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REVIEW ARTICLE

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

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ABSTRACT

Objective: This study aimed to systematically review and critically appraise the literature describing the phonetic characteristics and accuracy of the consonants, vowels and tones produced by Mandarin-speaking children with cochlear implants (CIs).

Design: The protocol in this review was designed in conformity with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement. EBSCOhost, PubMed, Scopus, PsycINFO, ProQuest Central databases were searched for relevant articles which met the inclusion criteria.

Study sample: A total of 18 journal papers were included in this review.

Results: The results revealed that Mandarin-speaking children with CIs perform consistently more poorly in their production of consonants, in particular on fricatives, have a smaller and less well-defined vowel space, and exhibit greater difficulties in tone realisation, notably T2 and T3, when compared to their normal-hearing (NH) peers. The results from acoustic and accuracy analyses are negatively correlated with CI implantation age, but largely positively correlated with hearing age.

Conclusions: Findings of this review highlight the factors that influence consonant, vowel and tone production in Mandarin-speaking children with CIs, thereby providing critical information for clinicians and researchers working with this population.

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Speech production; consonant; vowel; tone; cochlear implant; children; Mandarin

1. Introduction

China has the world's largest population (approximately 1.4 billion) and approximately 21 million people are reported with hearing impairment in the official figure (China Disabled Persons' Federation 2012). Of these, more than half a million children and adolescents aged 0–18 years suffer from hearing impairment and the majority of young children (0–3 years old) have severe to profound hearing loss (Li, Bunta, and Tomblinl. 2017; China Disabled Persons' Federation 2008). In addition, the estimated figure of newborns with congenital hearing impairment is rising at the rate of 0.1%–0.3% annually in China (Finitzo, Albright, and O'Neal 1998; Kral and ODonoghue 2010; Schimmenti et al. 2011; Zhang et al. 2013). A large body of evidence indicates that severe to profound hearing loss has a significant negative impact on the speech and language development of prelingual children and results in developmental delays across all language domains (Davis, Davis, and Mencher 2009, 1–28).

Cochlear implants (CIs) are considered to be one of the most effective interventions for children with severe to profound sensory hearing loss in terms of the development of speech perception, speech recognition and language skills (Carney and Moeller 1998; Korver et al.- 2017). With advanced technological solutions for early diagnosis and cochlear implantation surgery over the past 20 years, together with recent favourable policies by the Chinese government (Liang and Mason 2013), cochlear implantation has seen substantial increases for Chinese children with severe to profound hearing loss. Chen et al. (2016) reported that 18,600 children had cochlear implantation funded by the Chinese government until 2015. The figure of child recipients of CIs is expected to increase further in the future as implanting skills are becoming more widespread and the age at which implantation can take place is decreasing, with suggestions that children as young as 3 months may soon be able to receive CIs (Colletti, Mandalà, and Colletti 2012; Miyamoto et al. 2017). As a result, speech and language habitation also becomes feasible at an earlier stage for children with severe to profound hearing loss.

With regards to the language environment of children with CIs, China has 56 recognised ethnic groups and more than 290 living languages, including Cantonese, Hakka, and Tibetan, to name but a few (National Bureau of Statistics 2010; Olivet Seminary 2020). Mandarin (also referred to as Putonghua) is the only official national language of China (Ministry of Education of the People's Republic of China 2009) and the country's most commonly spoken one accounting for 70% of the population of China (Olivet Seminary 2020).

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The phonological system of Mandarin includes 22 consonants (i.e. /p pʰ t tʰ k kʰ m n ŋ f s ɕ ʂ x ʐ ts tsʰ tɕ tɕʰ tʂ tʂʰ l), 22 vowels (i.e. /i u y o ɤ ɚ ɛ ə a ɿ ʅ ai ei ao oʊ ia iɛ ua uo yɛ iao ioʊ uai uei), and 4 lexical tones (i.e. high-level tone (T1), high rising tone (T2), falling rising tone (T3), high falling tone (T4)) and a neutral tone (T0) (Chen 2000; Law and So 2006; Yip 2002).

Children's phonological development is typically explored in two principal ways. On the one hand, studies have examined speech productions auditorily using various approaches to phonetic transcription (Howard and Heselwood 2002). These are then usually expressed in terms of an analysis of their accuracy and error patterns (Montanari, Mayr, and Subrahmanyam 2018, 2020; Shriberg et al. 1997; Sosa and Bunta 2019). Alternatively, children's productions have been analysed acoustically. These studies provide a more precise record of children's speech patterns, but are usually confined to individual segments or tones (e.g. Mayr and Siddika 2018; McCarthy et al. 2014), and may not always reflect what is perceptually salient.

