Speech detection in noise for young bilaterally implanted children: Is there evidence of binaural benefit over the shadowed ear alone?

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Abstract

Objectives. To measure binaural benefit over the shadowed ear alone for young bilateral cochlear implant (CI) users. It was hypothesized that children who received bilateral CIs at a young age (< 4 years), and had significant bilateral experience, would demonstrate lower detection thresholds for speech sounds in background noise in the bilateral CI over the unilateral CI condition when the added CI was ipsilateral to the noise source.

Design. Children receiving bilateral CIs at the Eye and Ear Hospital Clinic in Melbourne were invited to participate in a wider research project evaluating outcomes; those participating in the wider project who were bilaterally implanted by 4 years and were approximately 2 years postoperative were included in the present study. For 20 participants, detection SNRs were measured for speech presented from in front and noise from 90^0 in at least 3 of 4 device/noise conditions, viz: left CI/noise right and right CI/noise left, plus bilateral CIs/noise right and/or bilateral CIs/noise left.

Results. As some participants could only complete testing in 3 conditions within the one test block, the unilateral versus bilateral comparison was performed for one CI (i.e., one noise direction) for 15 participants and for both CIs (i.e., noise left and noise right) for 5 participants. Group analysis indicated no significant difference in detection SNR between the unilateral and bilateral CI conditions when adding the left CI or right CI (for the overall group) or when adding the first or second CI (for the 15 participants with sequential bilateral CIs). Separate analyses indicated no significant difference in detection SNR between the unilateral and bilateral CI conditions for the majority of individuals; this occurred irrespective of whether the analysis indicated that the CI added in the bilateral condition was poorer-performing, better-performing, or not significantly different compared to the other CI. Four individuals demonstrated a significant improvement in the bilateral condition when the CI added in the bilateral condition was a better-performing (n =1), poorer-performing (n = 2), or not significantly different CI (n = 1). There was no relationship between the detection SNR difference between each CI and the detection SNR difference between the unilateral and bilateral conditions.

Conclusions. The hypothesis of a lower detection SNR in the bilateral condition was not supported by the group results or by the results for the majority of individuals. For the 4 participants who did demonstrate benefit over the shadowed ear alone, that benefit cannot be separated from the potential benefit gained as a result of the CI added in the bilateral condition being the better-performing CI for 1 of the 4. Variation in outcomes could not be related to demographic factors for this group, which was relatively homogeneous for age at bilateral CI and experience; an older, more experienced group may demonstrate greater binaural benefit in these conditions. These results can be used during counselling for families regarding postoperative expectations for young children, especially in the first 2 years.

Introduction

For listeners with normal hearing, speech perception, particularly in background noise, is improved when listening with two ears in contrast to one. Binaural loudness summation, binaural redundancy, binaural unmasking, spatial release from informational masking, and the headshadow effect may all contribute to this improvement, depending upon the particular arrangement of speech and noise sources. Binaural loudness summation results in a small increase in loudness when the signals from two ears are combined. Binaural redundancy is the benefit resulting from the opportunity for the auditory system to gain two representations of the same signal. Improvements due to binaural unmasking, spatial release from informational masking, and the headshadow effect are dependent upon the target speech signal and the background noise arriving from different locations. This results in a different balance of speech and noise arriving at each ear. Binaural unmasking and spatial release from informational masking occur when the listener combines and compares the information arriving at the two ears to generate a central representation of the auditory signal which then improves perception of the target speech. The headshadow effect is due to the acoustic shadow cast by the head, which results in a higher signal-to-noise ratio (SNR) at the ear which is further from the noise source. The listener benefits from being able to attend primarily to the auditory signal arriving at that ear. In real life the SNR changes dynamically at both ears; the term “better-ear glimpsing” describes the benefit gained when the listener switches attention rapidly between the signals from either of the two ears. The listener with unilateral hearing can benefit from the headshadow effect, but only when the noise is further from the hearing ear. In contrast, the listener with unilateral hearing is unable to benefit from binaural summation, binaural redundancy, binaural unmasking, spatial release from informational masking, or better-ear glimpsing (Kidd et al. 2008; Bronkhorst and Plomp 1989; Brungart and Nandini 2012; Culling 2007; Deatherage 1966; Reynolds and Stevens 1960).

For around two decades from the mid-1980s, the majority of adults and children with hearing loss who received a cochlear implant (CI) were provided with a unilateral device. More recently, an increasing proportion of adults and children have received bilateral CIs. Bilateral implantation ensures that the ear with the greater potential for a superior outcome is always implanted. The provision of two CIs also ensures that the user has ongoing access to sound in the event of a temporary or permanent problem with the functioning of one CI; this advantage can be of significant functional and psychological benefit to CI users and their families. Perhaps most importantly, bilateral CIs have the potential to provide access to the binaural effects described above, and to provide greater access to the headshadow effect. Studies investigating the benefits to speech perception for adults using bilateral CIs have shown that the majority gain benefit from the headshadow effect (see, for example, van Hoesel and Tyler 2003; Müller et al. 2002). The evidence for other benefits was more equivocal, with some studies showing benefit (see, for example, Buss et al. 2008; Gifford et al. 2014; Long et al. 2006; Müller et al. 2002) and others not (van Hoesel et al. 2008).

There is now also a significant body of evidence demonstrating the benefits to speech perception for children using bilateral CIs; an excellent review of the studies involving only children is provided by Sparreboom et al. (2010). There is clear evidence that the majority of children gain benefit from the headshadow effect (Galvin et al. 2007; Mok et al. 2007; Peters et al. 2007), but little or no evidence of benefit from binaural summation (Litovsky et al. 2004; Mok et al. 2007; van Deun et al. 2010). Building on the evidence of binaural unmasking for infants and young children with normal hearing (Nozza et al. 1988; Schneider et al. 1988), a limited number of studies have attempted to evaluate the benefit due to binaural unmasking for children using bilateral implants in studies involving direct stimulation or free-field presentation.

The potential for children with bilateral CIs to access binaural cues has been demonstrated in a controlled environment using direct stimulation of a single electrode in both ears (Van Deun et al. 2009). Six of 7 participants demonstrated a significantly lower detection threshold for dichotic versus diotic stimuli, with a mean binaural masking level difference of 6.4dB. The participants had a congenital or very early onset of deafness, and did not receive their second, sequential CI until 2.8 to 11.6 years of age. Although the study provided insight into the perceptual capabilities of children using bilateral CIs, direct presentation of stimuli with large inter-aural timing differences is significantly different to the clinical situation.

Other studies have used free-field presentation of speech stimuli from 0^0 to evaluate performance with a unilateral CI contralateral to a noise source at 90^0, so that the unilateral CI was the "shadowed" CI. Performance using bilateral CIs was evaluated in the same speech/noise configuration, so that the "added" CI was ipsilateral to the noise source. Comparison across the unilateral versus bilateral device condition in this arrangement of speech and noise would primarily measure the benefit due to binaural unmasking, although the other processes described above may also contribute to any benefit gained. Two studies have reported group results on a closed-set, spondee discrimination in noise task presented in these conditions. In the first study, involving participants 3 to 13 years at sequential bilateral implantation and with 9 months of experience, the group (n=24) demonstrated a significant mean benefit of 6.8% spondees correct (Peters et al. 2007). The second study had a different focus, primarily evaluating spatial unmasking for participants aged 2 to 12 years and with 3 to 26 months of bilateral experience; nevertheless, the published figure suggests that the group (n=10) failed to gain a binaural benefit in the bilateral CIs condition when the CI added in the bilateral condition was ipsilateral to the noise source (Litovsky et al. 2006). Other studies have analysed results for individuals, reporting that a limited number or no participants demonstrated binaural benefit in these same speech/noise configurations. A closed-set adaptive, spondee discrimination in noise task was employed to evaluate two groups of 9 participants aged 5 to 15 years (Galvin et al. 2007) or 10 to 19 years (Galvin et al. 2010) at sequential bilateral implantation. No evidence of binaural benefit was found, although this may have been due to the participants' older age at bilateral implantation and/or minimal bilateral experience (6 to 12 months). Assessment of younger children sequentially bilaterally implanted before 4 years of age showed a significant binaural benefit on a speech detection in noise task for only 1 of 5 participants with 6 months of experience, and for the single participant with 24 months of experience (Galvin et al. 2008).

In each of these studies, the groups were generally relatively small, with only Peters et al. (2007) including more than 10 participants. All of the participants were sequentially implanted, with the majority (86%) not receiving their second implant until after the age of 5 years. Bilateral experience was limited, with the majority of participants having less than 1 year, and only 5 having around 2 years (Litovsky et al. 2006; Galvin et al. 2008). Some studies only assessed performance in the first CI alone and the bilateral CIs conditions, so that the better-performing CI was not identified (Galvin et al. 2007; Litovsky et al. 2006). The amount of benefit gained when using bilateral CIs over one CI alone will depend on the relative performance of the CI added in the bilateral condition as compared to the other CI when each was assessed alone. Although the first CI is more likely to be the better-performing CI, this may not be the case, especially for younger children with a short delay between implants. There is a need for additional investigations of the binaural benefit which may be gained by children in spatially separated speech and noise conditions. In particular, younger participants with greater bilateral experience may be more likely to demonstrate binaural benefit. For young children, an increased likelihood of a shorter inter-implant delay and higher levels of neural plasticity may result in less impact of unilateral auditory deprivation on the developing auditory system (Gordon et al. 2013). The variation in benefit shown by individuals in the studies discussed above highlights the need to involve larger participant groups in the evaluation of binaural benefit. Binaural benefit can also only be determined if performance with either ear alone is known.

The aim of the present study was to measure binaural benefit over the shadowed ear alone for young bilateral CI users. It was hypothesized that children who received bilateral CIs at a young age (< 4 years), and had significant bilateral CI experience, would demonstrate lower detection thresholds for speech sounds in background noise in the bilateral CI condition over the unilateral CI condition when the CI added in the bilateral condition was ipsilateral to the noise source. To aid the interpretation of the results of the unilateral/bilateral comparison, a comparison was also made of performance in each unilateral condition; the aim of this comparison was to determine if the CI added in the bilateral condition was a poorer- or better-performing CI.

Method

Approval for the conduct of this study was obtained from the Human Research Ethics Committee of the Royal Victorian Eye and Ear Hospital.

Participants

The 20 participants in this study were part of a larger group involved in a project evaluating bilateral CI use by children and young adults, so participant numbering is not consecutive. The selection criteria for this wider project were onset of hearing loss prior to adolescence, scheduled to receive (or had previously received) sequential or simultaneous bilateral CIs, no significant developmental or cognitive delays reported by professionals working with the child, sufficient oral language skills to participate in testing, a parent with sufficient English language skills to provide feedback on the child’s progress, and a record of generally attending scheduled clinic appointments. In line with the study aims, additional criteria for inclusion in this current study were the receipt of bilateral CIs prior to the age of 4 years and approximately 24 months bilateral CI experience.

Demographic information relating to etiology and onset or diagnosis of hearing loss, use of hearing aids prior to implantation and in combination with the first implant (CI1), implant type, age at CI1, and the time between CIs is provided in Table 1. All participants had a prelingual hearing impairment, the majority with 3-frequency pure tone averages in the profound range bilaterally. P38 and P65 had a severe loss in one or both ears respectively. These two participants, along with P15 and P29, also had a diagnosis of Auditory Neuropathy Spectrum Disorder. All participants were implanted with Nucleus[1] CIs. At the time of assessment, 19 participants had approximately 24 months of bilateral CI experience (mean: 24.5 mo; SD: 0.9), whilst participant 10 had 35 months of experience. For the group, the mean age at first implantation was 1 yr;3 mo (SD 6mo), the mean age at bilateral implantation was 2 yr;1 mo (SD 9 mo) and the mean age at assessment was 4 yr;3 mo (SD 9 mo). For the 15 participants with sequential CIs, the mean time between CIs was 1 yr;2 mo (SD 9 mo).

Assessment

Testing established the signal-to-noise ratio (SNR) at which the participant reliably detected the speech stimulus in background noise. Participants were trained to respond to the test stimulus with a game-based motor response as per the standard hearing-threshold-testing methods of play audiometry or, for participant 38, visual reinforcement audiometry (VRA) (Hodgson 1985).

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[1] Nucleus implants manufactured by Cochlear Limited, Macquarie University, Australia.

Table 1. Etiology and onset, hearing aid use pre CI1 and post CI1 (i.e., prior to CI2), implant type, age at CI1 and time between CIs, noise direction for testing, and mean (n = 9[1]) detection SNR in dB in each unilateral and in each bilateral condition tested for the 15 sequentially implanted participants and five simultaneously implanted participants. Values in bold are right versus left unilateral condition detection SNRs which are significantly different ($p < 0.05$), and values in bold italics are bilateral condition detection SNRs which are significantly different to the comparative unilateral condition detection SNR in the same row.

