



## Original Article

# Bimodal benefits in Mandarin-speaking cochlear implant users with contralateral residual acoustic hearing

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## Abstract

**Objective:** The present study aimed to measure bimodal benefits and probe their underlying mechanisms in Mandarin-speaking cochlear implant (CI) subjects who had contralateral residual acoustic hearing. **Design:** The subjects recognised words or phonemes from the Mandarin Lexical Neighborhood Test in noise at a 10-dB signal-to-noise ratio (SNR) with acoustic stimulation, electric stimulation or the combined bimodal stimulation. **Study sample:** Thirteen Mandarin-speaking subjects wore a CI in one ear and had residual acoustic hearing in the contralateral ear. Six of the subjects (5.2–13.0 years) had pre-lingual onset of severe hearing loss, and seven of them (8.6–45.8 years) had post-lingual onset of severe hearing loss. **Results:** Both groups of subjects produced a significant bimodal benefit in word recognition in noise. Consonants and tones accounted for the bimodal benefit. The bimodal integration efficiency was negatively correlated with the duration of deafness in the implanted ear for vowel recognition but positively correlated with CI or bimodal experience for consonant recognition. **Conclusions:** The present results support preservation of residual acoustic hearing, early cochlear implantation and continuous use of bimodal hearing for subjects who have significant residual hearing in the non-implanted ear.

**Key Words:** Bimodal stimulation, cochlear implants, hearing aids, Mandarin speech recognition, consonants, vowels, tones, integration efficiency

## Introduction

Mandarin is spoken by more than one billion people worldwide. As a tonal language, Mandarin conveys lexical information mainly through four fundamental frequencies (F0) and corresponding harmonic variations: flat, raising, falling-raising or falling. These patterns are the most robust acoustic features for tone identification by normal-hearing subjects (Liang, 1963). Due to reduced spectral resolution, tone recognition is degraded in hearing-impaired subjects (Liu et al, 2000), particularly in cochlear implant (CI) subjects listening in noise (Wei et al, 2004; Huang et al, 2005; Luo et al, 2009). A potentially effective means to improve CI tone recognition is to utilise F0 and lower harmonics via preserved low-frequency acoustic hearing in either the implanted ear (electro-acoustic stimulation) or the contralateral ear (bimodal stimulation). Indeed the additional low-frequency acoustic hearing has significantly improved CI speech-in-noise recognition in non-tonal languages (von Ilberg et al. 1999; Turner et al. 2004; Kong et al, 2005; Cullington & Zeng, 2011).

However, limited research has been conducted on the effect of combined electric and acoustic stimulation on tonal language processing. In a simulation of combined electric and acoustic stimulation in normal-hearing listeners, Luo & Fu (2006) found that additional low-frequency acoustic cues below 500 Hz improved Mandarin speech recognition in speech-spectrum-shaped noise. In actual Mandarin-speaking CI subjects, the benefit of combined stimulation has not been consistently demonstrated. In bimodal Mandarin-speaking child subjects, Yuen et al. (2009) reported a significant bimodal benefit when speech and noise were spatially separated but no benefit when both speech and noise were presented by a single speaker. In bimodal Mandarin-speaking adult subjects, Li et al. (2014) found that the bimodal benefit depended on both test materials and test conditions: tone recognition was better with bimodal stimulation than with CI in noise but not in quiet, vowel recognition was better with bimodal stimulation in quiet but not in noise, while consonant recognition was not different between bimodal stimulation and CI in either quiet or noise.

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**Abbreviations**

CI	cochlear implant
F0	Fundamental frequency
SNR	signal-to-noise ratio
M-LNT	Mandarin Lexical Neighborhood Test

One reason for the inconsistent bimodal benefits across studies may be related to different phonemic contributions to speech recognition in different auditory stimulation conditions. In non-tonal languages, consonants carry the most information in recognition of isolated words (Owens et al, 1968; Fogerty & Humes, 2010), whereas vowels are more important than consonants in recognition of sentences (Kewley-Port et al, 2007; Fogerty et al, 2012). In tonal languages, such as Mandarin, vowels contribute more than consonants in recognising both isolated words (Chen et al, 2015) and sentences (Chen et al, 2013) in normal-hearing individuals. However, the relative contribution of tone to word or sentence recognition could not be evaluated with their noise-replacement paradigm (Chen et al, 2013, 2015). Using a power probability model, Fu et al. (1998) found that consonants, vowels, and tones contributed equally to Mandarin sentence recognition in normal-hearing subjects listening to noise-vocoded speech. To characterise the bimodal effects, the present study would measure both Mandarin phoneme and word recognition and test the power probability model in the same group of actual bimodal subjects.

