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Lexical Tone Perception with HiResolution and HiResolution 120 Sound-Processing Strategies in Pediatric Mandarin-Speaking Cochlear Implant Users

Demin Han[1], **Bo Liu**[1], **Ning Zhou**[2], **Xueqing Chen**[1], **Ying Kong**[1], **Haihong Liu**[1], **Yan Zheng**[1], and **Li Xu**[2]

[1]Department of Otolaryngology–Head and Neck Surgery, Beijing Tongren Hospital, Beijing Institute of Otorhinolaryngology, Beijing, People's Republic of China

[2]School of Hearing, Speech and Language Sciences, Ohio University, Athens, Ohio

Abstract

Objectives—Lexical tone recognition tends to be poor in cochlear implant users. The HiResolution (HiRes) sound-processing strategy is designed to better preserve temporal fine structure, or the detailed envelope information, of an acoustic signal. The newer HiRes 120 strategy builds on HiRes by increasing the amount of potential spectral information delivered to the implant user. The purpose of this study was to examine lexical tone recognition in native Mandarin Chinese-speaking children with cochlear implants using the HiRes and HiRes 120 sound-processing strategies. Tone recognition performance was tested with HiRes at baseline and then after up to 6 mo of HiRes 120 experience in the same subjects.

Design—Twenty prelingually deafened, native Mandarin-speaking children, with ages ranging from 3.5 to 16.5 yr, participated. All children completed a computerized tone contrast test on three occasions: (1) using HiRes immediately before conversion to HiRes 120 (baseline), (2) 1 mo after conversion, and (3) 3 mo after conversion. Twelve of the 20 children also were tested 6 mo after conversion. In addition, the parents of 18 children completed a questionnaire at the 3-mo follow-up visit regarding the preference of sound-processing strategies and the children's experience related to various aspects of auditory perception and speech production using HiRes 120.

Results—As a group, no statistically significant differences were seen between the tone recognition scores using HiRes and HiRes 120. Individual scores showed great variability. Tone recognition performance ranged from chance (50% correct) to nearly perfect. Using the conventional HiRes strategy, 6 of the 20 children achieved high-level tone recognition performance (i.e., ≥90% correct), whereas 7 performed at a level not significantly different from chance (50–60% correct). At the final test, either 3 or 6 mo after conversion, all children achieved tone recognition performance with HiRes 120 that was equal to or better than that with HiRes, although some children's tone recognition performance was worse initially at the 1 or 3 mo follow-up intervals than at baseline. Eight of the 20 children showed statistically significant improvement in tone recognition performance with HiRes 120 on at least one of the follow-up tests. Age at implantation was correlated with tone recognition performance at all four test intervals. Parents of most of the children indicated that the children preferred HiRes 120 more than HiRes.

Conclusions—As a group, HiRes 120 did not provide significantly improved lexical tone recognition compared to HiRes, at least throughout the length of the study (up to 6 mo). There were

Address for correspondence: Li Xu, School of Hearing, Speech and Language Sciences, Ohio University, Athens, Ohio. E-mail: xul@ohio.edu.

large individual differences in lexical tone recognition among the prelingually deafened, native Mandarin-speaking children with cochlear implants using either HiRes or HiRes 120. Six of the 20 children performed at or near ceiling in the baseline HiRes condition. Of the remainder, approximately half showed significantly better tone recognition when subsequently tested with HiRes 120, although the extent to which this improvement may be attributable to factors other than the change in processing strategy (e.g., general development) is unknown. The children who benefited most from HiRes 120 tended to be those who were implanted at younger ages.

Introduction

A recent World Health Organization Ear and Hearing Disorders Survey in four provinces of China has established that an estimated 0.3% of the population in China suffers from profound hearing loss. Therefore, in a population of 1.322 billion people, those with profound hearing loss may be nearly 4 million in China (Bu et al. Reference Note 1). As of January 2008, a very small proportion of profoundly deaf individuals in China, approximately 5000, had received multichannel cochlear implants. This number is expected to increase dramatically in the coming years as a result of economic growth and philanthropic efforts. China recently received a donation of 15,000 cochlear implant units, all of which will be implanted in deaf children in the next 5 years (Huang, Reference Note 2).

Mandarin Chinese is spoken by more people than any other single language. Unlike western languages, it is a tone language, wherein the tone or pitch contour of each monosyllable conveys lexical meaning. The F0 (fundamental frequency) contour of the vocalic portions of Mandarin Chinese monosyllables can take one of four patterns: (1) flat and high, (2) rising, (3) low and dipping, and (4) falling. The meaning of the syllable, *ma*, for example, can be (1) “mother,” (2) “hemp,” (3) “horse,” or (4) “scold,” depending on the tone pattern. Because F0 information has not been delivered effectively by cochlear implant technology, it has been difficult for implanted Mandarin speakers to hear and use those phonological characteristics.

Most, if not all, contemporary speech-processing strategies are vocoder-centric or envelope-based speech-processing strategies (Loizou 2006; Wilson 2006). These strategies have proven to be quite successful for speech recognition in non-tonal languages (Zeng 2004). In these vocoder-centric speech-processing strategies, the speech signal is divided into a limited number of frequency bands, and the temporal envelope of each band is extracted using half-wave or full-wave rectification followed by low-pass filtering typically at 200 to 400 Hz. Interleaved pulse trains are amplitude modulated by the temporal envelopes and then delivered to a limited number of electrodes (Wilson et al. 1991).