Partic no.	Etiology/ Onset (or age at diagnosis)	Hearing aid use		Nucleus CI type CI1/CI2[2]	Age at CI1/time bw CIs (yr;mo)	Age at test (yr;mo)	Noise direction	Mean (SD) detection SNR (dB)	
		Pre CI1	*Post CI1*					*Unilateral CI condition [active CI]*	*Bilateral CI condition*
P10	Unknown Congenital[5]	Poor[3]	Removed[4]	24R	0;10 / 0;12	4;9	L	**-9.0 (1.0) [right/2nd]**	***-11.0 (1.4)***
							R	**-5.4 (0.9) [left/1st]**	-6.11 (1.1)
P11	Unknown 14m	Poor	None	24R	1;1 / 1;8	4;8	L	-9.2 (0.7) [right/1st]	-11.0 (1.4)
							R	-10.6 (1.3) [left/2nd]	-9.4 (1.9)
P13	Unknown Congenital[5]	Consistent	None	24R/24RE	1;3 / 1;0	4;2	L	-8.8 (1.6) [right/1st]	-8.1 (1.5)
							R	-9.2 (1.9) [left/2nd]	NT[6]
P15	Unknown Congenital[5]	Consistent	None	24R/24RE	0;8 / 3;2	5;9	L	-11.9 (1.8) [right/1st]	-13.0 (2.0)
							R	-13.2 (1.6) [left/2nd]	NT
P19	Unknown 8m	Poor	None	24R/24RE	0;11 / 1;6	4;4	L	-3.8 (1.1) [right/2nd]	***-8.2 (1.1)***
							R	**-9.4 (1.7) [left/1st]**	NT
P20	Unknown 18m	Consistent	Removed	24RE	1;8 /0;6	4;1	L	**-6.6 (0.9) [right/2nd]**	NT
							R	**-8.6 (0.9) [left/1st]**	-8.8 (1.2)
P22	Connexin26	Poor	None	24RE	0;7 / 0;8	3;3	L	**-6.6 (1.9) [right/2nd]**	NT

	Congenital						R	**-11.0 (1.7) [left/1st]**	-10.6 (2.2)
P29	Unknown Congenital[5]	Consistent	None	24RE	1;8 / 0;8	4;3	L	-8.8 (2.9) [right/1st]	-7.4 (2.4)
							R	-6.3 (1.0) [left/2nd]	-5.0 (1.4)
P35	Unknown Congenital	Poor	None	24RE	1;2 / 1;9	4;9	L	-8.6 (1.9) [right/1st]	-10.1 (1.1)
							R	-9.0 (1.7) [left/2nd]	NT
P37	Genetic Congenital	Partial[7]	None	24RE	2;0 / 0;9	4;9	L	**-9.4 (0.9) [right/1st]**	-9.4 (1.3)
							R	**-7.0 (1.4) [left/2nd]**	-6.6 (0.9)
P43	CMV[8] 19m	Short term[9]	None	24RE	2;2 / 0;3	4;5	L	-6.3 (1.0) [right/2nd]	NT
							R	**-5.4 (0.9) [left/1st]**	***-7.7 (2.0)***
P45	Unknown Congenital	Poor	Short term	24RE	1;7 / 0;11	4;5	L	**-7.8 (1.1) [right/2nd]**	-8.2 (2.3)
							R	**-10.6 (0.9) [left/1st]**	NT
P50	Connexin26 Congenital	Partial	Removed	24RE	0;10 / 1;0	3;10	L	-8.8 (1.6) [right/2nd]	NT
							R	-8.1 (1.8) [left/1st]	-7.2 (0.7)
P65	Kernicterus Congenital	Partial	Limited[10]	24RE	0;11 / 0;9	3;9	L	**-9.0 (1.0) [right/2nd]**	NT
							R	**-11.0 (1.0) [left/1st]**	***-13.0 (1.4)***
P84	Unknown Congenital[5]	Consistent	None	24RE/512	1;3 / 0;8	5;2	L	-11.9 (1.5) [right/1st]	-10.8 (1.2)
							R	-12.6 (1.7) [left/2nd]	NT
P38	Unknown	Consistent	N/A[12]	24RE	1;9 / 0;0	3;8	L	-7.2 (1.2) [right]	-6.6 (1.7)

(Sim[11]) Congenital							R	-6.3 (1.4) [left]	NT
P49 (Sim)	CMV Congenital	Partial	N/A	24RE	0;9 / 0;0	2;9	L R	-7.2 (1.9) [right] -7.4 (1.7) [left]	-5.9 (1.5) -6.6 (1.3)
P57 (Sim)	Unknown Congenital	Consistent	N/A	24RE	0;11 / 0;0	2;11	L R	**-11.0 (1.7) [right]** **-6.7 (3.0) [left]**	-11.0 (1.4) NT
P71 (Sim)	Unknown 11m	Poor	N/A	24RE	1;4 / 0;0	3;4	L R	-7.4 (1.3) [right] -7.7 (2.0) [left]	-7.7 (3.2) NT
P87 (Sim)	Unknown Congenital[5]	Consistent	N/A	24RE	2;2 / 0;0	4;2	L R	-8.8 (1.9) [right] -10.3 (2.0) [left]	-8.8 (1.2) NT

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[1] n = 5 for P19 and P45. [2] CI2 type specified if different from CI1 type. [3] Average usage ≤1 hour/day. [4] Child continually removed aid (n=3). [5] Early diagnosis and assumed to be congenital. [6] Not tested because participant concentration, cooperation and/or availability did not allow testing in all four conditions. [7] Usage time ≤50%. [8] Cytomegalovirus. [9] For P43, parents chose not to persist after one month of bilateral hearing aid use due to lack of evidence of benefit; for P45, hearing aid worn with CI1 discarded at 2 months postoperative (8 months prior to CI2). [10] Very limited use due to otitis media. [11] Simultaneously implanted. [12] Not applicable as simultaneously implanted so no post-implantation hearing aid use.

Testing was conducted in a low-reverberation sound-proof booth. Tannoy Reveal loudspeakers were positioned at ear level at a distance of 115cm at 0^0 and at 90^0 to the right and to the left of the participant. Speech was always presented from 0^0 and noise from + or - 90^0. During play audiometry, the participant and the assistant tester were seated at a low table, with the participant facing the front loudspeaker and the assistant contralateral to the loudspeaker presenting the noise. During VRA, the participant sat on the parent's lap facing the front loudspeaker and the assistant tester sat facing the participant on a low stool below the level of the loudspeakers.

