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TITLE PAGE

Factors Affecting Sound-Source Localization in Children with Simultaneous or Sequential Bilateral Cochlear Implants.

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ABSTRACT

Objectives:

The study aimed to determine the effect of inter-implant interval and onset of profound deafness on sound localization in children with bilateral cochlear implants, controlling for cochlear implant manufacturer, age and time since second implant.

Design:

The authors conducted a retrospective, observational study using routinely collected clinical data. Participants were 127 bilaterally implanted children aged 4 years or older, tested at least 12 months post-second implant. Children used implants made by one of three manufacturers. Sixty-five children were simultaneously implanted, of whom 43% were congenitally, bilaterally profoundly deaf at 2 and 4 kHz and 57% had acquired or progressive hearing loss. Sixty-two were implanted sequentially (median inter-implant interval = 58 months, range 3 to 143 months) of whom 77% had congenital and 23% acquired or progressive bilateral profound deafness at 2 and 4 kHz. Children participated in a sound-source localization test with stimuli presented in a random order from 5 loudspeakers at -60, -30, 0, +30 and +60 degrees azimuth. Stimuli were pre-recorded female voices at randomly roved levels from 65 to 75 dB(A). Root mean square (RMS) errors were calculated. Localization data were analysed via multivariable linear regression models, one applied to the whole group and the other to just the simultaneously implanted children.

Results:

Mean RMS error was 25.4 degrees (SD = 12.5 degrees) with results ranging from perfect accuracy to chance level (0 to 62.7 degrees RMS error). Compared to simultaneous implantation, an inter-implant interval was associated with worse localization by 1.7 degrees RMS error per year ($p < 0.001$). Compared to congenital deafness, each year with hearing thresholds better than 90 dB HL at 2 and 4 kHz bilaterally prior to implantation led to more accurate localization by 1.3 degrees RMS error ($p < 0.005$). Every year post-second implant led to better accuracy by 1.6 degrees RMS error ($p < 0.05$). Med-El was associated with more accurate localization than Cochlear by 5.8 degrees RMS error ($p < 0.01$) and with more accurate localization than Advanced Bionics by 9.2 degrees RMS error ($p < 0.05$).

Conclusions:

Inter-implant interval and congenital profound hearing loss both led to worse accuracy in sound-source localization for children using bilateral cochlear implants. Inter-implant delay should therefore be minimized for children with bilateral profound hearing loss. Children presenting with acquired or progressive hearing loss can be expected to localize better via bilateral cochlear implants than their congenitally deaf peers.

INTRODUCTION

Spatial listening includes the ability to hear where sounds come from. This skill is important for children in social, recreational and educational settings as well as for their personal safety. In individuals with normal hearing, sound localization (i.e. the ability to indicate which of multiple sound-sources a sound came from, in the horizontal plane) is possible because central auditory processing makes use of inter-aural level differences (ILDs), inter-aural time differences (ITDs) and spectral cues (Musicant & Butler, 1984). These cues are disrupted for people with hearing impairment (Noble et al., 1994). One aim of auditory rehabilitation is to restore binaural cues by providing appropriate hearing technology for both ears, with the hope that spatial listening skills might be restored or developed to some extent despite the hearing impairment.

Profoundly deaf children can learn to localize sounds significantly better with two cochlear implants (CIs) than one (Steffens et al. 2008; Lovett et al. 2010; Godar & Litovsky 2010; Galvin et al. 2010; Grieco Calub & Litovsky 2010; Vincent et al. 2012). However localization accuracy for children with bilateral CIs (BiCIs) varies from near-normal to an inability to localize above chance level (Grieco-Calub & Litovsky 2010; Van Deun et al. 2010, Murphy et al. 2011). The reasons for this variation appear complex and are not yet fully understood (Litovsky & Gordon 2016). It is likely that clinicians and CI manufacturers can influence some of the factors affecting sound localization, therefore greater understanding of this area could benefit many profoundly deaf children.

A number of variables with the potential to influence localization have been identified by previous researchers. First, auditory deprivation is likely to negatively affect localization via neural degeneration and cortical reorganization (Sharma et al. 2007a, 2007b; Sparreboom et al. 2011; Gordon et al. 2011; Litovsky & Gordon 2016). Consistent with this, shorter inter-implant interval, younger age at second implant (CI2) and later onset of hearing-impairment are associated with better localization in behavioural studies of children (Steffens et al. 2008; Grieco-Calub & Litovsky 2010; Van Deun et al 2010; Strom-Roum et al. 2012; Asp et al. 2015). However, a limitation of these studies is the high inter-correlation of time-dependent variables, e.g. age at first CI (CI1), age at CI2, age at test and inter-implant interval (Grieco-Calub & Litovsky 2010; Van Deun et al., 2010; Asp et al. 2015) which makes differentiation between the effects of these variables difficult. Further, due to other limitations in previous studies, the effect of inter-implant interval on localization ability is not well understood. For example, most studies are likely underpowered due to insufficient sample size (Van Deun et al., 2010; Asp et al., 2011; Vincent et al., 2012), or make comparisons across different populations, i.e. post-lingually deafened adults versus congenitally deaf children (Litovsky et al., 2004).

