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Research Note

Mandarin-Speaking, Kindergarten-Aged Children With Cochlear Implants Benefit From Natural F_0 Patterns in the Use of Semantic Context During Speech Recognition

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Purpose: The purpose of this study was to investigate the extent to which semantic context and F_0 contours affect speech recognition by Mandarin-speaking, kindergarten-aged children with cochlear implants (CIs).
Method: The experimental design manipulated two factors, that is, semantic context, by comparing the intelligibility of normal sentence versus word list, and F_0 contours, by comparing the intelligibility of utterances with natural versus flat F_0 patterns. Twenty-two children with CIs completed a speech recognition test.
Results: Children with CIs could use both semantic context and F_0 contours to assist speech recognition. Furthermore, natural F_0 patterns provided extra benefit when semantic context was present than when it was absent.
Conclusion: Dynamic F_0 contours play an important role in speech recognition by Mandarin-speaking children with CIs despite the well-known limitation of CI devices in extracting F_0 information.

In Mainland China, cochlear implantation is becoming a common intervention for children with profound sensorineural hearing loss. Accordingly, recent years have seen a continuing surge of interest in auditory processing and speech perception by Mandarin-speaking children with cochlear implants (CIs; X. Chen et al., 2010; Han et al., 2007, 2009; Q. Liu, Zhou, Berger, Huang, & Xu, 2013; Mao & Xu, 2016; Su, Galvin, Zhang, Li, & Fu, 2016; Zheng et al., 2010; N. Zhou, Huang, Chen, & Xu, 2013; Zhu et al., 2011). Most of the previous research has focused on the recognition of segmental/suprasegmental phonemes (i.e., consonants, vowels, and lexical tones) and individual words. Although evaluation of sentence-level recognition is probably a better reflection of the ultimate benefit of implantation for the pediatric CI users and their linguistic skills for speech communication than performance with isolated phonemes and words, only a limited number of studies have used open-set sentences in the tests (e.g., Su, Galvin, Zhang, Li, & Fu, 2016; Zhu et al., 2011). Generally, a full spoken sentence provides the listener with the syntactic and semantic context to link a string of related words together. It is well established that children with normal hearing (NH) as young as 2 years old and young adults and older adults are all able to use sentential contexts to aid speech perception (Elliott, 1995; Fernald, 2001; Howes, 1954; Miller & Selfridge, 1950; Obleser, Meyer, & Friederici, 2011; Sheldon, Pichora-Fuller, & Schneider, 2008). However, it remains unknown to what extent children with CIs benefit from contextual semantic information during sentence recognition. The literature on this topic is very limited and provides inconsistent

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findings. For example, Conway, Deocampo, Walk, Anaya, and Pisoni (2014) found that there was no beneficial effect of sentential semantic context during spoken word recognition in children with CIs aged 5 to 10 years. This result is in accordance with the effortfulness hypothesis (McCoy et al., 2005), which suggests that few cognitive resources can be used by children with CIs to integrate contextual information because most of the resources are engaged in the effortful sensory processing of the degraded speech signal. In contrast, Eisenberg, Martinez, Holowecky, and Pogorelsky (2002) found that children with CIs aged 5 to 14 years demonstrated better recognition performance for words in sentences than for isolated words, which indicates that children with CIs are able to make use of some language processing strategies to integrate semantic context, although their linguistic skills lag behind peers with NH.

