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Novel Approaches to Measure Spatial Release from Masking in Children with Bilateral Cochlear Implants

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Abstract

Objectives—To investigate the role of auditory cues for spatial release from masking (SRM) in children with bilateral cochlear implants (BiCIs) and compare their performance with children with normal hearing (NH). To quantify the contribution to speech intelligibility benefits from individual auditory cues: head shadow, binaural redundancy, and interaural differences; as well as from multiple cues: SRM and binaural squelch. To assess SRM using a novel approach of adaptive target-masker angular separation, which provides a more functionally relevant assessment in realistic complex auditory environments.

Design—Children fitted with BiCIs (N=11) and with NH (N=18) were tested in virtual acoustic space (VAS) that was simulated using head-related transfer functions (HRTFs) measured from individual children with BiCIs behind the ear and from a standard head and torso simulator for all NH children. In Experiment I, by comparing speech reception thresholds (SRT) across four test conditions that varied in target-masker spatial separation (co-located vs. separated at 180-degree) and listening conditions (monaural vs. binaural/bilateral listening), intelligibility benefits were derived for individual auditory cues for SRM. In Experiment II, SRM was quantified using a novel measure to find the minimum angular separation (MAS) between the target and masker to achieve a fixed 20% intelligibility improvement. Target speech was fixed at either +90 or −90-degree azimuth on the side closer to the better ear (+90-degree for all NH children) and masker locations were adaptively varied.

Results—In Experiment I, children with BiCIs as a group had smaller intelligibility benefits from head shadow than NH children. No group difference was observed in benefits from binaural redundancy or interaural difference cues. In both groups of children, individuals who gained a larger benefit from interaural differences relied less on monaural head shadow, and vice versa. In Experiment II, all children with BiCIs demonstrated measurable MAS thresholds < 180-degree and on average larger than that from NH children. Eight of 11 children with BiCIs and all NH children had a MAS threshold < 90-degree, requiring interaural differences only to gain the target intelligibility benefit; whereas the other three children with BiCIs had a MAS between 120 and 137-degree, requiring monaural head shadow for SRM.

Conclusions—When target and maskers were separated at 180-degree on opposing hemifields, children with BiCIs demonstrated greater intelligibility benefits from head shadow and interaural

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differences than previous literature showed with a smaller separation. Children with BiCIs demonstrated individual differences in using auditory cues for SRM. From the MAS thresholds, more than half of the children with BiCIs demonstrated robust access to interaural differences without needing additional monaural head shadow for SRM. Both experiments led to the conclusion that individualized fitting strategies in the bilateral devices may be warranted to maximize spatial hearing for children with BiCIs in complex auditory environments.

Keywords

Pediatric bilateral cochlear implant; spatial release from masking; interaural differences; head shadow; binaural redundancy

Introduction

When learning in complex auditory environments, such as noisy classrooms, children's listening can benefit from auditory cues that promote spatial hearing. Adult listeners can use auditory cues that are associated with sound sources at different spatial locations to segregate a target stream from competing talkers (Bregman 2009; Bronkhorst 2015 for a review). At a young age of 2–3 years, children with normal hearing (NH) already demonstrate speech intelligibility benefits or unmasking when the target sound is spatially separated from the competing speech maskers, as compared to when the sounds are co-located (Garadat & Litovsky 2007; Garadat et al. 2009; Hess et al. 2018). Such intelligibility benefit is known as spatial release from masking (SRM), which describes an aspect of spatial hearing that children have access to since a young age. To quantify SRM, the speech reception threshold (SRT) is measured with the target and masker co-located, then again with a spatial separation (e.g., 90-degree) between the target and masker.

For children with early onset of profound to severe hearing loss who received bilateral cochlear implants (BiCIs), there is growing evidence that bilateral implantation provides access to spatial hearing, such as the abilities to localize sounds (Zheng et al. 2015; Grieco-Calub & Litovsky 2010; Van Deun et al. 2009; Asp et al. 2012), distinguish spatial separation between two sound sources (Godar & Litovsky 2010; Grieco-Calub & Litovsky 2012; Sparreboom et al. 2015; Bennett & Litovsky 2019), and improve signal in noise threshold when interaural differences are introduced between the target signal and masker (Van Deun et al. 2010a; Todd et al. 2016).

Several studies have specifically measured SRM in children with BiCIs (Litovsky et al. 2017 for a review). Typically, a spatially co-located condition is often used with both the target and masker in front of the listener. One spatial separation condition is when the masker is displaced asymmetrically to one side either at −90 or +90-degree azimuth. In this spatial separation set-up, two sets of spatial cues were available for unmasking: the monaural head shadow and the interaural timing and level differences (ITDs and ILDs) (Van Deun et al. 2010b; Misurelli & Litovsky 2012; Misurelli & Litovsky 2015; Hess et al. 2018; King et al. 2020). SRM is typically referred to as the intelligibility benefit by having access to both monaural head shadow and ITDs/ILDs. Another spatial separation condition has also been investigated with symmetrically displaced maskers at ±90-degree, one at each side of the listener, which effectively removed the access to monaural head shadow leaving only interaural difference cues for SRM (Cameron & Dillon 2007; Misurelli & Litovsky 2012; Misurelli & Litovsky 2015).

For most BiCI users, monaural head shadow has been shown as the primary cue that listeners consistently relied on for SRM (Loizou et al. 2009; Schleich et al. 2004; Litovsky et al. 2017). The acoustic head shadow leads to a better signal-to-noise ratio (SNR) of the target speech in the ear further away from the sound source and subsequently facilitates monaural listening. Using an asymmetrical masker separation condition, with access to head shadow, Hess et al. (2018) showed that seven out of nine children between 2–3 years old with BiCIs demonstrated a meaningful SRM ≥ 2 dB. For most children with BiCIs who received the second CI prior to 4–5 years of age, SRM ranged from 3 to 7 dB (Misurelli & Litovsky 2012; Ching et al. 2014; Killan et al. 2015; Mok et al. 2010; Van Deun et al. 2010b). Further, Misurelli and Litovsky (2012) derived the intelligibility benefit that was due to head shadow only and showed that, while NH children gained an averaged 6 dB intelligibility improvement from head shadow, children with BiCIs on average demonstrated a much smaller benefit of 3 dB from the same cue.

SRM may also in part arise from the access to ITD and ILD cues by listening with both ears (Bronkhorst & Plomp 1988; Bronkhorst 2015). But for adult BiCI users, the utility of ITDs/ILDs for SRM was minimal, and even interferes with speech-in-noise perception when interaural differences were the primary cues available (D'Onofrio et al. 2020). While the lack of SRM from interaural differences might be due to the poor quality of these cues conveyed through the CI devices and varying etiology and neural health (Kan & Litovsky 2015; Laback et al. 2015), literature has suggested that children with BiCIs may indeed benefit from having access to spatial hearing. For instance, Ehlers et al. (2017) showed just-noticeable-difference threshold for ILD within physiological limit in all 16 BiCI pediatric users measured. Several studies showed that children with BiCIs demonstrated free-field sound localization abilities when using their own clinical speech processors that were not bilaterally synchronized (Grieco-Calub & Litovsky 2010; Beijen et al. 2007; Van Deun et al. 2009; Van Deun et al. 2010a; Asp et al. 2012). When asked to detect a target signal of amplitude modulated pulse trains in noise, children with BiCIs demonstrated an improvement in the detection threshold by 5–6 dB when an interaural phase difference of 180-degree was introduced (Van Deun et al. 2010a; Todd et al. 2016).

However, children with BiCIs on average received < 1 dB SRM from ITD and ILD cues only and with large individual variability (Van Deun et al. 2010b; Misurelli & Litovsky 2012; Misurelli & Litovsky 2015). While the best performers could receive up to 2–4 dB in SRM, some children with BiCIs showed an "anti-benefit" (i.e., negative SRM), or an interference, with access to only interaural differences from spatial separation (Misurelli & Litovsky 2012; Misurelli & Litovsky 2015). When the target and maskers are spatially separated at 90-degree, children have access to up to approximately 600–700 μs ITD and 10–15 dB ILD depending on the frequency range from the masker for comparison with the target at front (i.e., 0 μs ITD and 0 dB ILD). There has been no study to date in investigating if SRM will improve for children with BiCIs under a larger angular separation that provides better salience for interaural differences and monaural head shadow.

In this study, two experiments were designed to measure SRM in children with BiCIs under a larger angular separation in virtual auditory space (VAS) that was simulated with head-related transfer functions (HRTFs). We used sentences as target speech masked by same-sex two-talker babble with the goal to maximize informational masking to promote the use of auditory spatial cues for unmasking as seen among NH children (Cameron & Dillon 2007; Griffin et al. 2019).

In Experiment I, we measured SRM as SRT improvement in dB with a fixed 180-degree spatial separation, with the target and maskers located on opposite side of the listeners, which maximized cue salience for both acoustic head shadow and interaural difference cues. In Experiment II, we introduced a novel measure of SRM by measuring the minimum angular separation (MAS) threshold between the target and masker to achieve a fixed 20% intelligibility benefit in percent correct, allowing the MAS threshold to be >90-degree if necessary.

In Experiment I, we compared SRTs from four test conditions to derive intelligibility benefits in dB that children received through the access of monaural head shadow and interaural differences. During this procedure, benefits from accessing a third auditory cue, namely binaural redundancy, will also be quantified (Dieudonné & Francart 2019). In the present study, we used a framework (Figure 1) similar to Dieudonné & Francart (2019) in quantifying intelligibility benefits or unmasking by access to three individual auditory cues: head shadow, interaural differences, and binaural redundancy.

Binaural redundancy arises from coherent inputs in both ears ascending the auditory pathway and is most useful for improving intelligibility in quiet (Dunn et al. 2008). When speech is presented in noise, its effect for speech unmasking is much smaller and dependent on the type of devices and other factors such as hearing history (Buss et al. 2008; Ching et al. 2005; Dunn et al. 2008; Müller et al. 2002; Plomp 1976; Tyler et al. 2002). There is evidence that binaural redundancy provides a small intelligibility benefit of ~1 dB for children with BiCIs (Van Deun et al. 2010b; Nittrouer et al. 2013). Binaural redundancy has also been measured as part of the binaural squelch phenomenon to demonstrate intelligibility benefits from spatial hearing, particularly among children with BiCIs (Van Deun et al. 2010b). Binaural squelch describes an SRT improvement by gaining access to ITDs/ILDs through listening with two ears, as compared to monaurally, even though the added ear has a poorer signal-to-noise ratio (SNR) of the target speech.

In Experiment II, we assessed SRM through the MAS threshold measured adaptively. In real-world listening situations, it is not always possible for listeners to incur a fixed spatial separation (either 90- or 180-degree) between the target and masker talkers. The existing SRM measure of SRT improvement with a fixed angular separation provided very limited clinical relevance for real-world listening scenarios. By using an adaptive procedure to measure the smallest spatial separation each child needed for a fixed intelligibility improvement in percent correct, the MAS will provide a more ecologically valid measure of SRM. Further, we designed the MAS measure such that the threshold can be as large as 180-degree, allowing examination of individual differences in using monaural versus binaural cues. More specifically, children achieve SRM by using only interaural differences when MAS threshold is < 90-degree with both the target and masker in the same hemifield; whereas when MAS threshold is > 90-degree, additional monaural head shadow is elicited for SRM.

Through two experiments, we sought to answer the following research questions.

1. What is the contribution of individual auditory cues associated with SRM for children with BiCIs? How do they compare with children with NH?
2. If children with BiCIs demonstrate benefits with access to auditory cues beyond monaural head shadow, what are the relative effect size of benefits between these cues?
3. Using the new SRM measure of MAS threshold, can children with BiCIs demonstrate spatial benefits within a hemifield (< 90-degree angular separation)? How do they compare with children with NH?

In Experiment I, under the fixed 180-degree spatial separation, we predict that head shadow is still the most robust cue for children with BiCIs. We hypothesize that, while intelligibility benefits might have long saturated with such large fixed angular separation for NH children, the enhanced salience in interaural difference cues is expected to be more beneficial for children with BiCIs. Alternatively, if most children with BiCIs demonstrated anti-benefits by using ITD and ILD cues from 180-degree separation, our findings will suggest that these children's limited access to such cues is likely due to other factors beyond the cue magnitudes provided by the spatial separation.

In Experiment II, we hypothesize that children with BiCIs show a larger MAS threshold than NH peers due to generally poorer SRM that may arise from the heavily distorted auditory cues (i.e., head shadow and interaural differences) from the CI devices. When the masker is in the same hemifield as the target, monaural head shadow cue is minimized, leaving interaural differences as the primary cue for SRM. We hence further predict that children with BiCIs will have an MAS > 90-degree due to the need to use the head shadow cue in addition to interaural differences. We also expect that some children with BiCIs will not have a measurable MAS, failing to achieve the target intelligibility benefit with <180-degree spatial separation. Finally, we explore the role of age factors through correlation analyses from individual children with BiCIs and their outcome measures from both experiments.

Experiment I

Methods

Participants—Nine children with BiCIs and 18 children with NH participated in Experiment I. Table 1 shows the demographics and etiology of the children with BiCIs. All children in the BiCI group used both devices consistently as confirmed parental report during the visits, and used their everyday clinical maps in the speech processors during testing. The NH children were a subgroup of children reported in Author 1 & 2 (submitted) with chronological age approximately matching the bilateral experiences of the BiCI group. The NH children were between 6.9 to 12.3 years old (M = 10.2 yrs, SD = 1.6) and had pure-tone hearing threshold ≤ 20 dB hearing level from 125 to 8000 Hz in both ears; all were typically developing with no known developmental delays, hearing or speech impairments. Prior to study participation, parents or legal guardians provided written consent and all children provided assent. All experimental procedures were approved by the Health Sciences Institutional Review Board at the University of Wisconsin-Madison.

Speech Stimuli—Target speech consisted of short sentences with three keywords from the Australian Speech in Noise Test (AuSTIN; (Dawson et al. 2013)). The AuSTIN corpus contains Bamfor-Kowal-Bench-like (BKB) sentences and was previously developed for testing speech-in-noise in children with CIs from 6 years old. An example sentence was "he LOCKED the CAR DOOR" with the three keywords capitalized. Masker speech was short excerpts (e.g., continuous discourses) of science stories written for children on various topics, such as climate change, space travel and animal psychology. Target speech was spoken by one female talker and masker speech was spoken by a different female talker. The two female speakers had an approximately 30 Hz difference in fundamental frequency as calculated in Praat (Boersma 2002). For test conditions in noise, two science stories from the same masker talker were presented simultaneously as the two-talker masker.

Experimental Design—To quantify intelligibility benefits from individual auditory cues, each child was tested in four speech-in-noise conditions which varied in both target-masker spatial configuration and ear condition (see Fig. 1). In the two binaural ear conditions, audio was presented in both ears to all children to simulate the VAS. In the two monaural ear conditions, children listened with the ear ipsilateral or closer to the target sound source; audio in the ear contralateral to the virtual target was muted. In each condition, the SRT was measured using a one-down-one-up adaptive procedure to track the 50% keyword accuracy (Levitt 1971). Speech intelligibility benefit from individual cues was subsequently quantified as dB improvement by comparing SRTs from test conditions using the equations outlined below.

$$\text{Head Shadow} = \text{SRT}_{\text{Co-located, Monaural}} - \text{SRT}_{\text{Seperated, Monaural}} \tag{1}$$

$$\text{Binaural Redundancy} = \text{SRT}_{\text{Co-located, Monaural}} - \text{SRT}_{\text{Co-located, Binaural}} \tag{2}$$

$$\text{SRM} = \text{SRT}_{\text{Co-located, Binaural}} - \text{SRT}_{\text{Seperated, Binaural}} \tag{3}$$

$$\text{Binaural Squelch} = \text{SRT}_{\text{Seperated, Monaural}} - \text{SRT}_{\text{Seperated, Binaural}} \tag{4}$$

$$\begin{aligned}&\text{Interaural Differences}\\&= \text{SRM} - \text{Head Shadow}\\&= \text{Binaural Squelch} - \text{Binaural Redundancy}\\&= \left(\text{SRT}_{\text{Co-located, Binaural}} - \text{SRT}_{\text{Seperated, Binaural}}\right) - \left(\text{SRT}_{\text{Co-located, Monaural}} - \right.\\&\left.\text{SRT}_{\text{Seperated, Monaural}}\right)\end{aligned} \tag{5}$$

$$\text{Total Unmasking Benefits} = \text{SRT}_{\text{Co}-\text{located, Monaural}} - \text{SRT}_{\text{Seperated, Binaural}} \quad (6)$$

HRTF Recording for VAS—VAS was created using head-related transfer functions (HRTFs). For children with BiCIs, VAS used individual children's HRTFs that were recorded behind the ears (BTE) by approximating the microphone locations on the CI speech processors. Similar approach has been used in previous work to create VAS for adults with BiCIs (Majdak et al. 2011). For NH children, we used HRTFs that were recorded from a KEMAR manikin (GRAS Sound & Vibration, Holte, Denmark) at the ear canal entrance (i.e., in the ear, ITE). The same hardware equipment was used for all HRTF measurements, including a pair of omni-directional microphones (HeadZap binaural probe microphones, AuPMC002, AuSim, Mountain View, CA), pre-amplifiers (MP-1, Sound Devices, Reedsburg, WI), and a Tucker-Davis Technologies (TDT) System 3 sound card with RP2.1 real-time processor. During HRTF recording, a custom-built routine in MATLAB (Mathworks, Natick, MA) played Golay codes, recorded back the signals, and performed deconvolution to calculate the head-related impulse responses[1] (HRIRs). HRIRs were recorded from 37 loudspeaker locations spanning from −90° to +90° azimuthal positions in 5° resolution. The loudspeaker arc has a 1.2 m radius. For individual HRTF recordings, an additional routine was incorporated using an optical motion sensing system with four infrared cameras (OptiTrack, Natural Point Inc., Corvallis, OR) to ensure children's head was oriented toward 0° (±5°) azimuth and at the center (±20 mm) of the loudspeaker array.[2]

Fig. 2 shows the interaural time and level differences from −90-degree to +90-degree on the horizontal plane, from HRTFs from individual children with BiCIs and from KEMAR. Notably, ITDs from individual BTE HRTFs were similar to those from the ITE KEMAR HRTF across all azimuthal positions. However, in comparison with ITE KEMART HRTFs, large individual variability was observed in ILDs with smaller magnitudes beyond 4 kHz at the peripheral azimuthal positions > ±60-degree from individual BTE HRTFs. The averaged dynamic ranges of ILDs from BTE HRTFs (i.e., ±10 dB at 2, 4, and 6 kHz) from children with BiCIs were similar to a previous report from adults (Jones et al. 2016). Note that the ITDs and ILDs demonstrated here were in the acoustic signals captured by the microphones before any signal processing. It did not capture the actual interaural difference cues that individual children with BiCIs received at the electrode sites along the cochlea, which is likely to be even more variable and inconsistent after the signal processing chain.

