Spatial release from masking in children with bilateral cochlear implants and with normal hearing: Effect of target-interferer similarity

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In complex auditory environments, it is often difficult to separate a target talker from interfering speech. For normal hearing (NH) adult listeners, similarity between the target and interfering speech leads to increased difficulty in separating them; that is, informational masking occurs due to confusability of the target and interferers. This study investigated performance of children with bilateral cochlear implants (BiCIs) when target and interferers were either same-sex (male) talkers, or different-sex talkers (male target, female interferer). Comparisons between children with BiCIs and NH, when matched for age, were also conducted. Speech intelligibility was measured for target and interferers spatially co-located, or spatially separated with the interferers positioned symmetrically ($+90°$ and $-90°$) or asymmetrically (both at $+90°$, right). Spatial release from masking (SRM) was computed as the difference between co-located and separated conditions. Within group BiCI comparisons revealed that in the co-located condition speech intelligibility was worse with the same-sex vs different-sex stimuli. There was also a trend for more SRM with the same-sex vs different-sex stimuli. When comparing BiCI to NH listeners, SRM was larger for the NH groups, suggesting that NH children are better able to make use of spatial cues to improve speech understanding in noise. © *2015 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4922777]

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I. INTRODUCTION

The ability to selectively attend to a target talker while ignoring interfering stimuli is a complex skill utilized in many daily listening environments. This skill is often contemplated within the context of Cherry's (1953) early description of the "cocktail party problem," which highlights the difficulty that listeners experience when extracting information from a target speech source in a multi-talker environment. The cocktail party problem is defined in part by the consequences that arise as a result of the target speech competing with other auditory sources in the listening environment. The effect of this competition, described as "masking," amounts to a reduced ability to hear and understand the target source. Over time, the concept of masking has been more specifically defined in the literature to help create common language around auditory phenomena related to the cocktail party problem. The field of auditory psychophysics differentiates between "energetic" and "informational" masking. The former occurs when target and interfering stimuli contain energy within the same critical bands at the same time, and is thought to be accounted for by processing at the level of the auditory periphery (Fletcher, 1940). In contrast, it is theorized that informational masking is driven by auditory and attentional mechanisms mediated by neural levels beyond the periphery (i.e., the central auditory pathway), and is in part due to confusability of the target and interferers under conditions in which both are audible. Thus, with informational masking, listeners demonstrate increased difficulty in segregating target sources from interferers (Durlach *et al.*, 2003; Lutfi, 1993). The inability to distinguish between target and interfering speech can cause confusion for listeners in many daily environments, including classrooms, social environments and work-related spaces. The questions that drive the present study are focused on conditions in which listeners can utilize spatial cues to segregate a target talker from other talkers.

In normal hearing (NH) adults, an increase in similarity between the targets and interferers typically leads to an increase in masking by a larger amount than would be expected if only the overlap in energy of the target and interferers was being accounted for (i.e., energetic masking). Masking can be greater for speech targets when the interferers also comprise of speech sounds, as opposed to noise, and in particular, speech sounds that bear similarity such as same-sex vs different-sex target and interferers, or same-talker vs different-talker combinations (Brungart, 2001; Brungart *et al.*, 2001; Cullington and Zeng, 2008; Freyman *et al.*, 1999; Hawley *et al.*, 2004). Relevant to the current study is the finding that, in NH adults, when informational masking is robust, spatial cues are particularly helpful for target-interferer segregation. That is, listeners show greater spatial release from masking (SRM) for similar target-masker configurations than conditions with less similarity, or smaller potential confusability (Arbogast *et al.*, 2002; Brungart, 2001; Culling *et al.*, 2004; Cullington and Zeng, 2008; Freyman *et al.*, 2001; Hawley *et al.*, 2004).

Recent studies on this topic have also focused on target-interferer segregation in children. The motivation behind that work is to understand developmental factors that might contribute to source segregation abilities in young children,

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with possible clinical applications emerging from this work (Johnstone and Litovsky, 2006; Litovsky, 2005; Litovsky *et al.*, 2006; Misurelli and Litovsky, 2012). For children who are deaf and use cochlear implants (CIs), the task of segregating speech from noise provides a compelling marker for the extent to which children can benefit from the use of bilateral cochlear implants (BiCIs) vs unilateral stimulation. Unlike the plethora of data in NH adults, studies investigating the cocktail party problem in children remain small in number. Also notable is that, to date, these studies have used target-interferer stimuli that consist of noise, or different-sex talkers, under the presumption that clarity of the task for the children (i.e., instructions to "listen to the female and ignore the male") would be maximized (Garadat and Litovsky, 2007; Johnstone and Litovsky, 2006; Litovsky, 2005; Litovsky *et al.*, 2006; Misurelli and Litovsky, 2012; Runge *et al.*, 2011).

The purpose of the present study was to understand the role of target-interferer similarity for SRM, as manipulated with talker sex, in NH children and in children who are deaf and fitted with BiCIs. In the previous study on these populations of children (Misurelli and Litovsky, 2012), it was likely that spectral properties of the different-sex stimuli (i.e., lower fundamental frequency of male versus female talkers) resulted in a listening task in which the target and interfering sources were easily distinguishable for listeners with NH. Therefore, in some cases, the introduction of spatial cues may have provided little additional benefit. In order to shift the focus of source segregation away from benefit possibly due to differences in spectral cues, the current study used same-sex target and interfering speech. This design was intended to improve our understanding of the effect of heightened similarity between the voices, and hence uncertainty about the content of the target, which in adults with NH can result in more informational masking (Durlach *et al.*, 2003).

It has been shown that children who use BiCIs have difficulty distinguishing target speech from interferers even with different-sex talkers (Litovsky *et al.*, 2006; Misurelli and Litovsky, 2012). This may be due to the degraded clarity of spectral cues provided by the CI device, resulting in interferer and target voices that are perceptually similar in the same way that same-sex voices are. Previous research has suggested that gender distinction is a challenge for CI users (Cleary and Pisoni, 2002; Fu *et al.*, 2005). Unlike NH individuals who able to use both fundamental frequency (F0) and vocal tract length (VTL) cues to aid in talker identification and discrimination, CI users must rely mostly on only robust F0 cues (Fuller *et al.*, 2014; Pyschny *et al.*, 2007). We predicted that, if children with CIs did indeed perceive same-sex and different-sex talkers as similar, then performance with the two types of interferers would be similar. In other words, due to the limited number of spectral channels in a CI, perceptual confusability would be similar with either type of stimuli. Alternatively, if children with CIs perform differently with the two types of interferers, this would suggest that they are in fact able to take advantage of some spectral cues in order to distinguish between different sex talkers.

A second focus of this study was the age of participants: children with NH and with BiCIs were recruited so that they would be matched either according to hearing age (HA, the amount of time exposed to sound) or chronological age (CA). Relatively little is known about how bilaterally implanted children, whose auditory input is known to be uncoordinated to the two ears, compare to children with NH in these multi-source environments. We hypothesized that, even when matched for HA, the BiCI groups would perform worse on tasks of spatial hearing than the NH groups, due to a number of factors, including the fact that they receive minimal or absent binaural cues (Litovsky *et al.*, 2012; van Hoesel, 2004). We were also interested in examining age effects within populations of children with NH or BiCIs. Although NH children are able to use spatial cues for source segregation, developmental effects have been reported in free field (Misurelli and Litovsky, 2012; Yuen and Yuan, 2014) and for contralateral unmasking headphone stimulations (Wightman and Kistler, 2005). This difference could be due to the fact that informational masking also depends on development of central auditory mechanisms and non-auditory factors such as attention (Leibold and Bonino, 2009; Lutfi *et al.*, 2003; Wightman *et al.*, 2010).