A second factor with the potential to influence localization ability is the cochlear implant system used. Physical characteristics such as the number, separation and insertion depth of the electrodes vary between systems, as do microphone characteristics. Each of these could feasibly influence the binaural perception of sound. Differences in speech processing strategies including peak-picking versus continuous interleaved stimulation (Wilson et al., 1991), and variation in the knee-points, speed, complexity and frequency specificity of compression circuits may be influential on ILD representation (Vaerenberg et al., 2014). Representations of temporal fine structure also differ between systems and might feasibly influence a user’s ability to exploit ITDs (Eklöf & Tideholm, 2018; Thakkar et al., 2018). It is therefore important to control for differences in implant and speech processing characteristics when examining localization outcomes.

Finally, age and binaural listening experience are known to influence children’s localization outcomes. Normally-hearing children continue to improve on tests of sound localization until the age of around 5 to 7 years (Van Deun et al. 2009; Lovett et al. 2012). For sequentially implanted children, localization skills develop over the course of several years after receiving their CI2 (Litovsky et al. 2006; Asp et al. 2011; Kühn et al. 2013; Sparreboom et al. 2015). It is therefore important that age-related changes are accounted for when investigating localization ability development in CI users.

Given these potential influences on localization ability, and our lack of understanding of how they impact sound-source localization, the present study aimed to investigate the effects of inter-implant interval and onset of profound deafness on sound-source localization, whilst controlling for CI manufacturer, age, and time since CI2 on both simultaneously and sequentially implanted children.

METHODS

Participant selection and data collection

This study was a retrospective, observational study using routinely collected clinical data. Children using BiCIs, under the care of our service, aged 4 years or older and without language and/or developmental delay that would preclude participation (as assessed by a relevant professional at a prior clinical appointment) were invited for assessment. In line with candidacy criteria in the UK (NICE TAG 166, 2009) unaided hearing threshold levels were 90 dB HL or worse at 2 and 4 kHz bilaterally prior to implantation. Data were excluded from analysis for children with visual impairment that prevented them from seeing the loudspeakers (N=1), children who withdrew co-operation before completing the full number of test trials (N=1), children whose language comprehension was not sufficient to understand the task (N=3), and children who completed the test trials but were uncooperative or distracted to the point where the tester deemed their responses unreliable (N=7). Sound-source localization data from the remaining 127 children, with interval post-CI2 ranging from 1 to 6 years, were analysed. Characteristics of these children are summarised in Table 1.

Measurement of sound-source localization

Tests were administered via the A-B-York Crescent of Sound (Kitterick et al. 2011), a semi-circular array of loudspeakers and monitors. The loudspeakers (Plus XS.2., Canton) were arranged at a height of 1.1m in a semi-circle of radius 1.45m and were controlled by custom software that produced simultaneous output via a digital-to-analogue converter (Ultralite Mk3, MOTU) and five dual-channel amplifiers (RA-150, Alesis). The software also controlled video monitors situated below the active loudspeakers, used as part of the patient response. The children sat on a chair in front of a table, facing the central loudspeaker and equidistant from all loudspeakers. The study used the localization test developed by Kitterick et al (2011) and Lovett et al. (2012). Active loudspeaker locations were located at −60, −30, 0, +30 and +60 degrees azimuth (negative angles denote locations to the left). The positions of the test equipment relative to the child are shown in Figure 1. The test software dictated that the maximum number of active loudspeakers was five. Stimuli were pre-recorded voices saying “Hello, what’s this?”. Five different female talkers were used, 1 of whom was randomly selected on each trial by the software. The average presentation level was 70 dB(A), randomly roved by ±5 dB in 1 dB steps. Children were instructed to face directly ahead whilst listening for the stimuli, however no attempts were made to restrict head-movements during stimulus presentation.

The assessments were usually administered by one audiologist working alone. This tester would be seated across the room, operating the equipment via a desk-top keyboard and monitor. A second tester was also present if this was recommended in the child’s medical notes. The second tester sat close by the child to help focus their attention. The testers were not blinded to the child’s medical history or implant model as knowledge of these was necessary to provide informed clinical care, ensure device function and counsel the family. However, as this was a retrospective study, testers were blind to how the data would be used for the purposes of this study.