The HRTF recordings were conducted in a sound booth (IAC, RS 254S) with low reverberation, with a broadband 60 dB decay at 46 ms. To simulate a virtual sound source location in VAS, the HRIRs recorded from the loudspeaker position were convolved with speech recording in MATLAB. Calibration was done by playing sounds from the 0-degree azimuthal virtual location, where ILD was at 0 dB, and scaling the left ear signal from the

[1]HRIR is the time-domain signal of HRTF, which is expressed in the frequency domain.
[2]The tolerance of physical deviation from loudspeaker array center was determined after extensive pilot testing with NH children to ensure that most children were able to make such small movements to self-adjust accurately.

circumaural headphone to the desired presentation level. This method effectively maintained any naturally occurring ILD across other virtual sound source locations.

Experimental Set-up—A PC computer was used to play sounds via an RME Babyface Pro DSP sound card (Haimhausen, Germany) and collect scoring responses. Testing was conducted in a sound attenuated booth. Auditory stimuli were delivered through Sennheiser HD600 (Wedemark, Germany) circumaural headphones to NH children or through direct audio input (DAI) to the CI processors for children with BiCIs. All Cochlear Nucleus speech processors use a uniform compression rule, which maps microphone input signals at levels beyond 65 dB SPL to the current unit of individual's comfortable level (Vaerenberg et al. 2014). We took careful consideration in designing the delivery of auditory stimuli through DAI while maintaining the SNR in the signal. Currently, there is no effective mechanism to directly measure how the DAI's voltage is mapped onto individual child's dynamic range between the threshold and comfortable levels in the CI. Prior to testing with children with CIs, we recorded electrical outputs of the clinical speech processor using a default MAP to confirm that the initial playback levels were below compression. By using DAI to eliminate most default front-end processing algorithms that are applied to microphone signals, such as adaptive dynamic range optimization (ADRO), we further ensured that the target and masker SNR was preserved during testing.

Procedure—To provide children with an opportunity for task practice and target voice familiarization, all children were first tested with SRT in quiet before any noise conditions. For the BiCI group, additional runs for speech in quiet were tested with the virtual sound source placed on either side of the ears, with at least two repetitions of each virtual location to confirm whether they had a better ear. In the case where the averaged SRT in quiet was within 2 dB between the ±90-degree target locations, we asked the child to identify a better ear based on listening preference. If a better ear was not identified, we placed the target virtual location at +90-degree azimuth as for all children with NH.

On each trial, children used a computer mouse to initiate the sentence presentation. In conditions with noise, each trial began with the masker speech playing for 2 s before the target sentence was presented. The two-talker masker was always presented at 55 dB SPL (re 20 μPa). Children were instructed to verbally repeat the target sentence. An experimenter sitting outside the sound booth scored all the keywords that were repeated correctly. An adaptive one-down-one-up procedure was used (Levitt, 1979) to capture the SRT at 50% keyword accuracy. For all test conditions, the target speech level was initially set at 60 dB SPL (re 20 μPa) and changed based on trial accuracy. A trial was considered correct when two or more keywords were correctly identified, and incorrect when one or none of the keywords were repeated back accurately. A correct trial led to reducing target speech level in the subsequent trial, whereas an incorrect trial resulted in increasing target level in the subsequent trial. The initial step size was 8 dB until the first reversal, after which the step size reduced to 4 dB and subsequently 2 dB after the second reversal. An experimental run terminated after seven reversals.

All speech in noise conditions were tested in pseudo-randomized order, with each condition repeated for two to three runs depending on testing time. For each child, individual SRT reported in each speech-in-noise condition was averaged across multiple repeated runs. To calculate an SRT, a logistic regression was fitted to all SNRs tested in the experimental run using procedures developed by Fründ, Haenel, and Wichmann (2011) and extracting the 50% accuracy point on the curve.

Results

All statistical analyses were conducted in R (version 3.5.3). Performances in the BiCI group cannot be easily assumed to conform to a normal distribution due to individual differences in etiology, hearing history, and device configuration. Hence, non-parametric tests were chosen to examine between-group effects by comparing the two groups' distributions. The *a priori* level of significance was set at $\alpha = .05$ for all statistical tests.

Speech Intelligibility in Noise—Fig. 3 shows the SRT at 50% keyword accuracy measured in all four speech-in-noise conditions for both groups of children. A two-tailed two-sample Wilcoxon Rank-Sum test was conducted comparing average SRTs from the NH and BiCI groups in each speech-in-noise condition. Results showed that the BiCI group had averaged SRTs that were significantly higher than the NH group in all speech-in-noise conditions, all p's < .001. The performance gap was smallest at 5.0 dB in the spatially co-located, monaural condition with none of the cues available, and largest at 9.3 dB in the spatially separated, binaural condition with all three auditory cues available.

An important aspect of the data is the large individual variability in SRTs, which was similar for both groups of children and with a range as large as 10 dB in each group. However, most NH children had SRT < 0 dB, even in the most difficult listening condition of monaural listening with co-located target and maskers (Fig. 3a). All children in the BiCI group had SRT > 0 dB for when the target and maskers were co-located and close to their better ear. However, all but one child (subject CIGG) in the BiCI group had SRTs ≤ 0 dB with spatial separation between target and maskers at 180-degrees.

Speech Intelligibility Benefits—Speech intelligibility benefits were calculated using equations (1)–(6). Fig. 4 illustrates the intelligibility benefits from individual cues (top row) and from combinations of multiple cues (bottom row). First, a one-sample Wilcoxon Signed Rank test was conducted to examine whether the averaged intelligibility benefit from each group of children was significantly > 0 dB. For children with BiCIs, benefits were significantly > 0 dB for all individual and combinations of multiple auditory cues [(a) interaural differences, V = 39, p < .001; (b) head shadow, V = 45, p = .0020; (c) binaural redundancy, V = 38, p = .037; (d) SRM, V = 45, p = .0020; (e) binaural squelch, V = 43, p = .0059; (f) total unmasking benefits, V = 45, p < .001. For children with NH, benefits were significantly > 0 dB with access to each individual cues and multiple cues (all $p < .001$), except for binaural redundancy (V = 109, p = .16).

Next, to examine group difference, a two-tailed two-sample Wilcoxon Rank-Sum test was conducted for each of the six measures of intelligibility benefits. When compared with NH children, the BiCI group showed a significantly smaller effect of head shadow (W = 124, p = .027), SRM (W = 151, p < .001) and total unmasking benefits (W = 153, p = .0045).

No group differences were observed for binaural redundancy ($W = 68$, $p = .52$), interaural differences ($W = 115$, $p = .085$) or binaural squelch ($W = 117$, $p = .067$).

As seen in Fig. 4, inter-subject variability in intelligibility benefits was large but again similar between groups. Intelligibility benefits by some individuals from the BiCI group were clearly within the range demonstrated by the NH group, particularly for benefits from using individual auditory cues (i.e., Fig. 4a–c). All children with BiCIs received an intelligibility benefit of 2.5–8 dB from head shadow. One child with BiCI received an "anti-benefit" or interference of −2.5 dB by using interaural difference cues for spatial unmasking, while all other children demonstrated a benefit ≥ 0 dB and up to 6.2 dB from the best-performing child. Interestingly, a similar range of benefits between −2.3 and 9.9 dB was also found among NH children for the use of interaural differences, suggesting NH children might also experience interference through access to interaural difference cues.

To further examine individual differences in children's access to auditory cues for intelligibility benefits, for each group of children, we conducted correlation analysis between intelligibility benefits from each pair of cues (as seen in Fig. 5) using Spearman's correlation. For the BiCI group, the intelligibility benefits from head shadow and interaural differences were negatively correlated, $r = -.80$, $p = .0096$, but neither cue significantly correlated with benefits from binaural redundancy, ($p = .077$ with head shadow and $p = .49$ with interaural differences). For children in the NH group, similar relationship between the benefits from head shadow and interaural differences was found, $r = -.68$, $p = .0021$. In addition, benefits from binaural redundancy were significantly correlated with those from head shadow, $r = .64$, $p = .0043$, and interaural differences, $r = -.70$, $p = .0012$.

In summary, in Experiment I we showed that children with BiCIs demonstrated intelligibility benefits from monaural head shadow, binaural redundancy, and interaural differences. The BiCI group had a smaller head shadow effect than their NH peers; but both groups demonstrated similar benefits from binaural redundancy and interaural differences. Increasing the fixed angular separation to 180-degree led to SRM measures, as quantified by SRT improvement, that were more robust for children with BiCIs in general. However, in real-world listening, listeners rarely have access to a such large fixed angular separation in complex listening situations. Rather than SRT improvement in dB, we introduced a novel SRM measure through the minimum angular separation threshold for a fixed percent correct improvement in Experiment II to provide a more practical assessment of spatial hearing for children with BiCIs.

Experiment II

Methods

Participants—Eleven children with BiCIs and 18 NH children participated in Experiment II. These were the same children who participated in Experiment I, with two additional children in the BiCI group. All children completed both Experiments during the same visit or within a 3-month period over multiple visits.

Experimental Design and Procedure—The same target and masker speech stimuli from Experiment I were used for Experiment II. All stimuli were again delivered in VAS over headphones to NH children and through DAI to children with BiCIs. The same hardware equipment and software interface were used as in Experiment I.

In Experiment II, we measured the MAS each child required to achieve a fixed 20% intelligibility benefit. First, a one-down-one-up adaptive procedure (Levitt 1971) was used to estimate 50% SRT with target and masker spatially co-located. Target and maskers were on the side of the better ear for children with BiCIs and at 90-degree azimuth for NH children, identical to the condition in Fig. 2(b). For children who completed Experiment II during a different visit, we re-measured the SRT in this condition with 2–3 repetitions. During pilot testing, we found that the averaged SRT from multiple repetitions, which was 1–2 dB higher than the lowest SRT, might lead to non-measurable MAS in some children. Hence, the lowest 50% SRT obtained across multiple repetitions was used as the fixed SNR for the subsequent steps. Second, we confirmed that each child would have a measurable MAS < 180-degree before the next adaptive procedure. In this step, the masker location was set to 180-degree separation from the target; percent correct using 17 trials (i.e., 51 keywords) was measured. If the child scored > 70% correct in this step, suggesting their ability to gain the fixed 20% intelligibility benefit with < 180-degrees, we proceeded with the final step to obtain MAS adaptively for 70% keyword accuracy.

To measure the MAS threshold, we varied the virtual location of the masker using a two-down-one-up adaptive procedure (Levitt 1971) starting from an initial 180-degree angular separation from the target. The target was always fixed at the same virtual location as in the previous steps. The angular separation was reduced after two consecutive correct trials (i.e., ≥ 2 keywords correct) and increased after an incorrect trial. Guided by pilot data, the step sizes were initially larger, then halved after the first reversal. Specifically, the initial step size was 40 degrees until the first reversal, after which the step size reduced to 20 degrees and subsequently 10 degrees after the second reversal. Each experimental run terminated after seven reversals. The target and masker maintained a fixed SNR, which was the best 50% SRT measured when both were co-located. Fig. 6 illustrates an example experimental run of MAS from a NH child and a child with BiCIs. For most children, each experimental run to measure MAS lasted 20–30 trials before the adaptive track converged. A logistic regression was fit to all the test angles between target and maskers for approximating the psychometric function (Frund et al. 2011). The MAS was derived as the angular separation at 70% keyword accuracy on the curve. Depending on testing time, the measurement of MAS was repeated 2–3 times and reported as the average MAS across repetitions for each child.

Results

Fig. 7(a) shows the best SRT at 50% keyword accuracy measured for co-located target and masker for both groups of children. A two-tailed two-sample Wilcoxon Rank-Sum test showed that children with BiCIs as a group had significantly higher co-located SRT than NH children, $W = 198$, $p < .001$, similar to the group effect of co-located SRTs from averaging multiple repetitions as reported in Experiment I.

In the second step, with the 180-degree target-masker separation and SNR of the co-located SRT, all NH children scored between 88 and 100% correct and children with BiCIs scored between 74 and 90% correct. This intermediate step confirmed that all children from both groups were able to achieve the fixed 20% intelligibility benefit with a target-masker angular separation ≤ 180-degree. Hence, all children proceeded to the final step to measure individual MAS.

There is a statistically significant correlation between age and MAS threshold among children in the NH group, $r = -.58$, $p = .0066$. Fig. 7(b) illustrates group average and individual MAS values for the two groups. A one-tailed two-sample Wilcoxon Rank-Sum test showed that the BiCI group had larger MAS than the NH group, $W = 18$, $p < .001$. Children with BiCIs ($M = 91.5$-degree, $SD = 26.1$) needed larger target-masker separation than the NH children ($M = 43.7$-degree, $SD = 25.1$) to demonstrate the fixed 20% intelligibility benefit. The range of performance within group was similar for children with NH and those with BiCIs. The smallest (best) MAS threshold seen in the two groups was 12-degree and 54-degree for NH and BiCI, respectively. The largest (worst) MAS values were about 80 degrees larger, i.e., 94-degree and 138-degree for NH and BiCI, respectively. Notably, all but three children in the BiCI group reached the 20% intelligibility benefit with ≤ 90-degree separation, i.e., with target and maskers located in the same hemifield.

We further related MAS thresholds with SRTs and intelligibility benefits from Experiment I among children with BiCIs through Spearman's correlation. Results suggested that MAS was significantly correlated with SRT measured from the binaural and spatially separated condition, $r = .67$, $p = .030$. Fig. 8 shows the SRT as a function of MAS. Even though the small group of children with BiCIs may be under power, two additional intelligibility benefits from interaural differences ($r = -.56$) and SRM ($r = -.60$) were correlated to MAS at a significance level of $p = .10$. There was a trend among children with BiCIs that smaller MAS thresholds were related to larger intelligibility benefits from interaural differences and SRM, resulting in lower SRTs when children had access to all auditory cues for unmasking.

Discussion

For over a decade, children with profound deafness have been receiving BiCIs with the goal to improve functional hearing abilities through access to spatial hearing. To date, significant benefits of using bilateral devices over unilateral CI have been demonstrated for children in improving sound localization and speech-in-noise understanding, particularly when the target speech is spatially separated from the maskers (Litovsky et al. 2017 for a review). Recent work has shown that spatial hearing abilities by BiCI users, in particular adults, can further improve by coordinating inputs between bilateral devices and minimizing distortions in the binaural cues from head movements when listening in free field (Archer-Boyd & Carlyon 2019). For studies on children that assess SRM, sounds have typically been presented via loudspeakers in free-field, a paradigm that has some limitations. For example, it is unclear how small, inconsistent head movements impact the effect sizes of SRM reported in current literature. In the present study, we presented spatialized sounds in VAS using HRTFs directly through DAI to the devices for children with BiCIs and over headphones to children with NH. This approach effectively removed the impact of head movements and maximized the consistency of acoustic binaural cues at the level of the device input. Furthermore, this is the first study that used VAS to directly quantify the contribution of individual auditory cues for SRM for children with BiCIs.

Through two experiments, we measured the benefits from spatial hearing for speech-in-noise perception in children with BiCIs and compared their performance with NH peers. In Experiment I, we measured SRTs in four test conditions that varied in target-masker spatial separation (i.e., co-located to one side vs. 180-degree separated) and listening conditions (i.e., monaural vs. binaural listening). For children with BiCIs, the spatially co-located, binaural listening condition had an average SRT of 3.7 dB, which was slightly better than the 5–7 dB SRT previously reported using similar open-set sentences (Ching et al. 2014; King et al. 2020). One possibility of the slight SRT improvement might be due to the target position being closer to the better CI ear for some of the children. When compared with NH peers, children with BiCIs had significantly higher SRTs, needing an additional 5 to 9.3 dB SNR on average to reach 50% target speech intelligibility depending on the test condition. While this between-group difference is similar to that reported in studies that also used open-set sentences with children (Ching et al. 2011; Ching et al. 2014), it is larger than the group difference measured with closed-set digits, monosyllabic or disyllabic words (Van Deun et al. 2010b; Murphy et al. 2011; Misurelli & Litovsky 2012; Misurelli & Litovsky 2015; Hess et al. 2018). For closed-set speech materials, on each trial children are typically provided up to four choices of visual stimuli, one of which matches the target word heard. The problem solving involved in eliminating non-targets and identifying the target provides additional contextual and phonemic clues that increase probability of correct responses. By comparison, open-set sentences contain several keywords with lower predictability, relying more heavily on context for comprehension that was more difficult for children with BiCIs.

In the present study, the speech materials were designed to mimic one of the more challenging, but realistic communication scenarios for children when listening in noisy environments. The target speech materials were AuSTIN sentences (Dawson et al. 2013) spoken by a female talker, with a two-talker masker of another female talker. The use of two-talker, same-sex maskers was aimed at maximizing informational masking by reducing glimpsing or “dip-listening” (Freyman et al. 2001; Brungart et al. 2001; Buss et al. 2017) and increasing voice similarity (Johnstone & Litovsky 2006; Misurelli & Litovsky 2015; Leibold et al. 2018; Leibold et al. 2020; Cameron & Dillon 2007). Spatial cues associated with spatial separation between the target and masker are known to be most important under informational masking, where other acoustic cues are limited or absent (Hawley et al. 2004; Cameron & Dillon 2007; Jones & Litovsky 2011; Bronkhorst 2015; Gallun et al. 2013). The two-talker same-sex masker in the present study was expected to promote the use of auditory spatial cues for unmasking.

Previous work on SRM in children with BiCIs focused on target and masker that were spatially co-located at 0-degree (front) versus asymmetrically separated towards one hemifield (i.e., maskers at 90 degrees towards one side), or symmetrically separated (i.e., with one masker at −90-degree and another at 90-degree) (Van Deun et al. 2010b; Murphy et al. 2011; Misurelli & Litovsky 2012; Ching et al. 2014; Misurelli & Litovsky 2015; Hess et al. 2018; King et al. 2020). The 90-degree target-masker separation has produced important findings. For instance, SRM with asymmetrical conditions emerges in NH children as young as 2–3 years of age (Garadat & Litovsky 2007; Hess et al. 2018). In children with BiCIs SRM appears to be driven primarily by monaural head shadow (Van Deun et al. 2009; Misurelli & Litovsky 2012). When compared with NH peers, children with BiCIs have little to no SRM when interaural differences were the primary cues available as a result of minimizing head shadow cues (Misurelli & Litovsky 2012; Misurelli & Litovsky 2015).

However, the 90-degree separation in previous work might have underestimated SRM and limits its prediction of a child's spatial hearing ability in real-world listening situations, where target-masker angular separation can be larger than 90 degrees. Hence, in the present study, we extended the angular separation to 180-degree to maximize SRM and to account for the potential real-world listening scenario where the target and masker are positioned from opposite hemifields. With the 180-degree separation, the intelligibility benefits reported for children with BiCIs were generally larger than previously shown by literature using a 90-degree fixed angular separation (Van Deun et al. 2010b; Misurelli & Litovsky 2012; Misurelli & Litovsky 2015; Murphy et al. 2011; Hess et al. 2018; King et al. 2020; Ching et al. 2014). A primary goal for Experiment I was to identify intelligibility benefit due to individual cues i.e., head shadow, binaural redundancy, and interaural differences. For both groups of children, monaural head shadow provided the largest intelligibility benefit, followed by interaural differences; binaural redundancy provided very little SRT improvement. The finding that monaural head shadow is a primary benefit confirms prior reports (Van Deun et al. 2010b; Misurelli & Litovsky 2012; Misurelli & Litovsky 2015), which also underscores the importance of being able to listen with the ear with better SNR of the target speech.

Studies conducted in free field have argued that the lack of coordination between bilateral devices is a limiting factor for delivering acoustic spatial cues with fidelity (van Hoesel et al. 2008; Kan et al. 2013; Goupell et al. 2013). As reviewed by Kan and Litovsky (2015), CI processing encodes signal envelope by replacing the temporal fine structure with constant high-rate pulse trains. It results in the extraction of the signal envelope and the removal of temporal fine structure, the latter carrying important ITDs that are most useful for binaural hearing at frequencies < 1500 Hz. The signal envelope can be useful for level-dependent differences, i.e., ILDs, and ITDs in the envelopes. Notably, while envelope ITDs may be available in the signal envelope from the speech processors (Kan et al. 2019), they are more severely compromised and less useful than ILDs for spatial hearing tasks (Grantham et al. 2007; van Hoesel et al. 2008; Seeber & Fastl 2008; Kerber & Seeber 2012). In the present study, we delivered auditory stimuli directly to the clinical processor via DAI, to minimize inconsistency in ILDs and envelope ITDs due to head movements. Results showed that, on the group level, there was no significant difference in the intelligibility benefits from using interaural differences between children with BiCIs and their NH peers. This finding is particularly encouraging, such that children with BiCIs may have NH-like SRMs by using ITDs/ILDs from a sufficiently large angular separation between the target and masker. While a 180- degree separation is achievable in everyday communication situations, children with BiCIs should be counseled to advocate for similar target-masker spatial positions in social situations to leverage on maximizing head shadow and interaural difference cues for SRM.

As seen in Fig. 5, there was a strong and significant negative correlation between benefits from interaural differences and head shadow for both groups of children. The effect is stronger for children with BiCIs (r = −.80) than for NH children (r = −.68). It is evident that there is a trade-off between access to binaural versus monaural cues among individuals, such that children who showed poorer use of interaural differences were more likely to receive a larger benefit from head shadow, and vice versa. There may be clinical utility for measuring such individual differences, with the goal to implement individualized fitting of front-end signal processing strategies. For instance, for children who are better at using interaural difference cues, clinical device fitting may consider front-end processing strategies such as synchronized automatic gain control (AGC) to preserve the fidelity of ILDs (Archer-Boyd & Carlyon 2019). On the other hand, for children who primarily use head shadow, digital noise reduction (DNR) algorithms that further increases target SNR in the better ear may result in an even larger intelligibility gain (McCreery et al. 2012 for a review on DNR; Browning et al. 2019). Indeed, this points to a future direction to investigate how children with BiCIs may benefit from different front-end processing strategies to maximize the overall intelligibility benefits from SRM.

In Experiment I, all children with BiCIs demonstrated SRM from the maximum 180-degree angular separation. To further improve the ecological validity of the SRM measure, in Experiment II, we developed a novel approach to define SRM as the threshold of minimum angular separation (MAS) needed between target and masker for a fixed 20% intelligibility improvement. For adults with NH or BiCIs, alternating the spatial separation between the target and masker through head orientation has demonstrated improved SRM by displacing the target and masker in opposing hemifields and by engaging head shadow cues (Grange & Culling 2016a; Grange & Culling 2016b). Recent studies have shown that, when only interaural difference cues are available, SRM increases with increasing fixed angular separation up to approximately 50 degrees for NH adults (Gallun et al. 2013; Srinivasan et al. 2016) and BiCI users (Davis & Gifford 2018). The design of the present study and MAS threshold provided insight into the angles that yield a meaningful release from masking. Further, this paradigm also allowed us to examine individual children's use of interaural difference versus head shadow cues. When the target and maskers are in the same hemifield, monaural head shadow cues are minimized, leaving interaural difference as the primary cues for SRM.

In the NH group, all children achieved MAS ≤ 90-degree, needing only access to interaural differences for the 20% intelligibility benefit. The NH group included children between 6–12 years old. The significant age effect on MAS captures the finding of SRM maturation around 9–10 years of age using similar target and masker speech materials with high informational masking (Cameron & Dillon 2007).

In the BiCI group, we had predicted that, while some children might not have a measurable MAS, those achieved measurable thresholds would have an MAS > 90-degree because they required monaural head shadow for SRM. Surprisingly, children with BiCIs outperformed our predictions: Eight out of 11 children with BiCIs had MAS thresholds < 90-degrees. For these eight children, when interaural differences were the only cue available, they showed SRM ranging from 0–6 dB (see Fig. 8). The other three children seemed to draw benefits primarily from monaural head shadow, which was consistent with two of them (subjects CIBW and CIGH, Fig. 8) lacking benefits from interaural differences as measured in Experiment I. Children with BiCIs who achieved a < 90-degree MAS relied on up to ~10 dB ILDs available from the BTE HRTFs (see Fig. 2). In contrast, NH children had access to much larger ILDs up to 15–20 dB between 4–6 kHz from the ITE HRTFs. The BTE configuration appears to reduce the ILD cue magnitude, as shown here, and in prior work with adults (Jones et al., 2016). Future work aimed at further decreasing MAS for these children will be to consider using ITE microphones that preserve the natural acoustic magnitude of ILDs (Jones et al. 2016). Even though children with BiCIs did not demonstrate benefits from ITE microphone in a recent study using multiple distributed maskers (Holder et al. 2020), many questions regarding the microphone programming remain. For example, the utility of ITE microphones could be assessed for children, who show good MAS thresholds, to determine if access to larger ILDs can further improve performance.

It is worth noting that, by delivering stimuli in VAS and removing the impact of head movements, the present findings remove some aspects of naturalistic listening situations and provide an estimate of controlled situations. The difference between listening in the present study and everyday listening may be even more pronounced for children with BiCIs whose devices contained front-end processing strategies that were de-activated during testing. Further, the impact of head movements on SRM is not well understood, thus SRM with and without head movements would be an interesting and important comparison in future work. In addition, the small group of children with BiCIs in this study may not fully represent the clinical population of pediatric BiCI users. It is entirely possible that larger proportions of children with BiCIs may not have a measurable MAS due to the need for a much larger head shadow cue beyond the natural magnitude. This will then require a different approach to fit strategies that emphasizes reliance on signal processing in the device for unmasking, such as optimization algorithms based on the sound field including adaptive directional microphones (Wolfe et al. 2017; Johnstone et al. 2018; Leibold et al. 2020; Holder et al. 2020), rather than binaural processing in the auditory system.

The present study included a small group of children with BiCIs that cannot yet address how individual factors, such as bilateral experience, may influence children's access to auditory cues for SRM. Future work is warranted to further our understanding if improvement in listening strategies over time underlies any association between bilateral experience and SRM measures, which may lead to implications on clinical interventions that leverage on auditory plasticity in young children (see Litovsky & Gordon 2016).

Summary and Conclusion

The current study offered the following conclusions regarding SRM in children with BiCIs.

1. Under an enlarged spatial angular separation of 180-degree with target and masker in opposing hemifields, children with BiCIs showed an averaged intelligibility benefit of 5.9 dB from monaural head shadow, 0.8 dB from binaural redundancy, and 1.6 dB from interaural differences. These benefits, particularly from head shadow and interaural differences, are greater than

previously reported and are likely due to the larger magnitudes of auditory cues provided by the enlarged angular separation. When compared with their NH peers, children with BiCIs as a group had smaller intelligibility benefits using monaural head shadow, but similar benefits from interaural differences and binaural redundancy.

2. With access to interaural difference cues for SRM, there seemed to be a trade-off between using this cue versus monaural head shadow among children with BiCIs. Those who drew larger benefits by using interaural differences tend to benefit less from using monaural cues, and vice versa. The same but slightly weaker effect was observed in NH children.

3. When measuring the smallest angular separation needed to gain a fixed 20% intelligibility benefit, all 11 children with BiCIs had a measurable MAS < 180-degree and an average MAS larger than their NH peers. Eight children with BiCIs achieved an MAS < 90-degree, requiring access to interaural differences only for SRM.

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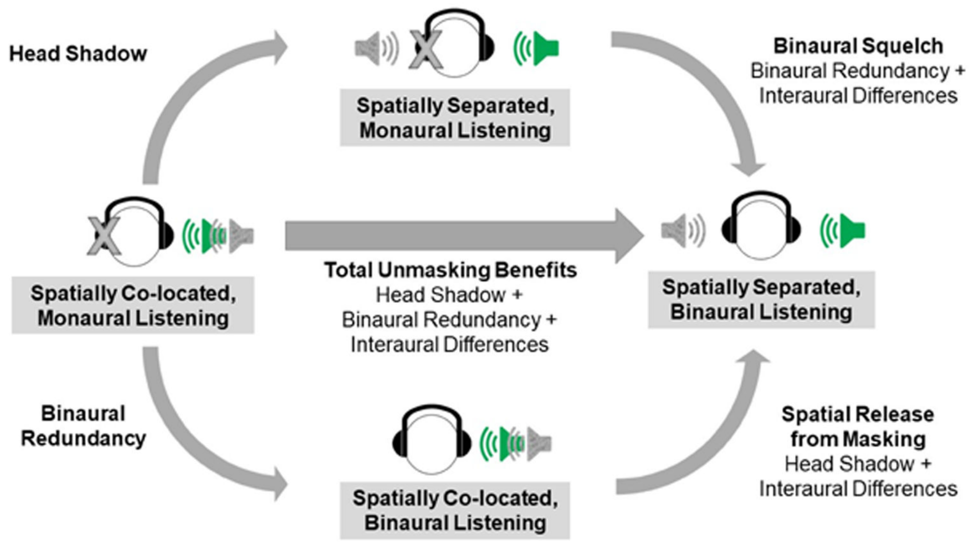

Fig. 1.