A third question we asked in this study concerned SRM when interferers are directed toward one ear, where monaural cues in the opposite ear may facilitate source segregation, compared to SRM in conditions in which interferers are placed symmetrically toward both ears, where listeners must rely more heavily on binaural cues. In a previous study with this comparison, the target talker and interferer voices were from different sexes (Misurelli and Litovsky, 2012). In NH children ages 5 and older SRM was found not only in the asymmetrical condition, but also in the symmetrical condition. In the present study we examined the extent to which same-sex target-interferers would result in enhanced SRM compared with the different-sex conditions. Furthermore, in children with BiCIs, who demonstrate SRM in the asymmetrical condition, we are interested in understanding whether symmetrical conditions enable SRM to occur as well.

It is reasonable to surmise that lack of coordination between the two CIs may render the symmetrical condition an impossible one for achieving SRM, in contrast with the asymmetrical condition, which does promote SRM (Litovsky *et al.*, 2006; Litovsky *et al.*, 2009; Misurelli and Litovsky, 2012; van Hoesel and Tyler, 2003). Previous studies on the cocktail party problem in hearing impaired listeners and CI users have quantified benefits with reference to whether one or both ears are stimulated. Commonly, the "better ear effect" (or "monaural head shadow") is observed (Gartrell *et al.*, 2014; Litovsky *et al.*, 2006) when bilateral stimulation is provided, and is thought to be due to a more favorable signal-to-noise ratio (SNR) in one ear (Hawley *et al.*, 2004; Zurek, 1993). Effects due to spatial separation are less commonly explored. The study was designed to test the hypothesis that less spatial unmasking would occur with interferers directed toward both ears (symmetrically) than directed only toward one ear (asymmetrically), and whether the increased masking with same-sex target and interferers would render spatial cues more effective.

In summary, the first issue of focus in the current project is the effect of using same- vs different-sex talkers for spatial unmasking in children with BiCIs. The second issue examines whether children who are fitted with BiCIs demonstrate similar effect sizes to NH children, and the relation of effect size to age (HA and CA) of the children. The third question explores the effect of interferer location and whether SRM depends on the availability of the "better ear" or can also occur in children when interferers are distributed symmetrically around the head, and in particular, when informational masking is induced with same-sex stimuli.

II. METHODS

This study compared SRTs and SRM *within* groups of children fitted with BiCIs, tested in two age groups [young (A) versus old (B)]. Those data were compared with data from NH children matched for hearing age or chronological age. Comparisons were also made between the older BiCI group (BiCI-B) and the younger NH group (NH-A), where the BiCI group had a greater HA of approximately 2 years.

A. Listeners

Thirty-seven (37) native English-speaking listeners were recruited, and all received payment for their participation. These listeners comprised five groups: two groups of children with NH (N = 8 each, 16 total), two groups of children with BiCIs (N = 7 and 6, 13 total), and one group of adults with NH (N = 8). Of these 37 listeners, 21 had also participated in our previously published study using different-sex stimuli (Misurelli and Litovsky, 2012). The listeners who participated in both studies consisted of 4 children with BiCIs, 11 children with NH, and 6 adults with NH. For this study, we recruited 9 additional children with BiCIs, 5 children with NH, and 2 adults with NH all of whom were tested with both sets of stimuli. The children whose data for the different-sex talkers that were published in the previous study are shown in Table I with a footnote next to the subject code. To investigate within-group comparisons for the BiCI groups, the four children with BiCIs (CIBW, CIBU, CIDQ, CICY) that were included in the previous study (Misurelli and Litovsky, 2012) were retested with the female interferer during the same visit as they were tested with the male interferer. Seven NH listeners were tested with both the male and female interferers for this study. In addition, 17 NH listeners, who had participated in our previous study (Misurelli and Litovsky, 2012) using female interferers, came back to the lab for testing with the male interferers only. For the above-mentioned NH listeners, time between testing each participant with the same-sex and different-sex target-interferer stimuli ranged from a few days to 14 months (exact ages at time of testing with the female and male maskers are reported in Table I). For this reason, we did not perform within-group statistical analysis of the same-sex vs different-sex results. Children groups were recruited according to hearing age (HA), defined as the amount of time the listener had been exposed to sound (both acoustic and electric). For the groups with NH, HA was equivalent to chronological age (CA). For the children with BiCIs, HA was calculated from the time of activation of the first CI in addition to any acoustic experience prior to CI activation (i.e., cases of sudden or progressive hearing loss). There were 4 listeners who had acoustic experience prior to receiving their first CI: 3 in the younger BiCI group with varying histories [CICA-hearing loss identified at 2 years; CIET-enlarged vestibular aqueduct syndrome (EVAS)/sudden hearing loss; and CICF-progressive hearing loss due to meningitis] and 1 listener in the older BiCI group (CIEK who had EVAS/progressive hearing loss).

Children with BiCIs were recruited from CI centers throughout the United States and traveled to Madison, WI to participate. These children visited the lab for three consecutive days and participated in a number of experiments. During all testing sessions, children's CI processors were set to their clinically programmed every-day listening mode, as confirmed by parent and audiologist reports. Prior to the first testing session a subjective loudness balancing procedure was conducted, and volume and sensitivity controls were adjusted to best equalize the loudness between the two CI devices. These children were separated into two groups according to their HA (see Table I for demographic information). In the younger group (BiCI-A), there were 7 children, with a HA of 5; 0 $\pm$ 0; 10 (mean and standard deviation for years; months), and a CA of 6; 4 $\pm$ 0; 9 (mean and standard deviation for years; months). This group had bilateral experience of 3; 2 $\pm$ 1; 1 (mean and standard deviation for years; months). In the older group (BiCI-B) there were 6 children, with a HA of 7; 2 $\pm$ 0; 10 (mean and standard deviation for years; months), and a CA of 8; 5 $\pm$ 0; 6 (mean and standard deviation for years; months). This group had fairly similar amount of bilateral experience to that of the younger group (3; 4 $\pm$ 0; 9 mean and standard deviation for years; months). Group BiCI-A had three children who received their CIs simultaneously and four children who received their CIs sequentially. In the sequentially implanted children, the first CI was activated by 18 months of age for all but one child who had a late identification of hearing loss (CIDW). For group BiCI-B, all children received their CIs sequentially. In this group, all but two listeners (i.e., CIDJ-hereditary hearing loss and CIEK-EVAS/progressive hearing loss) had their first CI activated by 18 months of age. For both BiCI groups, all children had at least one year of experience listening with two cochlear implants [mean, min, max (years; months) = 3; 3, 1; 7, 4; 5], and the main mode of communication noted by parents was oral. No children were known to have co-morbidity factors due to identified disabilities.

All children with NH were recruited locally from the Madison, WI area. Children with NH were selected to match BiCI listeners for age in such a way that we were able to compare performance based on HA or CA. NH children were recruited into two groups. In the younger group (NH-A) there were 8 children, with a CA of 4; 9 $\pm$ 0.8 (mean and standard deviation for years; months) at visit one (female masker) and with a CA of 5; 2 $\pm$ 1; 0 (mean and standard deviation for years; months) at visit two (male masker). In the older group (NH-B) there were 8 children, with a CA of 7; 5 $\pm$ 1.1 (mean and standard deviation for years; months) at visit one (female masker) and with a CA 8;

TABLE I. Subject demographics.

	Subject code	Chronological age (yr;mo)	Hearing age (yr;mo)	Bilateral experience (yr;mo)	Etiology	Age first CI activation (yr;mo)	Age second CI activation (yr;mo)	Time between first and second CI (yr;mo)	First CI (device, ear)	Second CI (device, ear)
BiCI-A (younger BiCI users)	[a]CIBW	7;0	6;0	3;3	Connexin-26	1;0	3;9	2;9	N24C, R	Freedom Contour, L
	CICA	6;6	4;1	4;1	Unknown, late ID	2;5	2;5	simultaneous	Med-El Pulsar, R	Med-El Pulsar, L
	CIEH	5;0	3;11	3;11	Hereditary	1;1	1;1	simultaneous	Nucleus Freedom, R	Nucleus Freedom, L
	CIET	6;4	5;6	1;7	EVAS/sudden HL	4;9	4;9	simultaneous	Med-EL Sonata, R	Med-EL Sonata, L
	CICF	6;7	6;2	4;3	Meningitis	1;6	2;4	0;10	Freedom Contour, R	Freedom Contour, L
	CICN	5;11	4;7	3;0	Connexin-26	1;4	2;11	1;6	Nucleus Freedom, R	Nucleus Freedom, L
	CIDW	7;0	5;0	2;0	Unknown, late ID	2;3	5;0	2;9	Advanced Bionics HiRes 90K, L	Advanced Bionics HiRes 90K, R
		mean = 6;4	mean = 5;0							
BiCI-B (older BiCI users)	CIDJ	9;0	7;4	3;11	Hereditary	1;8	5;1	3;5	N24C, R	Nucleus Freedom, L
	[a]CIBU	8;3	7;2	3;3	Connexin-26	1;1	5;0	3;11	Med-El Tempo, L	Med-EL Sonata, L
	[a]CIDQ	8;8	7;11	4;5	Unknown	0;10	4;3	3;6	N24C, R	Nucleus Freedom, L
	[a]CICY	7;11	6;11	3;1	Unknown	1;0	4;8 (reimplanted)	3;8	Advanced Bionics HiRes 90K, R	Advanced Bionics HiRes 90K, L
	CIEF	8;0	6;9	3;2	Unknown	1;4	4;10	3;6	Nucleus Freedom, R	Nucleus Freedom, L
	CIEK	7;5	6;8	2;2	EVAS/Progressive HL	4;9	5;2	0;5	Advanced Bionics HiRes 90K, L	Advanced Bionics HiRes 90K, R
		mean = 8;5	mean = 7;2							
		Chronological Age (yr;mo) visit 1 (female interferer)	Chronological Age (yr;mo) visit 2 (male interferer)							
NH-A (younger NH)	[a]CKX	5;7	6;5							
	[a]CNJ	5;5	6;5							
	COU	4;5	4;7							
	CMG	4;11	4;11							
	CPE	4;6	4;7							
	CKS	6;2	6;2							
	CPG	4;2	4;3							
	[a]CNS	4;3	4;3							
		mean = 4;9	mean = 5;2							
NH-B (older NH)	[a]CKB	7;8	8;7							
	[a]CKG	8;3	8;8							
	[a]CNW	7;8	8;3							
	[a]CNU	7;6	7;11							
	[a]CNB	5;3	6;7							
	[a]CNG	8;8	9;10							
	[a]CNH	7;6	8;8							
	[a]CNV	6;9	7;6							
		mean = 7;5	mean = 8;3							

[a]Children who also participated in Misurelli and Litovsky, 2012.

3 ± 0; 11 (mean and standard deviation for years; months) at visit two (male masker). The between group comparisons with the male masker were of most interest for the current paper. For the male masker, younger NH group (NH-A) matched the younger BiCI group (BiCI-A) for HA, and, on average, the children in the BiCI-A group were chronologically older than those in the NH-A group by 14 months. NH-B matched the older BiCI group (BiCI-B) for CA and, on average, the NH-B had 13 months more hearing experience than BiCI-B. In addition, 8 NH adult listeners (ages 18–25 years) were recruited from the student population at the University of Wisconsin–Madison. All NH listeners were given a hearing screening consisting of pure-tone thresholds of 20 dB hearing level (HL) or less at octave frequencies between 250 and 8000 Hz. Children were also screened using tympanometry in order to rule out any middle ear anomalies or infection on the day of testing. Tympanometric results indicated normal peak-compensated acoustic static admittance at each testing session. No participants that were recruited were excluded from participation due to a failed hearing screening.

This research was approved by, and carried out in accordance with, the University of Wisconsin–Madison Human Subjects IRB regulations. Before testing commenced, all adult participants signed a consent form and, for children, caregivers signed a consent form. Children with a CA of 7 years or older signed an assent form.

B. Testing environment

Testing was conducted inside a standard Industrial Acoustics Company (IAC) sound booth (dimensions 2.8 × 3.25 m) with a reverberation time (RT_{60}) of 250 ms. During testing, listeners sat at a small table, covered with foam, in the center of a semicircular array of loudspeakers (Cambridge Soundworks, Center/Surround IV), which were positioned at ear level approximately 1.5 m from the listener and were calibrated prior to each testing session. Subjects face a computer monitor located at 0° azimuth under the front loudspeaker, and used a computer mouse to provide responses to the stimuli by selecting icons displayed on the computer monitor. For NH listeners, testing was completed after two visits to the lab, with each visit lasting approximately one hour for adults and three hours for children. Children with BiCIs completed the task within their multi-day visits.

C. Stimuli

Target stimuli were a closed-set of 25 spondees (a two-syllable word with equal stress on both syllables) selected to be within the vocabulary of children ages 4 years and older (Litovsky, 2005), and were pre-recorded using a male talker (F0 = 150 Hz) [all root-mean-square (rms) levels equalized]. Interfering sentences were taken from the Harvard IEEE corpus (Rothauser *et al.*, 1969) and were pre-recorded separately using both a male talker (F0 = 155 Hz) (different talker than the male target talker) and a female talker (F0 = 240 Hz). Fundamental frequency (F0) of each talker was obtained using the software package PRAAT (Boersma and Weenink, 1996). F0 was determined from a string of the stimuli that was used for the experimental conditions. Sentences were filtered to match the long-term average speech spectrum of the target spondees (Hawley *et al.*, 1999; Hawley *et al.*, 2004; Litovsky, 2005). Two-talker interferers were created by overlaying two recordings from the same talker, either male or female. PRAAT software (De Jong and Wempe, 2009) was also used to analyze the interferers. The speech rate of the female interferer was 4.71 syllables/s, and the speech rate of the male interferer was 3.77 syllables/s. The analysis also confirmed that there were no silent gaps (or pauses) within the interfering stimuli. Figure 1 shows spectral differences between the target stimuli and the male and female interferers (scaled for equal rms).

D. Design and procedure

Speech reception thresholds (SRTs) were measured for target spondees in quiet and in the presence of interfering speech. For each listener, SRTs were measured in quiet with no interferers present and in 3 conditions with interferers fixed at 55 dB sound pressure level (SPL). More specifically, SRTs measured in the 4 conditions are denoted as: SRT_{Quiet} (target 0° front, no interferers), SRT_{Front} (target and interferers both 0° front), $SRT_{+90°/+90°}$ (target 0° front, interferers placed in an asymmetrical configuration at 90° to one side or another), and $SRT_{+90°/-90°}$ (target 0° front, interferers placed in a symmetrical configuration with one at +90° and one at −90°). In the asymmetrical condition, interferers were placed 90° to the right for the NH listeners and 90° to the side of the first CI for the BiCI listeners.

For the BiCI groups, SRTs for each of the conditions were obtained during the same 3-day visit for both the same-

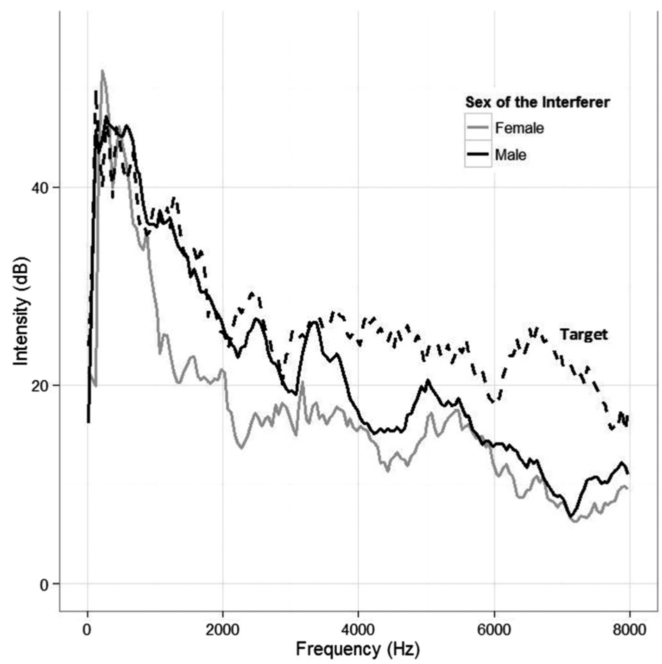

FIG. 1. The overall average spectrum are plotted for the target and interfering stimuli. The dashed black line represents the target stimuli. The solid lines represent the interfering stimuli (gray line = female interferers, black line = male interferers).

sex and different sex target-interferer combinations to investigate within-group comparisons. As mentioned above, 17 of the NH listeners were tested with the female interferer for a previous study and returned to the lab to be tested with the male interferer at a later date. Therefore, within-group comparisons using the female and male interferers were not conducted for the NH listeners. To minimize any order effects, all conditions were randomized within interferer type. Due to time constraints, fewer than three SRTs per condition were measured on 9 of the NH listeners (NH-A: 3, NH-B: 6) and 8 of the BiCI listeners (BiCI-A: 4, BiCI-B: 4). Conditions in which this occurred varied between listeners, but all listeners completed at least two SRTs per condition. SRTs were averaged for data analysis, resulting in one SRT per interferer for each of the four conditions. As described in Misurelli and Litovsky (2012), SRTs in children with NH and with BiCIs have been shown to be consistent across SRT measurements. Thus, each subject's SRT consisted of the averaged individual SRTs for each condition.