Another reason for the inconsistent bimodal benefit may be related to different degrees of acoustic and electric integration. For example, different electrode-to-pitch adaptation has been reported in bimodal CI users with poor low-frequency residual hearing (Reiss et al, 2015), which is associated with abnormally broad pitch fusion and speech perception interference between two ears (Reiss et al, 2016). Bimodal integration efficiency (see Materials and Methods section for definition) has also been reported to negatively correlate with the residual hearing in the non-implanted ear and the duration of deafness in the implanted ear of English-speaking bimodal subjects (Yang & Zeng, 2013). The present study would further examine potential relations between subjects' demographic and audiological variables and the bimodal integration efficiency.

## Materials and methods

### Subjects

Thirteen CI subjects ( $15.3 \pm 10.6$  years) who had residual low-frequency hearing in the contralateral ear participated in the experiment. Six of the subjects (5.2–13.0 years) had onset of severe hearing loss before the age of two (for the cut-off age of pre-lingual hearing loss, refer Kuhl, 2010), and seven of them (8.6–45.8 years) had onset of severe hearing loss after the age of two. No additional developmental delay or disability was reported by the subjects or their parents. Table 1 displays the subjects' demographic and audiological information. The present subjects were all native Mandarin speakers with a Taiwanese accent and had at least one year of extensive post-implantation training provided by the National Women's League Foundation for the Hearing Impaired in Taiwan. They had average open set word recognition in quiet with CI, with the mean being  $66\% \pm 9\%$  and the range being from 54% to 80%, similar to the level of performance reported in the previous study (Yang & Wu, 2005). Figure 1 shows their unaided pure tone thresholds across audiometric frequencies from 125 to

8000 Hz in the non-implanted ear. All the subjects signed a consent document approved by the University of California Irvine Institutional Review Board and were paid for their participation in the study.

### Test materials

The Mandarin Lexical Neighborhood Test (M-LNT) was based on the Neighborhood Activation Model (Luce & Pisoni, 1998) and designed to evaluate open set word recognition performance in hearing-impaired preschoolers (Yang & Wu, 2005). The M-LNT included four word lists, each consisting 25 lexically "easy" and 25 lexically "hard" words from normal-hearing children's daily conversations. Each word can be uniquely determined by a combination of consonant, vowel and tone, or in some cases a combination of only a vowel and a tone. The lists included 21 consonant types ([p], [p<sup>h</sup>], [m], [f], [t], [t<sup>h</sup>], [n], [l], [k], [k<sup>h</sup>], [x], [tʃ], [tʃ<sup>h</sup>], [ç], [tʃ], [tʃ<sup>h</sup>], [ʃ], [z], [ts], [ts<sup>h</sup>], [s]), 33 vowel types ([a], [o], [ɤ], [i], [ia], [iɛ], [u], [ua], [uo], [y], [yɛ], [ai], [ei], [au], [ou], [iau], [iou], [uai], [uei], [an], [ən], [aŋ], [əŋ], [iɛn], [in], [ian], [in], [uan], [uən], [uaŋ], [uən], [yɛn], [iɔŋ]), and four tone patterns (flat, raising, falling-raising and falling). The total numbers of consonants, vowels and tones, respectively, were 45, 50 and 50 in List A, 45, 50 and 50 in List B, 46, 50 and 50 in List C, and 46, 50 and 50 in List D. Although the M-LNT was designed for preschoolers, it had been used to test CI users older than 6 of age (Yang & Wu, 2005). Moreover, it included all consonants, tones and vowels except two ([ɤɛ] and [yn]) in Mandarin that could be used to test adults for evaluation of the phoneme-to-word relationship. All words were spoken by a male ( $F0 = 116.3 \pm 46.2$  Hz), experienced speech pathologist in Taiwan. The two hundred words were normalised to have the same long-term root-mean-square amplitude and were presented in speech-spectrum-shaped noise at a fixed 10 dB signal-to-noise ratio (SNR) to avoid ceiling effect.