The role of the tester was to present the stimuli and record the results. The role of the assistant tester was to maintain the participant's position (facing 0^0), concentration, and understanding of the task, to judge whether a response had occurred, and to provide social reinforcement for expected behaviour and appropriate responses. During VRA, the parent and the assistant tester were "blind" to the presentation of a stimulus through the use of earplugs and masking noise presented via headphones. Such "blinding" was not used during play audiometry because the parent was not involved in the testing, and the auditory isolation of the assistant would have limited their ability to converse with the participant to maintain his or her concentration on and understanding of the task. In addition, it would not have allowed the assistant to provide immediate social reinforcement of a correct response, and may have resulted in the assistant sometimes reinforcing an incorrect response, which would have compromised the participant's conditioning. A number of aspects of the experimental design compensate for the lack of "blinding" by increasing the reliability of the measurements: testing was conducted by experienced clinicians trained to avoid bias in judging responses; although able to hear the stimulus, the assistant was unaware of the presentation level; the first measured detection SNR was discarded; control trials without stimuli were included; outliers were discarded; and the reported result was an average of repeated measurements.

The stimulus was /baba/ recorded by a male speaker with a total duration of 900 ms. The masker was continuous speech-shaped broadband noise presented at 65 dBSPL. Supra-threshold stimuli were presented until the participant was conditioned to the stimulus; i.e., until the participant consistently and clearly made the required motor response with a reasonable and consistent time delay between the presentation of the stimulus and the participant's response. Detection thresholds were then sought (defined as a detection SNR). Beginning subthreshold, the presentation level of the speech stimulus was increased in 2dB steps until a response was elicited; the SNR at which this presentation was made was recorded as the first detection SNR. The presentation level was then decreased by 4dB and the process was repeated.

One-third of trials were randomly selected as non-stimulus control trials; these trials had the same duration as a stimulus trial, but no stimulus was presented. If the assistant tester judged that a response had occurred during a non-stimulus trial, this was recorded as a false alarm. The criterion for discarding the results from a test block was a false alarm rate of ≥0.25 for any one device/noise condition; no participant reached this false alarm rate in any condition. Within each test block, the first detection SNR in each device/noise condition was discarded. Any outliers were also discarded. A detection SNR was a potential outlier if it differed by 6 dB or more from any other single detection SNR obtained in that condition in that test block. On the rare occasion that a potential outlier was recorded, a second detection SNR was measured. If this second detection SNR did not differ from any other detection SNR by ≥6 dB, it was accepted as a replacement for the original potential outlier. Conversely, if this second detection SNR also differed by ≥6 dB, the original potential outlier was accepted as a true detection SNR.

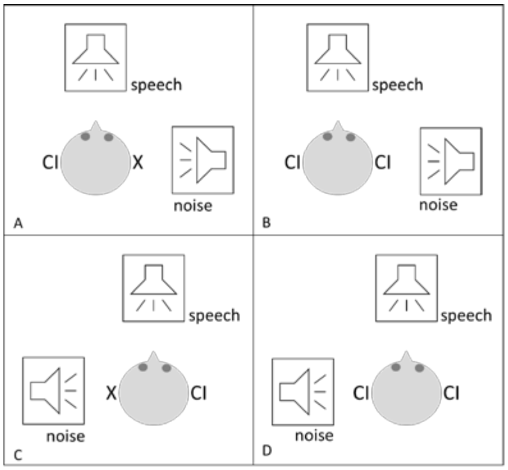

Figure 1: Diagram indicating the active and inactive (indicated by an X) CIs and the direction of speech and noise presentation for the device/noise conditions of left CI/noise right (panel A), bilateral CIs/noise right (panel B), right CI/noise left (panel C), and bilateral CIs/noise left (panel D). Comparisons of performance using each CI alone were made using the arrangement in panels A versus C, whilst comparisons of unilateral versus bilateral performance were made using the arrangements in panels A versus B and/or panels C versus D (depending on the number of conditions in which testing was completed by the individual participant).

The combined device/noise conditions for testing were: left CI/noise right, bilateral CIs/noise right, right CI/noise left, and bilateral CIs/noise left (as illustrated in Figure 1), with the majority of participants completing testing in 3 of these conditions (as described below). When sufficient detection SNRs (i.e., 4 to 6, as described below) had been measured consecutively in onedevice/noise condition, the assistant tester engaged the participant in 5 minutes of conversation within a play activity (e.g., completing a puzzle) to provide some exposure to listening in the next device condition to be tested. The order of device/noise conditions was varied across participants and across test blocks. The number of detection SNRs measured, the number of conditions tested in each test block, the number of test blocks completed, and the number of visits required depended on the concentration span and availability of each participant. For the majority of participants, 4 to 6 SNRs were measured in each of 3 conditions in each test block, the number of test blocks ranged from 2 to 4, and a total of 9 detection SNRs were measured in each of the 3 conditions. Typically, each test block was completed on a separate day with approximately one week between visits, although some participants were able to complete two test blocks in the one visit. Participants 19 and 45 completed only one test block, so that only 5 detection SNRs were measured and balancing of the order of conditions was not possible. The majority of participants could not complete testing in all 4 conditions in the one test block, and therefore data was obtained to compare performance with each CI alone, and to make the unilateral versus bilateral comparison for either the right or the left CI. Five participants were able to complete testing in all 4 conditions in the one test block, so that data was available to make the unilateral versus bilateral comparison for both the right and the left CIs. Presented in Table 1 are the device used and the relevant noise direction for each device/noise condition in which each individual participant was tested.

Results

Table 1 presents the mean detection SNR for each participant in each condition tested. A General Linear Model was used to analyse all results for the group, with device/noise condition as a fixed factor, subject as a random factor, and time between CIs and age at CI2 as covariates. No significant result was found for either covariate ($F(1,40) \leq 0.24$, $p \geq 0.624$), indicating that they were not related to the detection SNRs. No significant main effect of device/noise condition was found ($F(3,40) = 0.76$, $p = 0.305$), indicating that there was no significant difference in detection SNR for the group between the unilateral and bilateral CI conditions when adding the right CI, or when adding the left CI (these two comparisons are illustrated in panels A versus B and panels C versus D, respectively, of Figure 1). This result, of no significant main effect, also indicates that, for the group, there was no significant difference in detection SNR between the two unilateral conditions (i.e., right CI versus left CI; this comparison is illustrated by panels A versus C of Figure 1).

Arguably, for the sequential participants only, it would be more meaningful to consider each CI as the first or second CI rather than as the left or right CI. To this end, the same General Linear

Model was applied to the data for the sequential group only, with the levels of the device/noise condition altered to: CI1/noise contralateral to CI1, bilateral CIs/noise contralateral to CI1, CI2/noise contralateral to CI2, and bilateral CIs/noise contralateral to CI2. No significant result was found for the covariates ($F(1,14) \leq 0.15$, $p \geq 0.704$). No significant main effect was found ($F(3,14) = 1.0$, $p = 0.395$), indicating that, for the sequential group, there was no significant difference in detection SNR between the unilateral and bilateral CI conditions when adding the first CI or when adding the second CI. The result also indicates that, for the sequential group, there was no significant difference in the detection SNR between the two unilateral conditions (mean SNR CI1: -8.4dB (SD 2.5) versus CI2: -9.2dB (SD 2.0)).

For each individual participant, a one-way ANOVA was conducted on all data, with the main factor of device/noise condition having the same levels as described for the group analysis. Note again that 15 participants were able to complete testing in only 3 conditions, so that the levels of the device/noise factor were therefore left CI/noise right, right CI/noise left, and either bilateral CIs/noise left or bilateral CIs/noise right. Also as noted above, only 5 detection SNRs were measured for P19 and P45. A significant effect of device/noise condition was found for 9 participants: P43, P57, P20, P22, and P65 ($F(2,24) \geq 5.9$, $p \leq 0.009$), P19 and P45 ($F(2,12) \geq 4.8$, $p \leq 0.03$), and P37 and P10 ($F(2,12) \geq 16.2$, $p \leq 0.001$).

For these 9 participants with a significant main effect of device/noise condition, Tukey’s post-hoc testing (Family error rate = 0.05) was used to compare performance in the left CI/noise right versus right CI/noise left conditions to identify if there was a significantly better-performing CI and poorer-performing CI (this comparison is illustrated by panels A versus C of Figure 1). Figure 2 presents the mean difference in detection SNR (lowest SNR minus highest SNR) between the two CIs for all 20 participants.

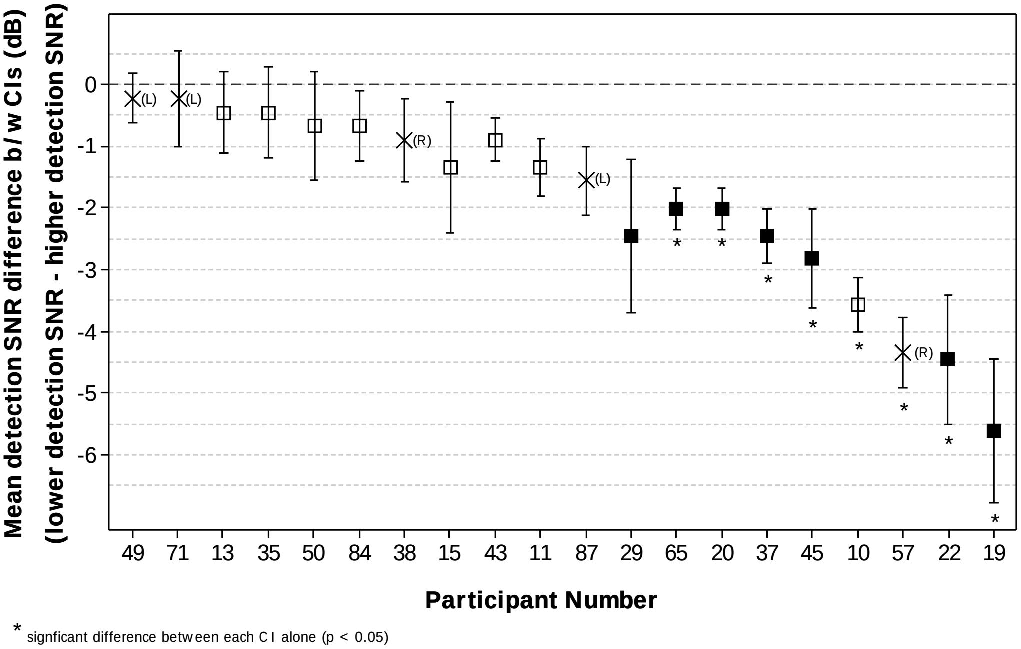

Figure 2: Mean (n = 9; n = 5 for P19 and P45) detection SNR difference in dB between each CI alone for each of the 20 participants. Error bars represent +/-1SE. Crosses represent simultaneously implanted participants; the CI with the lower detection SNR is indicated in parentheses. Squares represent sequentially implanted participants; closed squares indicate that the detection SNR was lower with CI1 and open squares indicate that the detection SNR was lower with CI2. Asterisks indicate a significant difference in detection SNR between implants ($p < 0.05$).

As shown, 8 participants, including one simultaneously implanted participant, demonstrated a significant difference in detection SNR between the two CIs. For these significant results, the relevant detection SNRs in each unilateral condition for each participant are bolded in Table 1. For the 7 sequentially implanted participants, the better-performing CI was CI1 for 6 individuals and CI2 for one individual.

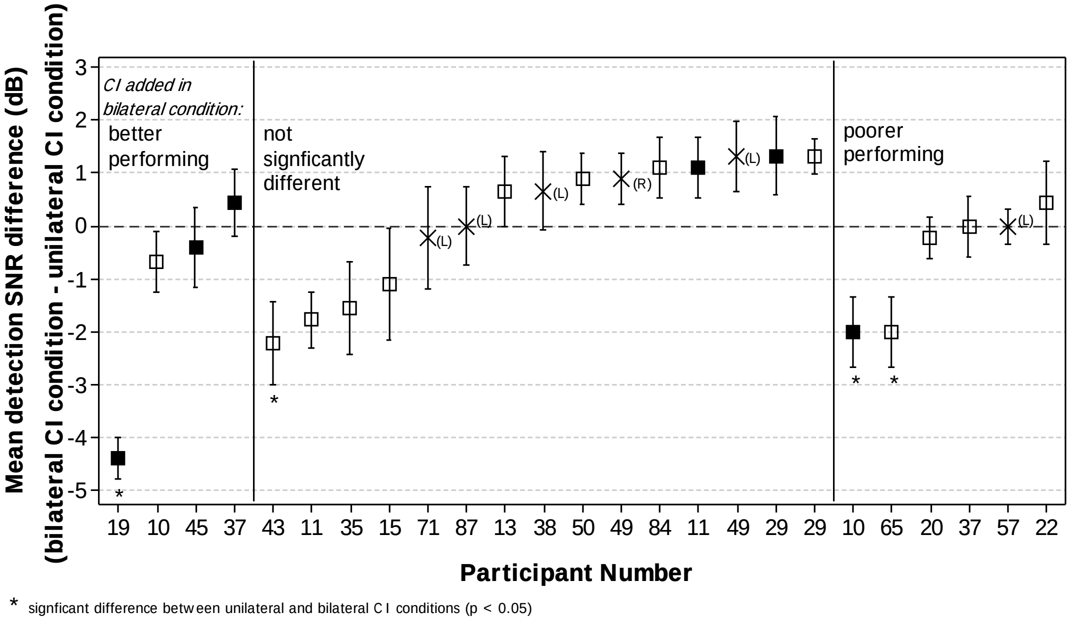

Figure 3: Mean (n = 9; n = 5 for P19 and P45) detection SNR difference in dB between the bilateral CI condition and the unilateral CI condition with the same noise source for each implant for each of 5 participants (P10, P11, P29, P37 and P49) and for one implant only for the remaining 15 participants. Error bars represent +/-1SE. Crosses represent simultaneously implanted participants; the CI added in the bilateral condition is indicated in parentheses. Squares represent sequentially implanted participants; closed squares indicate that CI1 was the CI added in the bilateral condition and open squares indicate that CI2 was the CI added in the bilateral conditions. Asterisks indicate a significant difference in detection SNR between the unilateral and bilateral CI conditions ($p < 0.05$).

For the 9 participants with a significant main effect of device/noise condition in the ANOVA, Tukey's post-hoc testing was also used to compare performance in the left CI/noise right versus bilateral CIs/noise right conditions and/or the right CI/noise left versus bilateral CIs/noise left conditions to identify if there was a binaural benefit over the shadowed ear (these comparisons are illustrated by panels A versus B and panels C versus D of Figure 1). Figure 3 presents the mean difference in detection SNR between the bilateral CI and unilateral CI conditions for all possible comparisons for the 20 participants (i.e., one comparison for the 15 participants tested in one bilateral condition and two comparisons for the 5 participants tested in each bilateral condition). Based on the results of the post-hoc testing reported above, the mean differences are classified as occurring when unilateral condition testing had shown the CI added in the bilateral condition to be a better-performing CI (left-hand panel), a not significantly different CI (middle panel), or a poorer-performing CI (right-hand panel). As shown, only 4 participants demonstrated a significant improvement in the bilateral CI condition: P19 (when the CI added in the bilateral condition was better performing), P43 (when the CI added in the bilateral condition was not significantly different), and P10 and P65 (when the CI added in the bilateral condition was poorer performing). For these significant results, the relevant detection SNRs in the bilateral condition for each participant is bolded and italicized in Table 1. Note that P10 did not demonstrate a significant improvement in the bilateral CI condition when the CI added in the bilateral condition was better performing.

As described above, the one-way ANOVA conducted for each individual ultimately led to the calculation of the number of individuals demonstrating a significant difference in performance between each CI alone and the number of individuals demonstrating a binaural benefit and. Although the process described above accounted for the family-wise error rate resulting from the two or three comparisons made across different device/noise conditions in the post-hoc testing for each individual, it did not account for the family-wise error rate resulting from the 20 separate ANOVAs conducted. It should be noted that, if the family-wise error across the 20 ANOVAs was set at 0.05 and the step-down Bonferroni method was applied, there were minimal changes to the results. The changes were that the one-way ANOVA no longer indicated a significant device/noise effect for P45 (original post-hoc testing above indicated a significant difference between each CI alone for P45) or for P43 (original post-hoc testing above indicated a significant binaural benefit for P43 when the CI added in the bilateral condition was not significantly different to the other CI). Thus, with this more conservative approach, a significant difference between each CI alone would be demonstrated for 7 out of 20 individuals rather than for 8, and a significant binaural benefit would be demonstrated in 3 out of 25 comparisons rather than in 4.

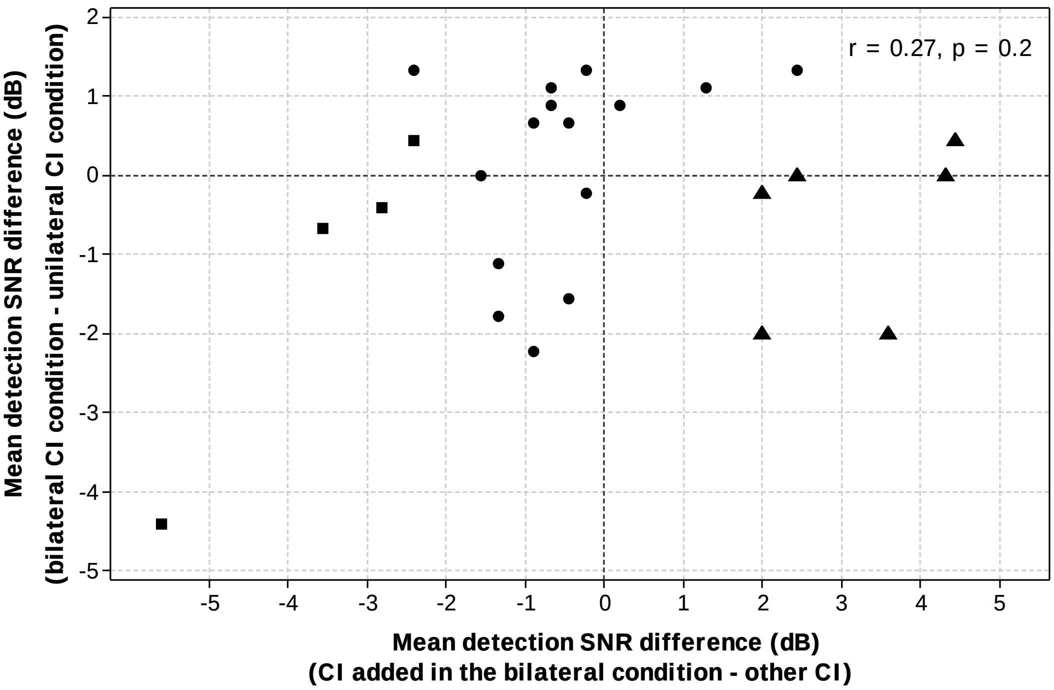

Figure 4: Mean detection SNR difference in dB between the bilateral CI condition and the unilateral CI condition as a function of the mean detection SNR difference between each CI alone (calculated as the unilateral condition SNR for the CI added in the bilateral condition minus the unilateral condition SNR for the other CI). Squares represent instances in which the CI added in the bilateral condition was the better-performing CI when each CI was assessed in the unilateral condition, circles represent instances in which the performance with each CI was not significantly different, and triangles represent instances in which the CI added in the bilateral condition was the poorer-performing CI.

Given the variation in results across participants, the relationship between the magnitude of the binaural benefit and the magnitude of the difference between CIs was examined and is illustrated in Figure 4. The figure presents the mean detection SNR difference between the bilateral CI and the unilateral CI condition (i.e., the binaural benefit) as a function of the mean detection SNR difference between each CI alone. The factor of interest, with respect to the performance with each CI alone, was "what was the performance with the CI added in the bilateral condition relative to that of the other CI when each was assessed in the unilateral condition?". This question was asked for each of the 25 unilateral/bilateral comparisons made across the 20 participants. As such, the mean detection SNR difference between each CI alone presented on the x-axis of Figure 4 was calculated as the detection SNR for the CI added in the bilateral condition minus the detection SNR for the other CI. A Pearson correlation coefficient indicated that there was no significant relationship between the magnitude of any binaural benefit and the magnitude of any difference between each CI alone (r = 0.27, p = 0.2).

Discussion

The group analysis provided no evidence of lower detection SNRs for speech sounds in background noise in the bilateral CI condition over the unilateral CI condition, thus the hypothesis was not supported by the group results. There was also no evidence of a difference in detection SNRs between the right and left CI for the overall group, or between the first and second CI for the sequentially implanted participants. For this modest sized group of 20 individuals, the number of unilateral versus bilateral condition comparisons made was relatively small (n = 25), thus potentially limiting the power of the analysis to detect a binaural benefit. The 25 mean detection SNR differences displayed in Figure 3 represent the outcome of these 25 unilateral versus bilateral comparisons included in the group analysis. These results in Figure 3 do not suggest that the result was driven by low power. The mean detection SNR in the bilateral CI condition was higher than that in the unilateral CI condition (a result above 0 for the difference score displayed in Figure 3) for 11 of the 25 comparisons; as 2 comparisons were completed for some individuals, this represents results obtained for 9 of the 20 individuals. The mean detection SNR in the bilateral CI condition was equal to that in the unilateral CI condition (a result at 0 for the difference score displayed in Figure 3) for an additional 3 comparisons, representing results for an additional 2 individuals. Thus, the unilateral versus bilateral condition difference scores were relatively evenly spread around the 0 line.

For individual participants, a comparison of performance in each unilateral condition was made to determine if the CI added in the bilateral condition was a poorer- or better-performing CI. For the participants with simultaneous implants, a majority (4 out of 5) showed no significant difference in detection SNRs between the two CIs. This result was expected given that the pre-operative hearing experience and/or auditory deprivation, and the postoperative CI experience are likely to be the same or very similar between the ears for these young children. Similar electrophysiological, speech perception, and programming outcomes for each CI have been demonstrated previously for groups of children implanted simultaneously. Wave latencies for eIII and eV evoked at activation of each implant were not significantly different for a group of 10 children (Gordon et al. 2007a*)*. Spatial unmasking benefit was not significantly different with noise moved to -90^0 versus +90^0, suggesting detection abilities were similar with left and right CIs for the group of 10 children (Chadha et al. 2011). Speech perception scores (on age-dependent open or closed-set word tests) were not significantly different with either implant alone for a group of 6 children at 6 to 12 months and at 18 to 36 months postoperative (Gordon and Papsin 2009). Unpublished data for 28 children from the present authors' laboratory has also shown no significant group difference between CIs for electrical stimulation levels (threshold- and comfortable-levels) measured during standard clinical programming sessions in the early post-activation period and after 2 years of bilateral CI experience (personal communication, R. Abdi, December 14th 2015).

For the remaining participant with simultaneous CIs, the detection SNR was 4.3 dB lower with one CI compared to the other. There is some evidence from previous studies that programming and electrophysiological outcomes in the first 2 years postoperative may differ between CIs for a small minority of young children who receive simultaneous CIs. Unpublished results for a group of 28 children from the present authors' laboratory indicate that the right CI-to-left CI ratio for the behaviourally determined input dynamic range was greater than 1.5 for 4 individuals at one or more of the basal, medial and apical regions of the electrode array at 2-years postoperative (personal communication, R. Abdi, December 14th 2015). Gordon et al. (2007a) found that the pattern of change in the latency of wave eV over the first 15 months of bilateral CI use was not consistent between ears for one of two children. These authors suggested that the pathways related to each CI may be at least partially independent, and that the effects of the hearing loss or the activity-dependent developmental processes may be different between ears. Functional outcomes can also differ; a strong preference for one CI over the other was reported for one child from a group of 19 (Galvin et al. 2012). At 12 months postoperative, the child typically wore the right CI for only 2.5 hours daily, despite wearing the left CI full time. Given the small numbers of participants across studies who demonstrated different outcomes with simultaneous CIs, it is difficult to identify factors which may have contributed to the variation between CIs. For the present participants, age at onset of hearing loss, preoperative hearing levels, preoperative hearing aid use, and consistency of CI use were known to be similar across ears. All participants were programmed at the Royal Victorian Eye and Ear Hospital Clinic by experienced paediatric clinicians using a standardised approach, including the use of default settings in each CI for mapping parameters such as processing strategy and pulse width. Differences in neural survival, intraoperative trauma, electrode array position, and auditory processing abilities could all potentially contribute to differences in outcomes with each CI.

For the present participants with sequential bilateral implants, around half (8 out of 15) also showed no significant difference in detection SNRs between the two CIs. For children who receive their sequential CIs at a young age, and with a short inter-implant delay, similar electrophysiological and speech perception outcomes with each CI have been demonstrated following bilateral CI experience. Although EABR studies have shown delayed wave eV latencies for the newly implanted ear versus the ear with CI experience (Gordon et al. 2007a), these inter-ear differences decreased with bilateral CI experience for children first implanted at a younger age (≤ 2 years) and with a short delay between implants (Gordon et al. 2007b). Similar speech perception outcomes (on age-dependent open or closed-set word tests) with each implant alone have been shown for a group of 15 children first implanted before 3 years of age and receiving a second implant within 12 months (Gordon and Papsin 2009).