Prior to testing, each listener participated in a brief familiarization task, in order to verify that they could accurately identify visual icons associated with each auditory target spondee. The experiment was designed with the intent of measuring SRTs in quiet and in noise, but not in order to test vocabulary. For that reason, if an individual listener was unable to identify particular spondees, then those target stimuli were not used in the experimental testing (similar approaches were used in our previous studies by Litovsky and colleagues). Out of the 37 listeners, only two used a target list less than 25 words, with no list less than 19 words (NH-A: 1 listener, BiCI-A: 1 listener). Practice in the quiet and front conditions was conducted for all listeners in order to allow each listener to become familiar with various aspects of the testing (i.e., listener position, computer controls, stimuli). Data collected during the practice session was not included in the analysis, and was used solely to assure each listener was comfortable with the experimental task. A trained tester accompanied all child listeners in the booth.

The experimental test consisted of a 4-alternative-forced-choice task (Garadat and Litovsky, 2007; Johnstone and Litovsky, 2006; Litovsky, 2005; Litovsky *et al.*, 2006; Misurelli and Litovsky, 2012), in which the target spondee was identified from four possible icons. On trials with male interferers, listeners were provided with experience hearing the interferer sentences and the male target; subsequently they were instructed to ignore the "boy talkers" and to pay attention to the man's voice (male target). On trials with female interferers, listeners were given experience hearing the interferer sentences and the male target; subsequently they were instructed to ignore the "lady talkers" and to pay attention to the man's voice (male target). Trials began with the word "ready," spoken by the male target, followed by one randomly chosen spondee from the list of 25. Similar to our previous studies, in conditions with interferers, the interferers were turned on first followed by the target. Interferers continued for approximately 1 s after the target was turned off. After the target was presented four pictures were displayed on the computer monitor, 3 of the 4 pictures were randomly selected from the closed-set of 25 and 1 of the 4 pictures corresponded with the target spondee. The listener was then asked to identify the picture that corresponded to the spoken spondee. Feedback was given only after incorrect responses. The feedback was pre-recorded phrases such as, "let's try another one" or "that must have been difficult." Regardless of whether the child identified the correct picture or not, children were reinforced after each response by a computer display of one digitized puzzle piece. Children were also reinforced with stickers and small prizes, and frequent "listening breaks" were given when necessary.

E. Speech reception threshold estimation

SRTs were measured using an adaptive tracking method. Target level was initially presented at 60 dB SPL, decreasing in intensity with correct responses and increasing in intensity with incorrect responses. Initially levels decreased by 8 dB following correct responses; after the first incorrect response target levels were adjusted using a 3-down/1-up procedure, and the step size was halved with each reversal of target level. Testing was terminated after four reversals. SRTs were calculated using Maximum Likelihood Estimation (MLE) methods, which define threshold as the point on the psychometric function at which the target intensity corresponded to 79.4% correct. This method is identical to the methods used previously by Litovsky and colleagues (Garadat and Litovsky, 2007; Johnstone and Litovsky, 2006; Litovsky, 2005; Misurelli and Litovsky, 2012).

F. Spatial release from masking (SRM)

SRM was calculated for each listener, and defined as the difference between SRT_{Front} and $SRT_{+90°/+90°}$ or $SRT_{+90°/-90°}$, such that,

(1) $SRM_{Asymmetrical} = SRT_{Front} - SRT_{+90°/+90°}$,
(2) $SRM_{Symmetrical} = SRT_{Front} - SRT_{+90°/-90°}$.

This approach is identical to that used by Misurelli and Litovsky (2012). Positive SRM values indicate an improvement in identification of the target when spatially separated from the interferers versus when the target and interferers are co-located; large SRM indicates greater benefit for speech intelligibility of the target with the sources spatially separated. Negative SRM indicates that a listener performed worse when the target and interferers were spatially separated compared with the co-located condition.

III. RESULTS

A. Speech reception thresholds

Mean (±SD) SRTs are shown in Fig. 2, where data collected with the male interferers (filled symbols) and data collected with the female interferers (open symbols) are compared. Within group comparisons are discussed for the BiCI groups. Visual inspection of the data in Fig. 2 suggests that the male interferer produced higher SRTs; this was the trend for all but one child with BiCIs. For one child SRTs remained the same for both the male and the female interferer. Repeated measures multivariate analyses of variance

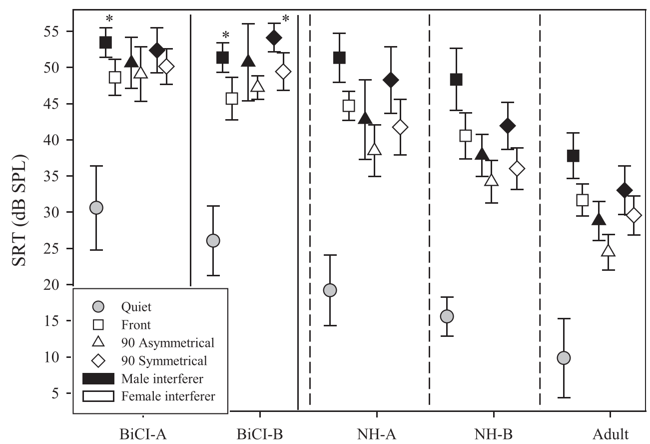

FIG. 2. Mean (±SD) SRTs are plotted for each group in each condition with both the male and female interferers. The gray circles represent SRTs in the quiet condition. Filled symbols represent SRTs with the male interferers. Open symbols represent SRTs with the female interferers. Within each group, each condition is represented by a different symbol (square: front, triangle: 90A, diamond: 90S). Significant differences within condition are indicated with an asterisk.

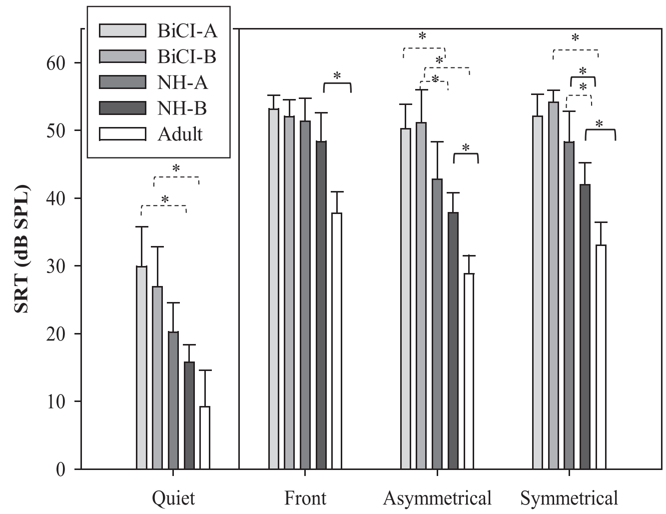

FIG. 3. Mean (±SD) SRTs are shown for each group in each condition (i.e., quiet, front, asymmetrical, symmetrical). Significant differences are bracketed and indicated with an asterisk. Solid brackets indicate significant differences within hearing type (i.e., A vs B). Dashed brackets indicate differences between hearing type (i.e., NH vs BiCI).

(MANOVA tests) were conducted for each of the BiCI groups (BiCI-A, BiCI-B) to compare SRTs (DVs: front, asymmetrical, symmetrical) with the male vs female interferers. Results revealed a significant difference in SRTs with the male vs female interferers, for both BiCI groups, in the front condition [BiCI-A: ($F(1, 6) = 21.94$, $p = 0.003$, $\eta_p^2 = 0.79$), BiCI-B: ($F(1, 5) = 15.79$, $p = 0.01$, $\eta_p^2 = 0.76$)]. This suggests that the CI users did not perceive the male and female talkers as being the same in this condition. CI users had access to non-spatial source segregation cues, to aid in pulling out information from the male target in the presence of female interferers more effectively than in the presence of the male interferers (i.e., more masking with the same-sex talkers than the different-sex talkers). Additionally, SRTs were significantly higher with the male vs female interferer for only the older BiCI group (BiCI-B) in the symmetrical condition ($F(1, 5) = 12.30$, $p = 0.02$, $\eta_p^2 = 0.71$).

Figure 3 summarizes between-group SRT data for the male interferer (same-sex stimuli). A similar graph with the female interferer (different-sex stimuli) is shown in our previous work (Misurelli and Litovsky, 2012). Between subjects one-way analysis of variances (ANOVAs) were conducted to compare the effect of group (BiCI-A, BiCI-B, NH-A, NH-B, Adult) for each of the four conditions (quiet, front, asymmetrical, symmetrical). There was a significant main effect of group for each condition [quiet: ($F(4, 32) = 22.16$, $p < 0.001$, $\eta_p^2 = 0.71$); front: ($F(4, 32) = 28.96$, $p < 0.001$, $\eta_p^2 = 0.78$); asymmetrical: ($F(4, 32) = 38.33$, $p < 0.001$, $\eta_p^2 = 0.82$); symmetrical: ($F(4, 32) = 45.23$, $p < 0.001$, $\eta_p^2 = 0.85$)]. Planned *post hoc* Bonferroni-corrected two-tailed paired t-tests revealed the following (results are displayed in Table II): (1) Comparisons of the two NH groups showed that NH-A had poorer SRTs than NH-B in only the symmetrical condition ($p = 0.009$), and NH-B had poorer SRTs than the adults in all conditions with interferers (front: $p < 0.001$; asymmetrical: $p = 0.001$; symmetrical: $p < 0.001$). (2) Comparisons of the two BiCI groups showed no differences between the older and younger groups in any of the conditions. (3) Comparisons between NH and BiCI younger groups (NH-A and BiCI-A; HA was equivalent and the NH group was chronologically ∼1 year older), revealed that the BiCI-A group had poorer SRTs in the quiet ($p = 0.003$) and asymmetrical conditions ($p = 0.012$). (4) Comparisons between NH and BiCI older groups (NH-B and BiCI-B; CA was equivalent and the NH group had a greater HA by ∼1 year), revealed that the BiCI-B group had poorer SRTs in the quiet ($p = 0.002$), asymmetrical ($p < 0.001$), and symmetrical conditions ($p < 0.001$). (5) Last, comparisons were made between the older BiCI group (BiCI-B) and the younger NH group (NH-A), where the BiCI group had a greater HA of ∼2 years. The BiCI-B group had poorer SRTs in the asymmetrical ($p = 0.006$) and in the symmetrical conditions ($p = 0.035$).

B. Spatial release from masking

The comparisons of interest in this study are the SRM measured with the symmetrical vs asymmetrical interferer locations, and with the same-sex vs different-sex interferers. Figure 4 displays individual SRM data points for the four groups of children, for both the male and female interferers; each plot shows $SRM_{Symmetrical}$ vs $SRM_{Asymmetrical}$ for one listener group. The diagonal line represents unity for $SRM_{Asymmetrical}$ and $SRM_{Symmetrical}$. The data points below the diagonal line denote cases in which listeners demonstrated more SRM with interferers located in the asymmetrical condition; data points on the diagonal indicate unity, i.e., no effect of interferer symmetry vs asymmetry; data points above the diagonal indicate that SRM was greater with the symmetrically distributed interferers. Moreover, data points in the right or top portions of each panel denote greater SRM in one or both conditions. Planned paired t-tests were conducted within each listener group, for each interferer separately, to evaluate the effect of distributing the interferers symmetrically vs asymmetrically relative to the listener's

TABLE II. Results of planned comparisons for between group SRTs.

Groups	Quiet	Front	Asymmetrical	Symmetrical
BiCI-A vs BiCI-B	$p = 1.0$	$p = 1.0$	$p = 1.0$	$p = 1.0$
NH-A vs NH-B	$p = 1.0$	$p = 0.73$	$p = 0.20$	[a]$p = 0.009$
NH-B vs Adult	$p = 0.29$	[a]$p < 0.001$	[a]$p = 0.001$	[a]$p < 0.001$
BiCI-A vs NH-A (HA equivalent and CA greater in BiCI than NH by 1;2)	[a]$p = 0.003$	$p = 1.0$	[a]$p = 0.012$	$p = 0.41$
BiCI-B vs NH-B (CA equivalent and HA greater in NH than BiCI by 1;1)	[a]$p = 0.002$	$p = 0.42$	[a]$p < 0.001$	[a]$p < 0.001$
BiCI-B vs NH-A (HA greater in BiCI than in NH by ~2yrs)	$p = 0.08$	$p = 1.0$	[a]$p = 0.006$	[a]$p = 0.035$

[a]Significance.

head. With the same-sex interferer $SRM_{Asymmetrical}$ was greater than $SRM_{Symmetrical}$ for all listener groups (BiCI-A: [$t(6) = 2.9$, *$p = 0.03$, two-tailed], BiCI-B: [$t(5) = 2.7$, *$p = 0.04$, two-tailed], NH-A: [$t(7) = 5.1$, *$p = 0.001$, two-tailed], NH-B: [$t(7) = 3.6$, *$p = 0.008$, two-tailed], Adult: [$t(7) = 2.6$, *$p = 0.036$, two-tailed]). With the different-sex interferers, $SRM_{Asymmetrical}$ was only greater than $SRM_{Symmetrical}$ for the adult group [$t(7) = 4.16$, *$p = 0.004$], but the results show non-significant differences for the four groups of children.

Figure 5 summarizes the differences in SRM that were observed with the two different interferer configurations, with the male (5A) and female (5B) interferers. Between subjects ANOVAs for each interferer (male, female) were conducted to compare the effect of group for $SRM_{Asymmetrical}$ and $SRM_{Symmetrical}$. Results with the male interferer (5A) show there was a significant main effect of group for both the $SRM_{Asymmetrical}$ ($F(4, 32) = 10.51$, $p = 0.001$, $\eta_p^2 = 0.57$) and the $SRM_{Symmetrical}$ ($F(4, 32) = 5.65$, $p < 0.001$, $\eta_p^2 = 0.41$). Planned *post hoc* Bonferroni-corrected two-tailed paired t-tests revealed the following (results are displayed in Table III): (1) No differences were found between the older and younger child groups for either the NH or BiCI groups. (2) Comparing children in the two older groups (matched for CA), NH-B had more SRM than BiCI-B in both conditions: $SRM_{Asymmetrical}$ ($p < 0.001$) and $SRM_{Symmetrical}$ ($p = 0.001$). (3) Comparing the children in the two younger groups (matched for HA), NH-A had more SRM than BiCI-A in only the $SRM_{Asymmetrical}$ ($p = 0.004$). (4) Comparing the younger NH group with the older BiCI group, NH-A had more SRM in only the $SRM_{Asymmetrical}$ ($p = 0.002$) (5) There were no differences for either condition when comparing the younger or older NH children with the Adult group, suggesting that adult-like SRM had been achieved by approximately 5 years old.

Results with the female interferer (5B) show there was a significant main effect of group for both the $SRM_{Asymmetrical}$ ($F(4, 32) = 12.10$, $p < 0.001$, $\eta_p^2 = 0.60$) and the $SRM_{Symmetrical}$ ($F(4, 32) = 6.0$, $p = 0.001$, $\eta_p^2 = 0.43$). Planned *post hoc* Bonferroni-corrected two-tailed paired t-tests revealed the following (results are displayed in Table III): (1) No differences were found between the older and younger groups in either the NH or BiCI children groups. (2) Comparing children in the two older groups (matched for HA), NH-B had more SRM than BiCI-B in both conditions: $SRM_{Asymmetrical}$ ($p = 0.001$) and $SRM_{Symmetrical}$ ($p = 0.006$). (3) Comparing the children in the two younger groups (matched for HA), NH-A had more SRM than BiCI-A in only the $SRM_{Asymmetrical}$ ($p = 0.001$). (4) Comparing the younger NH group with the older BiCI group, NH-A had more SRM in only the $SRM_{Asymmetrical}$ ($p = 0.002$). (5) There was no difference for either condition when comparing the younger and older NH children with the Adult group.

Last, repeated measures MANOVAs were conducted for each of the BiCI groups (BiCI-A, BiCI-B) to compare SRM (DVs: $SRM_{Asymmetrical}$ and $SRM_{Symmetrical}$) with the male vs female interferers. For the younger CI group (BiCI-A), results revealed significantly more SRM with the male interferer in only the $SRM_{Asymmetrical}$ ($F(1, 6) = 9.04$, $p = 0.02$, $\eta_p^2 = 0.60$). Although, on average, the older BiCI group (BiCI-B) also exhibited more SRM with the male interferers, large within group variability within groups was a likely determining factor in the cases where lack of significant differences in were observed.

IV. DISCUSSION

The ability to segregate a target talker from interferers is particularly important for children, who spend much of their time learning in multi-source, noisy environments. In children who are deaf and fitted with BiCIs, the question arises as to whether they are able to utilize their implantable devices in order to benefit from spatial separation of target speech and interferers. Furthermore, difficulties can arise when uncertainty exists regarding the particular sources to which they should attend, a challenge that can be exacerbated by similarity between sources (Brungart, 2001; Durlach *et al.*, 2003; Johnstone and Litovsky, 2006). Here, we compared speech intelligibility in the presence of speech interferers consisting of talkers that were either the same sex as the target talker, or a different sex than the target talker (the latter was also tested by Misurelli and Litovsky, 2012). Further, we investigated listeners' ability to take advantage of spatial cues for source segregation with these two types of interferers. To investigate age and hearing type comparisons, these effects were also tested in children and adults with NH.

A. Same-sex vs different-sex stimuli

Talker discrimination is essential to successful verbal communication. NH individuals rely on both fundamental frequency (F0) and vocal-tract length (VTL) to discriminate between talkers. The perceptual correlate of F0 is voice

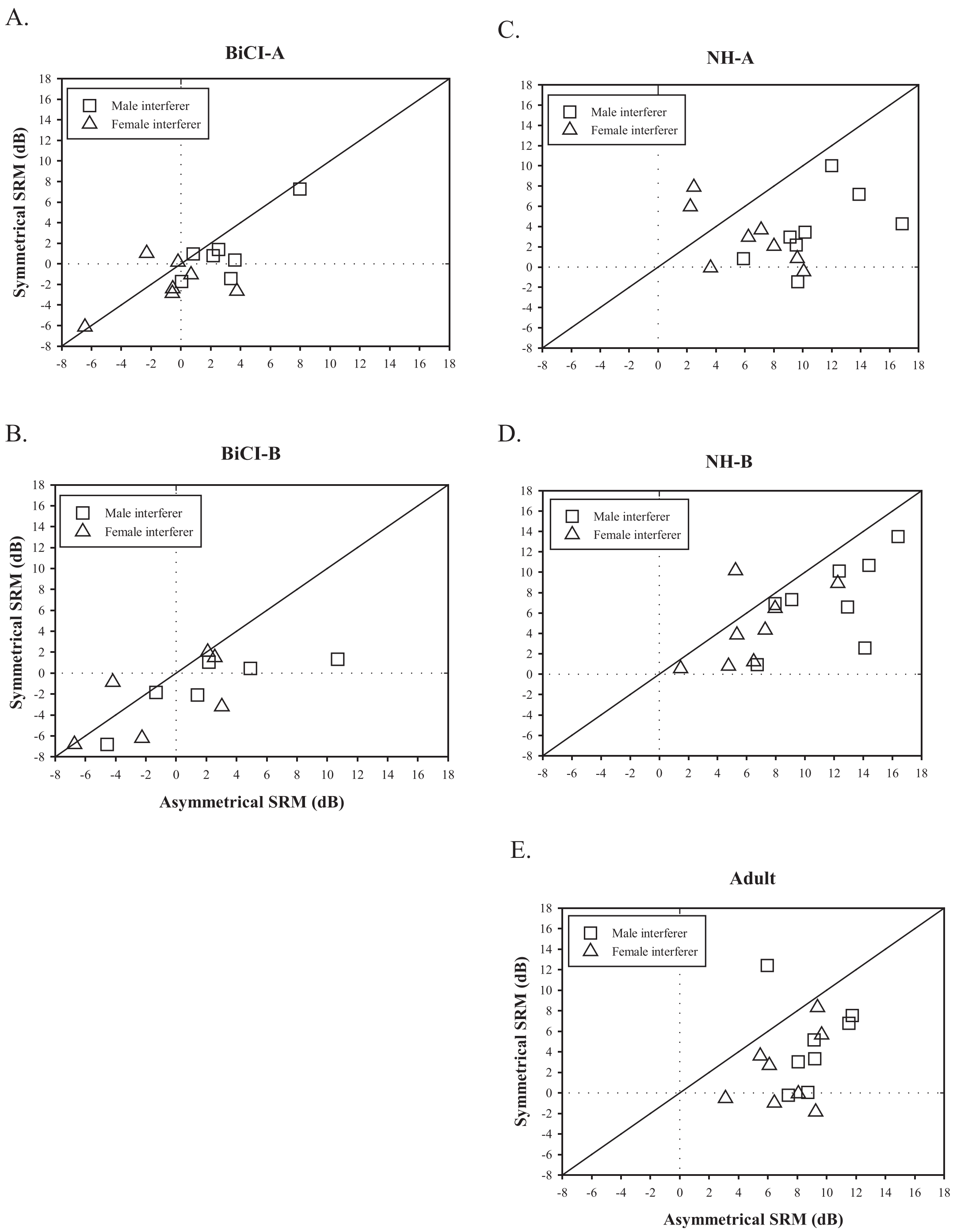

FIG. 4. SRM values for asymmetrical and symmetrical conditions are compared for each individual listener group [(A) BiCI-A, (B) BiCI-B, (C) NH-A, (D) NH-B, (E) Adult]. Each data point represents SRM for an individual listener. The squares represent SRM with the male interferers, and the triangles represent SRM with the female interferers. The diagonal line corresponds to equivalent SRM in the asymmetrical and symmetrical conditions.

pitch, and is helpful in overall gender discrimination. VTL, explained in terms of formant frequencies, depends on height and head size and provides the listener with additional information regarding the identity of the talker. In particular, VTL aids in discrimination of voices of the same sex. Although NH listeners are able to use both F0 and VTL to help in talker discrimination, it is more difficult to isolate target speech when the target and interferers are spectrally similar than when they are different, as demonstrated in both NH adults (Brungart, 2001; Durlach *et al.*, 2003) and children (Johnstone and Litovsky, 2006). Previous work has shown that CI users demonstrate the most benefit from F0 cues and, unlike NH listeners, they receive little to no additional benefit from VTL cues on gender identification or talker discrimination tasks (Fuller *et al.*, 2014; Pyschny *et al.*, 2007). Current CI technology has known limitations, including the small number of spectral channels. Therefore, it is not surprising that CI users have more difficulty discriminating between talkers and that they have worse speech intelligibility in noise than NH listeners (Litovsky *et al.*, 2009; Loizou *et al.*, 2009; Misurelli and Litovsky, 2012). When NH individuals listen to speech that has been

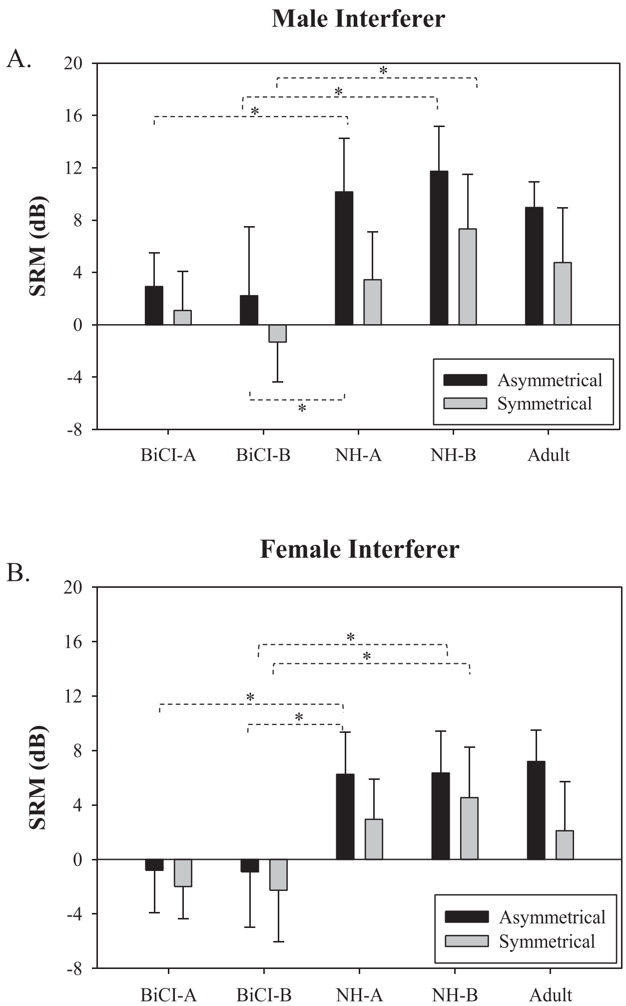

FIG. 5. Mean (±SD) SRM values are plotted for each group (i.e., BiCI-A, BiCI-B, NH-A, NH-B, Adult) for both the male (5A) and female (5B) interferers. Black bars represent asymmetrical SRM. Gray bars represent symmetrical SRM. Significant differences are bracketed and indicated with an asterisk. Dashed brackets indicate difference between hearing type (i.e., NH vs BiCI).

processed through multi-channel CI simulations they also demonstrate difficulty extracting the target speech from the noise (Dorman *et al.*, 1998; Qin and Oxenham, 2003). Talker discrimination has been shown to be poorer in CI users than in NH children (Cleary and Pisoni, 2002; Cleary *et al.*, 2005) and NH adults (Fu *et al.*, 2004). Discrimination between different sex talkers is possible for CI users, but difficulties in same-sex talker discrimination exist due to their inability to use subtle formant frequency cues (i.e., VTL). Evidence suggests that, when tested in quiet, CI users perform more poorly when distinguishing between voices of the same-sex (Cleary and Pisoni, 2002; Cleary *et al.*, 2005), and they can also be poor at discriminating between voices of different-sex talkers (Fu *et al.*, 2005). These challenges are exacerbated in more realistic environments with numerous sources played simultaneously (Li and Fu, 2011).

Our results show that SRTs were on average higher with the male (same-sex) interferers than with the female (different-sex) interferers (see Fig. 2). In addition, listeners were able to identify target speech in quiet at a much lower (better) SRT than when interferers were present. When we compared SRTs with same vs different-sex stimuli for the younger and older BiCI groups, statistical significance between stimuli sets was reached for both groups in the front (co-located) condition. This finding suggests that, in absence of spatial cues to help in segregation of the target and interferers, both groups needed a higher SNR in order to identify the target when the same-sex stimuli was presented. Added masking with spectrally similar or identical stimuli has been previously reported in NH adults (Arbogast *et al.*, 2002; Brungart *et al.*, 2001) and children (Johnstone, 2006). The finding that CI users showed similar effects of interferer type in the front condition suggests that on average, the CI users were able to perceive differences between the male and female interferers and therefore identify the target at a lower SNR when the different-sex stimuli was used, despite the relatively poor encoding of spectral information. This finding contradicts what has been found previously in studies with adult CI listeners (Stickney *et al.*, 2004). The difference in results for children and adult CI listeners may be due to the difference in testing material. The Stickney *et al.* (2004) study used sentences for the target stimuli, which are substantially more difficult to identify than the spondaic words used in the current study. In the current study, children may have been able to glimpse partial words to perform correctly, whereas in the sentence task used with adults the percent of words correctly identified was scored. Glimpsing of target words may have occurred for some children due to either the temporal and/or spectral properties of the stimuli. As confirmed by analyses on temporal modulations, the amplitude envelope of the speech interferers fluctuates, but because there were no overt silent periods (or pauses) in the interfering speech, "listening in the gaps" was likely not a major

TABLE III. Results of planned comparisons for between group SRM.

Groups	Asymmetrical (male)	Symmetrical (male)	Asymmetrical (female)	Symmetrical (female)
BiCI-A vs BiCI-B	$p = 1.0$	$p = 1.0$	$p = 1.0$	$p = 1.0$
NH-A vs NH-B	$p = 1.0$	$p = 0.44$	$p = 1.0$	$p = 1.0$
NH-B vs Adult	$p = 1.0$	$p = 1.0$	$p = 1.0$	$p = 1.0$
BiCI-A vs NH-A (HA equivalent and CA greater in BiCI than NH by 1;2)	[a]$p = 0.004$	$p = 1.0$	[a]$p = 0.001$	$p = 0.07$
BiCI-B vs NH-B (CA equivalent and HA greater in NH than BiCI by 1;1)	[a]$p < 0.001$	[a]$p = 0.001$	[a]$p = 0.001$	[a]$p = 0.006$
BiCI-B vs NH-A (HA greater in BiCI than in NH by ∼2yrs)	[a]$p = 0.002$	$p = 0.23$	[a]$p = 0.002$	$p = 0.07$

[a]Significance.

contributing factor. Although, partial glimpsing at places where the interferers had low amplitude cannot be completely ruled out, as it was not explicitly varied in this study. It is possible that in the current study different-sex stimuli differed enough in F0 (male target, F0 = 150 Hz; female interferer, F0 = 240 Hz) that the CI users were able to use F0 cues.

For CI groups with no difference in SRTs between the two sets of stimuli in the spatially separated conditions, no additional masking was demonstrated with the same-sex stimuli. When interferers were spatially separated, only the older BiCI group showed a significant difference in SRTs for the symmetrical condition with either same- or different-sex stimuli, suggesting that with interferers directed towards both ears the same-sex stimuli created significantly more masking. This same effect was not shown for any other spatially separated conditions. It may be that, for most CI users, spatially separating the stimuli poses a more difficult listening environment, independent of target-interferer similarity. NH listeners are able to use directional acoustic cues to differentiate exquisitely small changes in intensities and timing of signals arriving from front and side locations. CI users have minimal, if any, access to these binaural cues (Litovsky *et al.*, 2012). In addition, the microphones used in CI processors amplify a much more broad range of source locations, which may in fact create a more challenging listening environment in spatially separated conditions than when sources are co-located.