All the stimuli were digitally processed by MATLAB (The MathWorks, Inc., Torrance, CA) and generated through a 24-bit, 44,100 Hz sound card (Creative Labs E-MU 0404 USB digital audio system, Creative Technology Ltd., Singapore). The presentation sound level of the stimuli was linearly adjusted at a gain up to 60 dBA with a flat frequency response over the 20–20,000 Hz range on an individual basis until the most comfortable level was reached for each subject in each stimulation mode. To eliminate individual differences across hearing aids, a headphone (HAD200, Sennheiser Electronic GmbH & Co., Wedemark, Germany) was used in acoustic stimulation. In electric stimulation, the stimuli were delivered to the subject's clinical CI processor through a directly-connected audio cable. In bimodal stimulation, both headphone and direct CI connection were used to present the stimuli.

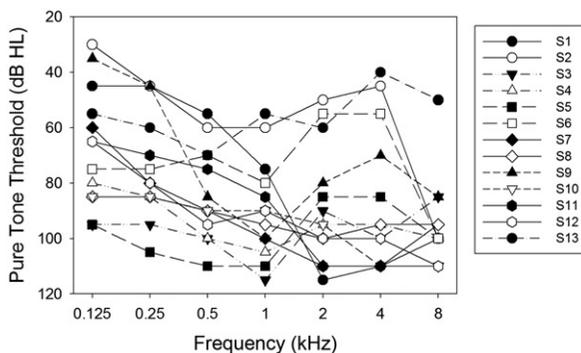
### Procedures

Each of the subjects sat in a sound-treated booth and practiced with one randomly selected list of the M-LNT words to familiarise themselves with the target sound and the recognition task. During the actual test, the remaining three lists were randomly selected to test word recognition in one of the three stimulation modes. The order of stimulation modes to be tested was also randomised. In each stimulation mode, all the subjects except S4 and S5 listened to the 50 words from one list and wrote down the words on an answer sheet. Subject S4 and S5, who were too young to write down their answers, responded by speaking out the words to an operator who

**Table 1.** Subjects' demographic and audiological information.

ID	Gender	Age (years)	CI ear	Severe hearing loss onset (years)	HA experience (years)	Duration of deafness in CI ear (years)	CI/bimodal experience (years)	PTA (dB HL)	CI processor
S1	F	45.8	L	33.2	33.8	9.3	3.3	48	Freedom (BTE)
S2	M	11.1	R	0.4	10.8	8.0	2.7	45	MED-EL OPUS2
S3	M	16.9	L	4.0	14.4	9.5	3.4	97	Freedom (BTE)
S4	M	5.2	L	1.3	3.9	2.9	1.0	88	Freedom (BTE)
S5	F	6.0	R	0.3	4.8	0.8	4.9	103	Freedom (bodyworn)
S6	M	18.2	L	12.7	16.6	0.9	4.6	73	AB Harmony
S7	F	25.6	R	19.1	22.2	5.3	1.2	77	Freedom (BTE)
S8	F	13.0	L	2.0	0.3	0.5	10.5	87	Freedom (BTE)
S9	F	8.6	L	3.0	5.6	3.0	2.6	55	MED-EL OPUS2
S10	M	12.2	R	1.0	8.8	2.1	9.1	87	Sprint (bodyworn)
S11	F	10.9	R	4.0	6.9	1.0	5.9	70	Sprint (bodyworn)
S12	M	12.0	R	1.0	10.8	3.8	7.2	80	AB PSP
S13	M	13.3	L	2.5	10.8	3.6	7.2	62	AB PSP
Mean (SEM)	N/A	15.3 (2.9)	N/A	6.5 (2.7)	11.5 (2.5)	3.9 (0.9)	4.9 (0.8)	74.7 (5.1)	N/A

CI: cochlear implant; HA: hearing aid; PTA: pure tone threshold average at 125, 250 and 500 Hz in the non-implanted ear.



**Figure 1.** Audiograms of the unaided, non-implanted ear in the present 13 subjects.

transcribed their responded words. Each word was written in Mandarin phonetic symbols specific to Taiwanese. No word was repeated, and no feedback was provided. The subject controlled the pace of the test, with the test being completed typically within three hours.

Word recognition was calculated as a percentage of the correctly answered words. The number of correctly recognised consonants, vowels or tones was further calculated by individually scoring the phonemes in each word. The consonant, vowel or tone recognition score was obtained by dividing the number of correctly identified consonants, vowels or tones over the total number of consonants, vowels or tones, respectively, on each word list.