For speakers of tonal languages, such as Mandarin Chinese, the effect of semantic context on word recognition is modulated by fundamental frequency contours. Fundamental frequency, hereafter referred to as F_0, is the lowest frequency of a periodic complex sound and the acoustic correlate of pitch for speech and music. Specifically, for participants with NH, flattening the F_0 contours of a word list that is composed of semantically unrelated words within a syntactically legitimate sentential frame dramatically reduces the intelligibility. In contrast, the same manipulation of F_0 contours flattening only produces a slight decrease in the intelligibility of the normal sentences with semantically coherent words when presented in quiet. In other words, there is an increase in the beneficial effect of semantic context when natural F_0 contours are flattened. This result is attributed to the limited role of lexical tones (the primary acoustic cues of which are F_0 contours) in sentence intelligibility, although lexical tones are as important as segmental phonemes in signifying lexical meanings at the word level (Wang, Shu, Zhang, Liu, & Zhang, 2013). That is, segmental phonemes (consonants and vowels) provide enough information for sentence recognition and comprehension, whereas lexical tones contribute little to the process. Our recent study (H. Zhou et al., 2017) further documented developmental changes in the modulation effect of F_0 contours on the use of semantic context, showing that middle school-age children benefited more from semantic context in recognizing speech with flattened F_0 contours, which is similar to the results of young adults reported by Wang et al. (2013). In contrast, elementary school-age children relied more on natural F_0 contours than middle school-age children during Mandarin speech recognition. As CIs are known to provide poor signal transmission for F_0 cues, it has not been explored how F_0 contours and semantic context jointly affect speech recognition by Mandarin-speaking children with CIs.

The goal of the current study was to investigate the contributions of semantic context and F_0 contours to speech recognition by Mandarin-speaking, kindergarten-aged children with CIs. Our experimental design manipulated these two factors by comparing the intelligibility of normal sentence versus word list and by comparing the intelligibility of utterances with natural versus flat F_0 patterns. Similar manipulations have been used in our previous studies (Wang et al., 2013; H. Zhou et al., 2017). As early implanted children can develop some cognitive and language skills that are important for using sentence context during speech recognition (Conway et al., 2014; Smiljanic & Sladen, 2013), we predicted that Mandarin-speaking, kindergarten-aged children with CIs would benefit from the availability of semantic context. Given that early implanted children can perceive F_0 patterns of lexical tones and sentence modality (question vs. statement) well above the chance level of accuracy despite poor F_0 information conveyed by current speech processing strategies for CI users (Y. Chen, Wong, Chen, & Xi, 2014; Li, Soli, & Zheng, 2017; Tao et al., 2015; Van Zyl & Hanekom, 2013), we further predicted that Mandarin-speaking, kindergarten-aged children with CIs could also benefit from the presence of natural F_0 contours in the speech stimuli. However, we could not make a specific prediction concerning the potential Semantic Context × F_0 Contours interaction effect. For adults and children with NH, the increased beneficial effect of semantic context concomitant with flat F_0 contours is associated with their consonant and vowel perception. For children with CIs, there is evidence that their consonant and vowel perception is impaired (Lin & Peng, 2003; Luo, Fu, Wei, & Cao, 2008), which would inevitably affect the Semantic Context × F_0 Contours interaction pattern. Whether flattening the F_0 contours would lead to an increase or decrease in the use of semantic context for speech intelligibility needs to be tested, and this provided the primary motivation for this study.

Methods

Participants

The current study was approved by the institutional review board of the National Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University. Twenty-two prelingually deaf children with CIs (12 boys) participated in the experiment. All the children were recruited from rehabilitation centers for deaf children in Beijing and were unilateral recipients of Nucleus 24 devices (Cochlear Beijing Limited) with nine implanted in the right ear and 13 implanted in the left ear. They all had no less than half a year of implant experience when tested. No children wore hearing aids in the contralateral ear, reported to have residual hearing, or were exposed to formal musical training. The demographic information of the children with CIs is summarized in Table 1.

Stimuli

There are four types of speech materials, which were created by respectively manipulating semantic context (normal sentence vs. word list) and F_0 contours (natural vs. flat; see Figure 1). Similar manipulations have been adopted in our previous studies (Jiang, Li, Shu, Zhang, & Zhang, 2017; Wang et al., 2013; H. Zhou et al., 2017). The normal sentences were 20 declarative Chinese sentences

Table 1. Participant characteristics of children with CIs (cochlear implants).

Measure	Age at testing	CI age	CI duration
M	59.77	31.86	27.91
SE	2.25	3.21	2.90
Range	48–87	9–60	5–58

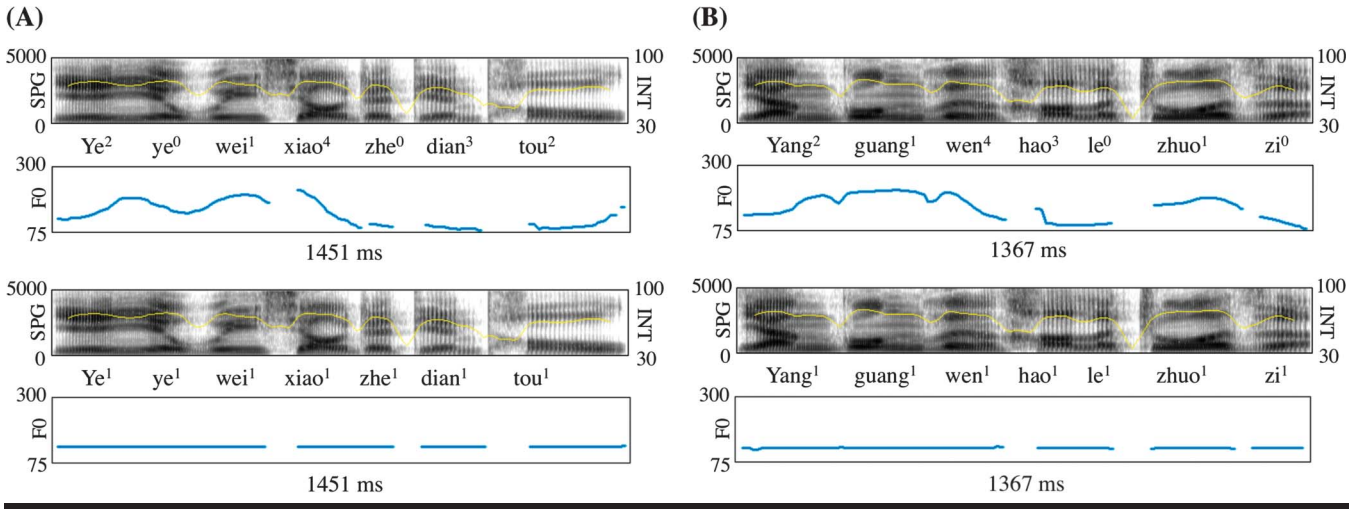
Note. Data are expressed in months. CI age = age at implant; CI duration = duration of CI use.

with each sentence composed of three to five words (two to four content words plus zero to two functional words) that were familiar to the kindergarten-aged children with CIs. Words from the entire pool of the normal sentences were pseudorandomly selected to form the word lists that contained the same number of content and functional words with the normal sentences. Word lists were syntactically correct but semantically meaningless at the whole sentence level. That is, compared with a word list, a normal sentence provides the extra information of "who does what to whom" at the sentence level. For example, in the normal sentence "爷爷微笑着点头" (Grandpa smiled and nodded), "爷爷"(grandpa), "微笑"(smile), and "点头"(nod) are content words, and "着" is a functional word signifying that something is happening; in the word list "阳光问好了桌子" (Sunlight said hello to the desk), "阳光"(sunlight), "问好"(say hello), and "桌子"(desk) are content words, and "了" is a functional word signifying that something has happened. A male native Chinese speaker read the normal sentences and word lists. Monotonous normal sentences/word lists with flat F_0 contours were created by flattening the natural F_0 contours at the mean F_0 of each stimulus.

Procedures

The experimental procedure followed our previous studies (Wang et al., 2013; H. Zhou et al., 2017). Listeners were tested individually in a sound-attenuated booth with ambient noise level below 15 dB(A). Listeners were seated 1.5 m directly in front and at ear level of a single three-way loudspeaker. The sound level of the stimuli was calibrated to 65 dB SPL at the subject's head. Each listener was presented with a total of 40 trials—10 normal sentences and 10 word lists with natural or flat F_0 contours. Because stimuli with natural or flat natural F_0 contours were the same except for the F_0 patterns, a counterbalanced design was adopted to control for order effect. Each child listened to half of the total normal sentences/word lists with natural F_0 contours, and the other half with the flat F_0 contours to ensure that the listener was not presented with the same sentences (or word lists) with natural or flat F_0 contours. The four types of stimuli were presented pseudorandomly across subjects with not more than two stimuli of the same type presented consecutively. Listeners were instructed to report what they heard and were encouraged to guess as much as they could when they were unsure. The task was self-paced, and listeners advanced from one trial to the next by pressing a key. Each sentence could only be heard once. Practice sentences (which were not used in the real experiment) were provided before the experiment, which represented samples of all conditions. The spoken responses were recorded with a digital voice recorder and then scored offline by the first co-author of this research note and checked by an independent auditor blind to the experiment. Only four words were reported to be incorrectly marked, and the auditor discussed with the first co-author to reach an agreement.

Figure 1. Acoustic features of sample speech stimuli. Broadband spectrograms (SPG: 0 to 5 kHz), intensity envelopes (INT: 30 to 100 dB), and fundamental frequency contours (F_0: 75 to 300 Hz) are displayed for (A) normal sentence and its pitch-flattened counterpart; (B) word list and its pitch-flattened counterpart. The samples are written in Pinyin (the official Romanization system for Standard Chinese), and the figures in the upper right corners signify lexical tones.

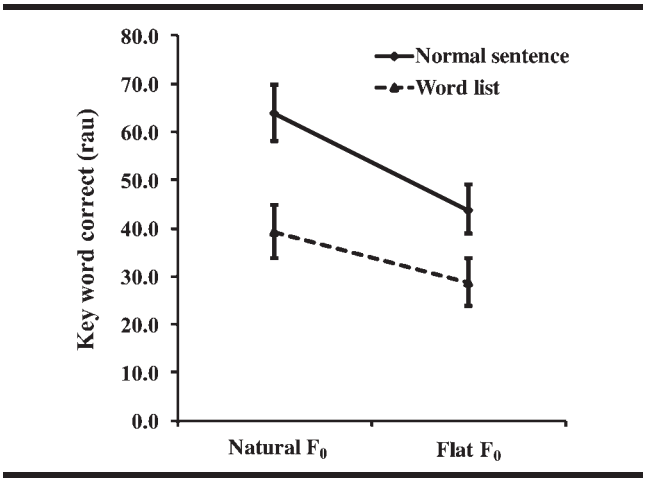


Results

Speech recognition accuracy was determined by a keyword-correct count (Scott, Rosen, Wickham, & Wise, 2004; Wang et al., 2013; Zhang, Xie, Li, Chatterjee, & Ding, 2014). The number of keywords (i.e., content words, varied across sentences from two to four) identified correctly by each listener was counted and converted to a percentage of the total number of words and then converted to rationalized arcsine unit scores to reduce saturation effects and help restore homoscedasticity (Studebaker, 1985; see Figure 2).

