Spatial release from masking in normal-hearing children and children who use hearing aids

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Listening to speech in competing sounds poses a major difficulty for children with impaired hearing. This study aimed to determine the ability of children (3–12 yr of age) to use spatial separation between target speech and competing babble to improve speech intelligibility. Fifty-eight children (31 with normal hearing and 27 with impaired hearing who use bilateral hearing aids) were assessed by word and sentence material. Speech reception thresholds (SRTs) were measured with speech presented from 0° azimuth, and competing babble from either 0° or $\pm 90^\circ$ azimuth. Spatial release from masking (SRM) was defined as the difference between SRTs measured with co-located speech and babble and SRTs measured with spatially separated speech and babble. On average, hearing-impaired children attained near-normal performance when speech and babble originated from the frontal source, but performed poorer than their normal-hearing peers when babble was spatially separated from target speech. On average, normal-hearing children obtained an SRM of 3 dB whereas children with hearing loss did not demonstrate SRM. Results suggest that hearing-impaired children may need enhancement in signal-to-noise ratio to hear speech in difficult listening conditions as well as normal-hearing children. © 2011 Acoustical Society of America. [DOI: 10.1121/1.3523295]

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I. INTRODUCTION

Children spend many hours in acoustic environments where target speech signals are embedded in competing sounds from multiple sources (Barker and Newman, 2004). In these environments, perception of target speech is assisted by a listener's ability to segregate the multitude of sounds into separate auditory streams, one cue to which is the angle of incidence of different sounds. Although there are relatively few data on young children, many studies on adults have shown that speech intelligibility improved when target speech and competing sounds were spatially separated (Dirks and Wilson, 1969; Bronkhorst and Plomp, 1988; Hawley *et al.*, 1999; Freyman *et al.*, 1999; Noble and Perrett, 2002; Bronkhorst, 2000). This improvement, commonly referred to as spatial release from masking (SRM), has been attributed to effects of head-shadow and binaural processing (Culling *et al.*, 2004; Hawley *et al.*, 2004; Akeroyd, 2006).

The head-shadow effect arises because the size of the head and the position of the ears cause the level and spectral shape of sounds to vary with the location of the sound source relative to each ear (Shaw, 1974). Head diffraction produces an attenuation of sound on the far side of the head, usually referred to as head shadow, as well as a boost on the near side of the head. The resulting variations in interaural level are largest at high frequencies, due to the short wavelengths of high-frequency sounds relative to the size of the human head. In addition, the binaural system provides listeners with timing differences between signals arriving at the two ears which are

most useful at low frequencies. Speech intelligibility can be improved through selective attention to the ear with the more favorable signal-to-noise ratio (SNR) or binaural processing to make use of the interaural differences that occur when target speech and competing sounds are spatially separated (Zurek, 1993; Bronkhorst, 2000).

There is some evidence to suggest that normal-hearing children demonstrate SRM at a young age. Litovsky (2005) reported experiments in which children between 4.5 and 7 yr of age were required to identify spondaic words produced by a male talker. The target stimuli were presented from a loudspeaker in front (0° azimuth) and competing sounds, either sentences produced by a female talker or modulated speech-shaped noise, were presented from a second loudspeaker located either in front (0° azimuth) or to the right (90° azimuth) of the listener. Spatial separation between target speech and competing sounds resulted in an improvement of speech reception threshold (SRT) by 3.5–7.5 dB. This spatial advantage obtained by children was similar in magnitude to that obtained by adults. Although masking was greater with speech-shaped noise than with sentence-maskers, and with two maskers compared with one; the number or type of masker did not alter the size of benefit from spatially separating the competing sounds from target speech. In a subsequent study, Garadat and Litovsky (2007) showed that the spatial advantage obtained by children who were 3 yr of age was not significantly different from that of children between 4 and 5 yr of age. These two studies indicated that the absolute SNR to achieve the same level of word recognition was higher for children than for adults, but SRM was similar in the two age groups. These findings suggest that normal-hearing children as young as 3 yr of age demonstrate adult-like ability to

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benefit from spatial separation of target speech from competing sounds in listening conditions that provided differential SNRs at the two ears.