#### Data analysis

Repeated Measures Analysis of Variance (RM ANOVA; SPSS 16.0, IBM Corporation, Armonk, NY) was used to evaluate the effect of stimulation mode and phoneme type on recognition performance. The sphericity assumption was assessed by Mauchly's test, and  $F$ -values were adjusted using a Greenhouse–Geisser correction if the assumption had been violated. A  $p$  value less than 0.05 was taken to be a significant difference.

A probability model (Fu et al, 1998) was used to describe the relationship between Mandarin phonemes (consonant, vowel and tone) and isolated words:

$$P_w = (P_c^{w_c} P_v^{w_v} P_t^{w_t})^j \quad (1)$$

where  $P_w$ ,  $P_c$ ,  $P_v$  and  $P_t$  are the word, consonant, vowel and tone recognition scores, respectively, while  $w_c$ ,  $w_v$  and  $w_t$  are the weighting coefficients for consonant, vowel and tone, respectively. Power  $j$  was set to be 2.67 (Fu et al, 1998). The weighting coefficients in each stimulation mode were further compared by a two-tailed  $t$ -test.

The bimodal integration efficiency, IE, was used to quantify the ability to integrate acoustic and electric information in bimodal stimulation (Yang & Zeng, 2013). It was defined as the ratio of the actual bimodal score,  $P'_{bs}$  and the predicted bimodal score,  $P_{bs}$ :

$$IE = \frac{P'_{bs}}{P_{bs}} \quad (2)$$

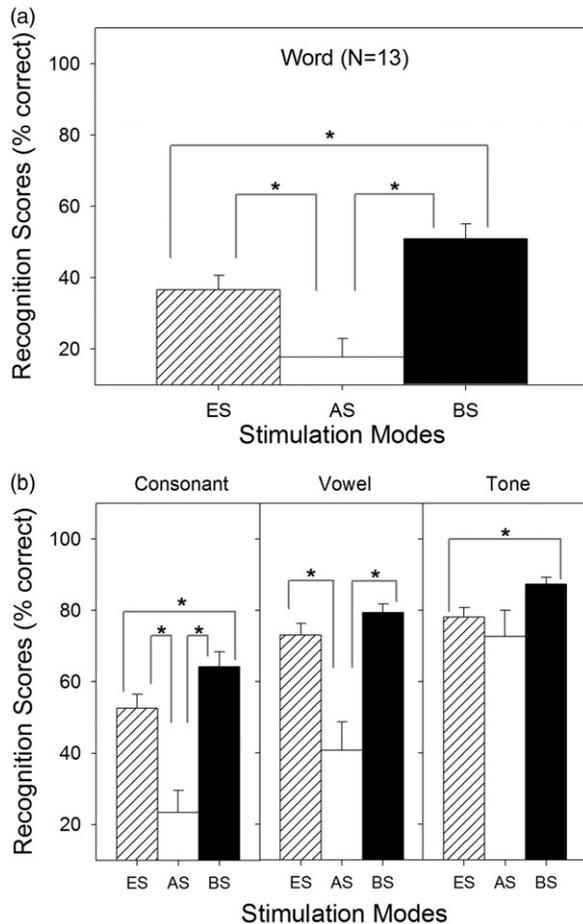
where  $P_{bs}$  was predicted by independent addition of the score  $P_a$  in acoustic stimulation and the score  $P_e$  in electric stimulation:

$$P_{bs} = P_a + P_e - P_a P_e \quad (3)$$

Linear regression analysis (SigmaPlot 10.0, Systat Software, Inc., San Jose, CA) was used to correlate bimodal integration efficiency with subjects' demographic and audiological variables listed in Table 1.

#### Results

As the two hearing loss onset groups produced no significant difference in word recognition in any of the three stimulation modes [ES:  $F(1,5)=0.6$ ,  $p=0.49$ ; AS:  $F(1,5)=0.2$ ,  $p=0.67$ ; BS:  $F(1,5)=0.48$ ,  $p=0.52$ ], the data were combined for further analysis. Figure 2(a) displays word recognition scores and their standard errors in three stimulation modes. The stimulation mode produced a significant main effect [ $F(1.4,17.1)=19.5$ ,  $p<0.05$ ],



**Figure 2.** (a) Average scores of the M-LNT word recognition; (b) consonant, vowel, and tone recognition in speech-spectrum-shaped noise (SNR = 10 dB) with electric stimulation (ES: hatched bars), acoustic stimulation (AS: unfilled bars) and bimodal stimulation (BS: filled bars). Error bars represent one standard error of mean ( $N=13$ ). Asterisks indicate significant difference ( $p < 0.05$ ) between stimulation modes.

with the bimodal stimulation having the highest word recognition score of 51%, which was 14 percentage points higher than the electric stimulation [ $F(1,12) = 15.4$ ,  $p < 0.05$ ] and 33 percentage points higher than the acoustic stimulation [ $F(1,12) = 40.1$ ,  $p < 0.05$ ]. The percent correct scores were also significantly different between the electric and acoustic stimulation modes [ $F(1,12) = 8.0$ ,  $p < 0.05$ ].

Figure 2(b) shows phoneme recognition scores in three stimulation modes. Averaged across the three stimulation modes, tones had the highest percent correct score of 79%, followed by vowels (64%) and consonants (47%) accordingly [ $F(1.5,18.5) = 55.3$ ,  $p < 0.05$ ]. The stimulation mode was also a significant factor, with the bimodal stimulation mode having the highest score (77%), followed by the electric stimulation mode (68%) and the acoustic stimulation mode (46%) accordingly [ $F(2,24) = 17.4$ ,  $p < 0.05$ ]. As there was a significant interaction between the phoneme type and stimulation mode [ $F(2.5,29.5) = 11.4$ ,  $p < 0.05$ ], only significant differences were noted (asterisks in the panel). Specifically, consonant recognition was the highest with bimodal stimulation (64%), which was 12 and 41 percentage points higher than with the

**Table 2.** Nonlinear regression analysis of a probability model in acoustic (AS), electric (ES) and bimodal stimulation (BS). Significant predictors are marked in bold.

Stimulation mode	Regression		Weighting coefficients				
	$R^2$	$p$ value	Phoneme	Value	SE	$t$ -Statistic	$p$ value
AS	0.968	<0.0001	<b>Consonant</b>	0.314	0.099	3.17	0.010
			<b>Vowel</b>	0.280	0.110	2.54	0.030
			Tone	0.165	0.389	0.43	0.680
ES	0.948	<0.0001	<b>Consonant</b>	0.256	0.061	4.17	0.002
			<b>Vowel</b>	0.497	0.099	5.01	0.001
			<b>Tone</b>	0.280	0.089	3.16	0.010
BS	0.892	<0.0001	<b>Consonant</b>	0.259	0.079	3.29	0.008
			<b>Vowel</b>	0.404	0.143	2.83	0.018
			<b>Tone</b>	0.384	0.149	2.57	0.028

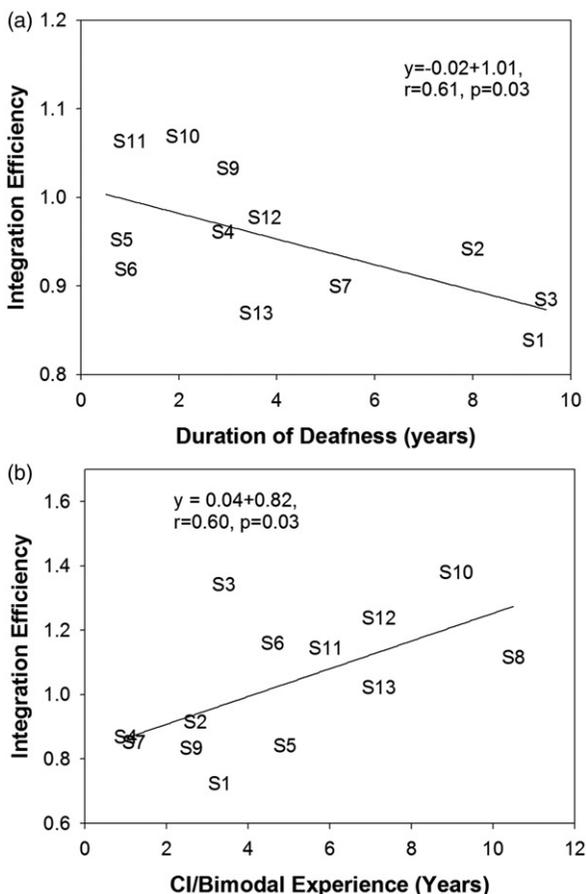
electric stimulation [ $F(1,12) = 10.4$ ,  $p < 0.05$ ] and acoustic stimulation [ $F(1,12) = 42.9$ ,  $p < 0.05$ ], respectively. Vowel recognition was similar between the bimodal (79%) and electric stimulation (73%) [ $F(1,12) = 6.5$ ,  $p = 0.07$ ], with both being significantly higher than the acoustic stimulation (41%) [ $F(1,12) = 13.9$ ,  $p < 0.05$ ]. Tone recognition was significantly higher with the bimodal stimulation (87%) than with the electric stimulation (78%) [ $F(1,12) = 14.8$ ,  $p < 0.05$ ] but not higher than with the acoustic stimulation (73%; [ $F(1,12) = 3.7$ ,  $p = 0.08$ ]) due to its large individual difference and small size.