A repeated-measures analysis of variance was carried out to examine the main effects of semantic context and F_0 contours and the interaction between the two factors. The results revealed significant main effects of both semantic context, $F(1, 21) = 44.492$, $p < .001$, partial $\eta^2 = .679$, and F_0 contours, $F(1, 21) = 56.646$, $p < .001$, partial $\eta^2 = .730$, indicating that semantic context and natural F_0 contours both contribute to better speech recognition by children with CIs. The interaction between Semantic Context × F_0 Contours was also significant, $F(1, 21) = 4.961$, $p = .037$, partial $\eta^2 = .191$, indicating that the beneficial effect of semantic context is larger for the stimuli with natural F_0 contours as compared with flat F_0 contours (24.5 vs. 14.9 rationalized arcsine unit for the stimuli with natural or flat F_0 contours, respectively). Post hoc analyses were then carried out to examine the simple effects. The results showed that the normal sentence was better recognized than the word list with natural F_0 contours, $F(1, 21) = 56.45$, $p < .001$, partial $\eta^2 = .729$, or flat F_0 contours, $F(1, 21) = 13.85$, $p < .001$, partial $\eta^2 = .397$; stimuli with natural F_0 contours were better recognized than their counterparts with flat F_0 contours [normal sentence: $F(1, 21) = 53.43$, $p < .001$, partial $\eta^2 = .718$; word list: $F(1, 21) = 11.02$, $p = .003$, partial $\eta^2 = .656$].

Figure 2. Word report scores (in rationalized arcsine units [rau]) of the significant Semantic Context × F_0 Contours interaction effect. Error bars represent standard errors across subjects.



Discussion

The current study examined the extent to which kindergarten-aged children with CIs could use semantic context and F_0 contours during Mandarin speech recognition. Our results showed that children with CIs benefited from both sentential semantic context and natural F_0 contours during Mandarin speech recognition, and more importantly, natural F_0 patterns provided extra benefit when semantic context was present.

In this study, children with CIs showed relatively low performance on speech recognition in all four conditions. For example, in the condition of normal sentence with natural F_0 contours, they showed a lower rate (62.9%). By comparison, in two previous studies (Su et al., 2016; Zhu et al., 2011), the accuracies of open-set sentence recognition by Mandarin-speaking pediatric CI users were 84.7% and 82.8%, respectively. This is not surprising considering the fact that the children in the previous studies were older at testing and had longer CI experience than those in the current study. Although all children in these three studies (including this study) were implanted within the sensitive period for the development of the central auditory system (Sharma, Dorman, & Spahr, 2002), age and learning experience both played an important role in their speech perception and language development. For example, only a small proportion of children started to show very limited closed-set sentence recognition (33%–42%) after 6 months of CI use, whereas more than half of the children could identify about half of the sentences by 12 months of CI use (Y. Chen, Wong, Zhu, & Xi, 2016; Zheng et al., 2011). Furthermore, children's performance on open-set word recognition improved during the first 36 months of CI use and plateaued after 48 months of CI experience (H. Liu et al., 2015). Children with CIs in the current study had on average 2.4 years of CI experience, so it can be argued that the amount of auditory experience for the children with early CIs in this study might be too short to develop speech recognition skills compared to children with NH of the same age. To address this issue, future studies need to have a longitudinal design in order to monitor whether and when the sentence recognition gap is closed and how the CI-assisted incremental acquisition of language skills such as vocabulary and grammar may contribute to sentence recognition.

The beneficial effect of semantic context on speech recognition by children with NH has been confirmed in many previous studies. For example, 4-year-old children were found to be better at detecting mispronounced words in high-predictability sentences than in low-predictability sentences (Cole & Perfetti, 1980). Similarly, preschool children were more rapid to repeat target words presented in semantically appropriate contexts than in anomalous sentences (H. Liu, Bates, Powell, & Wulfeck, 1997). Our recent study showed that a normal sentence was better recognized than a word list by elementary school-age and middle school-age children with NH (H. Zhou et al., 2017). Our new data of this study revealed that kindergarten-aged children

with CIs were also able to use semantic context to assist speech recognition. Our results are not in accordance with the effortfulness hypothesis, which predicts that children with CIs have fewer resources available for semantic integration because more efforts have to be put into the low-level perceptual processes (McCoy et al., 2005). On the contrary, our findings indicate that early CI-implanted children may develop spoken language processing strategies for integrating F_0 cues and semantic context that can be used to compensate for their perceptual difficulties. Consequently, the disadvantage in word list recognition was attenuated when the children with CIs were tested with sentences where semantic context was available.