Schematics showing four test conditions to measure intelligibility benefits from auditory cues that contribute to spatial unmasking: Head shadow, binaural redundancy, and interaural differences. The effects of spatial release from masking, binaural squelch, and spatial unmasking are benefits from using multiple cues. Arrows indicate the speech intelligibility benefits received as SRT improvement from the available auditory cues, by comparing the pair of test conditions. Loudspeaker symbols indicate virtual location of target (green) and two-talker masker (grey) either co-located to the same side of the listener or distributed with a 180-degree spatial separation. The target virtual location was always to the side of the better ear for children with BiCIs or to the right ear for children with NH (+90-degree azimuth).

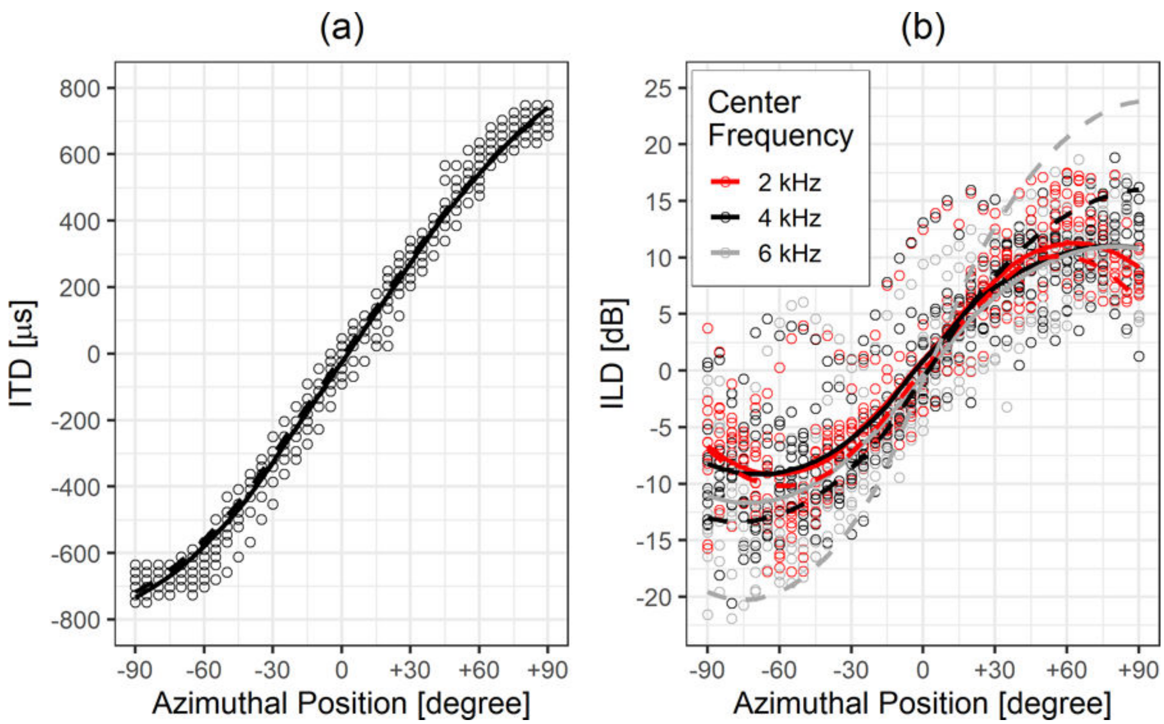

Fig. 2.

Interaural time and level differences calculated from behind-the-ear head-related transfer functions (HRTFs) for individual children with bilateral cochlear implants (open circles) from −90- to +90-degree azimuthal positions in 5-degree resolution. Curve fit to interaural differences from individual behind-the-ear (BTE) HRTFs is shown in solid lines; to in-the-ear (ITE) KEMAR HRTFs in dashed lines. BTE HRTFs have good agreement with ITE KEMAR HRTFs on ITD magnitudes, but smaller ILD magnitudes toward the peripheral angles > 60-degree.

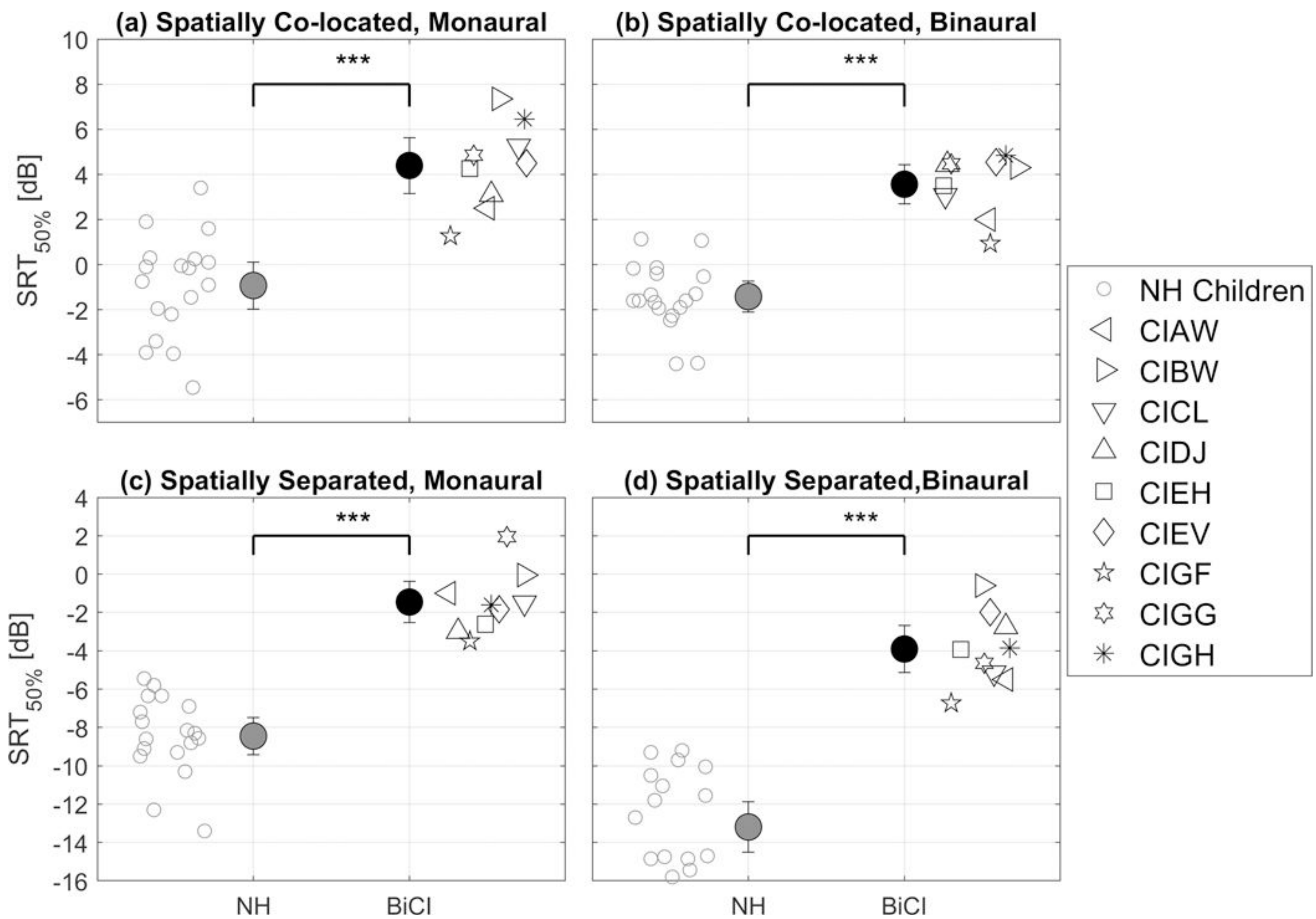

Fig. 3.

Mean (± 95% confidence interval) speech reception thresholds measured at 50% keyword accuracy for children in the NH and BiCI groups. Individual data was shown next to group mean. *** p <.001.

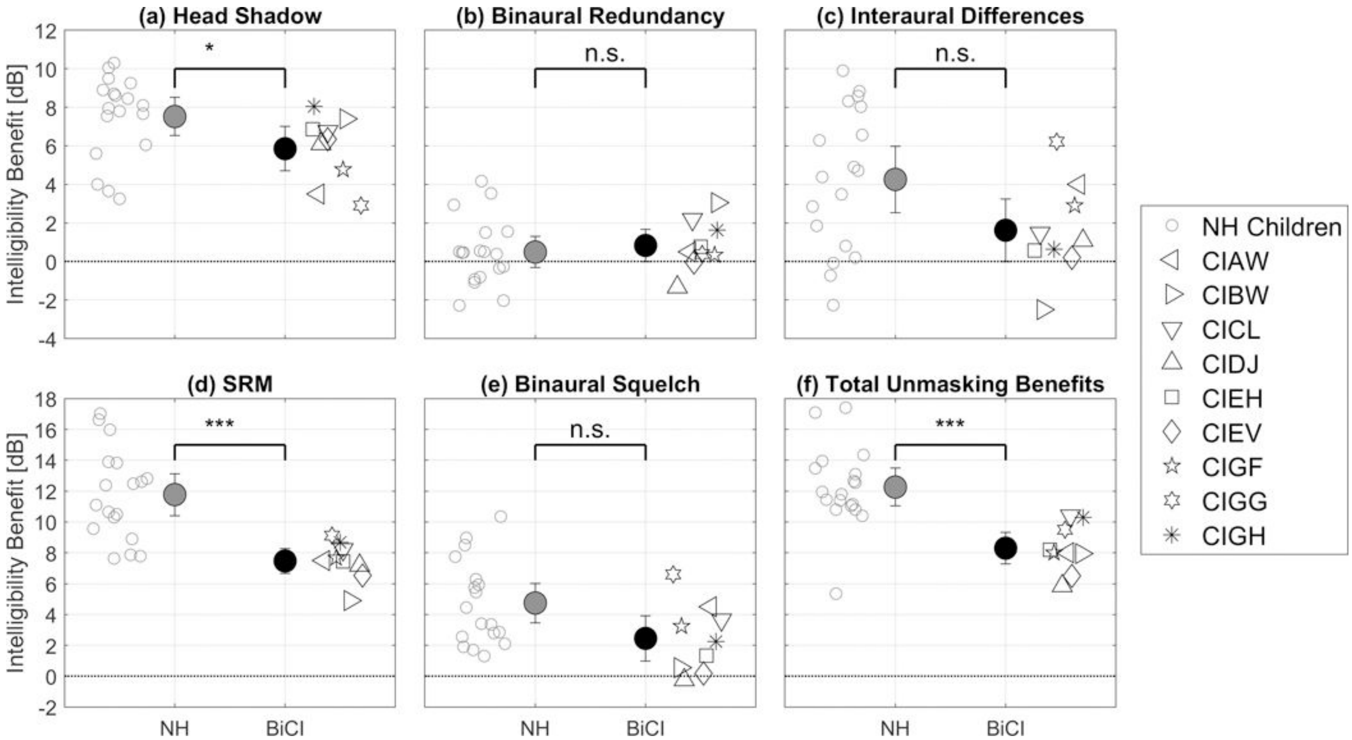

Fig. 4.

Mean (± 95% confidence interval) intelligibility benefits are plotted for children in the NH and BiCI groups. Individual data are shown next to the group mean. Top row of panels showing intelligibility benefits from individual cues (a) head shadow, (b) binaural redundancy, (c) interaural differences. Bottom rows showing benefits from access to multiple cues (d) SRM, (e) binaural squelch, and (f) total unmasking benefits. Dotted reference line denotes 0 dB or no benefit; data below reference line suggest individuals received an "anti-benefit" or interference from the specific cue. n.s = p > .05, *p<.05, ***p<.001.

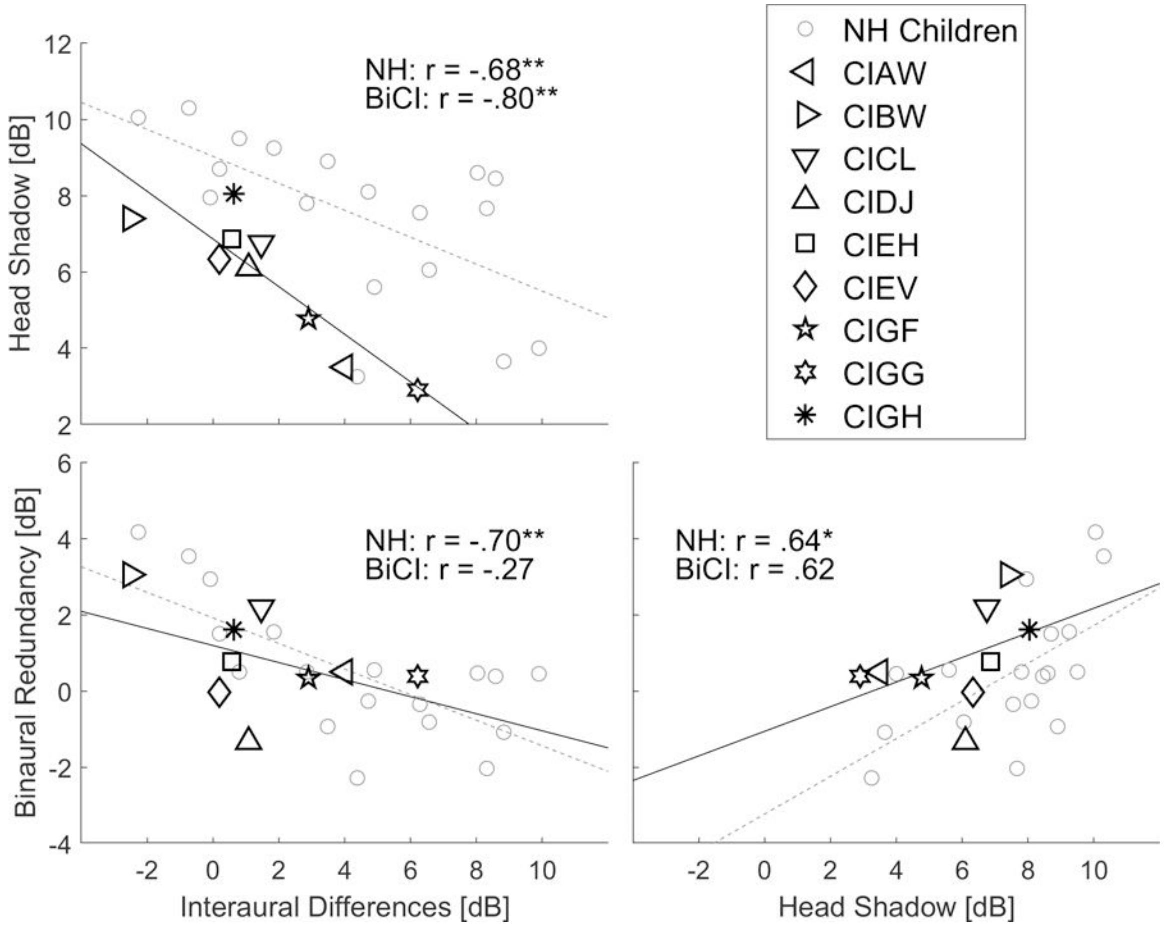

Fig. 5.

Intelligibility benefits as related between pairs of individual cues for spatial unmasking. Individual data is plotted for NH children in grey circles and for children with BiCIs of varying shapes. Spearman correlations were reported for each group, *p<.05, **p<.01.

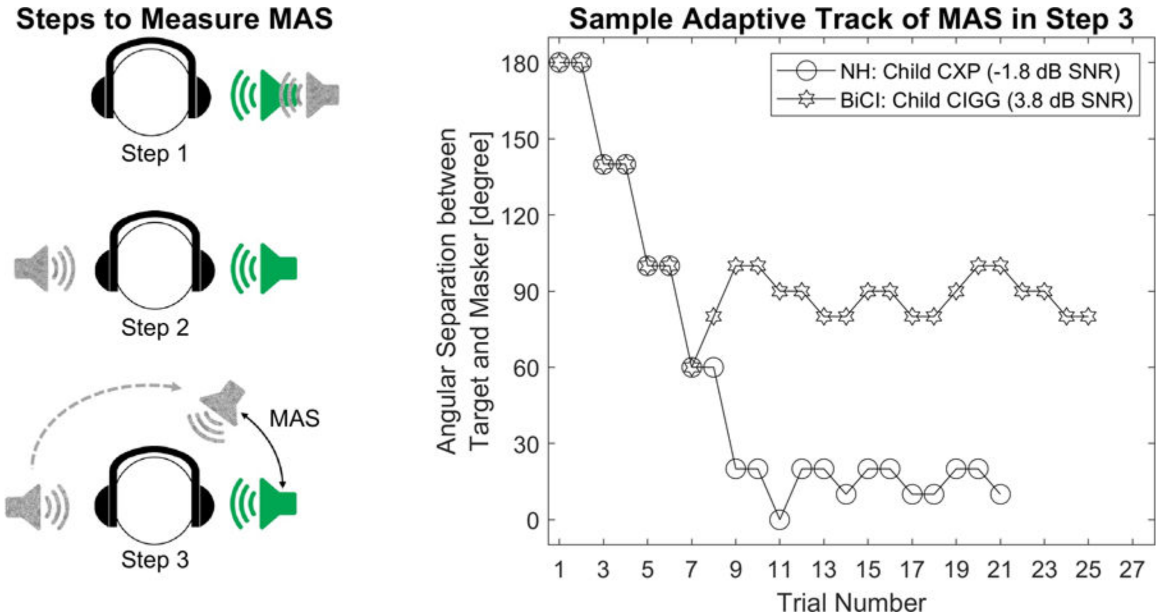

Fig. 6.
Schematics (left panel) illustrating the steps in measuring minimum angular separation (MAS) needed between target and masker in achieving a 20% intelligibility improvement: (1) co-located SRT measured adaptively (one-down-one-up) at 50% accuracy, (2) percent correct measured with a 180-degree target-masker separation and SNR at SRT from (1) to confirm at least 70% accuracy, and (3) with the same fixed SNR, adaptively moving masker location closer to target to achieve 70% accuracy. The final angular separation in Step 3 is the MAS. Example two-down-one-up adaptive track (right panel) from a NH child and a child with BiCIs during MAS measurement in Step 3.