In Mandarin, tones constitute the earliest area of development in monolingual children with normal hearing (NH), followed by vowels with consonants acquired last (So and Zhou 2000; Tang et al. 2019a; Hua and Dodd 2000). Overall, children with NH will have acquired most of the tones and phonemes in the Mandarin inventory by the age of 5 (Li and To 2017; So and Zhou 2000). In contrast, the speech development of children with CIs appears to follow a different trajectory. Chuang et al. (2012) reported that tones were only produced accurately in 76.1% of instances by children with CIs with a hearing age of approximately 4 years, with accurate consonant production in 67.7% of instances and accurate vowel production in 81.6% of instances. Moreover, the vowel spaces and tone contours of children with CIs were smaller and flatter than those of their NH peers (Tang et al. 2019b; Yang et al. 2015). Therefore, a good understanding of the specific phonological development patterns of Mandarin-speaking children with CIs is essential for the provision of good speech support for them.

Speech production constitutes an essential outcome measure in the assessment of children with CIs. However, there are few studies that have examined speech production in Mandarin-speaking children with CIs, with most published work focussing on expressive vocabulary development and speech intelligibility (Han et al. 2007; Li et al. 2020). Where studies do report speech production measures in Mandarin-speaking children with CIs, they often show conflicting results and are based on different materials and methods (Chuang et al. 2012; Deroche et al. 2019; Han et al. 2007; Mao, Chen, and Xu 2017; Tseng, Kuei, and Tsou 2011). For instance, Han et al. (2007) reported that Mandarin-speaking children with CIs performed better on T3 than T2 using a perceptual analysis. However, Mao, Chen, and Xu (2017) reported the opposite result using a neural network approach, with greater accuracy on T2 than T3. Such examples illustrate that it is difficult to draw firm conclusions across studies with disparate materials and methodologies. Besides, the different findings across studies on children with CIs' Mandarin productions may also be caused by issues pertaining to the broader research methodology. To the best of our knowledge, no systematic review has thus far specifically focussed on speech production in Mandarin-speaking children with CIs, nor the factors that help or hinder target-like patterns.

This review aims to bridge that gap in the literature by critically appraising the reported outcomes for consonant, vowel and tone development in Mandarin-speaking children with CIs for the first time, and by considering the factors that facilitate or hinder acquisition, such as hearing age or chronological age. Moreover, this review also intended to examine the methodology used of studies for speech production assessments in Mandarin-speaking children with CIs systematically.

2. Methods

2.1. Search strategy

The protocol in this review was designed in conformity with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Moher et al. 2009). The search strategy was developed and executed initially in November 2020. To include updated publications, the latest literature search was executed in March 2021. Five databases, i.e. EBSCOhost, PubMed, Scopus, PsycINFO, ProQuest Central database were searched for relevant articles. Various combinations of the keywords "Mandarin" (or "Putonghua") AND "speech production" (or "consonant production" or "vowel production" or "tone production") AND "children" (or "child" or "paediatric") AND "cochlear implant" (or "cochlear implants" or "cochlear implantation") were used as search items.

2.2. Inclusion and exclusion criteria

Studies were included in the review if (1) they had been published between January 1990 and March 2021, (2) they included CI users under 18 years of age as participants, (3) they focussed on measuring the production of consonants, vowels, and tones in monolingual Mandarin speaking-children with CIs and (4) full-text versions were available in scholarly journals. We deliberately adopted a broad age range to ensure all relevant studies on paediatric CI users are included. Studies that included a combination of children who used HAs and CIs were also included if participant details and results from these studies could be clearly extracted. Moreover, studies on bilingual or multilingual children were only considered if they also included Mandarin-speaking monolingual children with CIs, and only the patterns of the latter were considered. Finally, this review only focussed on children with CIs' speech production. As a result, studies featuring speech intelligibility and speech perception were only included if they also addressed consonant, vowel or tone production.

All studies were identified by the first author (J.L.) following the above search strategy and inclusion criteria. The process was subsequently screened and confirmed by the two other authors (R.M; F.Z.).

3. Results

3.1. Procedure for retrieval of studies and summary of the main features of the included studies

A total of 738 relevant records were found after the initial literature search in November 2020 and the latest search on 18th March 2021 (see Supplementary Figure 1). Of these, 231 were duplicates, 37 were not primary research papers (e.g. review papers, editorials), and one was not in English, leaving 469 records after initial screening. In the process of de-duplication, we followed Kwon et al.'s (2015, 185) gold standard approach.

Accordingly, citations were considered duplicates if they shared the same author, title, date of publication, volume, issue and start page information. On the other hand, citations from the same authors that report different analyses, outcomes and/or aims in the same sample were not considered duplicates. Following scrutiny of the abstract and full-text versions of these, 451 additional articles were excluded based on the stipulated eligibility criteria and a total of 18 eligible studies were eventually included.