Current CIs provide inadequate information for pitch perception due to reduced frequency resolution and lack of fine-structure cues transmitted by the devices (Cullington & Zeng, 2008; Fu, Shannon, & Wang, 1998). Because tonal languages, such as Mandarin Chinese, use pitch (F_0 contours) to convey lexical information, whether Mandarin-speaking children with CIs can acquire lexical tones successfully has been intensively examined over the last years (Y. Chen et al., 2014; Li et al., 2017; Tao et al., 2015; Van Zyl & Hanekom, 2013). The studies showed that lexical tone recognition by children with CIs is generally good (well above chance level), although their performance still lags behind age-matched controls with NH. Consistent with previous studies, our results further demonstrated that children with CIs have the ability to use natural F_0 contours to assist speech recognition at both word and sentence levels. Our data on the beneficial effects of F_0 for CI users are also consistent with a recent study that showed CI users could capitalize on F_0 cues for gender recognition of speech signals (Fuller et al., 2014).

One novel and surprising finding was the significant F_0 Contours × Semantic Context interaction. Specifically, when natural F_0 contours were flattened, the beneficial effect of semantic context on speech recognition decreased. This means that children with CIs benefited from natural F_0 contours in the use of semantic context. Top-down semantic context information and bottom-up acoustic–phonetic cues are known to be the two sources of information that contribute separately and interactively to word recognition as a function of age and learning experience (Fernald, 2001; McQueen & Cutler, 2001; Tyler & Marslen-Wilson, 1981). We interpreted the interaction pattern as reflecting the different roles of segmental (consonant and vowels) and suprasegmental (lexical tones) phonemes in the intelligibility of Mandarin sentence and accessibility of both top-down and bottom-up information to children with CIs. For Mandarin-speaking adults and children with NH, segmental phonemes provide enough information for semantic context to be effective with lexical tones having little effect (Wang et al., 2013; H. Zhou et al., 2017). However, children with CIs have been shown to have deficits in recognizing consonants and vowels (Lin & Peng, 2003; Luo et al., 2008). It is likely that the bottom-up processing deficits may produce insufficient information for semantic context to be fully effective. Under such circumstance, natural F_0 contours would help children with CIs to identify more lexical tones and recognize more words, thus enabling semantic context to play a more important role during speech recognition. That is, the use of semantic context by children with CIs is confined by their ability to recognize both segmental and suprasegmental phonemes.

It needs to be pointed out that there is a significant limitation of this study that no linguistic or cognitive skills were measured. Further investigation is needed to address how various interrelated linguistic and cognitive skills, such as vocabulary, grammar, reasoning, and working memory, benefit separately or interactively with natural F_0 contours, the use of semantic context during Mandarin sentence recognition.

In conclusion, the current results demonstrate the important role that natural F_0 contours play during Mandarin speech recognition by kindergarten-aged children with CIs despite the well-known limitation of CI devices in extracting F_0 information. Our findings are also relevant for those who interact with children with CIs: Intelligibility of speech directed at children with CIs may be enhanced through simple changes in the speaking style (i.e., speak utterances with dynamic F_0 contours) and use of semantic context.

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References

Chen, X., Liu, S., Liu, B., Mo, L., Kong, Y., Liu, H., … Zhang, L. (2010). The effects of age at cochlear implantation and hearing aid trial on auditory performance of Chinese infants. *Acta Oto-Laryngologica, 130,* 263–270.

Chen, Y., Wong, L. L., Chen, F., & Xi, X. (2014). Tone and sentence perception in young Mandarin-speaking children with cochlear implants. *International Journal of Pediatric Otorhinolaryngology, 78,* 1923–1930.

Chen, Y., Wong, L. N., Zhu, S. F., & Xi, X. (2016). Early speech perception in Mandarin-speaking children at one-year post cochlear implantation. *Research in Developmental Disabilities, 49–50,* 1–12.

