# Spatial release from masking in children with normal hearing and with bilateral cochlear implants: Effect of interferer asymmetry

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Spatial release from masking (SRM) was measured in groups of children with bilateral cochlear implants (BiCIs, average ages 6.0 and 7.9 yr) and with normal hearing (NH, average ages 5.0 and 7.8 yr). Speech reception thresholds (SRTs) were measured for target speech in front (0°), and interferers in front, distributed asymmetrically toward the right (+90°/+90°) or distributed symmetrically toward the right and left (+90°/−90°). In the asymmetrical condition both monaural "better ear" and binaural cues are available. In the symmetrical condition, listeners rely heavily on binaural cues to segregate sources. SRM was computed as the difference between SRTs in the front condition and SRTs in either the asymmetrical or symmetrical conditions. Results showed that asymmetrical SRM was smaller in BiCI users than NH children. Furthermore, NH children showed symmetrical SRM, suggesting they are able to use binaural cues for source segregation, whereas children with BiCIs had minimal or absent symmetrical SRM. These findings suggest that children who receive BiCIs can segregate speech from noise under conditions that maximize monaural better ear cues. Limitations in the CI devices likely play an important role in limiting SRM. Thus, improvement in spatial hearing abilities in children with BiCIs may require binaural processing strategies. © *2012 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4725760]

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## I. INTRODUCTION

Cochlear implants (CIs) provide hearing to people who are deaf through electrical stimulation to the auditory nerve. A growing number of recipients are now receiving CIs in both ears. The use of bilateral cochlear implants (BiCIs) was clinically motivated, in part, by the fact that in normal-hearing (NH) listeners, binaural hearing plays an important role in facilitating sound localization and speech understanding in noise. In the BiCI literature, the emphasis to date has been primarily on the benefit arising when two CIs are used vs when a single CI is used. Numerous studies to date have shown that adult BiCI users have significantly better sound localization abilities with BiCIs vs a single CI (e.g., van Hoesel and Tyler, 2003; Nopp *et al.*, 2004; Litovsky *et al.*, 2009). In addition, these patients generally show better speech recognition in noise when using BiCIs vs a single CI (van Hoesel and Tyler, 2003; Schleich *et al.*, 2004; Litovsky *et al.*, 2009). The largest benefits are not due to coordinated stimulation in both ears; rather, they can typically be attributed to monaural "head shadow" (better-ear effect) cues. Binaural "summation" (redundancy in information with two ears) and the "squelch" effect, which require binaural integration of inputs to the two ears, are generally small and inconsistent in adult BiCI users (Litovsky *et al.*, 2009; Loizou *et al.*, 2009).

Adult BiCI users vary in their etiology, hearing experience, and age at onset of deafness. Many patients studied to date will have spent years, if not decades, deprived of hearing between the time of hearing loss onset and implantation. Unlike adult BiCI users, the majority of children receiving CIs are being implanted at a young age, before the development of speech and language. Most of these children are born deaf and receive no benefit from auditory input until their CIs are activated. Although these children spend very little time deprived of hearing, most have very little exposure to sound prior to implantation. The present study thus focused on spatial unmasking of speech in children who use BiCIs. This population, like adults, generally appears to show significant benefits from two vs one CI. For example, benefits have been measured for sound localization (van Deun *et al.*, 2010; Grieco-Calub and Litovsky, 2010) and on spatial discrimination of target stimuli, such as minimum audible angle (MAA) (Litovsky *et al.*, 2006; Grieco-Calub *et al.*, 2008; Godar and Litovsky, 2010; Grieco-Calub and Litovsky, 2012). Interestingly, however, resolution of spatial hearing in children with BiCIs is significantly worse than that of children with NH, as they show a higher root-mean-square error on localization and higher MAAs on discrimination. The source of this gap in performance is not well understood.

The present study was concerned with measuring spatial unmasking in children who use BiCIs and in NH children to determine whether a gap exists on this measure as well. All children who use BiCIs were recruited prospectively for a larger study, and had at least 1 yr of experience with BiCIs. We focused on testing in a "bilateral listening mode," i.e., when both CIs are activated. We did not compare performance with a condition in which one CI is deactivated since the unilateral listening mode is unnatural (and usually unpreferred),

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[a)] Author to whom correspondence should be addressed. Electronic mail: Litovsky@waisman.wisc.edu thus disadvantaged *a priori*. An area of focused interest in the NH literature is that of speech understanding when target speech is either spatially co-located with interfering sources (maskers/interferers), or spatially separated from interferers. In NH listeners, the improvement, or benefit, due to spatial separation is known as spatial release from masking (SRM). SRM can be as large as 12–15 dB in NH adults and depends on numerous factors, including the number of sources (Culling *et al.*, 2004; Hawley *et al.*, 2004), type of interfering sources (Hawley *et al.*, 2004; Cullington and Zeng, 2008), perceived spatial separation of the sources (Freyman *et al.*, 1999, 2001), and room acoustics (Culling *et al.*, 2003; Marrone *et al.*, 2008). In the existing literature, one way to quantify SRM is to add effects that are due to (1) a monaural head shadow which results in a more favorable signal-to-noise ratio (SNR) at the better ear and (2) binaural unmasking (e.g., Zurek, 2003; Hawley *et al.*, 2004). This approach may be reasonably suitable for environments that contain only one interfering source from a single location. A different approach to quantifying SRM, which has been proven to be reliable for environments containing one interferer type that is simultaneously distributed in multiple locations, involves additive components that arise from (1) spatial separation of the target and interferer(s) and (2) spatial asymmetry of the interferers. This model was originally described for noise interferers and more recently modified to successfully account for effects arising in the presence of speech interferers similar to those used in the present study (Jones and Litovsky, 2011).

SRM is generally the largest for conditions in which there are large angular separations between target and interferers. In adults with NH, Jones and Litovsky (2011) measured speech reception thresholds (SRTs) for conditions with a target at 0° (front) and two-talker interferers at either $+90°/-90°$ (two interferers symmetrically distributed, one talker on the right and one on the left) or $+90°/+90°$ (two interferers asymmetrically placed so that two talkers are co-located and both are on one side of the head). On average, the total amount of SRM (difference in SRT between spatially co-located and separated conditions) was a 12 dB improvement in SRT. Of that 12 dB improvement, 8.7 dB was accounted for by spatial separation and 3.3 dB was accounted for by the effect of asymmetry, i.e., there was greater SRM in the $+90°/+90°$ than in the $+90°/-90°$ condition. The model does not provide definitive conclusions about whether the division of SRM into separation and asymmetry components has significant parallels with the division of SRM into better ear and binaural unmasking components. In particular, in the symmetrical condition, having independent speech interferers at $+90°/-90°$ means that there are potential opportunities for momentary "glimpsing" of information through one ear at a time so that some better ear cues might be available in the symmetrical condition. Thus, we consider the symmetrical condition as having reduced, but not absent, better ear effects. In this condition, when better ear cues are minimized, listeners must rely on binaural cues or other cues such as voice pitch, for source segregation. In the binaural domain, the role of interaural time difference (ITD) has been shown to be more robust than the role of interaural level difference (ILD) cues in SRM (Culling *et al.*, 2004).