Seven of the present 15 participants with sequential CIs demonstrated a superior detection SNR with one CI compared with the other. For most (n = 6) of these children, the superior outcome with CI1 was likely due to the younger age, and therefore the greater neural plasticity, at implantation of CI1 versus CI2, the neural reorganization which may have occurred during the period of unilateral stimulation via CI1, and the longer duration of auditory stimulation via CI1. Superior speech perception outcomes with CI1 have been reported previously for large groups of children tested in quiet even after 18 to 36 months of bilateral experience; however the majority of these children were older than 4 years at bilateral implantation and had more than 2 years between implants (Gordon and Papsin 2009; Sparreboom et al. 2011). For the measurable demographic factors of age at CI1, time since first implantation, time between CIs, and age at bilateral implantation, the relationship between each of these factors and the degree of difference in performance with each CI alone was not significant for the overall participant group ($r \leq 0.24$; $p \geq 0.30$) or for the 15 participants with sequential implants ($r = 0.46$, $p = 0.086$ for the difference in performance with each CI alone and the time since first implantation; and $r \leq 0.30$; $p \geq 0.284$ for all other relationships). These are not surprising results given the selection criteria of bilateral implantation under 4 years and bilateral experience of 2 years. These criteria resulted in a relatively homogenous group with respect to these factors, and also to the other factors examined, which were related to the selection criteria and to the standard practice of early implantation at the implant clinic attended by all participants. The relatively homogeneity of the group made it more difficult to determine if any relationship existed between outcomes and demographic factors.

For one participant with sequential implants, the detection SNR for CI2 was superior to that for CI1. This was a more surprising result although, as noted above, a number of factors which may contribute to performance with an individual CI may differ across ears. It is therefore possible that obtaining a second implant may capture the "better" ear in terms of potential perceptual outcomes.

It is difficult to predict the relationship between detection SNRs and everyday speech perception performance in noisy situations. Interestingly, the parents of 18 of the participants reported that their child's daily listening and communication performance was similar with either CI alone; the remaining two reported that their child only ever wore bilateral CIs, so that they were unable to comment on performance with either CI alone.

The aim of the present study was to measure binaural benefit over the shadowed ear. For the majority of individual participants, the results did not support the proposed hypothesis that detection SNRs would be lower in the bilateral CI condition. For the 20 participants, 25 unilateral versus bilateral condition comparisons were made (with the unilateral/bilateral comparison made with each CI for 5 participants). Of these 25 comparisons, only 4 comparisons for 4 different participants indicated a superior detection SNR in the bilateral CI condition. For the one participant for whom the CI added in the bilateral condition was the better-performing CI, it is not possible to separate improvement due to any binaural benefit from that due directly to the addition of the better-performing CI. For the remaining 3 participants demonstrating a superior result in the bilateral CI condition (of around 2dB), the CI added in the bilateral condition was the poorer-performing CI or was not significantly different. Thus, these participants demonstrated a binaural benefit from the addition of the second CI. There were no particular unique demographic characteristics for these 3 participants with sequential implants. It is worth noting that the participant (P10) for whom the unilateral/bilateral comparison was made with each CI, did not demonstrate a superior detection SNR when the better CI was the CI added in the bilateral condition. It must also be considered if any participants demonstrated an inferior detection SNR in the bilateral CI condition. Given that the CI added in the bilateral condition was ipsilateral to the noise source, the overall signal received by the participants in the bilateral CI condition contained more noise. Thus, it is an important result that the introduction of the noisy signal via the CI added in the bilateral condition did not result in a significantly higher (poorer) detection SNR for any participant.

The general finding of no *binaural* benefit for the majority of participants, with some evidence of benefit for only a small number of participants, is consistent with a previous study employing the same test protocol with a very small number of young participants with less (6 months) bilateral experience (Galvin et al. 2008). It is also consistent with the lack of benefit shown for small numbers of older participants assessed on closed-set speech discrimination in the same speech/noise configuration in the unilateral and bilateral CI conditions (Galvin et al. 2007; 2009). One study did report a mean group benefit for spondee discrimination in a similar speech/noise configuration (Peters et al. 2007), but did not report if a significant benefit was gained by individual participants.

An examination of demographic factors which may have influenced the results showed that, for this group, there was no relationship between the degree of difference in performance between the unilateral and bilateral CI conditions (i.e., the binaural benefit) and the degree of difference in performance in the unilateral condition between the CI added in the bilateral condition and the other CI (refer to Figure 4). Nor was the binaural benefit related to the demographic factors of age at CI1, time since first implantation, time between CIs, or age at bilateral implantation (overall group: $r \leq 0.26$; $p \geq 0.266$; sequential participants: $r \leq 0.13$; $p \geq 0.642$). As noted above, the potential for identifying relationships with these demographic factors may have been limited by the fact that the group was relatively homogenous for most of these factors.

As reviewed above, previous studies have provided clear evidence that bilateral implantation provides greater perceptual benefits to children. Nevertheless, there is insufficient evidence to conclude that children using bilateral implants gain access to all of the binaural hearing benefits gained by a listener with normal hearing through the use of two ears. In the present study, the group and most individual participants failed to demonstrate a binaural benefit with the addition of a second CI over the shadowed CI alone. For this relatively small group, the spread of binaural benefit measures (i.e., unilateral versus bilateral difference scores) does not suggest that the result was driven by low power. Of the 21 comparisons made for 18 different individuals when the CI added in the bilateral condition was *not* the better-performing CI, a binaural benefit was demonstrated for 3 participants on one comparison each. It is possible that binaural hearing skills for these young children will develop with more bilateral CI experience. Eapen et al. (2009) evaluated the type and degree of benefit received by adult bilateral implant recipients as experience increased over the 1 to 4 year postoperative period. When compared to other benefits, such as the headshadow effect, the period of development was longer for the “binaural squelch effect” (the term used by the study authors to refer to the benefit gained in the bilateral condition over the shadowed ear alone). With respect to particular types of benefits of bilateral hearing, such as the benefit over the shadowed ear evaluated here, it will be worthwhile for future studies to evaluate very long-term outcomes for children with simultaneous CIs. These children will have received bilateral input from the time of first implantation, and potentially from infancy, giving maximum opportunity for the development of the binaural auditory system. Current evidence-based information, such as that reported here, should be incorporated into preoperative counselling. It is important that families are informed of the likely and significant benefits of bilateral implantation, but also the fact that some binaural benefits may not be available to an individual and/or may take a number of years to develop.

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