Of 18 included studies, 10 primarily focus on tone production in Mandarin-speaking children with CIs, 2 on consonant production, 4 on vowel production, and two cover two or more areas of speech production. A total of 10 studies were conducted in Beijing, 5 in Taipei and one each in Guangzhou, Tainan, and Beijing & Shanghai. This geographical diversity is significant as it coincides with different varieties of Mandarin (Szeto et al. 2018).

All included studies employed non-randomized control trial designs. Of these, 13 papers involved comparisons of children with CIs and children with NH while 5 studies only included children with CIs. Four studies are descriptive, 8 studies used a cross-sectional design, while the remaining 6 used a cohort design (3 prospective, 3 retrospectives).

3.2. Consonant production in children with CIs

The 4 included studies (Chuang et al. 2012; Yang et al. 2017; Peng, Weiss, et al. 2004b; Tseng, Kuei, and Tsou 2011) on consonant production are shown in Supplementary Table 1. Of these, two only included children with CIs, the remaining two also contained an NH control group. Two studies involved an auditory analysis (i.e. Chuang et al., 2012; Peng, Weiss, et al. 2004b), one an acoustic analysis (Tseng, Kuei, and Tsou 2011), and one included both (Yang et al. 2017). Overall, they showed that the children with CIs had different developmental patterns. The auditory and acoustic analyses show more protracted consonant development in children with CIs and lower accuracy rates than in children with NH as well as less distinct patterns across the categories. However, the relative chronology of early to late-acquired consonants is comparable to typical developmental patterns. In what follows, the results of these are discussed in detail.

The results of the auditory-based studies revealed greater accuracy by children with NH than children with CIs. Specifically, Chuang et al. (2012) showed that children with CIs aged around 6 years were outperformed in consonant accuracy by their NH age-sex-education level matched peers (67.7% vs. 98.0%, $p < 0.002$) in a reading task that encompassed 74 two-word items, including 21 word-initial consonants. Similarly, the children with CIs aged around 5;2 in Yang et al. (2017) were significantly less accurate on 4 late-acquired fricatives than their NH peers (/f/: (CI 61.1% vs NH 100%); /ɕ/: (CI 60% vs. NH 97.7%); /ʂ/: (CI 39.5% vs. NH 98.2%) and /s/: (CI 10.8% vs. NH 89%)). Interestingly, while both the children with CIs and with NH mainly substituted fricatives with stops, the children with CIs showed more diverse substitution patterns, including glides and deletions. Additionally, they not only replaced the four fricatives with other Mandarin consonants but also made use of sounds that do not occur in the language. For example, alveolar /s/ was substituted with the palatal fricative /ç/. In contrast, the children with NH only substituted the fricatives with homorganic affricates or Mandarin fricatives at a different place of articulation. Finally, Peng, Weiss, et al. (2004b) presents consonant accuracy scores from children with CIs, however, they did not include an NH control group. The results revealed similar average accuracy rates overall on the 21 word-initial consonants as in the studies just discussed (i.e. 57.9%) with the greatest accuracy on plosives (77.8%), followed by nasals (67.5%), affricates (50.2%) and fricatives (45.0%) with /l/ and /ʐ/ the least accurate (37.5%).

Two studies examined Mandarin consonants acoustically (Yang et al. 2017; Tseng, Kuei, and Tsou 2011). Yang et al.'s (2017) study of fricative productions revealed that children with CIs did not distinguish the four target categories in terms of the acoustic measures taken (i.e. duration, spectral peak location, normalised amplitude, spectral mean, spectral variance, spectral skewness and spectral kurtosis) while the children with NH exhibited significant differences between them. Moreover, compared to the children with NH, the children with CIs had a lower normalised amplitude, lower peak location in /f s ɕ/, lower spectral energy for /s/ and less consistency. Tseng, Kuei, and Tsou (2011) extracted plosives and affricates from the produced sentences and showed that none of the children with CIs could finish the five articulation phases (i.e. the occlusion, the transient, the friction, the aspiration and the transition phases) that occur in typical productions of plosives and affricates (Lieberman and Blumstein 1988; Kent and Read 2002). Additionally, over 80% of the participants with CIs did not have clear boundaries within the plosives or affricates except for the transition phase (Tseng, Kuei, and Tsou 2011).

3.3. Vowel productions in children with CIs

Supplementary Table 2 summarises the studies on vowel production in Mandarin-speaking children with CIs. All 6 included studies (Chuang et al. 2012; Tseng, Kuei, and Tsou 2011; Wang et al. 2017; Yang et al. 2015; Yang and Xu 2017, 2021) investigated the vowel productions of children with CIs and NH acoustically and two studies, i.e. Chuang et al. (2012), and Yang and Xu (2021) also ran an auditory analysis of vowel productions. With regard to the auditory analysis, the two studies showed that children with CIs performed significantly less accurately in vowel production than their NH peers in both a word repetition task and a word production task (Chuang et al. 2012; Yang and Xu 2021). Moreover, the acoustic analyses revealed longer vowel durations, a smaller vowel space, more variation in vowel realisations and greater acoustic overlap across vowel categories in children with CIs than with NH.