B. Effects of interferer location

Benefits of speech understanding in noise can be attributed to three factors: monaural head shadow, when interferers are directed to only one ear, and therefore the opposite ear has an advantageous SNR; binaural squelch, or benefit from adding the ear with the poorer SNR; and binaural summation, in which target and interferers occur from the same direction, and redundancy, rather than spatial separation, provides the listener with cues to improve speech understanding. Although NH listeners are able to use all of these cues to gain considerable benefit when listening to speech in noise, BiCI users do not show nearly as much benefit. This is likely because they have limited access to binaural cues, and therefore rely primarily on the monaural head shadow cue. Adults who use BiCIs generally show better speech understanding in noise than people with only one CI (Litovsky *et al.*, 2009; van Hoesel and Tyler, 2003), but due to the lack of coordination between the two CI devices, binaural-driving benefits in BiCI users are still reduced compared to NH individuals. Speech understanding in noise for BiCI children (Van Deun *et al.*, 2010) and adults (Litovsky *et al.*, 2009; Loizou *et al.*, 2009; van Hoesel and Tyler, 2003) can be largely accounted for by monaural head shadow.

For this study we also sought to investigate spatial release from masking (SRM) with interferers directed either toward one ear (asymmetrical), where monaural head shadow cues are available, or both ears (symmetrical), where monaural cues are reduced and listeners must rely more on binaural cues. On average, BiCI groups showed more SRM (asymmetrical and symmetrical) with the same-sex stimuli compared to when the different-sex stimuli was presented, although statistically significant differences were only demonstrated in the younger BiCI ($SRM_{Asymmetrical}$) group. The lack of significant differences in all groups is likely due to the within-group variability on the speech in noise task. It is not surprising to see large amounts of variability in the BiCI groups, given that variability on performance on auditory tasks is a consistently demonstrated hallmark of the CI research literature. Much of this variability may be accounted for by demographic factors such as length of CI use, age at implantation, inter-CI gap, and bilateral experience.

What is of further interest here is the large variability that is also demonstrated within the NH child groups (see Fig. 5). It is known that auditory pathways continue to mature into adolescence (Boothroyd, 1997). Specific to this study, informational masking has been shown to have a developmental component (Leibold and Bonino, 2009; Wightman and Kistler, 2005). Wightman *et al.* (2010) tested NH populations ages 5 to 61 and showed that the most variability on a dichotic listening task involving informational masking was observed in NH children ages 6 to 12 years of age. This finding is congruent with our results, suggesting that the variability found in NH children groups ages 5 to 8 years may be due to continuing development of central auditory pathways.

We also compared the amount of asymmetrical and symmetrical SRM within groups. Previous work has shown that NH adults demonstrate more $SRM_{Asymmetrical}$ than $SRM_{Symmetrical}$ with same-sex (Jones and Litovsky, 2011) and different-sex stimuli (Misurelli and Litovsky, 2012). Although SRM is largest in asymmetrical conditions where both monaural and binaural cues are available, we have also recently shown that NH children as young as 4 years of age demonstrate SRM when sources are symmetrically distributed (Misurelli and Litovsky, 2012). This result provides evidence that by age 4, NH children are able to take advantage of binaural cues to benefit from spatial separation when interferers are directed towards both the right and left ears (Misurelli and Litovsky, 2012). The results of the current study show that significantly less $SRM_{Symmetrical}$ vs $SRM_{Asymmetrical}$ is demonstrated for all groups when same-sex stimuli were used; this same effect was only demonstrated in the adult group when using different-sex stimuli (see Fig. 4). It is likely that informational masking contributed to the increased difference between the symmetrical and asymmetrical SRM, such that in the symmetrical condition not only were monaural cues reduced, but the stimuli also lacked spectral differences, creating an extremely difficult listening environment compared to the asymmetrical condition.

C. Age and hearing type comparisons

In the present study, when BiCI and NH groups were matched for HA (see Fig. 3), the younger groups demonstrated higher SRTs (i.e., worse performance) in only the quiet condition and in the condition with asymmetrical interferers, but they did not differ in the condition with interferers co-located or symmetrically distributed. This suggests that younger children with NH also have difficultly segregating same-sex stimuli in conditions that lack any spatial cues (front) or in conditions in which monaural cues are reduced (symmetrical). When we matched NH and BiCI groups for CA (with the BiCI group having approximately one year less HA), the BiCI users had significantly worse performance (i.e., higher SRTs) in all of the conditions except the front condition. The lack of significant difference in the front condition may be caused by the difficulty in segregating target and interfering speech that listeners with NH also show when spatial cues do not exist and the stimuli is spectrally similar.

We also investigated group differences in SRM with NH and BiCI groups matched for either HA (NH-A and BiCI-A) or CA (NH-B and BiCI-B). The NH groups demonstrated more SRM with either set of stimuli when compared to the BiCI groups (see Fig. 5). All CA comparisons were significant, and only the asymmetrical HA comparisons were significant. Thus, when stimuli are spectrally similar, even younger NH children appear to have difficulty segregating target speech when monaural cues are reduced. Interestingly, although there is not a significant difference between groups, the younger NH group shows symmetrical SRM whereas the younger BiCI groups do not. The amount of variability in symmetrical SRM within both of the younger groups likely contributes to the lack of significance. When matching the younger NH group with the older BiCI group, in which the BiCI group was chronologically approximately 3 years older and had approximately 2 years more auditory experience, the NH group demonstrated significantly more SRM in the asymmetrical condition with either interferer. There was also a trend for more SRM in the NH group in the symmetrical condition. The overall difference in SRM between NH and BiCI groups suggests that cues necessary for spatial hearing are not delivered by current CI processor technology (Culling *et al.*, 2004). Additionally, the independent functionality of the current processors likely cause binaural cues to be either absent or inconsistent in BiCI users (van Hoesel and Litovsky, 2011).

We were also interested in comparing SRTs (Fig. 3) and SRM [Fig. 5(A)] with the same-sex stimuli *within* each hearing type (young vs old) to investigate whether speech understanding is improved as children mature. No significant differences in SRTs were found between younger and older NH children in the asymmetrical condition, suggesting that when both monaural and binaural cues are available, even with limited spectral cues, NH children as young as 4 years of age are able to significantly benefit from spatial separation of the target and interferers. However, consistent with our previous findings (Misurelli and Litovsky, 2012), SRTs were higher for the older NH children in only the symmetrical condition, and all conditions with interferers were better for adults than for the older NH children. This indicates that in spatially separated conditions, when monaural head shadow is reduced and listeners must rely more heavily on binaural cues, older NH children are able to identify the target talker at a lower level than younger NH children. Unlike in the NH children groups, no differences in SRTs in any conditions were shown between the younger and older BiCI groups. A lack of differences in SRTs in BiCI groups suggests that as children gain more experience with their CIs, the ability to segregate the target source at a lower level relative to the interferer does not significantly improve. Therefore, it is most likely the limitations of the CI device, rather than experience, which limit access of BiCI users to cues that aid in identification of the target source in noisy environments (van Hoesel and Litovsky, 2011).

Although age effects were shown for SRTs in the NH groups (see Fig. 3), no significant effects of age were shown for SRM (asymmetrical or symmetrical) within-in either the NH or BiCI groups (see Fig. 5). There was an overall trend in the NH listeners for older children with NH to demonstrate more SRM than the younger NH group, but significance was not reached. Presumably, the effects of SRT were not strong enough to affect SRM because SRM is a derived quantity from SRTs in the front and spatially separated conditions. This is consistent with Misurelli and Litovsky (2012), where we used different-sex stimuli, in that no significant within hearing type age effects of SRM were found.

V. CONCLUSIONS

(1) On average, SRTs in all conditions were poorer when both the target and the interferers were same-sex talkers, compared to when the target was a male talker and the interferers were female talkers. This suggests that using same-sex target and interfering stimuli introduces more masking.

(2) All groups showed significantly more SRM in the asymmetrical vs symmetrical condition, indicating that when target and maskers consist of same-sex stimuli, lack of monaural head shadow cues reduces the availability of spatial cues for source segregation.

(3) BiCI listeners showed a trend for more SRM with the same-sex than with the different-sex stimuli. This finding suggests that conditions in which confusability between target and masking speech arises may produce informational masking, and thus a greater reliance on spatial cues for source segregation occurs.

(4) SRM was generally larger in the NH groups than BiCI groups matched for chronological or hearing age. It is possible that NH children receive binaural cues with greater fidelity, and that access to these cues is a key factor in the ability to benefit from spatial separation of target speech and interferers.

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