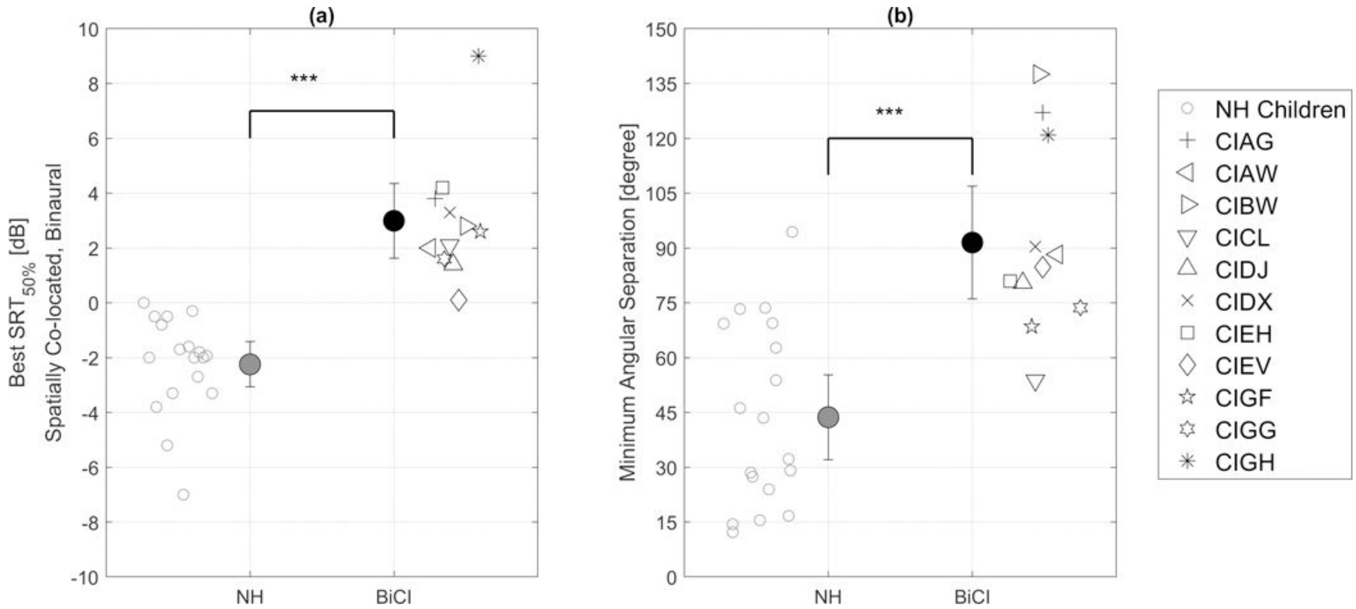

Fig. 7.

(a) Speech reception threshold (SRT; ± 95% confidence interval) for 50% intelligibility when target and two-talker masker were spatially co-located. Individual data are shown next to the group mean. (b) Minimum angular separation (MAS; ± 95% confidence interval) needed to obtain a 20% intelligibility gain from the spatial configuration of co-located target and masker. MAS was individually by maintaining a fixed SNR of the SRT from (a) and adaptively changing target-masker angular separation to reach 70% intelligibility.

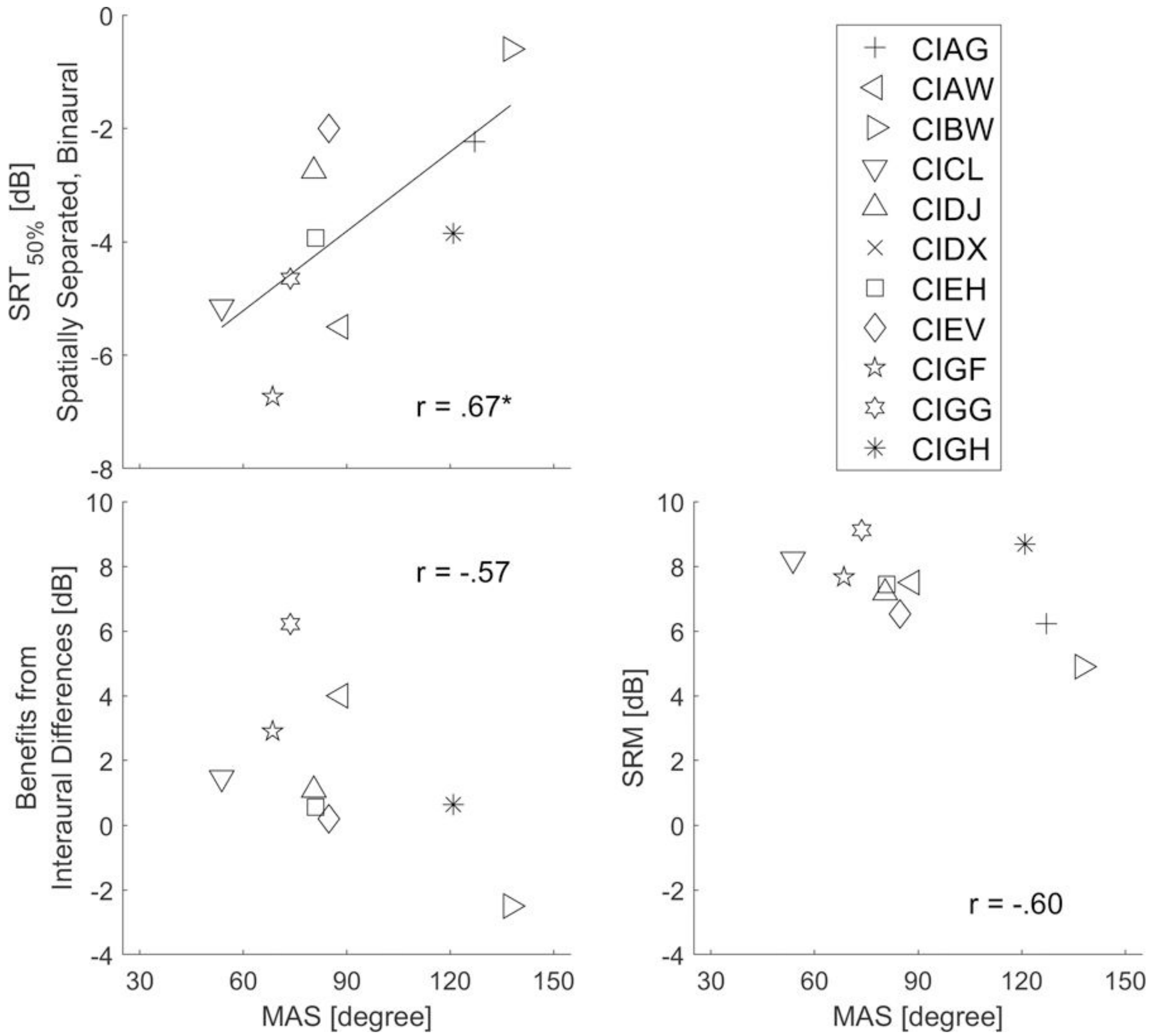

Fig. 8.

Relations between MAS from Experiment II and measures from Experiment I, including SRT and intelligibility benefits from individual differences and SRM. MAS was significantly correlated with SRT measured from the spatially separated and binaural listening condition.

Table 1.

Demographics of children with bilateral cochlear implants

Subject ID	Chronological Age [Yr; Mo]	1st CI Activation Age [Yr; Mo] and Ear	2nd CI Activation Age [Yr; Mo] and Ear	Bilateral Experience [Yr; Mo]	Etiology	Speech Processor	Better Ear†
CIAG	17; 5	1; 9 (Right Ear)	3; 1 (Left Ear)	14; 4	Connexin 26	Nucleus 6	Left
CIAW	17; 11	1; 2 (Right Ear)	5; 5 (Left Ear)	12; 5	Cytomegalovirus	Nucleus 6	Left
CIBW	15; 2	1; 0 (Right Ear)	3; 9 (Left Ear)	11; 4	Connexin 26	Kanso	Left
CICL	12; 11	1; 5 (Right Ear)	2; 9 (Left Ear)	10; 1	Connexin 26	Nucleus 6	Right
CIDJ	17; 2	1; 7 (Right Ear)	5; 0 (Left Ear)	12; 2	Hereditary	Nucleus 5	Right
CIDX	16; 0	1; 5 (Right Ear)	2; 7 (Left Ear)	13; 5	Connexin 26	Nucleus 6	Neither
CIEH	13; 2	1; 1 (Simultaneous)	1; 1 (Simultaneous)	12; 1	Hereditary	Nucleus 5	Neither
CIEV	16; 2	2; 8 (Right Ear)	10; 11 (Left Ear)	5; 2	Hereditary	Nucleus 6	Right
CIGF	10; 10	1; 1 (Simultaneous)	1; 1 (Simultaneous)	9; 9	Connexin 26	Nucleus 6	Right
CIGG	9; 10	0; 10 (Simultaneous)	0; 10 (Simultaneous)	9; 0	Connexin 26	Nucleus 6	Neither
CIGH	11; 9	1; 5 (Simultaneous)	1; 5 (Simultaneous)	10; 3	Unknown	Nucleus 6	Left

Note: All children used Cochlear devices. Some children with Nucleus 6 and one child with Kanso had no audio input port on the speech processors. These children completed the study with their everyday clinical maps using a pair of Nucleus 6 processors with audio input ports that were on loan from Cochlear.

†A better ear was determined through a better speech reception threshold (SRT) in quiet > 2 dB when the target was placed on the side closer to the ear in VAS.