3.3.1. Characteristics of formant frequencies in children with CIs

Three studies examined the formant frequencies of the peripheral vowels /i a u/, one study focussed on diphthong and triphthong realisations, and one study covered all three types of vowels. Specifically, Wang et al. (2017) asked 15 participants with NH and 30 participants at 1, 3, 6, 12, 18 and 24 months post-implantation to produce the three corner vowels /i a u/. The results indicated significant differences in formant frequencies across the groups, notably on the second formant frequency (F2) value for /i/, which was significantly lower in the children with CIs, and /u/, which was significantly higher in the children with CIs. Moreover, the children with CIs showed significant changes over time. Thus, after 12 months of CI use the first formant frequency (F1) of /a/ and F2 of /i/ significantly increased and the F2 of /u/ gradually decreased, resulting in larger vowel space, but no significant change was found after 18 months of CI use. Note that the study did not involve any vowel normalisation procedure, and hence did not control for physiological differences in vocal tract size, both across individuals and within the same individuals over time. In contrast, in Yang et al.'s (2015) study the F1 and F2 values of /i a u/ were converted into z-scores (Lobanov, 1971). The results indicated that the children with CIs had significantly lower F2 values for /i/ than the children with NH. These findings were subsequently supported by their later research (Yang and Xu 2021). Thus, in a word repetition task, which targeted 20 Mandarin vowels (i.e., /a i u y ɤ ɿ ʅ ai ei ia ie ye ua uo au ou iau iou uai uei/), children with CIs ($n = 25$) produced /a/ with significantly lower F1 values and /u/ with significantly higher F1 values than children with NH ($n = 20$). Chuang et al. (2012), in turn, showed that mel-converted F2 ranges are for /i/ and /u/ were significantly smaller for children with CIs than their NH peers in a vowel phonation task and a sentence production task. With regard to diphthong and triphthong productions, Yang and Xu (2017) captured formant movement across the entire vocalic trajectory. Thus, they measured the F1 and F2 frequencies of /aɪ aʊ uo iɜ iaʊ ioʊ/ at nine equidistant points in 14 paired children with CIs and 14 matched children with NH. The results showed differences in vowel-inherent spectral change across the two groups, with children with CIs exhibiting greater acoustic space and differences in the direction and curve variation of diphthong and triphthong trajectories (Yang and Xu 2017). Yang and Xu (2021) indicated similar results in a later study with children with CIs displaying distinct formant trajectories on diphthongs and triphthongs. Specifically, their realisations showed less separated vowel height on diphthongs, overarticulation on triphthongs, and reduction of triphthongs to diphthongs and of diphthongs to monophthongs. These results differed from the patterns found in the children with NH at the group level, despite some individual children with CIs realising their vowels much like the NH controls. Together, the formant frequency analysis showed that vowels produced by children with CIs are qualitatively different from those produced by children with NH, both for steady-state vowels and those that involve dynamic changes across their trajectories.

3.3.2. Vowel space, variability and acoustic distances in children with CIs

The vowel space of children with CIs and with NH was calculated in three studies on the basis of normalised F1 and F2 values of corner vowels. Tseng, Kuei and Tsou's. (2011) study of 15 children with CIs aged 3;7 to 12;5 and one child with NH showed that larger vowel spaces correlated with clearer vowel contrasts and higher speech intelligibility scores, as judged by trained linguists on a 5-point scale. Similar results were obtained in the studies by Chuang et al. (2012), Yang et al. (2015) as well as Yang and Xu (2021) which are based on a vowel phonation task, a picture naming task and a word repetition task respectively. Furthermore, these three studies showed that the vowel space of children with CIs was significantly smaller than that of children with NH.