Studies in children have been conducted with either one or two interferers, but with a standard spatial configuration of target and interferers whereby the latter are positioned asymmetrically relative to the head, i.e., interferers are located on one side of the head. SRM in NH children can range from 5–10 dB (Litovsky, 2005; Johnstone and Litovsky, 2006; Litovsky *et al.*, 2006; Garadat and Litovsky, 2007), and at least one report has shown that SRM in children aged 11–14 is around 13 dB (Cameron *et al.*, 2006). Regarding children who use BiCIs, relatively little is known about spatial unmasking. Mok *et al.* (2010) showed that children with BiCIs exhibit better speech perception in noise in spatially separated conditions than children who use a CI in one ear and a hearing aid in the opposite ear, suggesting advantages for BiCIs compared with unilateral CIs. Litovsky *et al.* (2006) and Chadha *et al.* (2011) reported that children who received BiCIs sequentially showed an improvement in speech understanding when interferers were shifted toward the side of their second CI, suggesting that children have a preference toward their first CI. Van Deun *et al.* (2010) reported that it was advantageous for all of the children with BiCIs to listen with both CIs rather than one when listening to speech in noise. In the latter, as shown in adult studies (e.g., van Hoesel and Tyler, 2003; Loizou *et al.*, 2009), it was suggested that the majority of the benefits for children with BiCIs are perceived due to better ear cues, but there was no evidence for spatial effects arising from binaural unmasking.

In the present study we were concerned with SRM in children with NH and in children who are deaf and fitted with BiCIs. Regarding NH children, in Litovsky (2005) SRM was studied in children grouped across the range of 4–7 yrs, and there was considerable variability; thus here we examined age effects by comparing younger and older children within a similar range. Children in the BiCI groups may vary by certain characteristics, including age at the time of activation of the first CI, age at the time of activation of the second CI, inter-CI gap, and in previous studies they also varied greatly by chronological age (CA). The present study was designed with the goal of narrowing some of the participant characteristics in these groups. Children in an older BiCI group were matched for CA with children in the older NH group. Their average hearing age (HA) (defined as the amount of time the child has been exposed to sound) was 2 years younger than the average HA of the children in the younger NH group. The younger BiCI group was matched for HA with the younger NH group, and the CA difference was relatively small because these children received their first CI during infancy. The HA and CA values for each group are shown in Table I. Comparisons between children who have NH (binaural hearing) and children who use BiCIs (bilateral hearing) offer the opportunity to ask whether SRM can be achieved to the same extent with these vastly different stimulation and listening modes.

This study was designed to test the hypothesis that (1) SRM would be reduced with symmetrical interferers (each at 90° but one on the right and one on the left) compared with asymmetrical interferers (both at 90° on the same side), due to the reduction of available monaural cues in the

TABLE I. Subject demographics.

| | | Subject Code | CA (yr) | HA (yr) | Etiology | Age at first CI activation (yr) | Age at second CI activation (yr) | Time between first and second CI (yr) | First CI | Second CI |
|---|---|---|---|---|---|---|---|---|---|---|
| BiCI-A (younger BiCI users) | 1 | CIDP | 4.9 | 4.0 | Connexin-26 | 11 months | 2.8 | 1.8 | Med-El Combi40+; left ear | Med-El Pulsar; right ear |
| | 2 | CIDQ | 6.6 | 5.8 | Unknown | 9 months | 4.4 | 3.4 | N24C; right ear | Nucleus Freedom; left ear |
| | 3 | CIDN | 7.0 | 5.8 | Genetic | 1.2 | 6.1 | 4.9 | Med-El Combi40+; left ear | Med-El Pulsar; right ear |
| | 4 | CIBW | 5.8 | 4.8 | Connexin-26 | 1.0 | 3.9 | 2.7 | N24C; right ear | Nucleus Freedom; left ear |
| | 5 | CIBU | 6.3 | 5.1 | Connexin-26 | 1.1 | 5.0 | 3.9 | Med-El Tempo; left ear | Med-El Pulsar; right ear |
| | 6 | CICY | 5.7 | 4.7 | Unknown | 1.0 | 4.7 | 3.7 | Advanced Bionics HiRes90K; right ear | Advanced Bionics HiRes90K; left ear |
| | 7 | CIDX | 6.8 | 5.4 | Connexin-26 | 1.5 | 2.7 | 1.1 | N24C; right ear | N24C; left ear |
| | 8 | CICB | 5.2 | 4.6 | Connexin-26 | 10 months | 2.1 | 1.2 | N24C; right ear | Nucleus Freedom; left ear |
| | | | **mean = 6.0** | **mean = 5.0** | | | | | | |
| BiCI-B (older BiCI users) | 1 | CIAY | 9.0 | 7.1 | Progressive, unknown | 5.2 | 6.0 | 10 months | N24C; right ear | N24C; left ear |
| | 2 | CIAW | 8.6 | 7.4 | Prenatal CMV exposure | 1.2 | 6.6 | 4.2 | N24C; right ear | Nucleus Freedom; left ear |
| | 3 | CIBB | 7.0 | 6.5 | Meningitis | 7 months | 7 months | simultaneous | N24C; right ear | N24C; left ear |
| | 4 | CIBI | 7.3 | 7.0 | Mondini malformation | 1.1 | 2.1 | 4 mo | N24C; right ear | N24C; left ear |
| | 5 | CIDQ | 7.7 | 6.9 | Unknown | 9 months | 4.4 | 3.4 | N24C; right ear | Nucleus Freedom; left ear |
| | 6 | CIEL | 7.6 | 6.7 | Unknown | 1.2 | 3.4 | 2.2 | N24C; right ear | Nucleus Freedom; left ear |
| | | | **mean = 7.9** | **mean = 6.9** | | | | | | |
| NH-A (younger NH) | 1 | CNS | 4.3 | | | | | | | |
| | 2 | CNI | 6.3 | | | | | | | |
| | 3 | CNF | 4.2 | | | | | | | |
| | 4 | CNJ | 5.5 | | | | | | | |
| | 5 | CNB | 5.3 | | | | | | | |
| | 6 | CNK | 4.1 | | | | | | | |
| | 7 | CKX | 5.7 | | | | | | | |
| | 8 | CNQ | 4.4 | | | | | | | |
| | | | **mean = 5.0** | | | | | | | |
| NH-B (older NH) | 1 | CNH | 7.6 | | | | | | | |
| | 2 | CNG | 8.8 | | | | | | | |
| | 3 | CKB | 7.8 | | | | | | | |
| | 4 | CNL | 8.0 | | | | | | | |
| | 5 | CNU | 7.4 | | | | | | | |
| | 6 | CKG | 8.3 | | | | | | | |
| | 7 | CNV | 6.9 | | | | | | | |
| | 8 | CNW | 7.8 | | | | | | | |
| | | | **mean = 7.8** | | | | | | | |

symmetrical distribution. In addition, we aimed to test the hypothesis that (2) children with a greater amount of listening experience (older HA) would demonstrate greater SRM. In the NH population, for whom binaural cues are delivered to the auditory system with fidelity, the demonstration of SRM in the symmetrical condition is indicative of the ability to segregate targets from interferers under conditions of reduced monaural cues, possibly indicative of the ability to utilize binaural cues for source segregation. There is evidence to suggest that by age 4 children have similar thresholds to adults for ITD discrimination (Ashmead *et al.*, 1991,) and binaural masking level differences (van Deun *et al.*, 2009). However, it is unclear as to whether children can utilize these cues on spatial unmasking tasks. There are some conditions under which children perform worse than adults, possibly due to immature binaural temporal processing (e.g., Litovsky, 2011a,b; Litovsky and Godar, 2010). Thus, the symmetrical SRM condition serves as a good tool for evaluating the development of functional binaural hearing abilities in children. By comparison, the asymmetrical condition, which is more typically used in SRM studies, is useful for determining whether children benefit from target-interferer spatial separation when multiple spatial cues are present.

