Small sample size. Only descriptive data presented

Liu et al. (2015)	<p>N=105 Age at implantation (years): (M=3.1, R=0.9-15.5, SD=2.3). Test intervals: 6, 12, 24, 36, 48, 60, 72, and 84 months after CI.</p>	LNT, MLNT	<p>Even after 6 years of CI use, there was a significant deficit in open-set word-recognition performance, compared with their normal hearing peers. Age at implantation had significant effects on open-set word-recognition performance.</p>	<p>Floor and ceiling effects when using the LNT/MLNT before 12 months of CI use and after 48 months of CI use, respectively.</p>
Y. Chen, et al. (2016)	<p>N=80 Age at implantation (years): (M=2.6, R=0.9-5.0, SD=1.0) Pure-tone threshold average (dB HL): (M=105, R=81-115, SD=9.1) Maternal education level (years): (M=9.7, R=0-19, SD=3.6) Test intervals: before CI, 3, 6, and 12 months after CI</p>	IT-MAIS/MAIS MESP MPSI	<p>Early speech perception results comparable to those of English-speaking counterparts</p> <p>Better pre-implant hearing level, younger age at implantation, and higher maternal education level were significantly associated with better early speech perception during the first year of CI use</p>	<p>Uncertain how similar the MESP and MPSI are to their English versions, therefore, whether direct comparisons could be made</p>

Table 2. Results of the IT-MAIS/MAIS, the MESP, and the MPSI from X. Q. Chen et al. (2010), Zheng et al. (2011) and Y. Chen et al. (2016). “-” represents no data reported. The rows labeled “proportion” show the percentage of participants who could be tested with the MESP or the MPSI at each test interval. The rows labeled “mean category” report the mean category score obtained up to a maximum of 4 categories for the LV-MESP and 6 categories for the SV-MESP. The rows labeled “mean test condition” report the mean test condition achieved for the MPSI (i.e., scores significantly higher than chance).

		Pre-implant		Post-implant	
Study		Baseline	3 months	6 months	12 months
X. Q. Chen et al. (2010)					
IT-MAIS/MAIS	Mean score	25%	52%	72%	83%
	Range	3-50%	26-70%	57-97%	63-100%
	SD	-	-	-	-
Zheng et al. (2011)					
IT-MAIS/MAIS	Mean score	30%	52%	68%	82%
	Range	-	-	-	-
	SD	23.6%	24.4%	19.4%	13.7%
LV-MESP	Proportion	43.6%	-	61.5%	30.8%
	Mean category	1.6	-	2.2	2.3
SV-MESP	Proportion	0	-	10.3%	53.8%
	Mean category	-	-	3	4.8
MPSI-Q	Proportion	0	-	10.3%	33.9%
	Mean score	-	-	33%	66%
MPSI-N	Proportion	-	-	-	30.8%
	Mean test condition	-	-	-	+10 dB S/N
Y. Chen et al. (2016)					
IT-MAIS/MAIS	Mean score	16%	46%	63%	80%
	Range	0-57%	10-79%	14-90%	53-100%
	SD	21%	19%	22%	15%

LV-MESP	Proportion	21.1%	50%	55.9%	40%
	Mean category	1.4	1.8	2.1	2.8
SV-MESP	Proportion	0	11.1%	32.4%	60%
	Mean category	-	4.8	4.0	4.7
MPSI-Q	Proportion	0	8.3%	20.6%	56.7%
	Mean score	-	61%	42%	60%
MPSI-N	Proportion	-	-	-	56.7%
	Mean test condition	-	-	-	+10 dB S/N

” represents time post-implant that a child could demonstrate the skill.

Skills	3 months	6 months	12 months	24 months	48 months
Major improvement in prelingual auditory skills					
Able to identify some closed-set words					
Emerging ability to identify closed-set vowels and consonants					
Able to derive meaning from closed-set sentences in quiet and in noise					

Emerging ability to identify lexical tones

above chance level

Major improvement in open-set word

recognition

High level of open-set word recognition

skill

Table 4. Summary of study characteristics and results from literatures regarding tone perception. M=mean, R=range, SD=standard deviation

Study	Participant demographics	Outcome Measured	Overall results
Han et al. (2009)	N=20 Age at test (years): (M=7.6, R=3.5-16.5, SD=4.1) Age at implantation (years): (M=5.21, R=1.3-13.5, SD=3.8) Duration of CI use (years): (M=2.4, R=0.6-4.2, SD=1.2)	A two-alternative, forced-choice tone contrast (identification) test	M=74%-82%, chance=50%
Xu et al. (2011)	N=25 Age at test (years): (M=9.5, R=2.1-21.5, SD=5.4) Age at implantation (years): (M=6.4, SD=5.2). CI use (years): (M=3.1, SD=2.5)	A two-alternative forced-choice tone contrast (identification) test	M=71%, R=50 to 97% (chance=50%).

Zhou et al. (2013)	<p>N=107</p> <p>Age at test (years): (R=2.4-16.2)</p> <p>Age at implantation (years): (M=4.0, R=1.1-13.0, SD=2.7)</p> <p>Duration of CI use (years): (M=1.3, R=0.1-4.9, SD=1.0)</p>	<p>A two-alternative forced-choice tone contrast (identification) test</p>	<p>Performance of the CI group ranged from chance to perfect (M=67%, SD=13%, chance=50%).</p> <p>No statistical differences were found between the performance of the six contrasts</p>
Y. Chen et al. (2014)	<p>N=96</p> <p>Age at test (years): (M=4.5, R=2.4-7.0, SD=1.0)</p> <p>Age at implantation (years): (M=2.7, R=0.7-5, SD=1.0)</p> <p>Duration of CI use (years): (M=1.6, R=0.8-4.4, SD=0.7)</p>	<p>Tone perception category in the MESP- a two-alternative forced-choice tone contrast (identification) test</p>	<p>M=77% (SD=13%; chance=50%). Tone 2/Tone 3 was the most difficult tone contrast to identify</p>
A. Li et al. (2014)	<p>N=20</p> <p>Age at test (years): (M=8.6, R=6.0-11.1)</p> <p>Age at implantation (years): (M=4.1, R=2.0-6.8)</p> <p>Duration of CI use (years): (M=4.4, R=3.7-6.6)</p>	<p>A two-alternative forced-choice tone contrast (identification) test</p>	<p>M=72%, R=54%-83%).</p> <p>Significant higher scores were found with the tone pairs that contained tone 4</p>
Tao et al. (2015)	<p>N=21</p> <p>Age at test (years): (M=10.8, R=6-16)</p> <p>Age at implantation (years): (M=4.3, R=2-12)</p> <p>Duration of CI use (years): (M=6.5, R=2-11)</p>	<p>A four-alternative, forced-choice tone recognition test</p>	<p>M=81%, chance=25%</p>

Mao et al. (2016)	N=66 Age at test (years): (M=5.3, R=2.13-17.20, SD=3.4) Age at implantation (years): (M=3.0, R=0.6- 16.5, SD=3.1) Duration of CI use (years): (M=6.5, R=0.2- 8.5, SD=2.0)	A two-alternative, forced-choice tone contrast (identification) test Test condition: quiet, +12, +6, 0, and -6 dB S/N.	Children with CIs exhibited a marked deficit in tone identification in noise and were more susceptible to noise than their NH peers.
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Table 5. Summary of study characteristics and results from the literature regarding factors influencing speech perception (Note: AT=age at testing, DCI= duration of CI use, AI=age at implantation, MEL=maternal education level, HL=pre-implant hearing level, HAT= a hearing aid trial).

Study	Outcome Measured	Participant demographics M=mean, R=range, SD=standard deviation	AT	DCI	AI	MEL	HL	HAT
X.Q. Chen et al. (2010)	Prelingual auditory development	N=259 Age at implantation (years): (M=1.8, R=0.7-3.0). Test intervals: before CI, 1, 2, 3, 6, and 12 months after CI.		✓*	✓*			✓*
Liu et al. (2015)	Open-set word recognition	N=230 Age at test (years): (M=8.0, R=2.8-17.5, SD=3.4) Duration of CI use (years): (M=4.1, R=1.1-11.8, SD=2.7) Age at implantation (years): (M=3.9, R=0.9-16.0, SD=3.0)		✓*	✓*			
Zhou et al. (2013)*	Lexical tone perception	N=110 Age at test (years): (R=2.4-16.2) Age at implantation (years): (M=4.0, R=1.1- 13.0, SD=2.7)	✓	✓*	✓*			

Y. Chen et al. (2014)	Lexical tone perception	N=96 Age at test (years): (M=4.5, R=2.4-7.0, SD=1.0) Age at implantation (years): (M=2.7, R=0.7-5.0, SD=1.0)	✓	✓	✓	✓	✓
	Sentence perception in quiet	Duration of CI use (years): (M=1.6, R=0.8-4.4, SD=0.7) Maternal education level (M=10.6, R=0-19, SD=3.6)	✓*	✓	✓*	✓	✓
	Sentence perception in noise		✓*	✓	✓*	✓*	✓*
Liu et al. (2015)	Open-set word recognition	N=105 Age at implantation (years): (M=3.1, R=0.9-15.5, SD=2.3). Test intervals: 6, 12, 24, 36, 48, 60, 72, 84 months after CI.	✓*	✓*			
Y. Chen et al. (2015)	Overall speech perception (combining results from the IT-MAIS/MAIS, the MESP, and the MPSI to generate a single score using the principal component analysis)	N=115 Age at test (years): (M=4.2, R=2.5-7.1, SD=1.1) Age at implantation (years): (M=2.7, R=0.7-5.0, SD=1.1) Duration of CI use (years): (M=1.4, R=0.8-3.2, SD=0.7)	✓*	✓*	✓*	✓	✓

Y. Chen et al. (2016)*	Overall speech perception (combining results from the IT-MAIS/MAIS, the MESP, and the MPSI to generate a single score using the principal component analysis)	N=80 Age at implantation (years): (M=2.6, R=0.9-5.0, SD=1.0) Pre-implant hearing level (dB) : (M=105, R=81-115, SD=9.10) Maternal education level (years): (M=9.7, R=0-19, SD=3.6) Test intervals: before CI, 3, 6, and 12 months after CI.	✓*	✓*	✓*	✓
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“✓” factors examined in the study but not significantly affected speech perception. “✓*” factors significantly affected speech perception. *Zhou et al. (2013) also examined several other factors besides the age at testing, age at implantation, and duration of CI use. These factors are family variables (family size and household income), cochlear implant variables (implant type, processor type, and speech processing strategy), and educational variables (communication mode and duration of speech therapy). However, none of these factors significantly affected tone perception performance except for age at implantation and duration of CI use. * Y. Chen et al. (2015) and Y. Chen et al. (2016) shared some participants but they were sampled at different durations of CI use. Participants from Y. Chen et al. (2016) had been using CIs for no more than one year while participants from Y. Chen et al. (2015) had been using CIs for more than one year.