In addition to the analysis of vowel spaces, some studies examined whether children with CIs differ from ones with NH in terms of the precision of their vowel categories, as assessed via vowel ellipses, which is based on scatterplots of the rescaled normalised F1 and F2 midpoint values of vowels, and in terms of acoustic distances. Thus, Yang et al. (2015) analysed the 7 monophthongs of Mandarin and demonstrated that children with CIs (mean age around 5 years and 2 months) had substantially larger vowel ellipses (2-6 times) than children with NH. In addition, even though the children with CIs were able to separate the three peripheral vowels /i a u/ acoustically, the substantial overlap was still evident in the acoustic vowel space of the non-peripheral vowels /y ɤ ɿ ʅ/, while the NH controls showed clearly distinct ellipses for all vowels (Yang et al. 2015). Moreover, the CI group revealed different patterns and larger mean acoustic distances across the vowel categories than the children with NH (Yang et al. 2015). Yang and Xu (2021) examined older children with CIs (mean age around 7 years and 3 months) and reported that the CI group showed more overlap and approximately two times larger ellipses for each of the 7 monophthongs (i.e., /a i u y ɤ ɿ ʅ/) than the NH group. Finally, Yang and Xu (2017, 2021) showed that the acoustic distances of diphthongs and triphthongs were larger in the children with CIs than the ones with NH and that the spectral rate of change of some diphthongs and triphthongs, specifically /uo iaʊ ioʊ/, in the participants with CIs was consistently smaller than in their NH peers. In sum, the results suggest that children with CIs have less precise vowel categories and exhibit greater variability.

3.3.3. Vowel duration in children with CIs

Studies examining vowel quantity indicate that children with CIs have longer vowel durations than children with NH irrespective of vowel category (Chuang et al. 2012; Yang et al. 2015; Yang and Xu 2017, 2021). Nevertheless, Yang and his colleagues demonstrated that the relative order of durations across vowel categories was the same for children with CIs and NH (Yang et al. 2015; Yang and Xu 2017). Thus, in both /y/ had the longest duration and /ʅ/ the shortest.

3.4. Tone production in children with CIs

Supplementary Table 3 summarises the eleven studies concerned with tone production by Mandarin-speaking children with CIs (Chuang et al. 2012; Han et al. 2007; Li et al. 2018; Mao, Chen, and Xu 2017; Peng, Tomblin, et al. 2004a; Xu et al. 2004; Xu et al. 2011; Zhou and Xu 2008; Zhou et al. 2013; Deroche et al. 2019; Tang et al. 2019b). They either involve judgments of accuracy by professional speech pathologists and lay native speakers or objective measures. The latter include acoustic analysis of tonal patterns as well as neural network analysis, in which tonal productions of children with NH functioned as the input to mathematical models that test tone production of children with CIs (Zhou et al. 2013). Overall, children with CIs have significantly lower accuracy rates in tonal production and different error patterns than children with NH. Moreover, the acoustic analysis indicated less distinguished acoustic values between the 4 lexical tones as well as flatter tone contours in children with CIs than children with NH. Further details are provided below.

3.4.1. Tone production accuracy in children with CIs

A total of nine studies examined tone production accuracy in children with CIs (Chuang et al., 2012; Han et al., 2007; Li et al., 2018; Mao, Chen and Xu, 2017; Peng, Tomblin, et al., 2004a; Xu et al., 2004; Xu et al., 2011; Zhou and Xu 2008; Zhou et al. 2013), six of which also included objective measures. Using a tonal performance rating approach, Xu et al. (2011) reported that their 9-year-old children with CIs from Beijing and Shanghai with a hearing age of around 3 years had a low tone accuracy score (52%) based on productions elicited in a picture-naming task. Similar results are reported in Peng, Tomblin, et al.'s (2004a) study of 9-year old children with CIs from Taipei (mean tone accuracy score: 53%). In contrast, Li et al.'s (2018) study which included children with CIs with a much younger CI implantation age (mean implantation age at 2.5 years old) and longer device use experience (mean age at 10.8 years old) reported a substantially higher tonal accuracy rate (i.e. 90% correct), as assessed in a word production task judged by two speech pathologists. Other studies have compared the accuracy of tone production in children with CIs with that of children with NH. They showed superior accuracy rates in the children with NH, but also revealed substantial variation across both sets of children, with the accuracy scores of children with CIs ranging from 46.8% to 76.1%, and those of children with NH from 78.0% to 99.7% (Chuang et al. 2012; Han et al. 2007; Mao, Chen, and Xu 2017; Xu et al. 2004; Zhou and Xu 2008; Zhou et al. 2013). In sum, the studies reviewed suggest that tonal accuracy scores are lower in children with CIs than children with NH, as well as negatively correlated with CI implantation age and positively correlated with the duration of CI use. Thus, children who are implanted earlier and have longer CI use experience tend to produce more target-like tones. These findings are consistent across geographically distinct Mandarin-speaking areas.