Cole, R. A., & Perfetti, C. A. (1980). Listening for mispronunciations in a children's story: The use of context by children and adults. *Journal of Verbal Learning and Verbal Behavior, 19,* 297–315.

Conway, C. M., Deocampo, J. A., Walk, A. M., Anaya, E. M., & Pisoni, D. B. (2014). Deaf children with cochlear implants do not appear to use sentence context to help recognize spoken words. *Journal of Speech, Language, and Hearing Research, 57,* 2174–2190.

Cullington, H. E., & Zeng, F. (2008). Speech recognition with varying numbers and types of competing talkers by normal-hearing, cochlear-implant, and implant simulation subjects. *The Journal of the Acoustical Society of America, 123,* 450–461.

Eisenberg, L. S., Martinez, A. S., Holowecky, S. R., & Pogorelsky, S. (2002). Recognition of lexically controlled words and sentences by children with normal hearing and children with cochlear implants. *Ear and Hearing, 23,* 450–462.

Elliott, L. L. (1995). Verbal auditory closure and the Speech Perception in Noise (SPIN) Test. *Journal of Speech and Hearing Research, 38,* 1363–1376.

Fernald, A. (2001). *Making use of semantic context in early language understanding*. Paper Presented at the Society for Research in Child Development, Minneapolis, MN.

Fu, Q. J., Shannon, R. V., & Wang, X. (1998). Effects of noise and spectral resolution on vowel and consonant recognition: Acoustic and electric hearing. *The Journal of the Acoustical Society of America, 104,* 3586–3596.

Fuller, C. D., Gaudrain, E., Clarke, J. N., Galvin, J. J., Fu, Q.-J., Free, R. H., & Başkent, D. (2014). Gender categorization is abnormal in cochlear implant users. *JARO: Journal of the Association for Research in Otolaryngology, 15,* 1037–1048.

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 and Hearing, 30,* 169–177.

Han, D., Zhou, N., Li, Y., Chen, X., Zhao, X., & Xu, L. (2007). Tone production of Mandarin Chinese speaking children with cochlear implants. *International Journal of Pediatric Otorhinolaryngology, 71*(6), 875–880.

Howes, D. (1954). On the interpretation of word frequency as a variable affecting speed of recognition. *Journal of Experimental Psychology, 48*(2), 106–112.

Jiang, W., Li, Y., Shu, H., Zhang, L., & Zhang, Y. (2017). Use of semantic context and F0 contours by older listeners during Mandarin speech recognition in quiet and single-talker interference conditions. *The Journal of the Acoustical Society of America, 141*(4), EL338–EL344.

Li, G., Soli, S. D., & Zheng, Y. (2017). Tone perception in Mandarin-speaking children with cochlear implants. *International Journal of Audiology, 56*(Suppl. 2), S49–S59. https://doi.org/10.1080/14992027.2017.1324643

Lin, Y. S., & Peng, S. C. (2003). Acquisition profiles of syllable-initial consonants in Mandarin-speaking children with cochlear implants. *Acta Oto-Laryngologica, 123,* 1046–1053.

Liu, H., Bates, E., Powell, T., & Wulfeck, B. (1997). Single-word shadowing and the study of lexical access. *Applied Psycholinguistics, 18,* 157–180.

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,* 1677–1682.

Liu, Q., Zhou, N., Berger, R., Huang, D., & Xu, L. (2013). Mandarin consonant contrast recognition among children with cochlear implants or hearing aids and normal-hearing children. *Otology & Neurotology, 34,* 471–476.

Luo, X., Fu, Q., Wei, C., & Cao, K. (2008). Speech recognition and temporal amplitude modulation processing by Mandarin-speaking cochlear implant users. *Ear and Hearing, 29,* 957–970.

Mao, Y., & Xu, L. (2016). Lexical tone recognition in noise in normal-hearing children and prelingually deafened children with cochlear implants. *International Journal of Audiology, 26,* 1–8.