## II. METHODS

### A. Listeners

Participants were 38 native English-speaking children ($n = 30$) and adults ($n = 8$), all of whom received payment for their participation. There were two groups of children with BiCIs, two groups of children with NH, and one group of adults with NH. The HA in children with BiCIs was defined according to the parental report and audiologist records. The HA included the sum of the time a child had been exposed to sound, that is, the amount of time since activation of first CI, plus any prior acoustic experience (i.e., in cases of progressive hearing loss). The HA of each NH child was equivalent to CA. Children with BiCIs fell into one of two groups (demographic information is described in Table I): BiCI-A (younger) with HA of 4.0 –5.8 yr ($N = 8$, HA mean and standard deviation = 5.0 ± 0.6 yr, CA mean and standard deviation = 6.0 ± 0.8 yr, bilateral experience mean and standard deviation = 2.1 ± 1.1 yr) and BiCI-B (older) with HA of 6.5–7.4 yr ($N = 6$, HA mean and standard deviation = 6.9 ± 0.3 yr, CA mean and standard deviation = 7.9 ± 0.8 yr, bilateral experience mean and standard deviation = 4.0 ± 1.6 yr). These children were recruited from cochlear implant centers throughout the United States and traveled to Madison, WI for participation in the research. All but one subject received their CIs sequentially (CIBB was simultaneously implanted at 7 months of age). The first CI was activated prior to 18 months of age in all but one subject (CIAY), who had post-lingual onset of deafness. The main mode of communication was oral for all BiCI users, as noted by parents. None of the BiCI users had known co-morbidities due to other identified disabilities. During all testing sessions children's CI programs were set to those used most often in daily listening, based on parental and audiologist reports. A loudness balancing procedure, using subjective responses from the participant, was conducted at the first testing session and volume control and/or sensitivity were adjusted to equalize the loudness between the two CI devices as best as possible.

NH children were recruited from the Madison, WI area to match BiCI groups by HA and were divided into two groups: NH-A (younger) with HA of 4.1–6.3 yr ($N = 8$, HA mean and standard deviation = 5.0 ± 0.8 yr), and NH-B (older) with HA of 6.9–8.8 yr ($N = 8$, HA mean and standard deviation = 7.8 ± 0.6 yr). In addition, 8 adults (ages 18–25 yr) were recruited from the student population at the University of Wisconsin—Madison to serve as a comparison group. All NH listeners had hearing sensitivity within normal limits, as indicated by pure-tone air conduction thresholds of 20 dB hearing level or less at octave frequencies between 250 and 8000 Hz.

Because middle-ear problems are common in young children, tympanometry was performed prior to the commencement of testing. According to tympanometric results, all NH subjects exhibited normal peak-compensated static admittance and no children were disqualified due to middle ear anomalies.

This research was approved by and carried out in accordance with the University of Wisconsin—Madison's Human Subjects IRB regulations. Children ages 7+ years signed an assent form, and parents or caregivers of children signed consent forms. NH children were paid an hourly rate for their participation. BiCI users received per diem payments, plus the cost of travel to Madison, and all costs associated with the travel were reimbursed to the family.

### B. Environment

Testing was conducted in a carpeted standard IAC sound booth (2.8 × 3.25 m) with reverberation time ($RT_{60}$) of 250 ms. Listeners sat at a foam-covered desk in the center of a loudspeaker array, facing a computer monitor placed at 0° azimuth. Listeners were approximately 1.5 m from the surrounding loudspeakers. Stimuli were presented from three loudspeakers (Cambridge Soundworks, Center/Surround IV) calibrated prior to each testing session using a sound level meter mounted at the approximate position of the listener's head. The experimental test session lasted approximately 1 h for adults and 3 h for children. Frequent breaks were given in order to maximize participant attentiveness.

### C. Stimuli

Stimuli consisted of both target words and interfering sentences. Target stimuli were a closed set of 25 bisyllabic spondees pre-recorded using a male talker. Target spondees were within the vocabulary of the children and were represented by easily identifiable icons (e.g., baseball, cupcake, etc.) (Litovsky, 2005). The root-mean-square levels of all target words were equalized. The interfering speech consisted of sentences from the Harvard IEEE corpus (Rothauser *et al.*, 1969), which were pre-recorded using a female talker. Sentences were filtered in order to match the long-term average speech spectrum of the target. Two-talker interferers were created by overlaying two recordings of the same voice. The target stimuli described here are identical to those used in a prior experiment with children 4–7 years old (Litovsky, 2005).

### D. Design and procedure

SRTs for known target words were measured in quiet and in the presence of interfering speech fixed at 55 dB SPL. For each listener, SRTs were measured under four conditions: $\mathrm{SRT}_{\mathrm{Quiet}}$ (target 0° front, no interferers); $\mathrm{SRT}_{\mathrm{Front}}$ (target and 2-talker interferers both 0° front); $\mathrm{SRT}_{+90°/-90°}$ also known as the Symmetrical condition (target 0° front, 2 interferers, one at +90° right and one at −90° left); and $\mathrm{SRT}_{+90°/+90°}$ also known as the Asymmetrical condition (target 0° front, 2 interferers, at 90° right or left). Note that in the latter condition interferers were placed on the right side for the NH children and near the side of the first CI for the children with BiCIs. When interferers occurred, the trial began with the interferer, the target was subsequently added to the running speech, and after target offset the interferer continued for approximately 1 s. All listeners were instructed to attend to the target (male) talker and to ignore the female voices.

Prior to testing, each listener participated in a brief familiarization session in order to determine that he or she could accurately identify all target spondees and corresponding pictures or icons. The task was designed to test speech intelligibility rather than vocabulary, and therefore any of the 25 target spondees that a child was not able to recognize were not used. Out of the 38 listeners, only 8 used spondee lists of fewer than the original 25 words, with no subject using a list of fewer than 20 words (BiCI-A: 2 listeners, BiCI-B: 2 listeners, NH-A: 3 listeners, NH-B: 1 listener). Listeners practiced on the Quiet and Front conditions in order to become familiar with the stimuli, as well as various aspects of the experimental task (e.g., computer controls, listener position). Data collected during the familiarization session was not used in the analysis.

Listeners performed a 4-alternative-forced-choice task (Litovsky, 2005; Johnstone and Litovsky, 2006; Litovsky *et al.*, 2006; Garadat and Litovsky, 2007). Each trial began with the carrier phrase "Ready" followed by a target spondee randomly chosen from the closed set of 25. Four of the previously familiarized visual pictures (three randomly selected pictures and one picture that matched the target spondee) were displayed on the computer monitor, each matching one of the spondees. The listener was instructed to identify the picture that matched the target word. Responses were provided by pointing to the object with a computer mouse; some children were aided by the experimenter in manipulating the mouse after the subject verbally indicated a response. Incorrect responses were followed by "negative" feedback consisting of a pre-recorded phrase (e.g., "let's try another one" or "that must have been difficult"). There was no auditory or visual feedback following correct responses. To engage and motivate the children during testing, a digitized "puzzle" of a child-friendly picture was revealed one piece at a time following each response, regardless of whether the child was correct or incorrect. Additional reinforcement via stickers and prizes was provided between testing conditions.

### E. Speech reception threshold estimation

SRTs were estimated using an adaptive tracking algorithm and calculated using maximum likelihood estimation methods for finding the point on the psychometric function at which performance yielded 79.4% correct as described previously (Litovsky, 2005; Johnstone and Litovsky, 2006; Garadat and Litovsky, 2007). The level of the target words varied according to a hybrid set of rules. Initially, target levels were 60 dB SPL. Levels decreased by 8 dB following each correct response. After the first incorrect response, levels were changed using a 3-down/1-up rule such that three consecutive correct responses resulted in a lower target level and single incorrect responses resulted in a higher target level. After each reversal the step size was halved, with the minimum step size limited to 2 dB. Each adaptive track ended after four reversals.

Unlike previous studies in which a single SRT measurement was obtained (e.g., Litovsky, 2005; Johnstone and Litovsky, 2006; Litovsky *et al.*, 2006; Garadat and Litovsky, 2007), the goal here was to estimate the repeatability of SRTs in each condition for individual children. We thus sought to obtain three SRT measurements from each child on each of the four conditions. In order to achieve this, the order of testing was randomized over all conditions. An average of the SRTs obtained for each condition for every child was then inserted in the group analysis. Due to time constraints, seven NH listeners and seven BiCI users were tested with fewer than three SRTs of each condition. Conditions in which this occurred varied between subjects. Subject CIDP (in group BiCI-A) had one SRT measurement in three of the four conditions, and therefore was excluded from the repeated measures analysis. When time constraints occurred, an emphasis was placed on obtaining more than one SRT measurement in the Front condition, which was used to evaluate release from masking.

### F. SRM calculation

SRM was computed for each listener from the mean SRTs in the Front and either Symmetrical or Asymmetrical conditions, such that

$$\mathrm{SRM}_{\mathrm{Symmetrical}} = \mathrm{SRT}_{\mathrm{Front}} - \mathrm{SRT}_{+90/-90}, \tag{1}$$

$$\mathrm{SRM}_{\mathrm{Asymmetrical}} = \mathrm{SRT}_{\mathrm{Front}} - \mathrm{SRT}_{+90/+90}. \tag{2}$$

In addition, we computed the SRM due to asymmetry, independent of the spatial separation, as follows:

$$\mathrm{SRM}_{\mathrm{Asymmetry}} = \mathrm{SRM}_{\mathrm{Asymmetrical}} - \mathrm{SRM}_{\mathrm{Symmetrical}}. \tag{3}$$

These are based on Eqs. (3), (4), and (5) of Jones and Litovsky (2011). It is important to note here that these values reflect the contributions of separation and asymmetry only at the locations tested here, i.e., at 90.

## III. RESULTS

### A. Speech reception threshold

In Fig. 1, panels A–D show each of the individual SRT values for each of the listeners, in all four conditions (A: Quiet, B: Front, C: 90 Asymmetrical, D: 90 Symmetrical). This plot provides a view of the individual variability observed across participants and within a participant. Within each panel, for each group the means (±SD) are also shown (filled circles in the right-most portion of the panels). To test whether repeated measures of SRTs resulted in similar findings for subjects at the conditions tested, SRTs were analyzed for listeners who completed all three repetitions for each condition (BiCI-A, $N = 2$; BiCI-B, $N = 4$; NH-A, $N = 3$; NH-B, $N = 6$; Adult, $N = 7$). Repeated measures analysis of variance were conducted on each group with a condition (Quiet, Front, Asymmetrical, Symmetrical) by trial number (1, 2, 3) as the within-subject factors. There were no significant interactions in any of the groups and there were no statistically significant differences between the three SRTs per condition (i.e., trials) for any of the groups, suggesting stable SRTs. Thus, averaging SRTs within conditions appears to be a reasonable approach.

Figure 2 shows group means (±SD) for all conditions, and results of statistical comparisons are highlighted (*). SRTs were analyzed using planned *t*-test comparisons of either within- or between-group differences. A Bonferroni correction for four comparisons was applied to each group. Results of the planned comparisons were as follows: (1) Younger NH children (NH-A) had poorer SRTs than older NH children (NH-B) in the Symmetrical [$t(14) = 3.18$, $p = 0.007$, two-tailed] condition, and there were no group differences in the Quiet, Front, or Asymmetrical conditions. (2) Older NH (NH-B) children had poorer SRTs than Adults in all conditions tested: Quiet [$t(14) = 3.24$, $p = 0.006$, two-tailed], Front [$t(14) = 4.86$, $p < 0.001$, two-tailed], Asymmetrical [$t(14) = 6.31$, $p < 0.001$, two-tailed] and Symmetrical [$t(14) = 4.0$, $p < 0.001$, two-tailed]. (3) There were no group differences in younger children with BiCIs (BiCI-A) and older children with BiCIs (BiCI-B), where, for most, SRTs were very close to a SNR of 0. (4) Comparing children in the two older groups (where CA is equivalent and HA is greater in NH than BiCI by a year), BiCI-B had poorer SRTs than NH-B on all four conditions tested: Quiet [$t(12) = 7.40$, $p < 0.001$, two-tailed], Front [$t(12) = 4.97$, $p < 0.001$, two-tailed], Asymmetrical [$t(12) = 7.42$, $p < 0.001$, two-tailed] and Symmetrical [$t(12) = 10.26$, $p < 0.001$, two-tailed]. (5) Comparing children in the two younger groups (where HA is equivalent and CA is greater in BiCI than NH by $\sim$12 months), BiCI users had poorer SRTs than NH children on all four conditions tested: Quiet [$t(14) = 9.93$, $p < 0.001$, two-tailed], Front [$t(14) = 5.25$, $p < 0.001$, two-tailed], Asymmetrical [$t(14) = 6.58$, $p < 0.001$, two-tailed] and Symmetrical [$t(14) = 4.59$, $p < 0.001$, two-tailed]. (6) To further test HA as a critical factor, we compared the older children with BiCIs (BiCI-B) with the younger NH children (NH-A), and here the BiCI users had a HA that was greater by an average of 2 years compared to the NH children. Results showed BiCI users had poorer SRTs than NH children on all four conditions tested: Quiet [$t(12) = 6.64$, $p < 0.001$, two-tailed], Front [$t(12)$

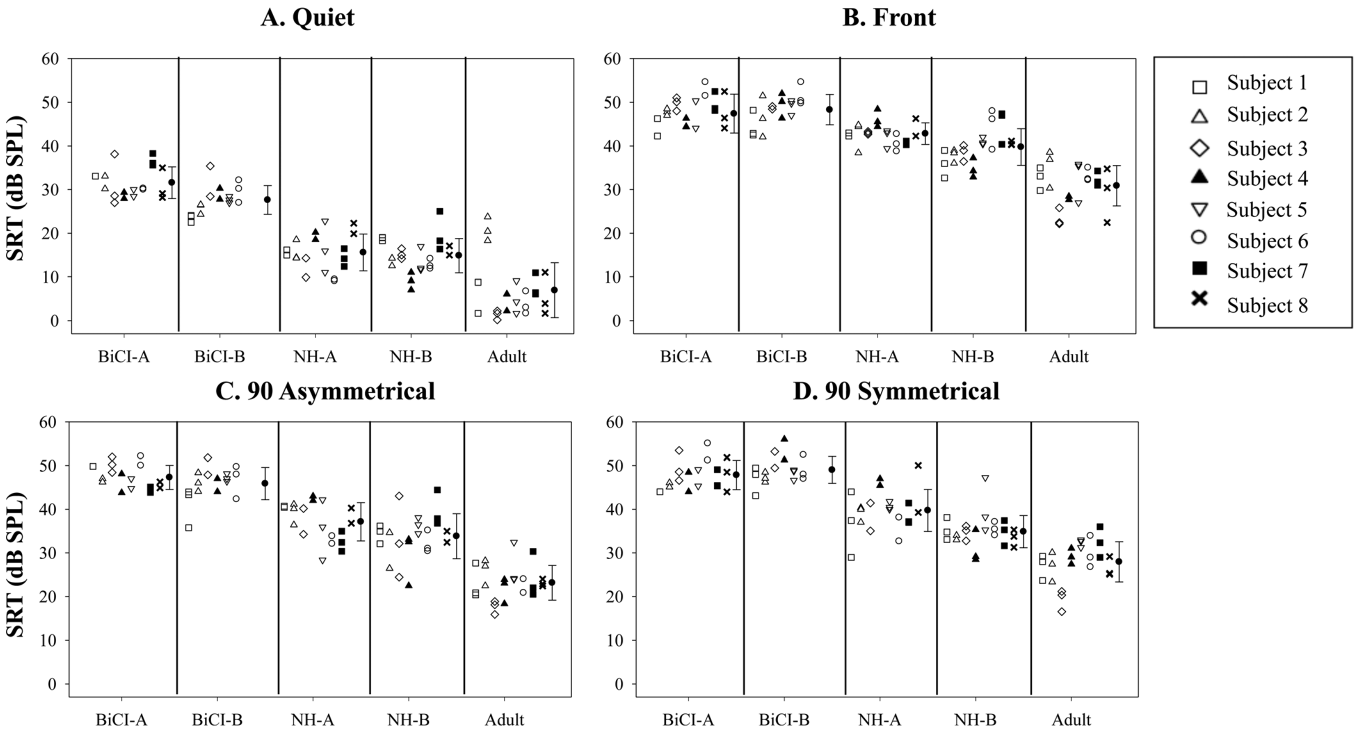

FIG. 1. SRTs are plotted for each group in each condition (A: Quiet, B: Front, C: 90 Asymmetrical, D: 90 Symmetrical). Within each group individual subjects are represented by a different symbol. For each subject individual symbols represent a single SRT. Group means (±SD) are shown to the right of all subjects in each group by the filled circles.

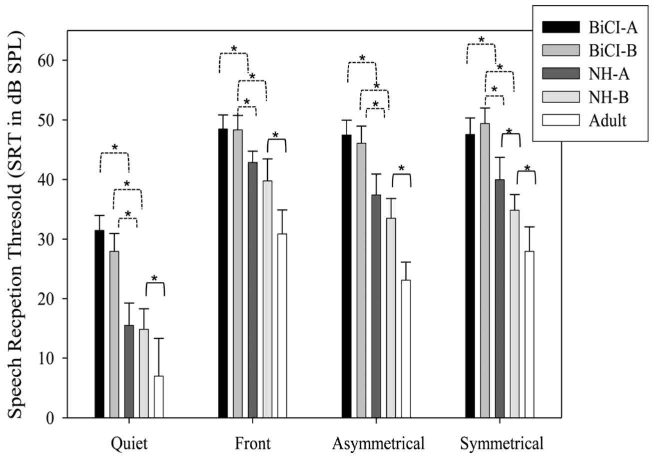

FIG. 2. Mean (±SD) SRTs are shown for each group in each condition (i.e., Quiet, Front, 90 Asymmetrical, 90 Symmetrical). Significant differences ($p < 0.05$) are bracketed and indicated with an asterisk (*). Solid brackets indicate differences within hearing type (i.e., A vs B). Dashed brackets indicate differences between hearing type (i.e., NH vs BiCI).

$= 4.72$, $p < 0.001$, two-tailed], Asymmetrical [$t(12) = 4.92$, $p < 0.001$, two-tailed], and Symmetrical [$t(12) = 5.25$, $p < 0.001$, two-tailed].

## B. Spatial release from masking

Figure 3 shows individual data points for $\mathrm{SRM}_{\mathrm{Symmmetrical}}$ as a function of $\mathrm{SRM}_{\mathrm{Asymmmetrical}}$ for each listening group (panels A–E). Each data point represents SRM for an individual listener, computed from their average SRTs regardless of how many SRTs they had per condition. Positive SRM indicates that a listener performed better when the interferers were spatially separated from the target than when they were co-located with the target. Negative SRM values indicate that performance was worse with spatial separation of target and interferers. The diagonal line represents equal SRM for the Asymmetrical and Symmetrical conditions. Data points below the diagonal suggest more SRM in the Asymmetrical than the Symmetrical condition. Data points toward the right indicate more SRM, hence a greater benefit with spatial separation of target and interferers. Planned paired sample *t*-tests were thus conducted for each group (BiCI-A, BiCI-B, NH-A, NH-B, Adult), showing that $\mathrm{SRM}_{\mathrm{Asymmetrical}}$ was greater than $\mathrm{SRM}_{\mathrm{Symmetrical}}$ for two groups. In the BiCI-B group the mean SRM values in the Asymmetrical and Symmetrical conditions were 2.25 and $-1.07$ dB, respectively [$t(5) = 2.75$, $p < 0.05$, two-tailed]. In the adult group, SRM values in the Asymmetrical and Symmetrical conditions were 7.43 and 2.81 dB, respectively [$t(7) = 4.78$, $p < 0.05$, two-tailed]. While there is a hint of these differences in the other three groups, there is lack of significance, which may be due to large individual variability.

SRM data are also shown in Fig. 4, grouped by condition for each subject population. The individual differences can be seen along the *y*-axis and group mean (±SD) for SRM values are plotted alongside the individual data, for Asymmetrical [Fig. 4(A)] and Symmetrical [Fig. 4(B)] conditions. Figure 4(C) summarizes the group means and highlights statistically significant comparisons (*).