3.4.2. Order of tone accuracy and error patterns in children with CIs

A number of studies have examined the order in which Mandarin tones are acquired by children with CIs (Han et al. 2007; Li et al. 2018; Mao, Chen, and Xu 2017; Peng, Tomblin, et al. 2004a; Zhou and Xu 2008; Zhou et al. 2013). They indicated that children with CIs performed consistently better on T1 (accuracy range 62.13%–98.58%) and T4 (accuracy range 50.6%–96.59%) than T2 (accuracy range 19.4%–81.54%) and T3 (accuracy range 41.1%–83.62%), with most studies exhibiting the following order of tonal accuracy: T1 > T4 > T3 > T2 (Zhou and Xu 2008; Zhou et al. 2013; Li et al. 2018; Han et al. 2007). Note, however, that in Peng, Tomblin, et al.'s (2004a) study, children with CIs performed virtually identically on T1 and T4, while they were superior on T2 than T3 in the other two included studies (Zhou and Xu 2008; Mao, Chen, and Xu 2017). Interestingly, these studies differed methodologically, with Peng, Tomblin, et al. (2004a) using a 5-level rating approach, and Zhou and Xu (2008), Mao, Chen, and Xu (2017) using neural network analysis. Together, the findings suggest that children with CIs are generally more accurate in their production of T1 and T4 than T2 and T3, but that a more fine-grained breakdown of their development on Mandarin tones is affected by methodological differences across the studies reviewed.

Finally, a few studies not only reported accuracy rates but also error patterns. Of these, the most common concerned children with CIs' attempted productions of T2, T3 and T4 being identified as instances of T1. In Mao, Chen, and Xu (2017) and Zhou and Xu (2008), account for over 30% of children's errors on T2 to T4. These patterns are not as commonly reported in children with NH who tend to confuse T2 and T3 (Zhou and Xu 2008). This suggests that children with CIs exhibit different error patterns in their productions of Mandarin tones than children with NH (Zhou and Xu 2008; Mao, Chen, and Xu 2017).

3.4.3. Tone contours and tone space in children with CIs

Many studies have examined tone productions in children with CIs acoustically, extracting fundamental frequency (f_0) patterns from spectrographic displays. Overall, they indicate different f_0 ellipses, based on the scatterplots of rescaled normalised f_0 patterns, and tone contours in children with CIs than their NH counterparts, as well as greater individual variation (Deroche et al. 2019; Xu et al. 2004; Tang et al. 2019b; Zhou and Xu 2008; Zhou et al. 2013). Specifically, Zhou and Xu (2008) compared f_0 ellipses, based on f_0 onset and offset patterns, in the tone productions of 14 children with CIs with a mean age of 5;2 and 61children with NH. The results showed smaller ellipses and larger areas of overlap in the CI group than the NH group. This finding was further confirmed in a later study with a larger sample size of participants with CIs ($n = 278$) and participants with NH ($n = 170$) (Zhou et al. 2013). Xu et al.'s (2004) study, in turn, which extracted f_0 curves with normalised duration, reported that the 4 children with CIs in their study with an average implantation age of 3;4 managed to produce similar T4 contours as their NH peers, but their T1, T2 and T3 contours were indistinguishable from each other. Using a similar approach, Tang et al. (2019b) investigated word production in 72 CI recipients who had a range of different implant ages and hearing ages in comparison to 44 NH controls. Their results revealed that children with CIs with an implantation age of <2 years could produce comparable lexical tone contours to those of children with NH while the older implantation age groups (2–3yrs, 3–4yrs and 4–5yrs) illustrated flatter f_0 curves than children with NH. An early implantation age is nevertheless not always a guarantee for target-like tone contours, even on the earlier acquired tones (T1 and T4). Thus, Deroche et al. (2019) demonstrated that participants with CIs with an implantation age of 2;9 shortened T4 or prolonged T1 to enhance their contrast, while children with NH focussed exclusively on marking distinct f_0 contours (Xu et al. 2004; Tang et al. 2019b). Finally, while most studies were confined to an analysis of lexical tones, Tang et al.'s (2019b) study also examined neutral tone and sandhi tone production. The results indicated that the children with CIs in the study had difficulties in producing the pitch variation required for sandhi tones and produced neutral tones with a shorter duration than children with NH. In line with the studies cited above, early implanted children with CIs (i.e. <2 years) outperformed later implanted ones (2–3 years, 3–4 years and 4–5 years) in their use of pitch variation but not duration control.

4. Discussion

The results above indicate that Mandarin-speaking children with CIs perform more poorly in their speech productions compared with their NH peers. Moreover, children with CIs with younger implantation ages and longer duration of CI use perform better. However, the findings of the reviewed studies also indicate that variation in the outcome variables examined is mediated by methodological differences. Hence, it is important to consider how both factors relating to individual differences, such as implantation age, CI use duration, language environment, and those relating to research methodology, such as the materials used and the approach to age matching, have influenced speech production accuracy.

4.1. Individual differences factors affecting speech production in children with CIs

The included studies reported significantly better consonant, vowel and tone production performance in children with CIs with younger implantation ages and longer CI use duration (e.g.