## Discussion

Despite the small number and age disparity of subjects, the present study found a significant bimodal benefit in Mandarin word (14 percentage points), consonant (12 percentage points) and tone (9 percentage points) recognition in noise but no such benefit in vowel recognition in noise. The size of the bimodal benefit in the present study was similar to that in previous studies (Yuen et al, 2009; Li et al, 2014).

### Phonemic mechanisms underlying the bimodal benefit

Table 2 shows phoneme weighting coefficients as a function of stimulation mode (rows). Phonemes with higher weights provide more relative contribution to word recognition in each stimulation mode. In acoustic stimulation, consonants and vowels contributed equally to word recognition [ $w_v \cong w_c$ ,  $t(24) = 0.22$ ,  $p = 0.82$ ], which was consistent with Fogerty et al.'s (2012) results in elderly hearing impaired listeners, but not with Chen et al.'s (2015) results in normal-hearing Mandarin-speaking listeners. The inconsistency may be due to different test materials (daily life words vs. noise-replaced words; open set vs. closed set) and different amounts of residual hearing (hearing-impaired vs. normal hearing). In electric stimulation, vowels were more important than consonants in predicting word recognition [ $w_v > w_c$ ,  $t(24) = 2.06$ ,  $p < 0.05$ ;  $w_c \cong w_t$ ,  $t(24) = 0.22$ ,  $p = 0.83$ ;  $w_v \cong w_t$ ,  $t(24) = 1.63$ ,  $p = 0.12$ ]. The result was inconsistent with Fu et al.'s (1998) simulation study, which may be due to different signal processing (actual CI vs. vocoder simulation) and different test materials (open set vs. closed set). In bimodal stimulation, all three phonemes contributed equally to the prediction of word recognition [ $w_v \cong w_c \cong w_t$ ,  $t(24) < 0.88$ ,  $p > 0.19$ ]. Note that the relative contribution of



**Figure 3.** Correlational analysis. (a) Bimodal integration efficiency for vowel recognition vs. duration of deafness in the implanted ear ( $N=13$ ); (b) bimodal integration efficiency for consonant recognition vs. CI/bimodal experience ( $N=13$ ).

consonants to word recognition increased from electric stimulation to bimodal stimulation. The increased role of consonants in bimodal stimulation is likely due to efficient use of F0 and lower harmonic cues via residual acoustic hearing (Luo & Fu, 2004; Wang et al, 2011; Sheffield & Zeng, 2012). On the other hand, the decreased role of vowels in bimodal stimulation likely reflects inefficient transfer of formant information via residual acoustic hearing (Luo & Fu, 2006; Sheffield & Zeng, 2012) and binaural interference due to abnormally broad spectral fusion between the two hearing devices (Reiss et al, 2016).

#### Factors associated with bimodal integration

The present study found significant correlations between bimodal benefits as measured by integration efficiency and two subject variables. Figure 3(a) shows that the duration of deafness in the implanted ear was negatively correlated with the integration efficiency in recognising Mandarin vowels. Figure 3(b) shows that the duration of CI and bimodal experience was positively correlated with the integration efficiency in recognising Mandarin consonants. These experience-related correlations are consistent with the auditory cortical development (Gordon et al. 2011; Stropahl et al, 2017) and cross-modal reorganisation (Kral et al,

2017; Stropahl et al, 2017) as a result of stimulation deprivation and introduction of auditory experience via CIs.

## Conclusions

The present study measured bimodal benefit in Mandarin-speaking CI users who had residual acoustic hearing in the contralateral ear. Despite of the limited sample size and age disparity, the present study found a significant bimodal benefit in word recognition in noise, which was mainly due to improved consonant and tone recognition in bimodal stimulation. Correlational analysis suggests that early implantation and extended CI or bimodal experience could help increase bimodal integration efficiency.

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