SRM has also been measured in children under conditions where equal SNRs were maintained at the two ears when target speech was separated from competing sounds. [Cameron and Dillon \(2007\)](#) measured SRTs of children between 5 and 11 yr of age using sentence material presented under headphones. The stimuli were spatially processed using head-related transfer functions, with target speech presented at 0° azimuth and competing sounds at either 0° azimuth or $\pm 90^\circ$ azimuth. The spatial advantage increased from 8.7 dB for 5-yr-old children up to 12.9 dB for 11-yr-old children. Subsequent work with adolescents revealed that spatial advantage continued to improve and reached adult-like performance by about 14 yr of age ([Cameron et al., 2009](#)).

Despite a general agreement in the literature regarding an improvement in SRT with age, the conclusions on the effect of age on SRM were inconsistent across studies. Studies with symmetrical maskers effectively presented under headphones with simulated anechoic conditions showed larger SRMs that increased with age ([Cameron and Dillon, 2007](#); [Cameron et al., 2009](#)). Studies with asymmetrical maskers in the presence of reverberation showed smaller SRMs. While some studies showed significant differences between children and adults, the effect of age is positive in some studies in some conditions ([Johnstone and Litovsky, 2006](#); [Vaillancourt et al., 2008](#); [van Deun et al., 2010](#)) but negative in others ([Litovsky, 2005](#); [Johnstone and Litovsky, 2006](#)).

An improved understanding of the development of SRM in children with normal hearing (NH) is important because they experience much difficulty when listening to speech in competing sounds ([Elliott et al., 1979](#); [Byrne, 1983](#); [Jamieson et al., 2004](#)). This knowledge is also important for examining the impact of the presence of hearing loss on the development of SRM in hearing-impaired children and for developing strategies to alleviate difficulties encountered by them in real life ([Ching et al., 2010](#); [Scollie et al., 2010a](#)).

Currently, limited data on SRM measured in children with hearing loss have been published. In [Litovsky et al. \(2006\)](#), a group of children with bilateral cochlear implants and another group who used a cochlear implant and a hearing aid in opposite ears (bimodal hearing) were tested using spondaic words. The target stimuli were always presented from a loudspeaker in front (0°) and competing babble was presented from a second loudspeaker located either in front (0°), to the left (-90°), or right ($+90^\circ$) of the listener. The results revealed that no SRM was obtained when competing sounds were moved from the front to the side of the first cochlear implant, but significant SRM occurred when competing sounds were moved to the side of the second cochlear implant or hearing aid. More recently, [van Deun et al. \(2010\)](#) used a similar test paradigm to assess children with bilateral cochlear implants and found that significant SRM occurred in both configurations. The authors attributed the spatial benefit to the effect of head shadow. Further, a larger SRM was obtained when the competing noise was near the second cochlear implant than when it was near the first cochlear implant, suggesting that the children functioned better with the first

cochlear implant than with the second cochlear implant for speech perception in noise. A third study directly investigated the use of interaural time difference cues by children who used either bimodal hearing or bilateral hearing aids ([Ching et al., 2005](#)). The introduction of an interaural time delay of 700 μ s in the maskers did not improve speech intelligibility for children with bimodal hearing, but led to an improvement of 1–2 dB for children with bilateral hearing aids whose hearing loss in the low frequencies was no worse than 65 dB hearing level (HL). There were no other studies that investigated SRM in children who use bilateral hearing aids.

To give some insight into the developmental trend of SRM in children with NH and those with hearing impairment (HI), and to evaluate the benefits of hearing aids in noisy environments by young children with hearing loss, the present study examined SRM of children aged between 3 and 12 yr. Two sets of age-appropriate speech test material were used, the Bamford–Kowal–Bench (BKB) sentence test and the Northwestern University Children’s Perception of Speech (NU-CHIPS) word test. The sentence material has face validity as it is close to everyday communication, but its applicability is limited by the language skills and age of the child ([Bench and Bamford, 1979](#)). The word material was based on age-appropriate vocabulary and has been found to be applicable to children as young as 3 yr of age ([Mackie and Dermody, 1986](#)). In order to relate the performance of children with HI to their normal-hearing peers, the same test paradigms were applied to a group of children of the same age range who have NH.