Yang et al. 2015; Zhou et al. 2013; Peng, Tomblin, et al., 2004a; Peng, Weiss, et al. 2004b; Xu et al. 2011; Han et al. 2007; Tang et al. 2019b; Xu et al. 2004). Both early implantation age and longer hearing experience have been widely reported as beneficial for children with CIs' development on segmental and suprasegmental features, see e.g. studies on English, Cantonese and Spanish (Connor et al. 2006; Dettman et al. 2016; Lehnert-LeHouillier et al. 2019; Sundarrajan et al. 2019). The influence of age at implantation is likely related to a sensitive period in children's central auditory development, which has been suggested to occur between 3;6 and 7 years (Sharma, Dorman, and Kral 2005; Sharma, Nash, and Dorman 2009; Schorr et al. 2005). Although the idea of a sensitive cut-off point in children's central auditory system development is still a matter of debate, the functional connectivity between the primary and higher order cortex gradually declines as children's age increases (Sharma, Dorman, and Spahr 2002; Sharma, Dorman, and Kral 2005). The decreased neural plasticity in late implanted children may adversely affect their neural organisation for audition and cause poor speech performance (Houston and Miyamoto 2010). The beneficial effect of longer device use experience, in turn, is related to language input and oral-aural communication practice (Sundarrajan et al. 2019; Lehnert-LeHouillier et al. 2019). For example, Sundarrajan et al. (2019) demonstrated that children with CIs with longer device use had better consonant accuracy and a larger consonant inventory. However, Blamey et al. (2001) reported that children with CIs only rapidly develop phones in the first five years post-implantation and then reach a developmental plateau. These issues notwithstanding, it is important to note that while the majority of studies included in the review are restricted to young pre-adolescent children with CIs, others exhibit a wider age range, such as Deroche et al. (2019) or Xu et al. (2011), and also include teenagers and young adults up to the age of 21, some of whom were late implanted.

Other factors, for example, speech support, language environment and bimodal device use, which have not been examined systematically thus far, may also impact the development of speech production in Mandarin-speaking children with CIs. As shown in this review, longer duration of auditory rehabilitation and training resulted in better speech production in Mandarin when the hearing age and implant age are similar (Chuang et al. 2012; Yang et al., 2015). In Yoshinga-Itano and Uhler (2015, 835–847), language education, social environment and family support were found to be related to the speech development of children with CIs. Moreover, the evidence in other target languages indicates that participants with CIs with longer speech support have better speech performance (Geers 2002; Bunta et al. 2016). With respect to the factor of language environment, Gibson et al. (2018) as well as Li, Bunta, and Tomblin (2017), for instance, showed that English-Spanish bilingual children with CIs have a different pattern in their phonological development than monolingual children with CIs. Moreover, bimodal device use has been reported as beneficial for children with CIs' speech development in both quiet and noisy environments (Cuda et al. 2019; Yang and Zeng 2017). Huang et al. (2018), reported that bimodal children with CIs achieve higher scores than unilateral children with CIs on a range of different auditory and speech development scales.

4.2. Methodological factors affecting Mandarin speech production in children with CIs

The included studies showing that children with CIs do not perform as well as children with NH are based on the two sets of children being matched in terms of their chronological age (Chuang et al. 2012; Yang et al. 2017; Wang et al. 2017; Deroche et al. 2019; Zhou and Xu 2008; Tang et al. 2019b; Yang et al. 2015; Yang and Xu 2017, 2021; Han et al. 2007; Xu et al. 2004; Zhou et al. 2013). However, children with profound hearing loss are only able to hear sounds from the point of implantation, and as such, chronological age does not allow comparisons to be made across similar hearing experiences. A more appropriate approach might be to match them in terms of their hearing age. In the few studies in which this was done, the difference between children with CIs and children with NH turned out to be narrower or non-existent (e.g. Iyer et al. 2017; Schramm, Bohnert, and Keilmann 2010). For example, Iyer, Jung, and Ertmer's (2017) reported that young children with CIs even outperformed their NH peers in terms of their English consonant inventory size. While matching in terms of hearing age gets around the difficulty of uneven input patterns, this approach comes with its own problems. Thus, chronological age is related to physical (i.e. neural, muscular, skeletal and in terms of vocal tract size) and cognitive development in young children (Denny and McGowan 2012; Arens et al. 2002; Fitch and Giedd 1999; Kent and Vorperian 1995; Vorperian et al. 2005, 2009; Tseng, Kuei, and Tsou 2011). There is therefore no easy solution and it is necessary to adopt a balanced approach when comparing children with CIs and NH.