The F0 and resolved lower harmonics provide the most dominant cues for pitch perception in normal hearing (although amplitude contour and periodicity fluctuations in the temporal envelopes also provide secondary cues for tone perception). However, for cochlear implant listeners, spectral resolution is limited by the small number of stimulation sites (from 12 to 22 in most current implant systems), thereby preventing F0 or its smaller frequency harmonics from being resolved. In studies using a noise-excited vocoder to simulate cochlear implant hearing in normal listeners, we and other researchers have shown that some 30 spectral channels are required to achieve close to normal tone recognition (Kong & Zeng 2006; Xu & Pfingst 2008; Xu et al. 2002).

Tone recognition has been explored in small numbers of patients fitted with a multichannel cochlear implant. Fu et al. (2004) have shown that tone recognition in a group of nine adult patients whose native language was Mandarin Chinese was relatively greater with the continuous interleaved sampling (CIS) and advanced combination encoder (ACE) strategies than with the spectral peak (SPEAK) strategy. The authors attributed the differences to the higher frequent pulse rates used in the CIS and ACE strategies (1200 Hz and ≥900 Hz, respectively) compared with the lower frequent rate (i.e., 250 Hz) used in the SPEAK strategy (Fu et al. 2004). The representation of voicing pitch contained in the temporal envelope requires a sampling rate that is faster than that which the SPEAK strategy provides. Other studies have shown that, in general, tone recognition performance in Mandarin- or Cantonese-speaking adult or pediatric patients with multichannel cochlear implants tended to be poor although a few individuals were found to do well (Ciocca et al. 2002; Huang et al. 1996; Lee et al. 2002; Sun et al. 1998; Wei et al. 2004; Wong & Wong 2004). For example, using live voice stimuli, Peng et al. (2004) found that 6 of 30 children with the Nucleus or MedEl devices scored ≥89% correct in a Mandarin tone contrast test. Ciocca et al. (2002) tested Cantonese tone contrast recognition in 17 children with cochlear implants, among whom 6 were SPEAK users and 11 were ACE users. All children scored around or slightly greater than chance. Similar results have been reported by Lee et al. (2002) and Wong and Wong (2004).

The HiResolution (HiRes) sound-processing strategy, implemented in the CII and 90K cochlear implant systems, is in principle a vocoder-centric strategy (Wilson 2006). However, there are some important differences in signal processing compared with conventional applications of CIS (Koch et al. 2004; Firszt, Reference Note 3). First, HiRes provides a wider input dynamic range of 84 dB at the front end compared with 30 to 40 dB in CIS. Second, the envelope extractor uses half-wave rectification without further low-pass filtering, thereby better preserving the temporal fine structure information of the signal. Finally, the stimulus pulses are delivered to the 16 electrodes at a high rate of up to 5600 Hz per electrode. A clinical trial in 51 postlingually deafened patients showed improved English speech recognition with the HiRes strategy compared with previous conventional strategies (CIS and SAS) (Koch et al. 2004).

Theoretically, two of the new features offered by HiRes might be expected to improve tone recognition. One is the high-rate stimulation. As mentioned above, Fu et al. (2004) suggested that a fast pulse rate was better than a slow rate for tone recognition. However, it should be noted that their data did not show evidence of a steady increase in tone recognition with pulse rate. The second HiRes feature is the temporal fine structure or detailed temporal envelope information provided in the stimulation. Using the auditory chimera technique, in which the envelope of one signal is combined with the temporal fine structure of another (Smith et al. 2002), we tested a group of normal-hearing, native Mandarin-speaking subjects and found that the fine structure is more important for tone perception than envelope information (Xu & Pfingst 2003). However, there is psychophysical evidence that cochlear implant users may not be sensitive to amplitude modulation at modulation rates greater than 300 Hz (Shannon 1992), thus casting some doubt as to whether the implanted listeners can make use of the temporal fine structure or detailed temporal envelope information delivered to them via the HiRes strategy.

In 2006, Advanced Bionics introduced a new sound-processing strategy, HiResolution® with Fidelity 120 (HiRes 120). HiRes 120 uses current steering to create multiple virtual spectral channels through simultaneous stimulation of adjacent electrodes. Earlier psychophysical evidence shows that simultaneous stimulation of two adjacent electrodes could result in pitch percepts distinct from those elicited by stimulation of the two electrodes individually (Bonham & Litvak 2008; Busby & Plank 2005; Donaldson et al. 2005; Firszt et al. 2007; Koch et al. 2007; McDermott & McKay 1994; Townshend et al. 1987; Wilson et al. 1994). In HiRes 120, for each pair of adjacent electrodes, the proportion of current delivered to each electrode varies in eight linear steps between 0 and 100%, thus potentially creating eight different stimulation sites between the two electrodes. For the 16 electrodes of the CII and 90K devices, 120 virtual channels can be created. Narrow frequency analysis filters are used to match the 120 channels. The rest of the signal processing of HiRes 120 is similar to the HiRes strategy.

A few clinical studies have been performed to determine the benefits of HiRes 120 for speech recognition (Brendel et al. 2008; Firszt et al. 2009; Koch et al. Reference Note 4). Results typically have shown that there was a small but significant increase in speech recognition, particularly in noise. Subjects also preferred the sound quality of HiRes 120 to HiRes and showed enhanced music enjoyment. An increase in the number of potential spectral channels might be particularly beneficial for lexical tone recognition and music perception because these abilities require much higher frequency resolution than speech recognition (Kong et al. 2004; Kong & Zeng 2006; Shannon 2005; Xu et al. 2002).

To our knowledge, there has been no study on tone recognition with the HiRes strategy in tone language-speaking patients. Thus, the first aim of this study was to examine tone recognition performance in subjects who use the HiRes strategy. Because more than 90% of all implantees in China are children, subjects were pediatric patients. The second aim was to examine whether HiRes 120 improved tone recognition in the same pediatric subjects after their devices were reprogrammed from the HiRes strategy to HiRes 120.

Materials and Methods

Subjects

As of October 2006, 50 prelingually deafened children had received CII or 90K cochlear implants (Advanced Bionics, Sylmar, CA) from the Cochlear Implant Center of Beijing Tongren Hospital. Twenty of those children, all native Mandarin Chinese speakers, agreed to participate in the study. Subjects were 11 boys and 9 girls with ages ranging from 3.5 to 16.5 yr (7.6 ± 4.1 yr). All had used their cochlear implants and the HiRes strategy for at least 7 mo. Detailed demographic information is summarized in Table 1. The use of human subjects was reviewed and approved by the Institutional Review Boards of Beijing Tongren Hospital and Ohio University.

Procedures

All 20 children were tested on Mandarin tone recognition using their daily HiRes program in the body-worn Platinum Sound Processor on the day they enrolled in the study. Each child was then fitted with the HiRes 120 strategy and sent home with only the new strategy in the processor. One month and 3 mo after conversion to HiRes 120, all the children were evaluated again with the HiRes 120 strategy. Twelve of them returned for a 6 mo follow-up test with HiRes 120. Parents of the children were asked to fill out a questionnaire regarding the preference of sound-processing strategy and sound quality related to the various aspects of auditory perception or speech production at the 3 mo follow-up.

Conversion from HiRes to HiRes 120

After baseline performance with the HiRes strategy was obtained, the children's HiRes strategy was replaced with HiRes 120 using the SoundWave (version 1.4.77) clinical programming software (Advanced Bionics, Sylmar, CA). The T (i.e., threshold) and M (i.e., most comfortable) levels from each child's HiRes strategy were used in the new HiRes 120 programs.

Tone Recognition Test

A two-alternative, forced-choice tone contrast test was used. The subject's task was to discriminate between a pair of monosyllabic words in which only the tone patterns differed [e.g., *wa* (tone 2) “a doll” and *wa* (tone 4) “a sock”]. The four Mandarin tones produce six possible tone contrasts. For each tone contrast, we provided three pairs of words for the subject to choose one pair that they knew the best. The chosen pair was then used in the subsequent test for that subject. A complete list of the 36 words (2 words × 6 tone contrasts × 3 pairs) is provided in the Appendix. For each of the 36 words, a picture (along with the Chinese characters and the *pinyin*, i.e., phonemic spellings) that represents the meaning of the word was provided for visual presentation. We chose the monosyllabic words based on the vocabulary level of young children. A pilot study of 113 normal-hearing, native Mandarin-speaking children of 3 to 9 yr of age confirmed the appropriateness of the words. The cohort of normal-hearing children scored nearly 100% correct on average on tone recognition (unpublished data).

The tone stimuli were recorded in a double-walled sound-treated booth (Acoustic Systems). The talkers were one male and one female native Mandarin-speaking adults with normal hearing. An ElectroVoice omnidirectional microphone (Model RE50B) connected to an external sound card was used for the recording. The distance between the lips and the microphone was kept at approximately 10 cm. Syllables of each pair of tone contrasts were recorded multiple times. Syllable pairs with the same duration (within 1 msec difference) were selected as stimuli (Xu et al. 2002). The purpose of using tone contrasts of equal duration was to remove the duration cue. All recordings were stored in a 16-bit format with a sampling rate of 44.1 kHz. All tokens were equalized in RMS levels.

The tone recognition test was conducted in a sound-treated room. A custom MATLAB (MathWorks, Natick, MA) program was used to present the acoustical and visual stimuli and to record the subject's responses. A graphical user interface displayed the two pictures of a pair of tone contrasts on a laptop computer screen. The speech stimulus corresponding to one of the pictures was presented through a pair of loudspeakers (Logitech V20) located in front of the subjects. The subjects were required to point to the picture corresponding to the word they heard. Before the formal testing, all children practiced for a few minutes to familiarize themselves with the task and to make sure that they understood the procedures. In the formal testing, there were 96 fully randomized stimulus presentations (i.e., 6 tone contrasts × 2 tones × 2 speakers × 4 repetitions). A rest was provided after 48 presentations to ensure the engagement of the children. The level of presentation was adjusted for each subject to their most comfortable level. Typically, those levels were between 65 and 70 dBA.

Questionnaire

At the 3 mo follow-up, a questionnaire was used to capture potential listening benefits or detriments in everyday situations to supplement information obtained from the tone test. Parents were asked which sound-processing option their child preferred, either HiRes (used before the study) or HiRes 120 (the current one). They also indicated a strength of the preference on a scale of 1 (weak preference) to 10 (strong preference). Parents also rated the following statements on a scale of 1 to 5 where 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, and 5 = Strongly Agree.

- My child understands speech better, especially in the presence of background noise.
- My child's speech is easier to understand.
- My child's speech sounds more natural.
- My child alerts to more sounds in the environment.
- My child shows more interest in music.
- My child sings more.

Data Analysis

Arcsin transformation of the tone recognition data (i.e., $y=2 \times \sin^{-1}\sqrt{p}$, where p is the percent-correct score) was performed before the data were subjected to an analysis of variance (ANOVA) or binomial-variable analysis. The rationale for arcsin transformation is that percent-correct scores have nonuniform variance, whereas transformed data have the property of stabilized variance of binomial data and thus are more suitable for ANOVA and other statistical analysis (Studebaker 1985; Thornton & Raffin 1978). The mean scores were compared among the baseline, 1, 3, and 6 mo follow-ups using a one-way unbalanced ANOVA. A binomial-variable analysis (Thornton & Raffin 1978) was used to determine statistical significance among the 1, 3, and 6 mo HiRes 120 follow-up scores and the baseline HiRes scores in individual subjects.

Results

Figure 1 shows the group mean data and the individual tone recognition scores at baseline with the HiRes strategy and at the 1, 3, and 6 mo test intervals with the HiRes 120 strategy. The mean tone recognition scores of all children tested at the baseline, 1, 3, and 6 mo intervals were 74, 75, 75, and 82% correct, respectively (Fig. 1, right panel). A one-way unbalanced ANOVA revealed no statistical differences across the four test sessions ($p > 0.05$).

The individual results were rank ordered based on baseline HiRes scores, which ranged from 51 to 97% correct (Fig. 1, left panel). Note that chance performance was 50% correct and scores ≤63.5% correct were considered not significantly different from chance performance (Thornton & Raffin 1978). Seven of the 20 children showed poor tone recognition performance with the HiRes strategy with scores not significantly different from chance (i.e., between 50 and 60% correct). In contrast, six other subjects showed good tone recognition performance with scores ≥90% correct. For all subjects, a binomial-variable analysis was performed to determine whether the differences between the baseline HiRes score and each of the HiRes 120 test intervals were statistically significant ($p < 0.05$) (Thornton & Raffin 1978). Eight subjects showed statistically significant improvement in tone recognition with the HiRes 120 strategy over the conventional HiRes strategy in one or two of the three intervals tested. Most of these children had low-to-moderate levels of baseline performance (<80% correct). However, one child (S9) showed initial improvement at the 1 mo interval but a dramatic decline to the baseline level at the 3 mo interval. Shortly after the 3 mo test session, an intermittent device failure was detected, and this subject was reimplanted. Two of the 20 subjects (S6 and S20) showed an initial decrease in tone recognition at the 1 or 3 mo intervals with HiRes 120, but both returned to the level comparable to the baseline scores at the 6 mo test interval. In three subjects (S2, S8, and S16), the benefit of using HiRes 120 was not evident until the 6 mo test session. None of the children had a final tone recognition score that was statistically significantly lower with HiRes 120 than with HiRes.

Figure 2 shows the group mean scores for each of the six tone contrasts at the baseline, 1, 3, and 6 mo test intervals. The variability was fairly large across subjects as indicated by the error bars. A two-way ANOVA revealed that both the main effects of test sessions and tone contrasts were significant ($p < 0.001$). The interaction between the test sessions and tone contrasts was not significant ($p > 0.05$). At baseline, tone 1 versus tone 2 and tone 2 versus tone 3 yielded the lowest scores. Such error patterns were also seen in a Mandarin tone contrast test in cochlear implant children (Peng et al. 2004). However, tone 1 versus tone 3 yielded the highest scores. At the 6 mo follow-up session, scores for all tone contrasts improved over the baseline, but the improvement was particularly evident for tone contrasts that yielded lower scores initially at the baseline (e.g., tone 1 versus tone 2 and tone 2 versus tone 3).

Many factors might underlie the large individual differences in tone recognition performance in children with cochlear implants. Figure 3 shows the relationship between tone recognition scores and age at implantation (left panels), chronological age (middle panels), and duration of implant use (right panels). The four rows of panels from top to bottom show the data for the baseline and 1, 3, and 6 mo intervals, respectively. Only age at implantation consistently showed statistically significant correlation with the tone recognition scores. It is worth noting that all children who achieved good tone recognition (≥80% correct) at any test interval had been implanted before 6 yr of age (Fig. 3, left panels). The significant correlation between tone recognition and chronological age was probably a result of a high correlation between chronological age and age at implantation in our group of subjects ($r = 0.96$; $p < 0.001$). No correlation was found between tone recognition and duration of implant use (Fig. 3, right panels). Admittedly, the presence of ceiling effects might limit the usefulness of correlational analyses with these results.

Parents of 18 children returned the preference and rating questionnaire at the 3 mo period (see Materials and Methods for the six statements). Parents of 3 of the 18 children (S9, S10, and S18) indicated that their children had no preference for either HiRes or HiRes 120, whereas parents of the remaining 15 children indicated that their children preferred HiRes 120 more than conventional HiRes (Fig. 4). For the 15 who preferred HiRes 120, one-third of them indicated a strength of preference ≤5 and two-thirds indicated a strength of preference ≥7 on a scale of 1 to 10. No parents indicated that their children preferred HiRes more than HiRes 120. The ratings from the parents of the 15 children who indicated a preference for HiRes 120 on the six statements are summarized in Figure 5. Most of the ratings were either “agree” or “strongly agree.” Interestingly, no correlations were found between the ratings and the tone recognition scores at the baseline with HiRes or at any of the follow-up intervals with HiRes 120.

Discussion

There were large individual differences in Mandarin tone recognition in children using the CII or 90K cochlear implants (Fig. 1). The tone recognition scores ranged from chance level to nearly perfect performance. Of the 20 children, 13 achieved performance significantly greater than chance, and 6 achieved scores ≥90% correct using the conventional HiRes strategy. Compared with most of the previous studies (e.g., Ciocca et al. 2002;Lee et al. 2002;Wong & Wong 2004), the tone recognition abilities of the subjects in this study seemed to be better. Peng et al. (2004) also reported that 6 of 30 children achieved performance comparable to our 6 good performers. However, they used live-voice stimulus presentations rather than the computerized tone-test paradigm used here. Thus, we caution direct comparison of the results of the two studies. Although not evaluated directly, the temporal fine structure or detailed temporal envelope information provided by the HiRes strategy may have contributed to the better performance compared with previous studies. Consistent with this, a new fine structure speech coding strategy in MedEl devices has been shown to provide significant benefit for music perception in adults compared to the previous fitted CIS strategy (Arnoldner, et al., 2007).

After conversion to HiRes 120, approximately one-third of the 20 children showed improved tone recognition scores at intervals of 1, 3, or 6 mo. If the six children who already reached high-level performance with HiRes are removed, approximately one-half of the remaining 14 children show improvement in tone recognition with HiRes 120. This encouraging finding suggests that some of the children might be able to benefit from the increased spectral resolution offered by current steering. It should be acknowledged that any differences between performance with HiRes 120 and baseline might be caused by factors other than the change of processing strategy, such as general cognitive development, greater familiarity with the task, and longer time with implant. However, the children who did not show improved benefit with HiRes 120 might not have had sufficient place-pitch discrimination ability to benefit from the increased number of potential spectral channels.

Donaldson et al. (2005) tested place-pitch discrimination in six adult patients with CII cochlear implants. They found that dual-electrode stimuli could produce two to nine discriminable pitches between the pitches elicited by stimulation of single electrodes. Firszt et al. (2007) replicated that study in 115 ears implanted with a CII or 90K device and found that the numbers of discriminable pitches between apical, middle, and basal pairs of electrodes were on average 5.3, 6.0, and 3.8, respectively. When the data were extrapolated across the electrode array, the total potential number of spectral channels ranged from 8 to 451, with an average of 63. These data indicate that, although many patients can discriminate numbers of pitches greater than the number of physical contacts, some patients cannot even discriminate adjacent electrodes. It would be of great interest to test the number of discriminable pitches in our children subjects, albeit technically difficult. Such data might shed light on whether place-pitch discrimination ability contributes to tone recognition performance. In any case, during multichannel stimulations, channel interaction is likely to obliterate the potential benefit of an increased number of virtual channels (Chatterjee & Schvartz, Reference Note 5). This may explain why a relationship between the number of identified spectral channels and English speech recognition scores using HiRes 120 was not evident in a small group of CII or 90K users (Firszt et al. 2009).

Several subjects showed significant improvement in tone recognition at the 6 mo interval but not at the 1 or 3 mo follow-up intervals (Fig. 1). One possibility is that the benefit of HiRes 120 for tone recognition might not be evident for some children until they have used the new sound-processing strategy for a prolonged period of time (e.g., ≥6 mo). The improvement may also simply be the result of a learning effect independent of strategy. Given the fact that cognitive development and age at implantation are intrinsically related, it is not possible to separate the effects of learning from strategy in these subjects.

However, it is worth noting that tone recognition was not correlated with duration of implant use but consistently correlated with age at implantation (Fig. 3). The good tone recognition performers were those who were implanted before 6 yr of age. Age at implantation has been shown to negatively correlate with speech recognition (e.g., Cheng et al. 1999;Connor et al. 2006;Kirk et al. 2002; O'Neill et al. 2002; Tyler et al. 2000;Waltzman et al. 1997;Zwolan et al. 2004), including tone-language speech recognition (Lee et al. 2002;Wu et al. 2006;Wu &Yang 2003) and tone production (Han et al. 2007). Notably, Peng et al. (2004) demonstrated significant correlations between age at implantation and Mandarin tone production—but not tone recognition—in 30 children implanted with Nucleus and MedEl devices. In contrast, the results of this study show progressively stronger correlations between age at implantation and tone recognition performance because the children had more experience with HiRes 120 (Fig. 3, left panels). Other than the differences in devices (thus, speech-processing strategies) and experimental procedures, it is not clear what contributed to the discrepancy in results between the Peng et al. study and the present study. The main body of the literature, as well as this study, implies that pediatric patients should be implanted early to receive maximum benefit from a cochlear implant. Duration of implant use may not predict improvement in performance if a child is implanted at an older age.

Despite there being no significant group improvement in tone recognition between HiRes 120 and HiRes (Fig. 1, right panel), parents of most of the children indicated a preference for HiRes 120 more than HiRes (Fig. 4). The parents' responses to the statements related to perception and production experiences all favored HiRes 120 (Fig. 5). Note that those statements were not related to tone recognition per se. There are several explanations for why the tone recognition results and parental reports may differ. On one hand, because parents were aware that their children were fit with HiRes 120, an expectation for the new strategy to be better might have influenced the parents' positive judgments. On the other hand, HiRes 120 might truly have provided improved hearing to the children, but the tone-perception test was not specific or sensitive enough to show those benefits.

This study implemented a single-subject longitudinal design that is often used in studies of potential benefit of a new speech-processing strategy. However, this design makes it difficult to separate out learning or experience from the effects of the new strategy. An alternative would be an ABAB or cross-over design in which one strategy is switched to the new one and switched back again. Another alternative would be to evaluate both strategies at each post-conversion test session. Another unanticipated problem was the ceiling effects in tone recognition in a small group of children. We are considering testing tone recognition in noise to further determine whether the potential increased spectral resolution offered by HiRes 120 provides additional benefit in noise.

Conclusions

No statistically significant difference in lexical tone recognition was observed between HiRes and HiRes 120 in the pediatric subject group as a whole. Individual results indicated that some Mandarin-speaking children benefitted from both of these sound-processing strategies. Six of the 20 children achieved a high level of tone recognition with the conventional HiRes strategy. Eight of the 20 children showed significant improvement in tone recognition after conversion to HiRes 120, although factors other than the change of processing strategy might be responsible for the improvement. In a few cases, the improvement in tone recognition after conversion to HiRes 120 was only evident after 6 mo of experience. Children who were implanted at younger ages demonstrated better tone recognition than children implanted at older ages. Parents of most of the children indicated that the children preferred HiRes 120 over HiRes. Their responses were highly positive regarding perception or production performance after conversion to HiRes 120. Although not explicitly tested here, informal comparison with the results of previous studies suggests that the two strategies tested here may provide somewhat better lexical tone recognition than earlier strategies.

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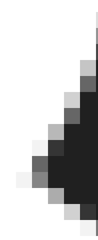
Appendix

Word list of the six Mandarin tone contrasts used in the tone recognition tests

Chinese character	pinyin	English translation	Chinese c
			Tone 1 vs. Tone 2
枪	qiang (1)	gun	墙
汤	tang (1)	soup	糖

Chinese character	pinyin	English translation	Chinese c
窗	chuang (1)	window	
三	san (1)	three	Tone 1 vs. Tone 3 伞

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Chinese character	pinyin	English translation	Chinese c
吃	chi (1)	to eat	

Chinese character	pinyin	English translation	Chinese c
屋	wu (1)	room	五
			Tone 1 vs. Tone 4

Chinese character	pinyin	English translation	Chinese c
灯	deng (1)	lamp	凳

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Chinese character	pinyin	English translation	Chinese c
杯	bei (1)	cup	

Chinese character	pinyin	English translation	Chinese c
猫	mao (1)	cat	
			Tone 2 vs. Tone 3
鼻	bi (2)	nose	笔
狐	hu (2)	fox	虎

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Chinese character	pinyin	English translation	Chinese c
鱼	yu (2)	fish	雨
娃	wa (2)	doll	Tone 2 vs. Tone 4 袜

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Chinese character	pinyin	English translation	Chinese c
图	tu (2)	map	

Chinese character	pinyin	English translation	Chinese c
	ye (2)	grandpa	叶
			Tone 3 vs. Tone 4

Chinese character	pinyin	English translation	Chinese c
鼠	shu (3)	mouse	

Chinese character	**pinyin**	**English translation**	**Chinese c**
米	mi (3)	rice	蜜

Chinese character	pinyin	English translation	Chinese c
	jian (3)	scissors	剑

Pinyin, phonemic spelling system for Chinese.

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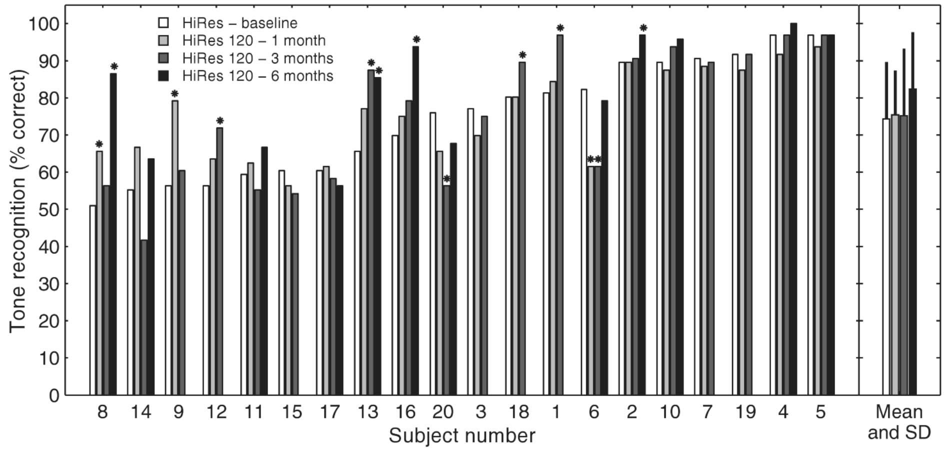

Fig. 1.

Tone recognition scores of the group (right) and the 20 individual children (left). For the group data, each bar represents data from one of the four test intervals: baseline with HiRes (white bar, *n* = 20) and follow-ups with HiRes 120 at 1 mo (light gray bar, *n* = 20), 3 mo (dark gray bar, *n* = 20), and 6 mo (black bar, *n* = 12). The error bar represents SD. For the individual data, a group of three or four bars represents tone recognition scores for one subject tested three or four times. The test intervals were the same as the group mean data and are indicated by the figure legend. Subjects were rank ordered based on the baseline tone recognition scores. The asterisks represent follow-up tone recognition scores that are statistically significantly different from the baseline scores (binomial-variable analysis, $p < 0.05$).

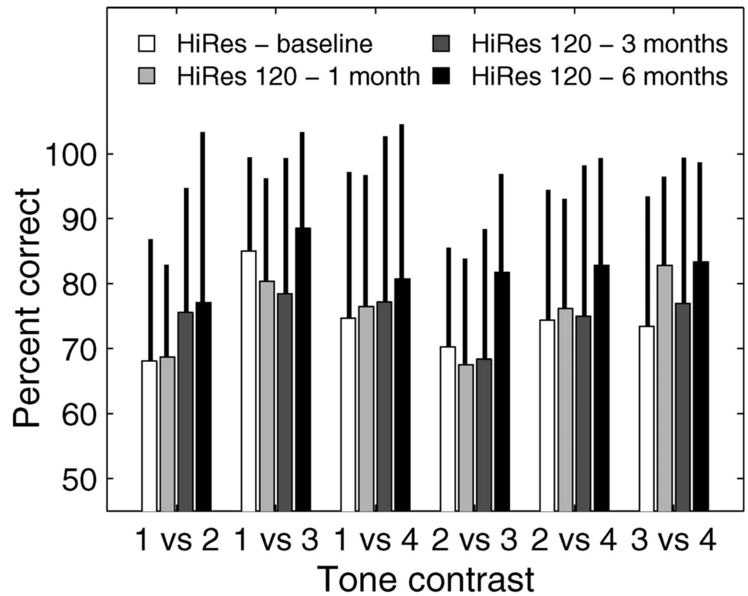

Fig. 2.

Group mean data on tone contrast recognition. Each bar represents data from one of the four test intervals: baseline (white bar, *n* = 20) and follow-ups at 1 mo (light gray bar, *n* = 20), 3 mo (dark gray bar, *n* = 20), and 6 mo (black bar, *n* = 12). The error bar represents SD.

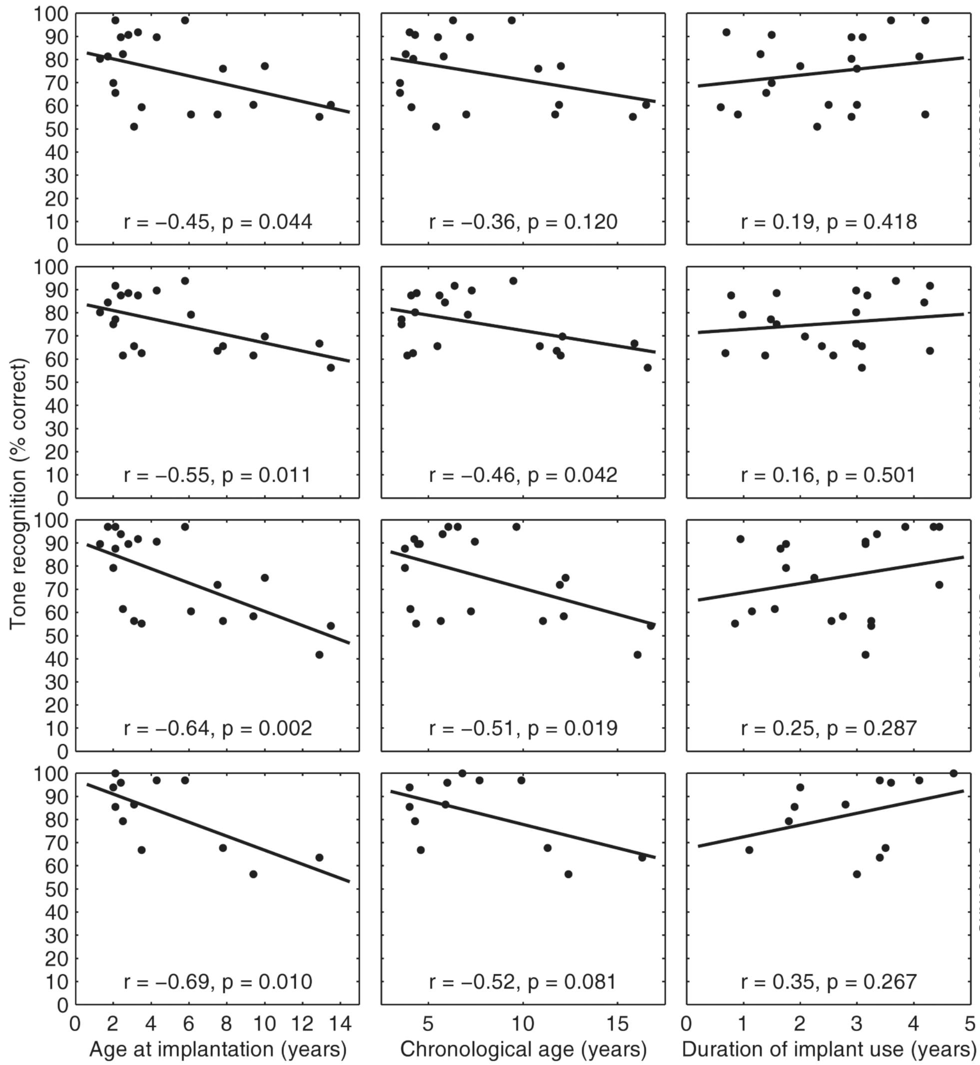

Fig. 3.

Relationship between tone recognition and age at implantation (left panels), chronological age (middle panels), and duration of implant use (right panels). The four rows of panels from top to bottom represent the four tone test intervals: baseline, 1, 3, and 6 mo follow-ups. The solid lines represent least-squared linear fit of the data. The correlation coefficient (*r*) and *p* values are shown at the bottom of each panel.

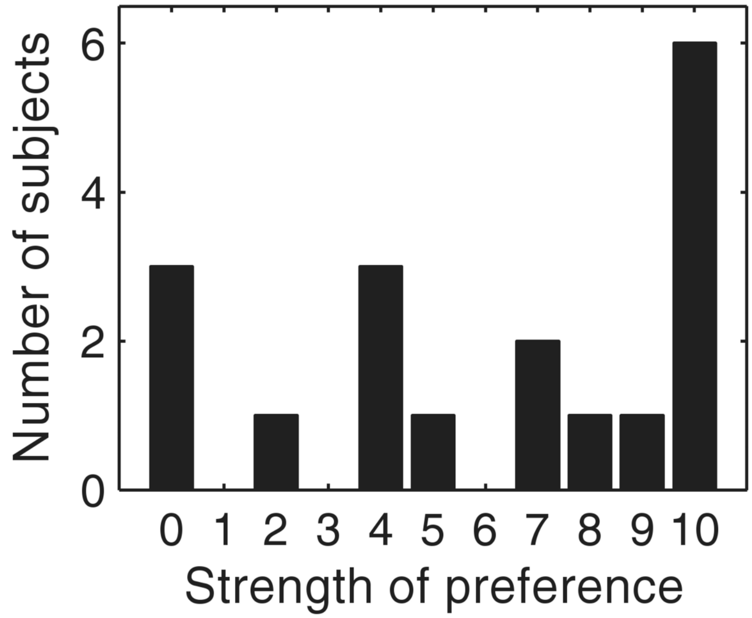

Fig. 4.

Distribution of strength of preference to HiRes 120 over HiRes speech-processing strategy. Parents of three children showed no preference to either strategy as indicated by the bar at 0. The total number of responses is 18.

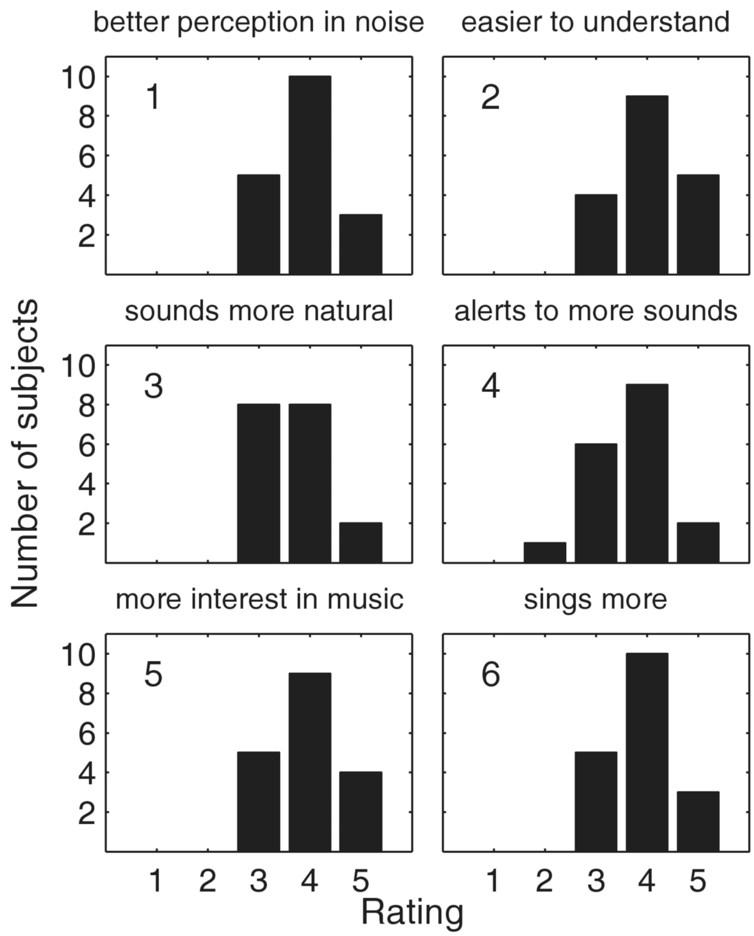

Fig. 5.
Distribution of ratings on the six statements by the parents of the 15 children who indicated preference to HiRes 120. The complete statements can be found in Materials and Methods. The key phrase for each statement is provided above each panel. The ratings of 1 through 5 are (1) strongly disagree, (2) disagree, (3) neutral, (4) agree, and (5) strongly agree.

Table 1

Subject demographic information

Subject NumberSex	Age (yr)	Age at Implantation (yr)(yr) Duration of Implant Use	Implant Device	Etiology
1M	5.8	1.74.1	CII	Unknown
2M	7.2	4.32.8	CII	Congenital
3F	12.0	10.02.0	90K	Unknown
4M	6.3	2.14.2	90K	Ototoxicity
5F	9.4	5.83.6	CII	Unknown
6F	3.8	2.51.3	90K	Hyperbilirubinemia
7F	4.3	2.81.5	90K	LVAS
8F	5.4	3.12.3	90K	Unknown
9F	7.0	6.10.9	90K	Ototoxicity
10M	5.5	2.43.1	CII	Unknown
11M	4.1	3.50.6	90K	Congenital
12M	11.7	7.54.2	CII	Ototoxicity
13M	3.5	2.11.4	90K	Unknown
14M	15.8	12.92.9	CII	Ototoxicity
15M	16.5	13.53.0	CII	Ototoxicity
16M	3.5	2.01.5	90K	Unknown
17M	11.9	9.42.5	CII	Congenital
18F	4.2	1.32.9	CII	Unknown
19F	4.0	3.30.7	90K	Unknown
20F	10.8	7.83.0	CII	Congenital
Mean	7.64	5.212.43		

LVAS, large vestibular aqueduct syndrome.