Group differences were analyzed separately for $\mathrm{SRM}_{\mathrm{Asymmetrical}}$ and $\mathrm{SRM}_{\mathrm{Symmetrical}}$ using planned *t*-test comparisons, and the Bonferroni correction for two comparisons was applied. Results of the planned comparisons were as follows: (1) Comparing children in the two older groups, BiCI-B had less SRM than NH-B in both conditions: $\mathrm{SRM}_{\mathrm{Asymmetrical}}$ [$t(12) = -2.62$, $p = 0.022$, two-tailed] and $\mathrm{SRM}_{\mathrm{Symmetrical}}$ [$t(12) = 1.29$, $p = 0.004$, two-tailed]. (2) Comparing children in the two younger groups, BiCI-A had less SRM than NH-A in only the Asymmetrical condition: $\mathrm{SRM}_{\mathrm{Asymmetrical}}$ [$t(14) = -4.02$, $p = 0.001$, two-tailed]. (3) Comparing the NH younger group with the BiCI older group that had 2 years more in HA, results showed BiCI-B had less SRM than NH-A in both the Asymmetrical and Symmetrical conditions: $\mathrm{SRM}_{\mathrm{Asymmetrical}}$ [$t(12) = -2.69$, $p = 0.020$, two-tailed], and $\mathrm{SRM}_{\mathrm{Symmetrical}}$ [$t(12) = -3.079$, $p = 0.010$, two-tailed] (4) Comparisons of the younger and older NH child groups with the Adult group showed no difference for either group in either condition.

As per Jones and Litovsky (2011) the amount of SRM due to asymmetry ($\mathrm{SRM}_{\mathrm{Asymmetry}}$) was computed for each subject as ($\mathrm{SRM}_{\mathrm{Asymmetrical}} - \mathrm{SRM}_{\mathrm{Symmetrical}}$) and these values are shown for the five participant groups in Fig. 5. Figure 5(A) shows individual data points for each listener, and Fig. 5(B) summarizes the group means (±SD) and highlights statistically significant comparisons (*). Visual inspection of the data suggests that adults had the largest values, on average, and that the BiCI-A group had the smallest average values. However, variability was quite high as can be seen from the error bars. Planned *t*-test comparisons were conducted to test for group differences of $\mathrm{SRM}_{\mathrm{Asymmetry}}$. Older NH (NH-B) children had a smaller effect of $\mathrm{SRM}_{\mathrm{Asymmetry}}$ than Adults [$t(14) = -2.38$, $p = 0.04$, two-tailed], and no other comparisons were significant, which is not surprising given the large within-group variation.

## IV. DISCUSSION

Children spend a vast amount of time communicating and learning in complex acoustic environments, in which multiple sound sources compete for attention and localization. The ability to segregate target speech from competing sources in the environment is likely to yield greater success in learning and attainment of critical communication skills. Studies in which spatial cues differ between target and interferers are aimed at assessing the extent to which listeners can utilize spatial cues in complex listening tasks for source segregation. Here we investigated this ability in adults and in four groups of children, two NH that varied in age, and two with BiCIs, that varied in auditory experience (HA) and CA.

### A. SRTs

Not surprising, results of the current study suggest that, on average, SRTs are lower for adult listeners when compared to all children groups. This may be due to a number of factors including continued maturation of central auditory mechanisms and attention throughout childhood (e.g., Lutfi

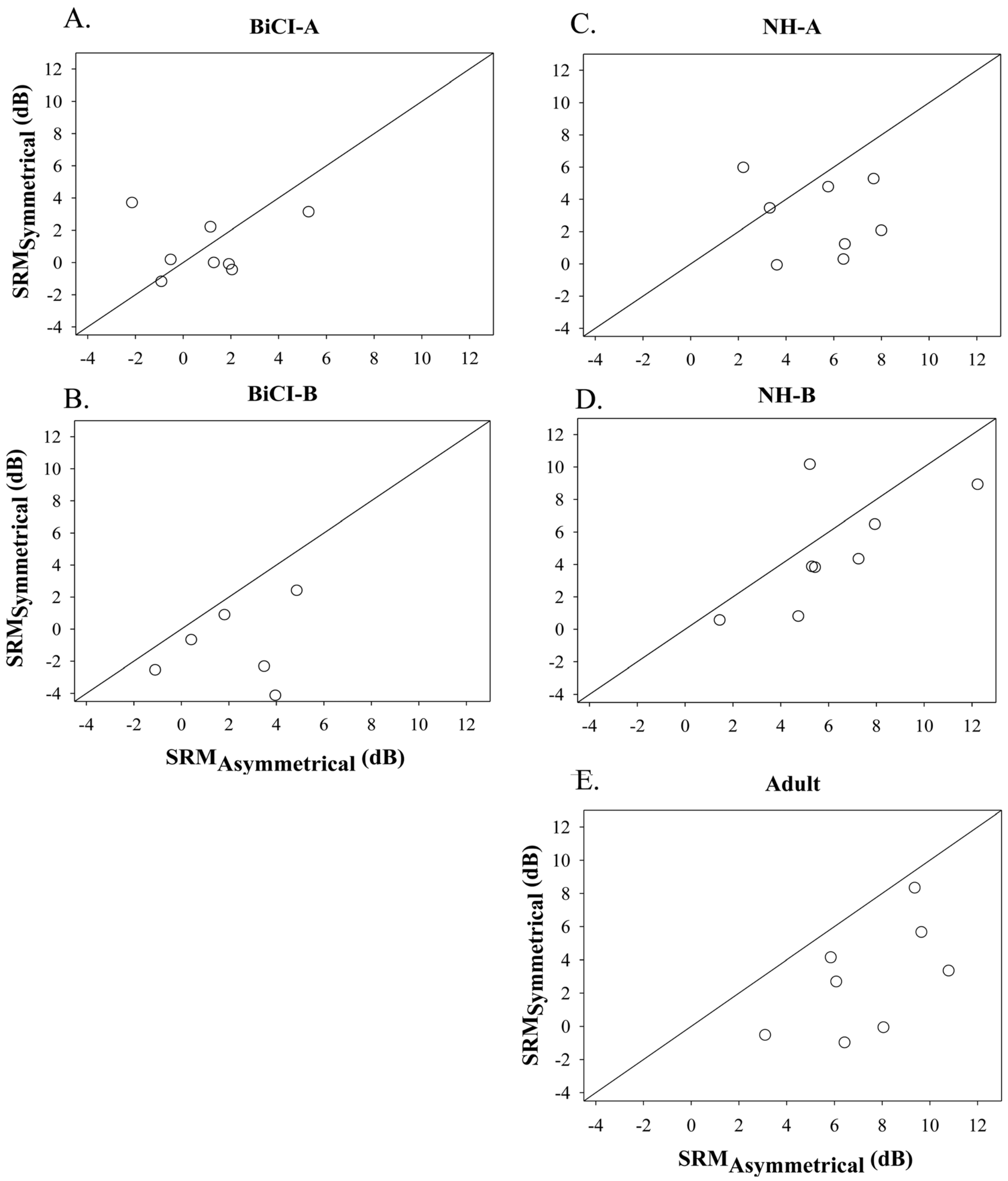

FIG. 3. SRM values for Asymmetrical and Symmetrical conditions are compared for each individual listener for each group. Panels A–E show groups as follows: A: BiCI-A, B: BiCI-B, C: NH-A, D: NH-B, E: Adult. Each data point represents one listener. The diagonal line corresponds to equivalent SRM in the Asymmetrical and Symmetrical conditions.

*et al.*, 2003; Leibold and Bonino, 2009). Within the children groups, on average, NH listeners had lower SRTs than children with BiCIs, that is, the level of the target required for them to understand speech at ∼80% correct was lower. This is important to note in quiet, and also in the presence of interferers, because it suggests that BiCI users need a better SNR than NH children in order to understand the same proportion of words. Similar reports have been noted in children who are hearing impaired and use hearing aids (Ching *et al.*, 2011) and in adults who use BiCIs (e.g., Litovsky *et al.*, 2009). This was observed regardless of the fact that the older BiCI group had been wearing two CIs for an average of 4 years. One of the hallmarks of research with cochlear implant users, which was also observed in the present study, is that of individual variability. There was overlap in the SRTs of the better-performing BiCI users and the worst-performing NH children, suggesting that some BiCI users have attained a level of performance that is within the normal range of performance, while other children with BiCIs have substantially poorer performance than their NH peers.

In this study we also examined, for the first time, the repeatability of SRT measurements. In our past work we had selected to obtain SRTs, rather than to measure percent correct, as we were ultimately interested in the effect of spatial cues on the level required for listeners to succeed in 80% speech intelligibility. Unlike previous studies in which a single

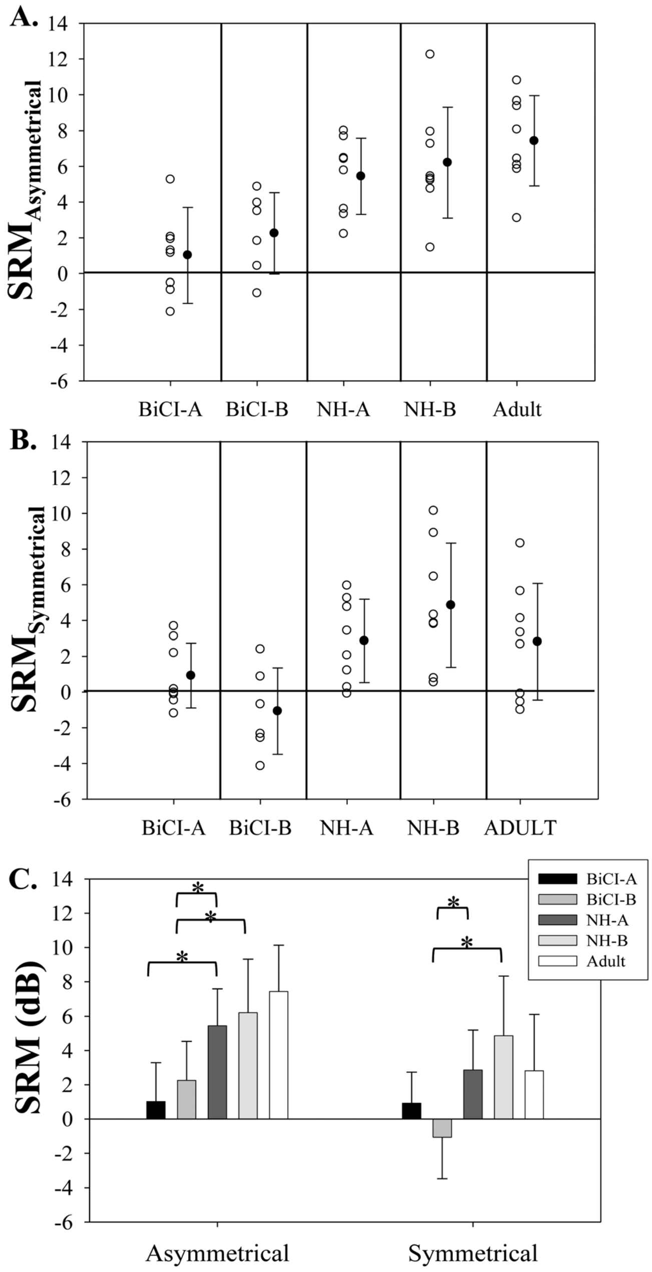

FIG. 4. SRM values are plotted for each group (BiCI-A, BiCI-B, NH-A, NH-B, Adult). Data points represent individual subjects. Group means (±SD) are shown to the right of all subjects in each group. (A) SRM Asymmetrical. (B) SRM Symmetrical. (C) Mean (±SD) SRM for both the Asymmetrical and Symmetrical conditions are summarized for each group in each condition. Significant differences ($p < 0.05$) are bracketed and indicated with an asterisk (*).

SRT measurement was obtained for each listener per condition (Litovsky, 2005; Garadat and Litovsky, 2007; Johnstone and Litovsky, 2006; Litovsky *et al.*, 2006; Ching *et al.*, 2011), here we introduced a repeated measures factor, such that listeners were tested on each condition several times during the testing session. SRTs were averaged for each subject across the repeated runs, and a single value consisting of the average was used in the data analysis. The findings that SRTs did not differ across repeated measures leads us to conclude that this approach is reliable for children as young as 4 years of age, and for children who are fitted with CIs.

When examining age effects on SRT measurements, older NH children had lower thresholds than younger NH children, but only on the Symmetrical condition with the target and interferers spatially separated toward both ears. This age effect was not observed in the BiCI groups. This finding is consistent with other reports showing that spatial hearing in NH children undergoes considerable maturation during childhood (Litovsky and Godar, 2010), and may be mediated by the continued maturation of auditory cortical mechanisms throughout childhood (Ponton *et al.*, 1992; Moore and Guan, 2001). The lack of age effects in the BiCI groups is likely related to the fact that bilateral CI processors do not provide binaural cues with fidelity; see below for further discussion.

## B. SRM

Previous research in NH populations has shown that, in Asymmetrical interferer configurations, SRM occurs for children as young as 3–4 yr (Garadat and Litovsky, 2007; Litovsky, 2005; Johnstone and Litovsky, 2006; Ching *et al.*, 2011). Here we add to this literature by demonstrating that when the interferers are placed symmetrically in the two hemifields, children who are 4–9 years old can benefit from spatial separation of target and interferers. Because monaural head shadow cues are greatly reduced in the Symmetrical condition, the results suggest that children were able to rely on binaural cues for release from masking. Previous work with NH adult listeners suggests that SRM is largest in conditions that contain both monaural and binaural cues and decreases when maskers are symmetrical so that binaural cues are reduced (Jones and Litovsky, 2011). Here the difference between Asymmetrical and Symmetrical SRM values was only significant for the Adult group and one of the child groups (BiCI-B, older), who had negative SRM in the Symmetrical condition (see Fig. 3). It should be noted that this range of SRM falls within the range considered to be within the margin of error for the test battery used here (±2 dB; see Litovsky, 2005). Thus, the spatial separation did not, on average, have a meaningful effect nor did it negatively impact performance. The challenge posed by the Symmetrical condition for BiCI users can be understood by considering the variety of factors they contend with. First, in this condition they are unable to use monaural cues. Second, the microphones are most likely amplifying the two interferers, thus creating a more difficult listening situation than the condition with the co-located stimuli. Third, binaural cues are likely to be minimal or absent.

This last factor points to a well-known characteristic of BiCIs: The lack of binaural coordination between the CI speech processors in the two ears, which likely causes binaural cues to be weak, absent or inconsistent (van Hoesel, 2011; Litovsky, 2011a,b). BiCI users are essentially fit with two monaural systems, which are not coordinated regarding their sampling time or onset time, thus the chances that binaural cues are preserved with fidelity is minimal (van Hoesel, 2011). In addition, speech processing strategies in CIs which use pulsatile non-simultaneous multi-channel stimulation extract envelopes of signals from the output

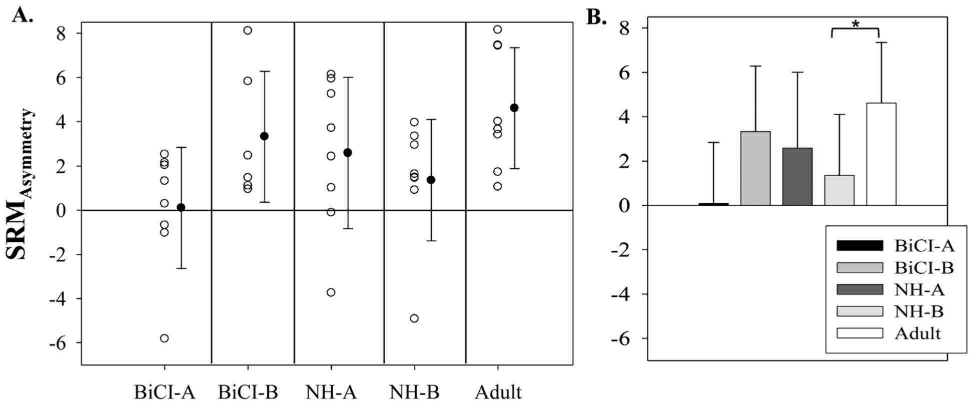

FIG. 5. SRM asymmetry is shown for each group. (A) Data points represent individual subjects. Group means (±SD) are shown to the right of all subjects in each group. (B) Mean (±SD) data are summarized. Significant differences ($p < 0.05$) are bracketed and indicated with an asterisk (*).

bandpass filters, discarding the fine structure. Thus, low-frequency interaural time differences, which are known to be important for source segregation (e.g., Culling *et al.*, 2004), are absent to BiCI users.

BiCI users most likely do have access to high-frequency ILD cues; however, the results in the present study suggest that those cues may not be optimal for SRM. In general, ITDs have been shown to play a more important role than ILDs for SRM (e.g., Culling *et al.*, 2004), hence the absence of ITDs is likely to have rendered Symmetrical SRM difficult to achieve. On a related note, as discussed above in relation to SRTs, the spectral degradation of the speech signal in CIs is likely to reduce the dissimilarity between the target and masker; hence the BiCI users are likely to have experienced more informational masking than the NH listeners. In a recent study on BiCI simulation with vocoders that varied the number of spectral channels, Garadat *et al.* (2010) demonstrated that binaural cues play a strong role in enhancing SRM when target and interfering speech are more likely to be confused.

The small SRM in the Asymmetrical conditions for the BiCI users may be due to the small dynamic range, and the microphone characteristics, which, even in the directional setting have a broad range of locations that are amplified in the frontal hemifield. Thus, unlike NH listeners whose acoustic system renders front and side speech signals as having more differentiated levels, CI users may receive front/side signals that are much less differentiated from one another. The Asymmetrical and Symmetrical data are consistent with a study by Loizou *et al.* (2009) in adult BiCI users, whereby SRM was studied using a method that replicated conditions in the experiment of Hawley *et al.* (2004) in NH adult listeners. Stimuli in the study of Loizou *et al.* consisted of target and interferers, convolved through head related transfer functions measured in a manikin, thus bypassing the microphone of the CIs. Stimuli were provided to listeners via direct connect input to the auxiliary port of the CI in each ear. Results showed that SRM due to binaural interaction was about 0 dB, in contrast with 6 dB in NH listeners. SRM due to monaural cues was about 4 dB in both groups of listeners, suggesting that when the CI microphones are bypassed at least the monaural head shadow cue observed in NH listeners is retained.

Recent research has suggested that children who receive BiCIs simultaneously perform better on speech in noise tasks than those who receive their CIs sequentially (Chadha *et al.*, 2011). The current study did not address that issue since it includes only one child who received BiCIs simultaneously (CIBB), with all the rest having been implanted sequentially. Interestingly, the one subject who received implants sequentially did not demonstrate markedly notable SRM (Asymmetrical: −1.09 dB, Symmetrical: −2.56 dB).

In this study, NH children were divided into two age groups in order to consider possible effects of maturation and development of speech intelligibility and spatial hearing abilities.

While there were age effects in SRTs, these effects were only in the Symmetrical condition. They were not powerful enough to affect significant SRM effects, presumably because SRM is derived from comparisons of the spatially separated and front conditions. Lack of robust age effect on SRM may be due to the dissimilarity between the stimuli used here (male target and female interferers), whereby informational masking is limited (Durlach *et al.*, 2003). Because informational masking in children is thought to have a strong developmental component (Lutfi *et al.*, 2003; Leibold and Bonino, 2009), the different-sex stimuli may have created a listening task that reduced the utility of spatial cues in source.

Finally, adults in this study did show SRM on the order of 7.43 and 2.81 dB in the Asymmetrical and Symmetrical conditions, respectively. This is within the range of SRM reported previously with the same target-interferer speech corpus and with target and interferers spoken by different-sex target, thus easily distinguishable from one another (e.g., Johnstone and Litovsky, 2006). However, the SRM was also smaller than that reported with the same speech corpus but for same-sex target-interferers (Jones and Litovsky, 2011). These differences are most likely due to the relatively easy task (male-target:female-interferers using a 4-AFC) and reduced or absent informational masking (Kidd *et al.*, 1998; Johnstone and Litovsky, 2006).

## V. CONCLUSIONS

(1) SRTs in NH children were poorer than in adults.
(2) There was an overlap in the SRTs of the better-performing BiCI users and the worst-performing NH children, suggesting that some BiCI users have attained a level of performance that is within the normal range of performance, while other children with BiCIs have a substantially poorer performance than their NH peers.

(3) SRTs were poorer in younger NH children than older NH children for conditions with interferers separated, suggesting an age related effect of using spatial cues to hear speech in noise, but this effect did not have significance when SRM values were analyzed, possibly because SRM is derived from the spatially separated and front conditions.

(4) When SRM was compared within each group between the Asymmetrical and Symmetrical conditions, only the BiCI-B and Adult groups showed a significant difference between the two, with more SRM in the Asymmetrical condition. Lack of a significant difference in SRM between the two conditions in other groups may be due to the large individual variability.

(5) When matched for CA (older groups), children with NH showed more SRM than children with BiCI for conditions with interferers distributed both asymmetrically and symmetrically.

(6) When matched for HA (younger groups), children with NH showed more SRM than children with BiCIs in the Asymmetrical condition. In the Asymmetrical condition, a combination of monaural and binaural cues are available.

(7) When comparing children with BiCIs who are chronologically older but have 2 years less hearing experience than the younger normal hearing children, the younger children with NH showed more SRM in both the Asymmetrical and Symmetrical conditions. This suggests that access to binaural cues through acoustic stimulation, whereby the cues are preserved with fidelity, may be a key factor in determining SRM.

(8) Contribution of individual variability to performance is an important next step in these measures, which may help to understand how the ability to use spatial cues for source segregation changes with age and experience in children with BiCIs.

## ACKNOWLEDGMENTS

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