II. METHOD

A. Participants

Fifty-eight children who were native speakers of Australian English with no known cognitive disorders or language impairments participated in this study. Thirty-one children had NH and 27 children had bilateral sensorineural HI and were using hearing aids. The NH group included 18 boys and 13 girls between the ages of 3.5 and 11.8 yr (mean = 7.1, SD = 2.2). They had pure-tone thresholds of ≤ 15 dB HL at octave frequencies between 0.5 and 4 kHz and ≤ 20 dB HL at 0.25 and 8 kHz. All had normal type A tympanograms, consistent with normal middle ear functioning, on the day of testing. The HI group included 16 boys and 11 girls between the ages of 3.2 and 11.9 yr (mean = 7.0, SD = 3.2). Table I gives demographic information, including age at initial fitting, four-frequency average hearing thresholds (4FA; average across 0.5, 1, 2, and 4 kHz) and audiometric slope (1–4 kHz) for each ear. The children had sensorineural hearing loss (4FA median: 47 dB HL; 4FA range: 25–104 dB HL) that was either flat or gradually sloping in configuration. The symmetry in terms of 4FA hearing thresholds between the two ears was ≤ 15 dB for all except 3 HI children.

B. Hearing aids

All children in the HI group used their personal hearing aids that were fitted according to standard clinical protocols by the national hearing-service provider for children in Australia ([King, 2010](#)). All devices were behind-the-ear models with more than one channel, and wide-dynamic-range

TABLE I. Demographic characteristics of children with HI.

Subject code	Gender	Age at first fitting (yrs)	Age at evaluation	Averaged hearing loss from 0.5 to 4 kHz (dB HL)		Slope from 1 to 4 kHz (dB/octave)		Hearing aids
				Left	Right	Left	Right	
S1	M	6.9	8.0	28.8	37.5	15	15	Siemens Music Pro
S3	F	0.3	8.8	45	46.3	-2.5	-7.5	Siemens Triano S
S5	M	4.6	4.8	48.8	61.3	0	-5	Siemens Music Pro
S6	F	2.4	10.7	56.3	71.3	-10	-5	Bernafon LS12
S8	F	1.7	10.7	45	50	0	10	Siemens Music Pro
S9	F	4.7	6.7	35	33.8	-2.5	-5	Bernafon LS12
S10	F	4.5	5.4	48.8	48.8	-5	0	Bernafon LS14
S11	M	5.6	11.9	42.5	37.5	2.5	0	Siemens Music Pro
S12	M	1.7	4.4	30	22.5	2.5	-7.5	Bernafon LS14
S13	F	2.5	10.7	71.3	73.8	-25	-15	Siemens Music Pro
S14	M	1.7	4.4	31.3	31.3	0	5	Bernafon LS14
S15	M	0.5	3.6	51.3	56.3	-2.5	2.5	Siemens Music Pro
S16	F	0.3	11.4	103.8	95	10	12.5	Siemens Music DSP
S17	M	5.0	9.9	48.8	42.5	5	5	Siemens Prisma 2
S18	F	4	7.5	50	50	2.5	2.5	Siemens Music Pro
S19	M	5.6	6.8	22.5	23.8	12.5	12.5	Siemens Music Pro
S20	M	3.3	11.8	26.3	28.8	-2.5	-2.5	Siemens Music Pro
S21	M	2.5	10.3	81.3	72.5	17.5	12.5	Widex Diva SD9M
S23	F	1.4	11.2	76.3	81.3	-20	-12.5	Siemens Prisma 2
S24	M	0.7	5.7	71.3	91.3	-5	-7.5	Siemens Music Pro
S33	M	2.6	3.2	33.8	38.8	-12.5	-10	Siemens Prisma 2
S43	F	2.1	4.5	51.3	51.3	-5	-7.5	Siemens Prisma 2M
S46	M	0.2	3.4	42.5	42.5	0	-2.5	Siemens Music Pro
S47	M	0.2	3.8	47.5	82.5	2.5	15	Siemens Music Pro
S48	F	1.9	4.2	96.3	76.3	22.5	7.5	Siemens Music Pro
S49	M	1.1	3.2	25	28.8	20	7.5	Bernafon AF120
S70	F	0.6	3.3	50	47.5	2.5	2.5	Siemens Prisma 2K

compression in each channel. The manufacturer and model of hearing aids used by each child were the same in both ears (see Table I). All hearing aids were selected using the National Acoustic Laboratories' prescription for non-linear hearing aids, version 1 (NAL-NL1) procedure (Byrne *et al.*, 2001), with the compression threshold set according to the prescription so that broadband speech at 50 dB SPL rms would just activate compression. Individual real-ear measurements were made at the centers where children received their hearing services using a Madsen Aurical system to verify that prescriptive targets were matched as closely as possible. It was decided not to change devices so that the sample was representative of the hearing aids in current use by the participants recruited for the study.

The hearing aid gain-frequency response and maximum power output were measured in an HA2-2cc coupler. The hearing aid gain at 50, 65, and 80 dB input levels was measured using a broadband speech-weighted noise, and the maximum output was measured using a swept pure tone at 90 dB SPL. Figure 1 shows the mean achieved gain in relation to the target gain at 65 dB input level. Because the present study focussed on measuring SRM of children who used bilateral hearing aids at their normal settings in omnidirectional mode, no attempts were made to adjust the hearing aids. Noise management, expansion, and directionality features were not engaged.

C. Stimuli

Two sets of speech test materials were used. The first was an Australian recording (female talker) of the NU-CHIPS (Mackie and Dermody, 1986) word material. In this

FIG. 1. Mean NAL-NL1 target gain (open symbols) and achieved hearing aid gain (filled symbols) as a function of frequency. Hearing aid gain was measured in an HA2-2cc coupler, using broadband speech-weighted noise presented at 65 dB SPL as stimuli. Error bars indicate 95% confidence intervals.

test, children were required to respond to each stimulus by pointing to one of four pictures that represented a target word. A four-alternative forced choice picture-pointing procedure has been used for assessing speech perception ability of young children in previous studies (Mackie and Dermody, 1986; Litovsky, 2005). The second was an Australian recording (male talker) of the BKB/Australian version (BKB-A) sentence lists (Keidser *et al.*, 2002). The competing sounds were eight-talker babble (four males and four females) designed to simulate realistic situations in everyday listening. All stimuli were recorded digitally on compact disks.

D. Test conditions

The SRT for 50% correct was determined in two listening conditions. In one condition, target speech and competing eight-talker babble were presented from the same loudspeaker placed at 0° azimuth (S_0N_0). In another condition (S_0N_{90}), target speech was presented from the front at 0° azimuth, and uncorrelated four-talker babble noise was presented from each of two loudspeakers placed at $\pm 90^\circ$ azimuth (effectively eight-talker babble). The competition was thus an eight-talker babble in all conditions. Target and competing babble (either the single eight-talker babble or the pair of four-talker babble signals, at $+90^\circ$ and -90° , simultaneously present) were calibrated at the test position with the participant absent. Test conditions and test lists were counterbalanced across participants.

E. Procedure

All testing were carried out in a sound-treated booth (4.6 m $\times$ 5.0 m) with carpeting. The reverberation time (T_{60}) of the room varied from 0.51 s at 0.25 kHz to 0.18 s at 4 kHz. The stimuli were presented via two compact disc (CD) players, with each output channel connected to remotely controlled attenuators, a mixer, digital equalizers, amplifiers, and loudspeakers. The frequency response of the playback system was flat between 0.16 and 6 kHz. An array of three loudspeakers was used for presenting the stimuli in free field. The loudspeakers were located at a distance of 0.8 m from the subject position, at 0°, and at $\pm 90^\circ$ azimuth. The height of the chair at subject position was adjusted individually for each child so that the center of the loudspeakers approximately aligned with ear level. The test room had a critical distance (the distance from the source at which the direct and reverberant fields are equal) of 0.5 m based on broadband Leq measurements with a noise stimulus matched in spectral shape to the long-term spectrum of speech. The critical distance increased with frequency from about 0.5 m at 0.25 kHz to 2.0 m at 4.0 and 8.0 kHz. Calibration of the test system was performed daily.