One training presentation was given from each of the 5 active loudspeakers and for these the children were shown which loudspeaker the voice had come from. Every child then proceeded to the test trials regardless of their accuracy on the training trials. Six test stimuli were presented from each active loudspeaker so that there were 30 test trials. The test software randomly varied the loudspeaker from which stimuli were presented. Two methods could be used for the localization test, to suit each child’s interest and ability. The video monitors could show numbers 1 to 5 beneath each active loudspeaker and the child was asked to say the corresponding number or to point to the loudspeaker that they thought the sound came from. The alternative method involved placing coloured blocks of differing shape in front of the child whilst each monitor displayed a photograph of a different block. The child’s task was to locate the source of the sound and pick up the block displayed on the monitor below that loudspeaker. Children’s continuing participation was praised regardless of their accuracy. Reminders to listen were given as needed.

Analysis

For each child, sound-source localization accuracy was measured via RMS error of the 30 test trials. Linear multivariable regression models were used to explore the effects of a number of explanatory variables on sound-source localization accuracy. These were inter-implant interval, age at onset of profound deafness, CI manufacturer, chronological age and time post-CI2. Inter-implant interval, age at onset of profound deafness, chronological age and time post-CI2 were continuous variables measured in months. Profound hearing loss was defined as unaided hearing threshold levels of 90 dB HL or worse at 2 and 4 kHz (these frequencies are used to determine candidacy in the UK and hearing threshold levels at other frequencies therefore were not always available). CI manufacturer was entered into the model as a categorical variable with Med-El arbitrarily chosen as the reference category. For each child left and right CIs were from the same manufacturer. Speech processor models were always the same for right and left ears, however CI electrode array model sometimes differed between ears, e.g. if a newer system was available at the time a second, sequential CI was given. In one case a simultaneously implanted child had been re-implanted with a different model following unilateral device failure (See Table 1). Regardless of manufacturer, all children were programmed in omnidirectional microphone mode. See Table 2 for a summary of CI system characteristics. As shown in Table 1, children using Advanced Bionics devices were all simultaneously implanted. To determine whether this limited our analysis, the effect of CI manufacturer on sound-source localization accuracy was also explored via a regression model using data from simultaneously implanted children only.

For congenitally deaf children, older age at CI1 and CI2 imply longer periods of auditory deprivation. This can be detrimental to sound localization ability (Van Deun et al. 2010; Grieco-Calub et al. 2010). However with acquired and progressive losses, older age at CI1 and CI2 may be due to having useful acoustic hearing for a longer time, resulting in less auditory deprivation, which might be expected to improve a child's localization with CIs (Grieco-Calub & Litovsky 2010; Killan et al. 2015). For these reasons, whilst age at CI1 and CI2 were recorded, they were not used in the regression analyses. Table 3 shows ages at CI1 and CI2 by manufacturer for the children born with profound hearing loss at 2 and 4 kHz in at least one ear.

RESULTS

Across all 127 children RMS error ranged from perfect accuracy to chance, i.e. 0.0 to 62.7 degrees[1]. Mean RMS error was 25.4 degrees (standard deviation, SD = 12.5 degrees). Figure 2 shows a scatterplot of RMS error as a function of inter-implant interval (months). Data-points at 0 months are from children who received simultaneous CIs. The mean RMS error for this group was 21.6 degrees (SD = 11.07 degrees), with a range broadly consistent with that seen for the remaining sequentially implanted children (mean RMS error = 29.5 degrees; SD = 12.7 degrees). RMS error is seen to increase with increasing inter-implant interval. Table 4 shows the results of the regression model, which confirms this relationship. Each month's wait between CI1 and CI2 was associated with less accurate localization by 0.14 degrees RMS error ($p < 0.001$).

Figure 3 shows the relationship between RMS error and age at onset of profound hearing loss (months). In this figure the data-points at 0 months are from congenitally profoundly deaf children. This group had mean RMS error of 28.6 degrees (SD = 12.1 degrees) and a similar range of RMS error to the acquired/progressive children, i.e. the other data-points in the figure, whose mean RMS error was 20.7 degrees (SD = 10.5 degrees). RMS error is seen to decrease with increasing age at onset of hearing loss. This was shown to be a significant effect by regression analysis, with RMS error improving by 0.11 degrees for each month delay in the onset of bilateral profound hearing loss ($p < 0.01$).

RMS error is plotted against age at test in Figure 4. No clear trend is evident, as confirmed by regression analysis ($p = 0.47$). Figure 5 shows RMS error against time post-CI2 (months).

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[1] Chance performance being 62 degrees RMS error, