

Bilaterally Combined Electric and Acoustic Hearing in Mandarin-Speaking Listeners: The Population With Poor Residual Hearing

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Abstract

The hearing loss criterion for cochlear implant candidacy in mainland China is extremely stringent (bilateral severe to profound hearing loss), resulting in few patients with substantial residual hearing in the nonimplanted ear. The main objective of the current study was to examine the benefit of bimodal hearing in typical Mandarin-speaking implant users who have poorer residual hearing in the nonimplanted ear relative to those used in the English-speaking studies. Seventeen Mandarin-speaking bimodal users with pure-tone averages of ~80 dB HL participated in the study. Sentence recognition in quiet and in noise as well as tone and word recognition in quiet were measured in monaural and bilateral conditions. There was no significant bimodal effect for word and sentence recognition in quiet. Small bimodal effects were observed for sentence recognition in noise (6%) and tone recognition (4%). The magnitude of both effects was correlated with unaided thresholds at frequencies near voice fundamental frequencies (F0s). A weak correlation between the bimodal effect for word recognition and unaided thresholds at frequencies higher than F0s was identified. These results were consistent with previous findings that showed more robust bimodal benefits for speech recognition tasks that require higher spectral resolution than speech recognition in quiet. The significant but small F0-related bimodal benefit was also consistent with the limited acoustic hearing in the nonimplanted ear of the current subject sample, who are representative of the bimodal users in mainland China. These results advocate for a more relaxed implant candidacy criterion to be used in mainland China.

Keywords

bimodal hearing, cochlear implants, Mandarin, acoustic residual hearing

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Introduction

The inherently low spectral resolution that the current cochlear implants (CIs) provide results in the well-known problems of poor pitch perception and low tolerance of noise in challenging listening environments. Many studies have examined the possible benefit of combining residual acoustic hearing (A), which on its own often provides minimal speech recognition, with electrical stimulation (E) provided by the CI, for tasks that demand fundamental frequency (F0) or fine spectral information. Some hearing-impaired listeners were implanted in the same ear that has residual acoustic hearing with a shallowly inserted short electrode array (e.g., Gantz & Turner, 2004; Turner, Gantz, Vidal, Behrens, & Henry, 2004). Many others had residual hearing in the ear opposite the standard long-array implant and were fit

with a hearing aid (HA) to be used in conjunction with the CI (e.g., Ching, Incerti, & Hill, 2004; Dorman, Gifford, Spahr, & McKarns, 2008; Gifford, Dorman, McKarns, & Spahr, 2007; Kong, Stickney, & Zeng, 2005; Mok, Grayden, Dowell, & Lawrence, 2006;

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Wilson, 2012). The bilaterally combined electrical and acoustic stimulation is known as bimodal hearing.

The benefit of bimodal hearing, defined as the performance with CI plus the contralateral HA minus that with CI alone, has been shown to be highly variable across subjects and inconsistent across tasks. Some studies have reported benefits for monosyllabic words, vowels, and transmission of some articulatory features (e.g., Dorman et al., 2008; Gifford et al., 2007; Yoon, Li, & Fu, 2012; Zhang, Spahr, Dorman, & Saoji, 2013), while others have reported very little or no benefit for consonant-vowel nucleus-consonant (CNC) words and consonant recognition (Gifford, Dorman, Sheffield, Teece, & Olund, 2014; Kong & Braid, 2011; Mok et al., 2006). When bimodal benefit was observed, the HA was shown to aid the transmission of the first and second formants of vowels (F1 and F2) and the voicing feature of consonants (Mok et al., 2006; Yoon, Li, Kang, & Fu, 2011). The more consistent benefit was reported for listening in background noise, particularly in fluctuating interferences (Dorman et al., 2008; Gifford et al., 2007; Kong et al., 2005; Turner et al., 2004; Zhang, Dorman, & Spahr, 2010). The role of low frequencies in noisy environments is thought to provide F0 information that is known to help listeners segregate auditory objects (e.g., Bird & Darwin, 1998) and identify syllable boundaries (Spitzer, Liss, Spahr, Dorman, & Lansford, 2009).

Previous research suggested that the large individual variability in bimodal benefit could be due to the CI-only performance, the amount and bandwidth of the acoustic hearing, test material, and integration between the two devices (e.g., Dorman et al., 2015; Yang & Zeng, 2013). Previous studies suggested that the higher (i.e., better) the hearing function is in the nonimplanted ear, quantified in terms of either aided or unaided pure-tone threshold average (Sheffield & Zeng, 2012; Yoon et al., 2011), bandwidth of the aided acoustic hearing (Neuman & Svirsky, 2013; Sheffield & Gifford, 2014; Zhang et al., 2010), or spectral resolution in the low-frequency region (Zhang et al., 2013), the more likely the HA will provide benefit when used in conjunction with the implant. The less studied variable, one that is now receiving increasing attention with the prevalence of bimodal and bilateral device uses, is central integration. Some bimodal users were found to attend to one information source only, therefore benefiting little from the second and often less optimal device (Kong & Braid, 2011). When integration did occur, some bimodal users would fuse pitches elicited from the two devices that are quite different over the frequency range of three to four octaves, a phenomenon known as abnormal broad binaural fusion. The abnormal fusion may also lead to the average of inputs from the two modalities to reduce uncertainty in the signal, and a distorted central representation of the signal spectrum (Reiss, Eggleston, Walker, & Oh, 2016). Yang and Zeng (2013, 2017)

suggested that the individual variability in bimodal integration efficiency could be explained by the degree and duration of hearing loss in the aided ear, with longer duration and more severe hearing losses predicting poorer integration.

The use of bimodal devices in Mandarin-speaking subjects presents an interesting scenario. Mandarin Chinese is a tonal language that uses pitch variation to convey lexical meanings. Given the importance of F0, which is the primary acoustic correlate of tones, low-frequency residual hearing on the contralateral side of the implant is expected to be particularly helpful for tonal-language CI users. On the other hand, the implantation criteria are much more stringent in mainland China compared to those of the English-speaking countries, producing a unique population of Mandarin-speaking bimodal users who have limited residual hearing in the aided ears (China Disabled Persons' Federation, 2011). Few studies have examined bilaterally combined acoustic and electrical hearing in Mandarin-speaking listeners, partly because it was difficult to find Mandarin-speaking bimodal users with substantial residual hearing in the nonimplanted ear. The limited number of studies in the literature also produced rather mixed results. Using a HA on the contralateral ear was found to improve tone recognition in adult Mandarin-speaking bimodal users, but this benefit was not always present in quiet conditions (Chang, Chang, Lin, & Luo, 2016; Li, Zhang, Galvin, & Fu, 2014; Yang & Zeng, 2017). The results for vowel and consonant recognition were also mixed in that the benefit was observed in some subject samples or in some test conditions but not others (Li et al., 2014; Yang & Zeng, 2017). When a significant bimodal effect was seen for word recognition, such benefit was accounted for by the improved recognition for tones and consonants, but not vowels (Yang & Zeng, 2017). Li et al. (2014), however, reported that residual hearing improved only vowel but not consonant recognition regardless of test conditions. For the pediatric population, bimodal benefit was observed only when speech and noise were not collocated (Yuen et al., 2009). The reported mixed results were very likely due to the differences in the subject characteristics in these studies.

In the present study, the bimodal effect in Mandarin-speaking listeners was examined using a subject sample that is representative of the CI population in mainland China (i.e., severe to profound hearing loss in the nonimplanted ear; China Disabled Persons' Federation, 2011). Dorman et al. (2015) indicated that bimodal users with audiometric thresholds > 60 dB HL at low frequencies are less likely to benefit from a HA. Given the importance of low-frequency information for tonal languages, we might still expect some benefits for this CI population especially for tone recognition tasks even

though the hearing losses were severe. If proven untrue, the results would advocate for a more relaxed criterion for implant candidacy. These results will also help guide clinical practices to determine whether a HA should be recommended for CI patients who have little residual hearing in the contralateral ear.

Mandarin Chinese tones not only differ in their F0 contour, which is the primary acoustic correlate, but also in duration and the envelopes of amplitude variation (Whalen & Xu, 1992; Xu, Tsai, & Pfingst, 2002). As discussed earlier, residual hearing was beneficial only for tone recognition in noisy conditions but not in quiet, and the magnitude of the benefit was also rather small (Li et al., 2014). Authors of the Li et al. (2014) study attributed the smaller-than-expected benefit to the secondary cues for tone recognition that the implants do provide, that is, duration and temporal envelopes that covary with the F0 patterns. To test the hypothesis that the benefit of the residual acoustic hearing would be more salient for tone recognition if less secondary cues were present, we used tone stimuli that were either naturally spoken or normalized to a fixed duration. In addition, we measured performance not only for tone and word recognition but also at sentence levels to evaluate whether bimodal effects, if any, contribute to speech understanding with contextual cues.

Materials and Method

Subjects

Seventeen Cochlear Nucleus® (Cochlear Corporation, Englewood, CO) users, who are native speakers of Mandarin, participated in our study. All subjects were diagnosed as having bilateral severe to profound hearing loss prelingually (before the age of 2). Six subjects were adults at the time of testing. The median duration of HA use was 14 years, and the median duration of CI use was 3.83 years (see demographic details in Table 1). The HAs of the subjects all used a wide dynamic input compression setting with no frequency compression. It should be noted that the target gain for HAs was not verified at the time of the experiments. The unaided and aided pure-tone thresholds measured for the ear opposite the implant at 125, 250, 500, 750, 1000, 2000, 4000, and 6000 Hz are shown for each subject in Figure 1. The low-frequency (125, 250, and 500 Hz) unaided and aided pure-tone averages are summarized in Table 1 for each subject. Group-mean unaided and aided audiometric thresholds at 125, 250, and 500 Hz were 75, 83, and 95 dB HL, and 68, 61, and 58 dB HL, respectively. None of the subjects had residual hearing in the ear that was implanted. All subjects gave written informed consent before participating in the study. The use of human

Table 1. Subject Demographic Information.

Subject ID	Gender	Age (years)	Duration of deafness (years) ^a	CI experience (years)	Hearing aid use (years)	PTA ≤ 500 (dB)	
						Unaided	Aided
S1L	M	20.87	16.84	4.02	16	72	43
S2L	F	11.03	5.25	4.95	9	73	48
S3R	M	19.30	14.50	4.80	18	88	70
S4L	F	26.82	21.85	4.98	26	80	45
S5R	F	16.99	13.92	1.75	14	88	80
S6R	M	22.03	17.20	4.83	21	88	58
S7L	M	15.14	11.31	3.83	14	77	70
S8L	F	22.22	17.35	4.87	21	93	68
S9L	F	12.40	7.09	5.31	11	90	57
S10R	F	13.90	11.01	2.05	13	88	57
S11L	F	16.92	13.54	1.38	14	80	48
S12R	M	8.60	4.92	3.68	7	72	58
S13L	F	16.31	13.25	2.66	11	80	85
S14R	M	38.02	35.81	2.20	25	77	67
S15L	M	5.85	3.50	2.35	3	95	72
S16L	M	6.15	4.44	1.71	5	97	77
S17L	M	5.99	2.00	3.99	0.1	92	58

Note. CI = cochlear implant; PTA = pure-tone average.

^aDuration between diagnosis of profound hearing loss and cochlear implantation.

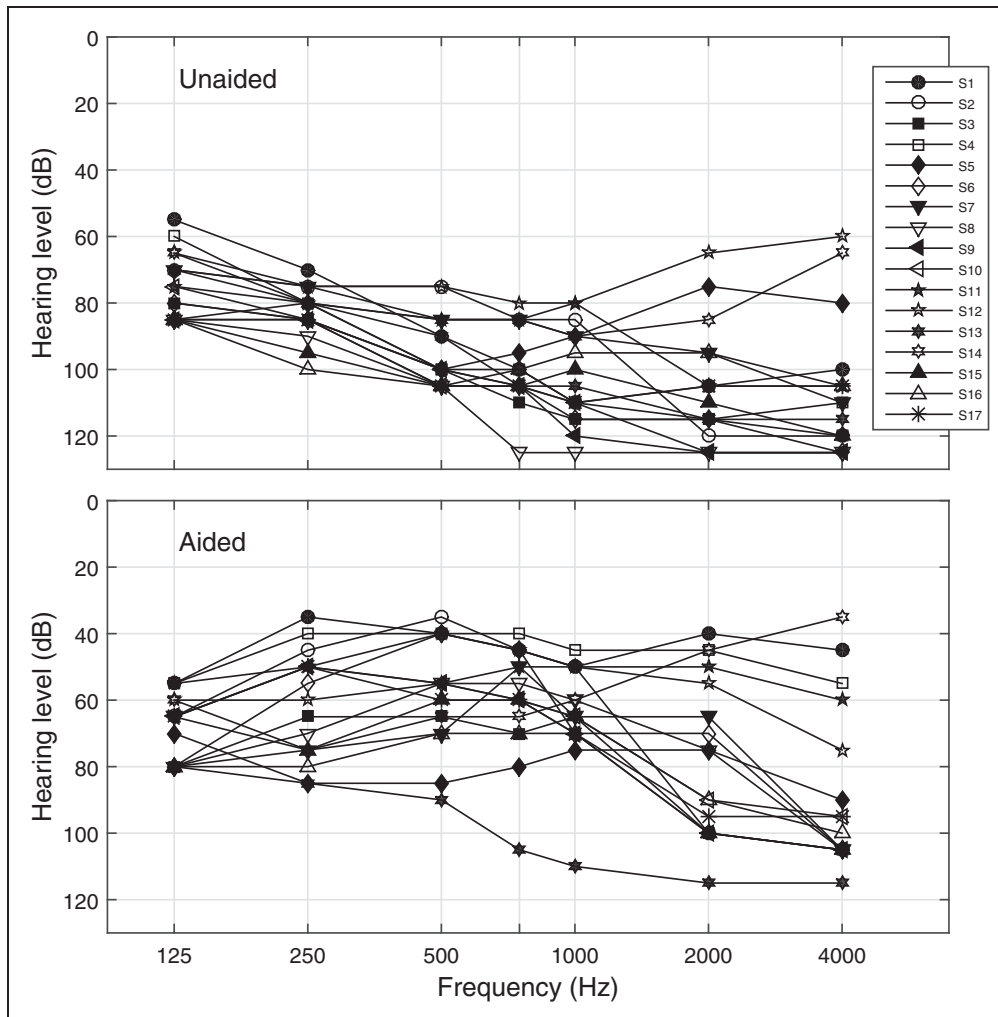


Figure 1. Individual pure-tone thresholds. Upper panel: unaided thresholds. Lower panel: aided thresholds. Symbols represent subjects.

subjects in this study was approved by the Institutional Review Board in the First Affiliated Hospital of Soochow University, Suzhou, China.

Speech Tests

The following tests were administered in a sound-treated room, with the HA alone (A), implant alone (E), and both (bimodal), but not necessarily in that order. When tested with the implant alone, the ear opposite the implant was plugged and wore a David Clark M-7A circumaural earmuff (David Clark, MA). Tone recognition, disyllabic word recognition, and sentence recognition were measured in randomized order. The speech materials were presented at 65 dB (A) via a single loudspeaker placed at 0 degree azimuth and 1 meter away from the subject.

A female and male, both native speakers of Mandarin, recorded the stimuli for the tone recognition

test. They each recorded the following syllables in four tones /wa/, /ya/, /ji/, /shi/, /fu/, /zhu/, /ge/, /ke/, /mo/, /po/, /qu/, and /xu/ at a sampling rate of 44100 Hz and a 16-bit digitization resolution. These open syllables (syllables ending with a vowel) were chosen to minimize the effect of nasal coda on amplitude contours of the tone stimuli (Zhou & Xu, 2008b). Multiple recordings were made for each stimulus, and the most clearly pronounced ones were chosen. Equal-duration tones were generated by normalizing the chosen naturally-spoken tone stimuli to have a duration of 400 ms using the Adobe Audition software (Adobe Systems Inc., San Jose, CA). Note that this manipulation did not change the fundamental frequency of the stimulus. This produced 192 tone stimuli (2 speakers \times 12 syllables \times 4 tones \times 2 duration conditions). The test was administered in two blocks of equal-duration and naturally-spoken tones. The naturally-spoken tones were presented in the first block. Within each block, the order of the stimuli was fully

randomized. Tone recognition was measured in a four-alternative forced choice paradigm, where the subject was instructed to click on one of the four buttons on the computer screen that indicate tones 1, 2, 3, and 4.

Disyllabic words and sentence recognition were measured using the Mandarin Speech Perception test that was developed and validated for measuring speech recognition in Mandarin-speaking adult and pediatric CI users (Fu, Zhu, & Wang, 2011; Zhu, Wang, & Fu, 2012). These speech materials are used in daily life and are familiar to the Mandarin-speaking CI population. The lists were phonetically balanced and were produced by a female speaker. There were 70 words in each disyllabic list. The words were nouns or verbs (e.g., 老师 [lǎoshī] teacher; 游泳 [yóuyǒng] swim). Each sentence list contained 10 sentences, and each sentence contained 7 words. Disyllabic word recognition was tested in quiet, and sentence recognition was measured in quiet and in a steady-state speech-shaped noise with a speech-to-noise ratio of 5 dB. The subjects were instructed to repeat what they heard. Two lists, chosen at random without replacement, were tested for each condition. The number of correctly repeated words was recorded for each condition, and a percent correct score was derived. To perform statistical analyses that make the assumption of normal distribution and homogeneous variance, the percent correct scores were Arcsine transformed. Scores displayed in the following figures are shown in percentages.

Results

The individual scores for tone recognition with equal-duration stimuli and naturally-spoken stimuli, disyllabic word recognition, sentence recognition in quiet and in noise are shown in Figure 2. For tone recognition, three subjects (S9L, S16L, and S17L) were not willing to test with the HA alone; therefore, these subjects were excluded from the analyses where paired comparisons were made between listening modes (i.e., A alone, E alone, and bimodal) for tone recognition. Mixed linear models were used to test listening mode as the within-subject factor and recognition score as the dependent variable. Results of the mixed linear models showed that performance was significantly different across listening modes for all five speech tests—Tone_E: $F(2, 14) = 7.14, p = .007$; Tone_N: $F(2, 14) = 4.21, p = .036$; Words: $F(2, 16) = 24.85, p < .001$; Sentence_Q: $F(2, 16) = 30.61, p < .001$; Sentence_{5dB}: $F(2, 16) = 17.03, p < .001$. Note that the subscript E stands for equal duration, N stands for naturally spoken, Q stands for quiet, and 5 dB indicates the speech-to-noise ratio.

Results of planned comparisons are reported in the following with p values adjusted for Bonferroni corrections. Results indicated that bimodal benefit relative to

the implant alone was significant for tone recognition with equal-duration stimuli, $t(16) = 2.53, p < .025$, and sentence recognition in noise, $t(16) = 2.54, p < .025$. Bimodal benefit relative to HA alone was significant for disyllabic word recognition, $t(16) = 6.76, p < .001$, sentence recognition in quiet, $t(16) = 6.98, p < .001$, and in noise, $t(16) = 5.3, p < .001$, but not for tone recognition. Performance with the implant alone was significantly better than that with the HA alone also for disyllabic word recognition, $t(16) = 6.16, p < .001$, sentence recognition in quiet, $t(16) = 7.69, p < .001$, and in noise, $t(16) = 4.27, p < .001$, but not for tone recognition. Results of these comparisons are indicated by text displayed in each panel in Figure 2.

Figure 3 summarizes the percentage-point bimodal benefit relative to the implant (benefit of A) and HA alone (benefit of E) for individuals for the five speech tests. The horizontal bars represent group means for each of the five speech tests. Note that our subject sample included both pediatric and adult listeners. Although the mix of adult and pediatric subjects may have introduced greater variability in the results, there was no statistically significant difference in the bimodal benefit that they received ($p > .05$ for all conditions). Figure 4 shows the percentage-point benefit of A as a function of the performance with the implant alone. The solid lines show the maximum possible percentage-point benefit that the HA can provide for a given implant-alone performance. The red circle indicates the 95% critical difference scores (confidence intervals; Thornton & Raffin, 1978), which were calculated based on the number of words tested in each speech recognition task. If a data point falls outside of the confidence interval in either direction, it indicates that for that subject, the bimodal performance was significantly different from the performance with the implant alone. Figure 5 shows the percentage-point benefit of E as a function of the performance with the HA alone. The solid lines and circles similarly indicate maximum possible benefit and the 95% critical difference scores.

The relationship between the bimodal effect (bimodal performance minus E) for each of the five speech tests and unaided audiometric thresholds is shown in Table 2. The scatter plots of the bimodal effect against thresholds at the three low frequencies are shown for tone recognition with equal-duration stimuli in the upper panels of Figure 6 and for sentence recognition in noise in the lower panels of Figure 6. Note that those were the two tasks where the bimodal effect was the most prominent. For equal-duration tones, threshold at 125 Hz was the strongest predictor for the amount of benefit that the HA provided, with more residual hearing predicting greater benefit. For sentence recognition in noise, both thresholds at 125 Hz and 250 Hz predicted the benefit of the HA, with 250 Hz being the stronger predictor. Although

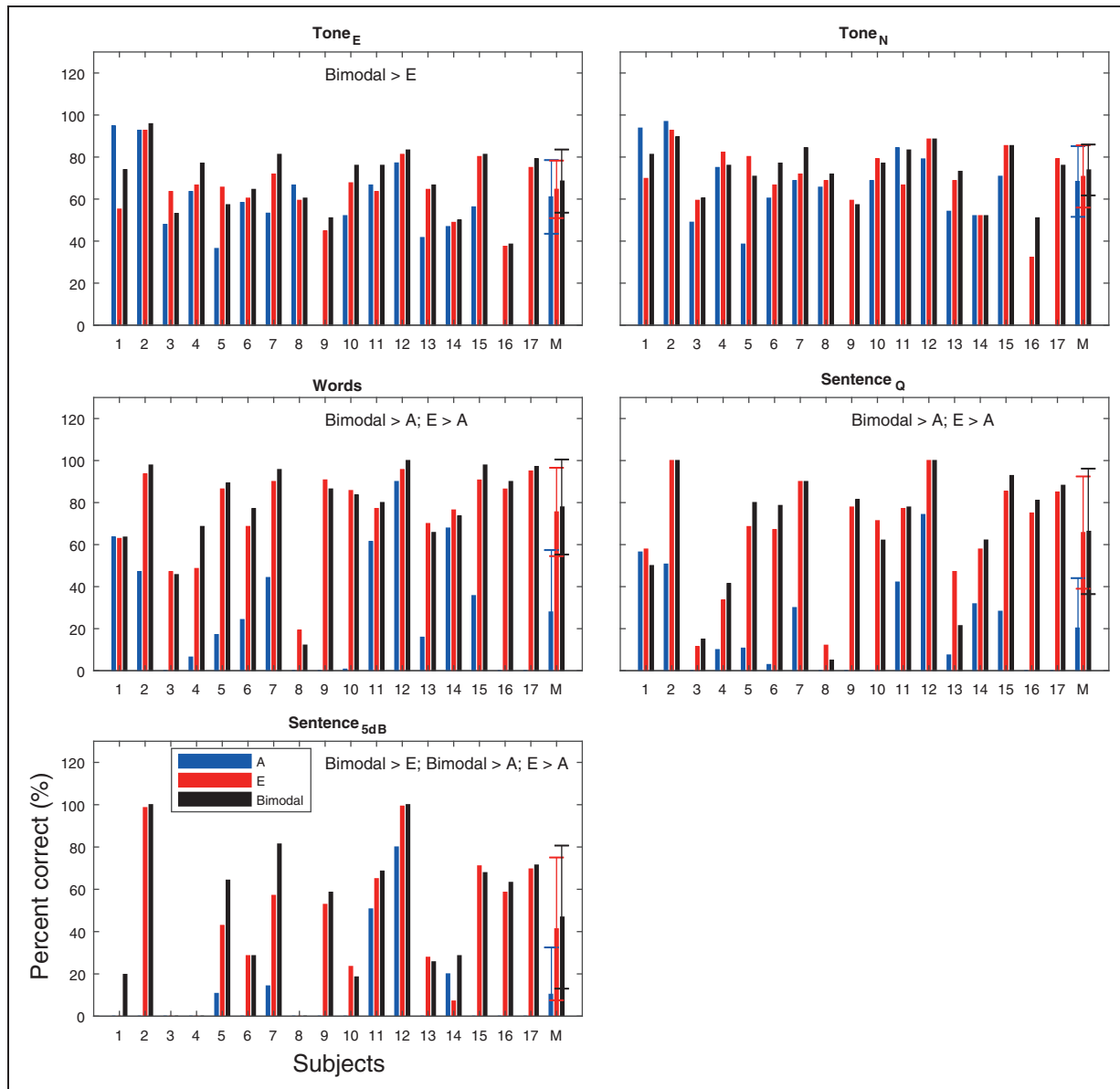


Figure 2. Individual performance with the A (hearing aid alone), E (cochlear implant alone), and bimodal hearing (combined stimulation). Each panel shows individual and group mean performance for one speech recognition task. Error bars represent standard deviation. In the panel titles, the subscript E stands for equal duration, N stands for naturally spoken, Q stands for quiet, and 5 dB indicates the SNR. SNR = speech-to-noise ratio.

the bimodal effect for word recognition was not significantly different from zero, the effect, regardless of direction, showed a weak correlation with the amount of residual hearing at 750 Hz and 1000 Hz (Table 2).

Discussion

The overall bimodal benefit observed in the present study was small. Significant benefit was seen only for tone recognition using equal-duration stimuli and sentence recognition in noise. The magnitudes of the benefit for

those two tasks were also rather small. On average, there was only a 4-percentage-point improvement for tone recognition in quiet using equal-duration stimuli and a 6-percentage-point improvement for sentence recognition in noise. The subjects who participated in our study had overall much poorer residual hearing (severe to profound loss) than those reported in the English-speaking studies. It should be noted that these subjects are representative of the bimodal users in mainland China. The current criteria for CI candidacy in China are much more stringent than those used in the United

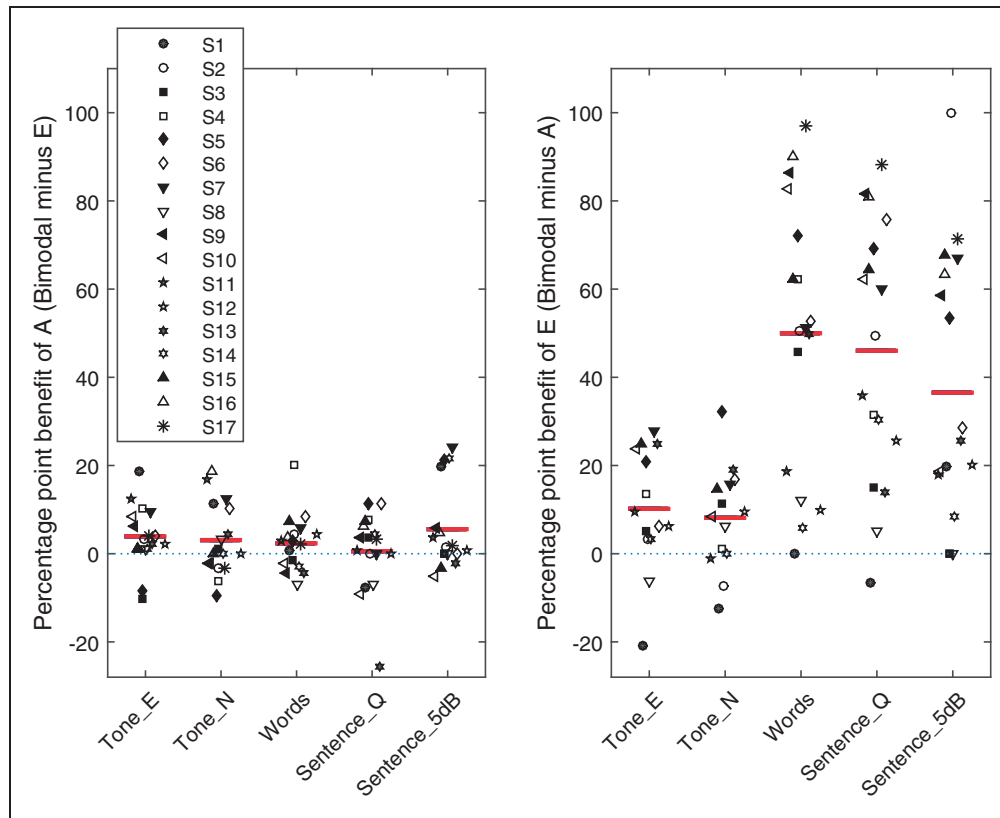


Figure 3. The benefit of A (bimodal minus E) and benefit of E (bimodal minus A) for each of the five speech recognition tasks. Each data point represents one subject. The horizontal bars represent group means. Symbols represent subjects.

States and many other countries. Bilateral severe to profound sensorineural hearing loss must be indicated (China Disabled Persons' Federation, 2011). The stringent criteria for CI candidacy resulted in very few Mandarin-speaking CI users who have substantial residual acoustic hearing. Although the literature has shown considerable variability in the magnitude of bimodal benefits in relation to audiometric thresholds, the general trend was that patients with better residual hearing are more likely to benefit from a contralateral HA (e.g., Dorman et al., 2015; Illg, Bojanowicz, Lesinski-Schiedat, Lenarz, & Buchner, 2014; Li et al., 2014). The results in the present study align with these previous findings and advocate for more relaxed implantation criteria to be used in China. These results may also provide guidance for clinical practices in terms of making recommendations for fitting a HA for the nonimplanted ear with limited residual hearing.

Many studies have reported a deficit in tone perception and production in tonal-language speaking prelingually deafened CI users (e.g., Han et al., 2007; Zhou, Huang, Chen, & Xu, 2013; Zhou & Xu, 2008a). The deficit has been attributed to the lack of explicitly coded F0 information in the envelope-based speech processing strategies used in the modern CI devices. The acoustic

residual hearing, supposedly with much higher frequency resolution compared with that provided by the implant, is expected to provide resolved F0 information, thus assisting tone perception. The primary acoustic correlate for Mandarin tones is the (time-varying) F0, but the Mandarin tones also differ in their amplitude envelopes that correlate with the F0 contours, and duration (Whalen & Xu, 1992; Xu et al., 2002). Tone 3 is produced consistently longer than Tone 2, while Tone 4 is the shortest. In the current study, Mandarin tones that were naturally spoken and those that were normalized in duration were both tested. The rationale was that without the duration cue, listeners would be expected to rely more on F0 information than if the tones were naturally spoken. If the HA provides such F0 information, the benefit of the HA would be greater for equal-duration tones than for naturally-spoken tones. Our results showed that the benefit of a HA was only statistically significant for recognizing tones with equal duration, but not for naturally-spoken tones, supporting the notion that the better resolved low frequencies would benefit tone perception when listeners rely less on the secondary cues. Again, although significant, the bimodal benefit for equal-duration tones was small, and perhaps not clinically meaningful,

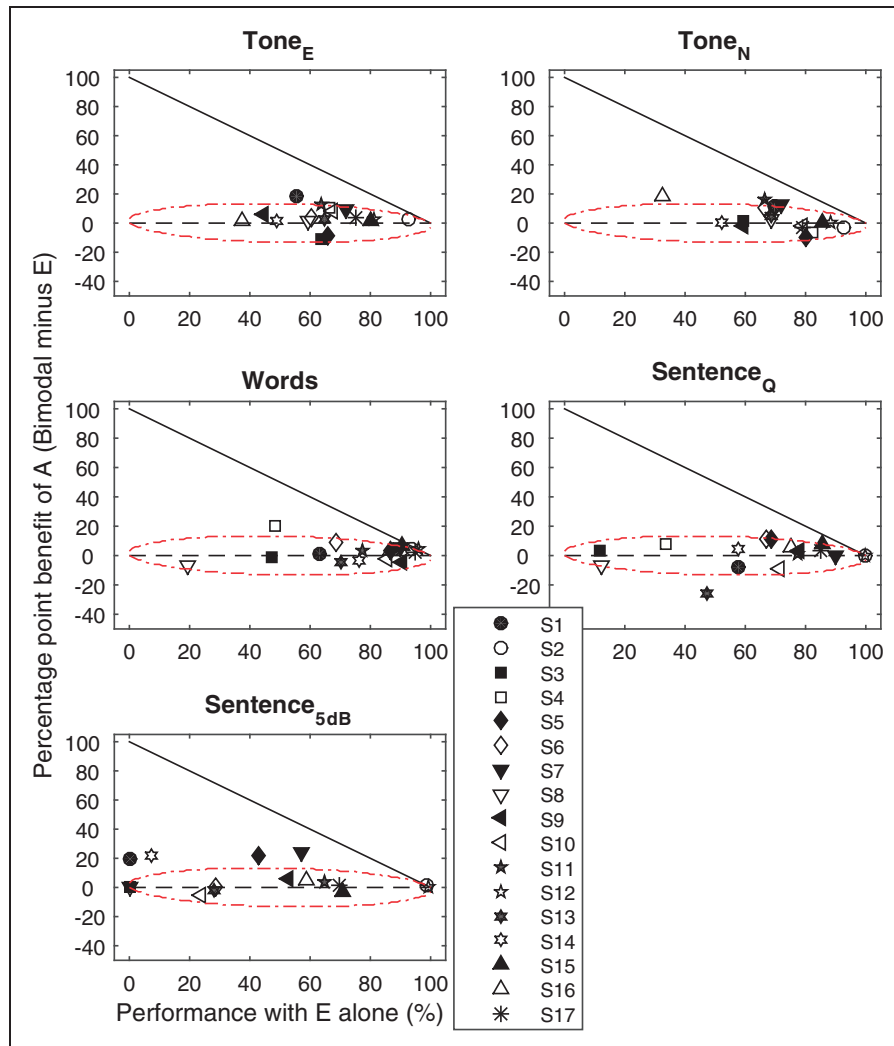


Figure 4. Benefit of the hearing aid (A) plotted as a function of the performance with the cochlear implant (E) alone. The solid lines indicate the maximum possible benefit. The circle in each panel indicates the 95% critical difference scores for the corresponding speech recognition task. Symbols represent subjects.

because rarely would tones be spoken without duration differences.

The results of the present study also showed that residual hearing in different frequency bands may contribute to bimodal effects for different speech recognition tasks. The magnitudes of bimodal effect for tone and sentence recognition in noise were both correlated with the unaided audiometric thresholds at low frequencies, i.e., 125 and 250 Hz. Consistent with the segregation theory and many previous reports, the results likely suggest that the subjects primarily used the F0-related low-frequency information for identifying voice pitch changes and segregating different auditory objects. Thresholds at frequencies higher than those that primarily contribute to voicing (i.e., 750 and 1000 Hz) showed a weak correlation with bimodal effect, regardless of direction, for word recognition. These frequencies correspond to the

first formant and the low end of the second-formant frequency range for vowels. Because tone and word recognition depended on residual hearing at different frequencies, any bimodal benefit for tone recognition may not necessarily contribute to other speech recognition tasks, which was in fact what was often observed with the current data.

Overall, there was no benefit observed for the speech-recognition-in-quiet tasks, consistent with previous studies that showed that even for subjects with good audiometric thresholds in the contralateral ear, benefit for speech recognition in quiet could be small (Dorman et al., 2015; Gifford et al., 2015, 2014). For current data, the lack of benefit for speech recognition in quiet could be due to a ceiling effect, particularly for word recognition, or poor frequency resolution associated with hearing loss providing little useful information at the relevant

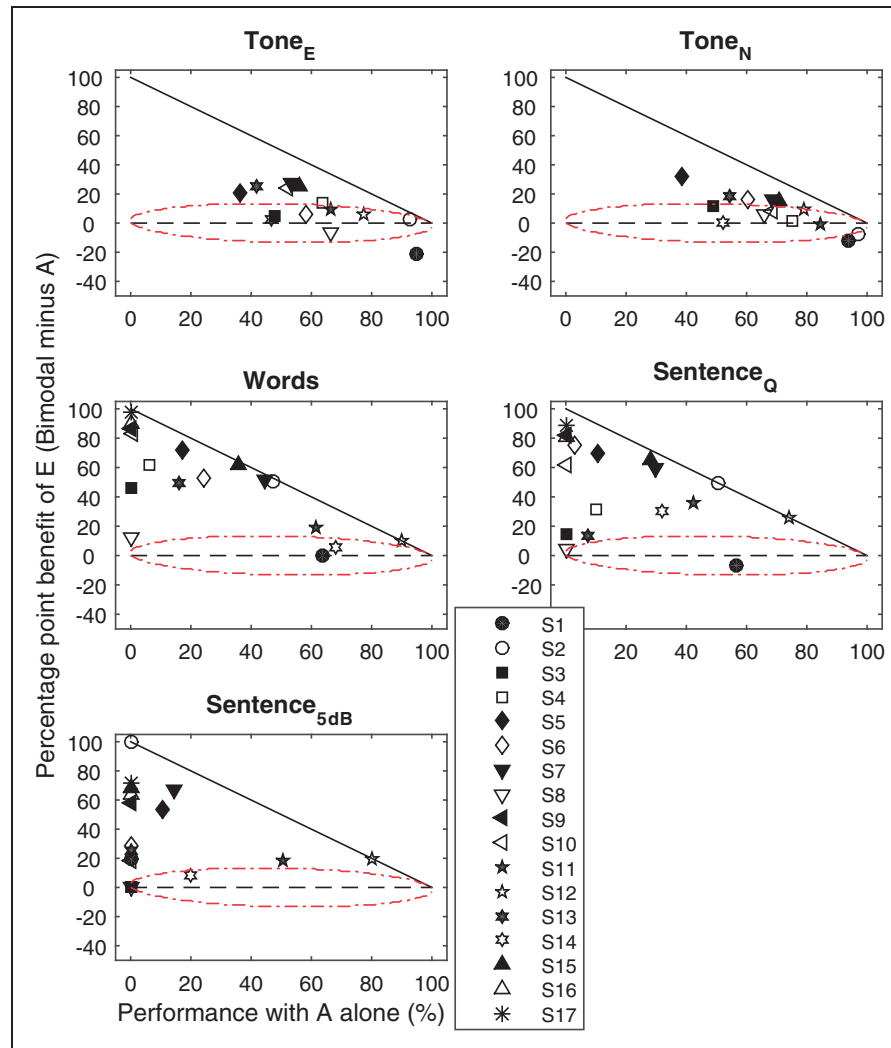


Figure 5. Benefit of the cochlear implant (E) plotted as a function of the performance with the hearing aid (A) alone. The solid lines indicate the maximum possible benefit. The circle in each panel indicates the 95% critical difference scores for the corresponding speech recognition task. Symbols represent subjects.

Table 2. Correlation Coefficients for Correlations Between Bimodal Benefit and Unaided Pure-Tone Thresholds.

Frequencies (Hz)		125	250	500	750	1000	2000	4000	6000	8000
Tone_E	<i>r</i>	-.5765	-.427	-.2728	-.249	-.0498	.2254	.1341	.1123	.1587
	<i>p</i>	.0154*	.0874	.2895	.3353	.8495	.3844	.6079	.668	.5429
Tone_N	<i>r</i>	-.0714	.0969	-.1209	-.1042	-.1386	-.0217	.111	.1743	.1879
	<i>p</i>	.7855	.7114	.6439	.6905	.5959	.934	.6715	.5033	.4703
Words	<i>r</i>	-.2698	-.141	-.2761	-.4968	-.4738	-.3947	-.2539	-.2726	-.0879
	<i>p</i>	.295	.5894	.2833	.0425*	.0547	.1169	.3255	.2899	.7374
Sentence_Q	<i>r</i>	.3075	.2573	.205	-.2104	-.1695	-.298	-.1667	-.2021	-.1147
	<i>p</i>	.2298	.3187	.4299	.4177	.5154	.2453	.5226	.4367	.6611
Sentence_5dB	<i>r</i>	-.5253	-.6079	-.4481	-.4537	-.3002	-.4626	-.5095	-.4009	-.5864
	<i>p</i>	.0304*	.0096*	.0712	.0674	.2417	.0615	.0367*	.1108	.0134*

**p* < .05.

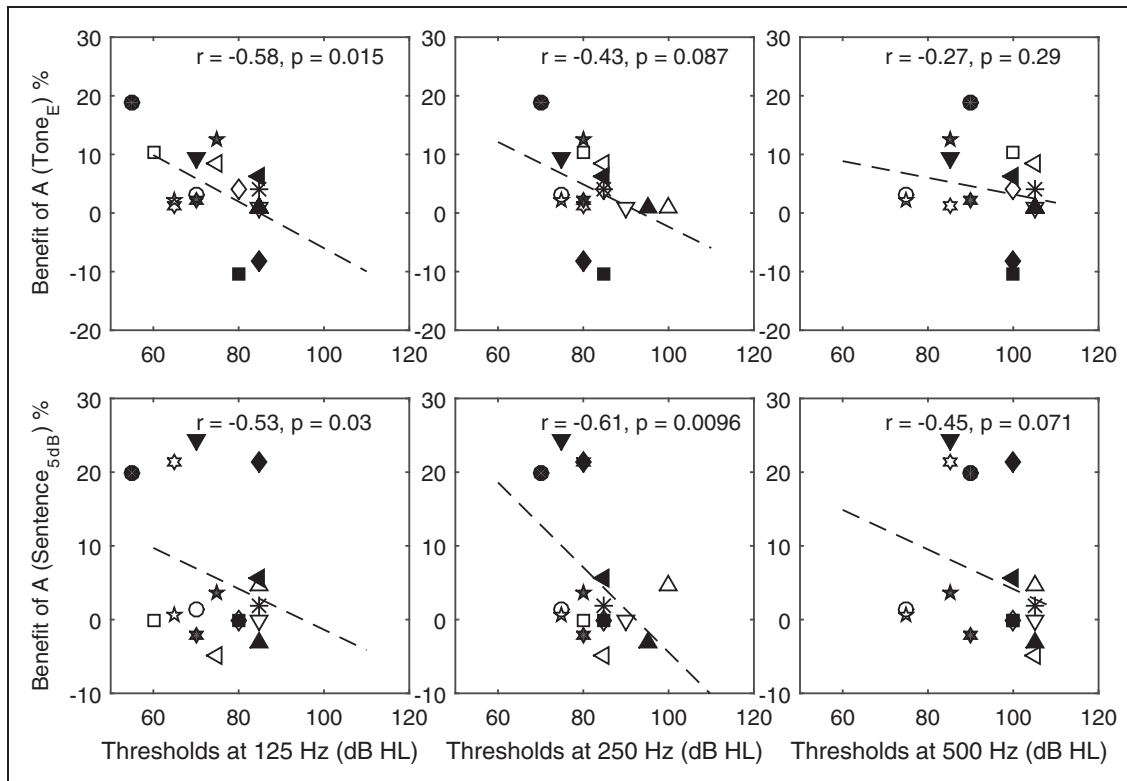


Figure 6. Scatter plots of benefit of A for tone recognition with equal-duration stimuli (upper panels) and sentence recognition in noise (lower panels) against unaided audiometric thresholds at 125 Hz, 250 Hz, and 500 Hz. Lines represent linear fit to the data. The correlation coefficients and p values are shown in each panel. Symbols represent subjects (refer to previous figures for legend).

frequencies to be combined with those delivered by the implant. The insufficient hearing function at high frequencies associated with sloping hearing loss may also explain why in previous studies bimodal effect was more consistently found for tone recognition but less so for phoneme recognition (Chang et al., 2016; Li et al., 2014; Yang & Zeng, 2017), and the benefit was more consistently found for speech in noise tasks than for quiet conditions (Dorman et al., 2008; Gifford et al., 2007; Kong et al., 2005; Turner et al., 2004; Zhang et al., 2010).

When inspecting individual data (Figure 4), it can be seen that very few subjects who performed better with the addition of the HA, compared with using the implant alone, fell outside of the 95% confidence interval. Instances of adverse effect of a HA were also seen. A few subjects were on the border line of the critical difference scores, and one subject (S13) performed significantly worse with the addition of the HA for sentence recognition in quiet than with the implant alone. These results may be understood in terms of less efficient or even abnormal central integration of the electrical and acoustic information, rather than having insufficient audibility per se. Yang and Zeng (2013) showed that simulated bimodal users could benefit from additional

low-frequency information to a much greater degree than real bimodal users. The results could be attributed to the better resolved acoustic information providing more useful information when combined with electrical stimulation in the normal hearing system (e.g., Sheffield, Simha, Jahn, & Gifford, 2016). Yang and Zeng (2013), however, suggested that the actual bimodal users may have difficulties integrating the same information that the simulated bimodal users were given, suggesting a central abnormality in deafened auditory systems. It is interesting to observe that when comparing bimodal performance relative to the performance with the HA alone (benefit of the implant), adverse effects were also seen in a few subjects for tone recognition tasks, which also suggested abnormal integration (Figure 5). Factors identified for predicting integration efficiencies of the bimodal devices include the amount of residual hearing, duration of deafness, experience with CIs, as well as binaural frequency-place mismatch (Reiss et al., 2015, 2016; Yang & Zeng, 2013, 2017). It remains unclear why subjects with little residual hearing would have greater difficulties integrating information centrally, although central neural degeneration is a possible factor. The low hearing function might in turn have resulted in a less consistent use of the HAs in these patients, making

integration a challenging or less experienced task for the brain when the two modalities are used together.

Two caveats to the methodologies used in the present study should be noted. As was mentioned in the Methods section, HAs were not verified at the time of the experiments. The aided thresholds (Figure 1) showed large variability across subjects, especially at high frequencies. Although audiometric thresholds are not perfect indications for HA output, they suggest however, for some subjects, at least some frequency components of the speech stimulus might not be audible at the presentation level (65 dB(A)). Audibility could be an alternative explanation for the overall small bimodal benefit and the lack of bimodal benefit for speech recognition in quiet that requires information at frequencies higher than voice F0s. Another limitation of the present study was that we used a group of prelingually deafened subjects comprising both pediatric and adult CI users, and the results were interpreted in the literature that consisted of results mainly from postlingually deafened adult CI listeners. We should therefore caution comparison of the absolute performances with those previously reported and caution interpretation using central auditory processing mechanisms inferred from adults.

In summary, findings of the present study were in line with those reported previously that residual hearing may provide more consistent benefit for speech recognition tasks that require higher spectral resolution, such as tone recognition and speech recognition in noise. Although significant bimodal benefits were found for these tasks, the effects were small. The results were not surprising given the amount of residual hearing in the nonimplanted ear of the current subject sample. These subjects were representative of the CI population in mainland China, where candidacy criterion is extremely stringent. The current results advocate for a relaxed implant criterion for Mandarin-speaking hearing-impaired patients to benefit from a contralateral HA.

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