The hearing-impaired children wore their personal hearing aids, which were checked by making electroacoustic measurements at each test session. Prior to testing with the NU-CHIPS word material, pictures of all test items were introduced to children with the associated auditory targets using live voice and then with recorded speech. This was done to ensure that they were familiarized with all items. During testing, recorded speech stimuli were presented in

the sound field. In the word test, children were required to respond by pointing to one of four pictures that represented the target word. In the BKB-A sentence test, a sentence was presented and the child's task was to repeat the sentence heard. All words in each sentence were scored individually. The experimenter monitored the child closely and prompted him/her to attend, if necessary, before a stimulus was presented. The children were given breaks when required and small rewards were given with parental permission. Verbal encouragement from the experimenter was used frequently, but feedback about the correct response was not provided. For children who requested to be accompanied by a parent during testing, the parent was seated behind the child.

An adaptive procedure was used to estimate the SRT in each test condition. The SNR was decreased if a listener correctly identified a word, or repeated more than 50% of words in a sentence correctly. The SNR was increased if a listener incorrectly identified a word or scored less than 50% of words in a sentence. At the start of an SRT measurement, the level of the target speech was fixed at 65 dB SPL, and the level of the babble noise was set at 55 dB SPL. Thus the adaptive test began with a SNR of 10 dB. The level of the babble was varied initially in steps of 5 dB. After the first two reversals, the step size was reduced to 1 dB. The test stopped after 12 reversals with the 1 dB step size were obtained, and the midpoints of the last ten reversals were used to calculate the SRT. All 58 children took the word test, 40 of whom (23 NH and 17 HI children) also took the sentence test. For children younger than 7 yr, the word test was administered first. For older children, the order of test material was counterbalanced across subjects. The SRT for each test condition was measured, and SRM was expressed as the difference between the SRTs for the two conditions ($S_0N_0 - S_0N_{90}$), in terms of dB SNR.

III. RESULTS

A. SRTs for word recognition

Table II shows the mean SRTs for word recognition in two noise conditions, S_0N_0 and S_0N_{90} .

An analysis of variance with SRTs as dependent variable, noise location (0° vs $\pm 90^\circ$) as a repeated measures factor, hearing status (NH vs HI) as a grouping variable, and age as a continuous covariate showed that the main effect of noise location was significant [$F(1,55) = 17.632$, $p < 0.0001$]. There were also significant effects for hearing status ($F = 25.657$, p

TABLE II. Mean SRTs (dB SNR) for word material presented in the S_0N_0 and S_0N_{90} conditions, and SRM of children with NH and children with HI who use hearing aids.

		S_0N_0	S_0N_{90}	SRM
NH ($n = 31$)	Mean	-2.61	-6.17	3.57
	SD	3.13	2.95	1.76
	Range	-8.5 to 4.0	-12.7 to 0.8	-0.9 to 6.9
HI ($n = 27$)	Mean	-0.02	-0.64	0.63
	SD	4.75	4.39	3.27
	Range	-8.5 to 11.4	-8.2 to 9.6	-6.5 to 7.6

TABLE III. Mean SRTs (dB SNR) for sentence material presented in the S_0N_0 and S_0N_{90} conditions, and SRM of children with NH and children with HI who use hearing aids.

		S_0N_0	S_0N_{90}	SRM
NH ($n = 23$)	Mean	-1.72	-4.48	2.75
	SD	1.66	2.33	1.72
	Range	-6.5 to 2.2	-8.9 to 0.8	-0.5 to 6.6
HI ($n = 17$)	Mean	-0.67	-0.84	0.17
	SD	3.34	3.21	2.35
	Range	-8.2 to 5.5	-7.2 to 5.9	-3.0 to 6.5

< 0.0001) and age ($F = 27.032$, $p < 0.0001$). The interaction of location and hearing status was significant [$F(1,55) = 20.307$, $p < 0.0001$]. *Post-hoc* analyses using the Tukey's Honest Significant Difference (HSD) test revealed that the mean SRT in the $\pm 90^\circ$ condition was significantly lower than the 0° condition for the NH group ($p < 0.001$) but not for the HI group ($p = 0.6$). The mean SRTs in the 0° condition were not significantly different between the NH and the HI group ($p = 0.07$), but the mean SRTs in the $\pm 90^\circ$ condition for the NH group was significantly lower (better) than that for the HI group ($p < 0.001$).

B. SRTs for sentence recognition

Table III shows the mean SRTs for sentence perception.

An analysis of variance of SRTs with noise location as a repeated measures factor, hearing status as a grouping variable, and age as a continuous covariate indicated significant effects of hearing status [$F(1,37) = 17.985$, $p < 0.001$] and age ($F = 21.446$, $p < 0.0001$), but the main effect of location was not significant [$F(1,37) = 1.052$, $p = 0.3$]. The interaction between location and hearing status was significant [$F(1,37) = 15.811$, $p < 0.001$]. *Post-hoc* analyses revealed that the SRTs for $\pm 90^\circ$ were significantly lower than those for 0° ($p < 0.001$) for children with NH, but not for children with hearing loss ($p = 0.9$). Whereas the SRTs for the 0° condition were not significantly different between the NH and the HI group on average ($p = 0.6$), the SRTs for the $\pm 90^\circ$ condition in the NH group were significantly lower than those in the HI group ($p = 0.001$). There was no other significant interaction.

C. Effect of test material on SRM

The SRM was calculated by subtracting the SRT in the $\pm 90^\circ$ condition from that in the 0° condition, and the descriptive statistics are given in Table II (word material) and Table III (sentence material). To determine the effect of test material, a repeated measure analysis of variance was performed with material (words vs sentences) as a repeated measure, hearing status (NH vs HI) as a grouping variable, and age as a covariate. Figure 2 shows the mean SRM for words and sentences obtained by children who took both tests. There was a significant main effect of hearing status [$F(1,36) = 27.907$, $p < 0.0001$], with the NH children obtaining more spatial advantage than the HI group, both for the word material ($p = 0.004$) and the sentence material ($p = 0.001$). The effect of age was not significant ($p = 0.780$).

FIG. 2. Mean SRM for word material (squares) and sentence material (triangles) for children with NH and children with HI who use hearing aids. Error bars indicate 95% confidence intervals.

The lack of significant interaction between material and hearing status ($p = 0.961$) suggests that the amount of SRM was similar for the word and sentence tests, both for the NH group (averaging 3.5 and 2.8 dB, respectively) and the HI group (averaging 0.6 and 0 dB, respectively). On average, the hearing-impaired children had a 3 dB deficit in SRM compared to normal-hearing children.

There was a positive correlation between the SRM for words and sentences (product moment correlation $r = 0.529$; $p = 0.001$), indicating that on average, children who obtained a higher SRM for word material also obtained a higher SRM for sentences.

IV. DISCUSSION

This paper reports speech intelligibility in noise and SRM in children with NH and children who use bilateral hearing aids.

A. Effect of age, hearing status, location, and test material on SRTs

This study found a significant effect of age on SRTs of words and sentences, consistent with previous studies (Byrne, 1983; Litovsky, 2005; Garadat and Litovsky, 2007). The decrease in SRT with increase in age shows that young children experience greater difficulty than older children when listening to speech in noise. This effect may be associated with age-related changes in the mechanical properties of the ear and the efficiency of neural coding (Schneider *et al.*, 1986); the maturation of central auditory processes, and the development of listening strategies (Allen and Wightman, 1994; Lufti *et al.*, 2003). Word familiarity may also improve with age, as has been hypothesized in previous studies (Byrne, 1983; Elliott *et al.*, 1983; Elliott *et al.*, 1979). In line with published literature, this study supports the use of age-appropriate norms for speech tests used clinically for children.

The finding that children who use bilateral hearing aids (HI group) attained similar levels of word recognition or

sentence perception as their normal-hearing peers (NH group) when tested with co-located speech and noise from the front (S_0N_0) lends support to the effectiveness of amplification provided by using the NAL-NL1 prescription for speech intelligibility. This result is consistent with published data on the effectiveness of the NAL-NL1 prescription for speech perception by children (Scollie *et al.*, 2010b).

On the other hand, when noise was spatially separated from target speech (S_0N_{90}), the SRTs were significantly worse for children with impaired hearing than those with NH. The same finding applies, regardless of whether word or sentence material was used in testing (Tables II and III). The results suggest that, on average, children with hearing aids were not able to use cues arising from the spatial separation between target speech and competing sounds to improve speech intelligibility. Although digital hearing aids can have delays up to 10 ms (Dillon *et al.*, 2003), and often vary with frequency, these delays principally arise from the analog to digital converter and the signal processing associated with frequency analysis. As these delays are highly reproducible from one device to the next (of the same make and model with the same features selected), they should not distort interaural time difference cues. Previous research has demonstrated the ability of listeners to adapt to small consistent differences in interaural time and level differences (Javer and Schwarz, 1995; King *et al.*, 2001). As with all hearing aids, there is the likelihood of distortion of interaural time- and level-difference cues in the frequency region, typically in the range 250–500 Hz (but depending on degree of loss and size of the vent), where amplified sound and sound leaking in past the earmold or through the vent have similar magnitude (Dillon, 2001). As this cross-over region is limited in frequency range, it seems unlikely that the hearing aids are responsible for the reduced spatial processing ability.

B. SRM: Effect of age and hearing thresholds

The mean SRM for normal-hearing children was 3.6 dB for word material and 2.6 dB for sentences. These values are broadly consistent with SRM measured in previous studies involving measurements where reverberation was present, even though these previous studies created different SNRs at the two ears by use of a single masking source or asymmetric positioning of multiple masker sources. The mean SRM values reported in this study are extremely similar to the value of 3 dB obtained by averaging SRM across previous studies involving young children (Litovsky, 2005; Johnstone and Litovsky, 2006; Vaillancourt *et al.*, 2008; van Deun *et al.*, 2010). The present study supports previous studies in showing that children are able to benefit from spatial separation of a target from a competing noise at a young age, implying that at least some of the auditory mechanisms that can mediate SRM (possibly including attending to the ear with the better SNR) are well developed early in life (Sanders *et al.*, 2006). This study found no effect of age on SRM. Several previous studies have also found no significant effect of age under at least some conditions (Litovsky, 2005; Garadat and Litovsky, 2007). Some previous studies have found a significant effect

under some conditions, but the direction of the effect varies between studies and/or conditions (Johnstone and Litovsky, 2006; Litovsky, 2005; Cameron and Dillon, 2007; Cameron *et al.*, 2009; Vaillancourt *et al.*, 2008; van Deun *et al.*, 2010). We hypothesize that when the target and masker are dissimilar (i.e., low informational masking) and there is reverberation present, the SRM is small, and there is little or no effect of age. This contrasts with tests performed under essentially anechoic conditions, and where the target and masker are easily confused (i.e., high informational masking), where the SRM is large and increases with age (Cameron and Dillon, 2007; Cameron *et al.*, 2009). It may be that the fewer cues available to separate the target from the competition, the more likely it is that spatial advantage increases with age. Further work is necessary to investigate the effect of age and the way in which age interacts with masker type and test condition.

This study shows that the SRM for children with HI who use bilateral hearing aids was effectively zero, on average. The children demonstrated a deficit of 3–5 dB in the spatially separated condition, compared to normal-hearing peers. Given that the hearing aids were well-matched to prescriptive targets (see Fig. 1), the observed deficit may be related not so much to audibility but to a reduced ability to extract speech information from an audible signal due to hearing loss (Bronkhorst and Plomp, 1989; Ching *et al.*, 1998). Studies on adult listeners indicated that even when audibility was increased by extending amplification bandwidth beyond 3.6 kHz (Ahlstrom *et al.*, 2009) or customizing amplification characteristics (Marrone *et al.*, 2008a), no increase in SRM was observed.