McCoy, S. L., Tun, P. A., Cox, L. C., Colangelo, M., Stewart, R. A., & Wingfield, A. (2005). Hearing loss and perceptual effort: Downstream effects on older adults' memory for speech. *The Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 58*(1), 22–33.

McQueen, J. M., & Cutler, A. (2001). Spoken word access processes: An introduction. *Language and Cognitive Processes, 16,* 469–490.

Miller, G. A., & Selfridge, J. A. (1950). Verbal context and the recall of meaningful material. *American Journal of Psychology, 63,* 176–185.

Obleser, J., Meyer, L., & Friederici, A. D. (2011). Dynamic assessment of neural resources in auditory comprehension of complex sentences. *NeuroImage, 56,* 2310–2320.

Scott, S. K., Rosen, S., Wickham, L., & Wise, R. J. (2004). A positron emission tomography study of the neural basis of informational and energetic masking effects in speech perception. *The Journal of the Acoustical Society of America, 115,* 813–821.

Sharma, A., Dorman, M. F., & Spahr, A. J. (2002). A sensitive period for the development of the central auditory system in children with cochlear implants: Implications for age of implantation. *Ear and Hearing, 23,* 532–539.

Sheldon, S., Pichora-Fuller, M. K., & Schneider, B. A. (2008). Priming and sentence context support listening to noise-vocoded speech by younger and older adults. *The Journal of the Acoustical Society of America, 123,* 489–499.

Smiljanic, R., & Sladen, D. (2013). Acoustic and semantic enhancements for children with cochlear implants. *Journal of Speech, Language, and Hearing Research, 56,* 1085–1096.

Studebaker, G. A. (1985). A "rationalized" arcsine transform. *Journal of Speech and Hearing Research, 28,* 455–462.

Su, Q., Galvin, J. J., Zhang, G., Li, Y., & Fu, Q. J. (2016). Effects of within-talker variability on speech intelligibility in Mandarin-speaking adult and pediatric cochlear implant patients. *Trends in Hearing, 20,* 1–16.

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 and Hearing, 36,* 102–110.

Tyler, L. K., & Marslen-Wilson, W. D. (1981). Children's processing of spoken language. *Journal of Verbal Learning and Verbal Behavior, 20,* 400–416.

Van Zyl, M., & Hanekom, J. J. (2013). Perception of vowels and prosody by cochlear implant recipients in noise. *Journal of Communication Disorders, 46,* 449–464.

Wang, J., Shu, H., Zhang, L., Liu, Z., & Zhang, Y. (2013). The roles of fundamental frequency contours and sentence context in Mandarin Chinese speech intelligibility. *The Journal of the Acoustical Society of America, 34,* EL91–EL97.

Zhang, J., Xie, L., Li, Y., Chatterjee, M., & Ding, N. (2014). How noise and language proficiency influence speech recognition by individual non-native listeners. *PLoS One, 9,* e113386.

Zheng, Y., Soli, S. D., Meng, Z., Tao, Y., Wang, K., Xu, K., & Zheng, H. (2010). Assessment of Mandarin-speaking pediatric cochlear implant recipients with the Mandarin Early Speech Perception (MESP) test. *International Journal of Pediatric Otorhinolaryngology, 74,* 920–925.

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,* 1418–1426.

Zhou, H., Li, Y., Liang, M., Guan, C., Zhang, L., Shu, H., & Zhang, Y. (2017). Mandarin-speaking children's speech recognition: Developmental changes in the influences of semantic context and F_0 contours. *Frontiers in Psychology, 8,* 1090.

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

Zhu, M., Fu, Q. J., Galvin, J. J., III, Jiang, Y., Xu, J., Xu, C., . . . Chen, B. (2011). Mandarin Chinese speech recognition by pediatric cochlear implant users. *International Journal of Pediatric Otorhinolaryngology, 75,* 793–800.