The studies included in this review have taken a variety of methodological approaches, ranging from auditory-based assessments to acoustic measures and neural network analysis, to name but the most commonly used ones. It stands to reason that the choice of design has had some effect on the results of children with CIs' Mandarin speech productions in the included studies. For example, Chuang et al. (2012) reported that children with CIs' vowel space differed from that of children with NH in a vowel phonation task, but not a sentence production task. Similarly, sentence production data have been indicated as more difficult in the analysis of vowels because acoustic properties of vowel production are influenced by different factors, such as prosodic patterns and flanking consonants (Tseng, Kuei, and Tsou 2011).

4.3. Speech production abilities in children with CIs and NH: cross-linguistic comparisons

The included studies in this review indicate poorer performance in consonant production by Mandarin-speaking children with CIs than children with NH. These findings are consistent with the majority of studies from other cultural and linguistic settings (e.g. Sundarrajan et al. 2019; Sosa and Bunta 2019; Reidy et al. 2017). Similar results were found, for instance, in children growing up with English, French or German (Asad et al. 2018; Gaul Bouchard et al. 2007; Seifert et al. 2002). These studies indicate that children with CIs show poorer performance on fricative production than plosive and nasal production, especially /s/, which was shown to be significantly less accurate in comparison with children with NH (Peng, Weiss, et al. 2004b; Reidy et al. 2017; Liker, Mildner, and Sindija 2007; Iyer, Jung, and Ertmer 2017; Grandon and Vilain 2020). This result was explained on the basis of/s/having spectral energy concentrated at high frequencies which may not be encoded by CI speech processors (Reidy et al. 2017). Despite these commonalities across languages, language-specific patterns in consonant production have also been observed in children with CIs and NH. For example, while the mean centre of gravity was found to be higher for /f/ than /s/ in

Mandarin (Yang et al. 2017), the reverse held true for French (Grandon and Vilain 2020).

The results of acoustic analysis for vowel productions by Mandarin-speaking children with CIs are consistent with those reported for children with CIs using Croatian, German and English in that they all exhibit smaller vowel spaces and more variant F2 patterns compared with children with NH (Liker, Mildner, and Sindija 2007; Neumeyer, Harrington, and Draxler 2010; Turgeon et al. 2017). For instance, Liker, Mildner, and Sindija (2007) showed that Croatian-speaking children with CIs have higher F2 values in /i e a o u/ than their NH peers. Neumeyer, Harrington, and Draxler (2010) demonstrated shorter Euclidean distances for five German vowels, i.e., /i: e: u: a: o:/ in the CI group than the NH control group. Together, these results suggest that children with CIs have a smaller vowel space and hence potentially less distinctive vowel categories. However, there is also evidence of language-specific developmental patterns. For example, Cantonese-speaking children with CIs achieved over 70% accuracy on /ou/ within two years post implantations. As such, it was the earliest acquired diphthong, which is in line with the development seen in children with NH. In contrast, Mandarin-speaking children with and without CIs had the lowest recognition accuracy on /ou/ of all vowel categories (Barry, Blamey, and Fletcher 2006; Stokes and Wong 2002; Yang and Xu 2021).

Studies of tone production in children with CIs using other tone languages, notably Cantonese, show similar results. Thus, in line with the findings from Mandarin-speaking children, Cantonese children with CIs exhibited significantly worse tone accuracy scores than their NH peers (Lee, Tong, and van Hasselt 2007). In addition, acoustic analysis in both Cantonese and Mandarin studies indicate that children with CIs show greater overlap in f_0 curves and more variability than children with NH and the high flat tone is the most clearly differentiated category in the plot (Zhou et al. 2013; Barry and Blamey 2004). However, the tone confusion matrices vary across languages. For example, the high rising tone (T2) and the low dipping tone (T3) are most commonly confused by Mandarin-speaking children with CIs, while the high and mid flat tones are most difficult for Cantonese-speaking children with CIs (Barry and Blamey 2004; Mao, Chen, and Xu 2017).

5. Conclusion and suggestions for future research

Overall, the results of this review indicate that Mandarin-speaking children with CIs perform more poorly in their production of consonants, in particular fricatives, have a smaller and less well-defined vowel space, and exhibit greater difficulties in tone realisation, notably T2 and T3, when compared to their NH peers. Moreover, the accuracy of their production of consonants, vowels and tones is negatively correlated with CI implantation age and there are indications that it is positively correlated with hearing age. However, note that few studies have systematically matched children with CIs and children with NH in hearing age when comparing speech production proficiency. Future research is hence needed that carefully considers potentially critical predictor variables, such as the role of chronological versus hearing age, age at implantation, the language of the environment and speech support that children receive. Moreover, future work is needed that develops batteries of tests for the systematic assessment of speech production abilities in Mandarin-speaking children (cf. Chen and Wong (2017) for a battery for testing speech perception). Together, they will allow us to gain a better understanding of the factors that affect speech production development in Mandarin-speaking children with CIs.

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