It should not be surprising that some children showed a negative SRM, i.e., a disadvantage from spatial separation. Partly this will be caused by random measurement error in the two SRT measurements. More fundamentally, however, the SPL at the ear for a speech-spectrum shaped signal increases when the source is moved from 0° to 90° azimuth because of head diffraction effects. The increase at the near ear more than offsets the decrease at the far ear, so head diffraction effects for the simultaneously present +90° and the –90° sources cause the overall level at the eardrum, and at the side of the head, to be about 3 dB greater than when the sources are both at 0° (Festen and Plomp, 1986; Cameron *et al.*, 2006). Unless the listener could use binaural processing to partially suppress noise masking internally, performance would be worse due to the resultant poorer SNR. There were, nonetheless, nine individuals who demonstrated masking release of 2 dB or greater, suggesting that they had access to spatial cues when wearing bilateral hearing aids and were able to use the cues for speech unmasking. Consistent with findings from Marrone *et al.* (2008a), Neher *et al.* (2009), and Ahlstrom *et al.* (2009) on adult users of bilateral hearing aids and earlier data on children (Ching *et al.*, 2005), the present results suggest that spatial advantages are possible with current hearing-aid technology and fitting in conditions where no adaptive features were engaged. Larger spatial advantage would be expected if directional microphones were used, but such use was not routine clinical practice for children at the time the data were collected.

The present study did not find a significant relationship between SRM and hearing thresholds of hearing-impaired children, in contrast to reported findings on post-lingually deafened adults (Marrone *et al.*, 2008b). SRM was also unrelated to the age at which children first received hearing aid fitting. As most children in the HI group were born before newborn hearing screening, a larger study group that includes children who receive early intervention is needed to determine the effect of age of intervention on development of SRM. This is currently under investigation in a separate study.

Our present results indicate that, as a group, the aided hearing-impaired children experienced a SRM deficit compared to their peers with NH. This finding is consistent with previous research showing that child users of bilateral hearing aids who achieved near-normal speech performance when listening to speech in co-located noise in a clinical setting experienced much difficulty listening to speech in noise in real life (Ching *et al.*, 2010; Scollie *et al.*, 2010a). It may certainly be expected that children who demonstrate a deficit in SRM in a clinical evaluation would have a greater need for the improvement offered by directional microphones in many environments (Ching *et al.*, 2009) than would children with no deficit in SRM.

V. SUMMARY AND CONCLUSIONS

This study was aimed at evaluating speech intelligibility in noise and SRM in normal-hearing and hearing-impaired children between 3 and 12 yr of age. Results showed that, on average, young children required better SNRs than older children to achieve the same level of performance, but attained the same amount of benefit from spatial separation between target speech and competing sounds. The amount of SRM obtained with each of two sets of test material was not significantly different. On average, the hearing-impaired children attained similar performance as their normal-hearing peers when speech and competing sounds originated from the same frontal source, but performed poorer than their normal-hearing peers when competing sounds were at $\pm 90^\circ$ azimuth.

As a group, children with hearing loss who use bilateral hearing aids showed effectively no advantage from spatial separation between target speech and competing sounds. There was considerable individual variability, with some children showing a SRM like their peers with NH, whereas others demonstrated a spatial disadvantage. It is unknown to what extent the lack of SRM is caused by the children's hearing aids distorting interaural cues, and to what extent by a deficiency in the children's auditory processing capabilities, though the latter seems more likely. Future research investigating this issue should also investigate whether any binaural processing deficiency is associated with early-life sound deprivation, and/or with current sensorineural hearing loss.

The present findings emphasize the need for assessing the performance of children using hearing aids or cochlear implants under conditions where the target and competition come from different directions. The SRT obtained by presenting target speech and competitor from different directions is likely to be more indicative of real-life deficit than a score obtained for speech and competitor coming from the

same direction. Consequently it will better indicate the enhancement in SNR needed by the child to hear speech in difficult listening situations as well as normal-hearing peers.

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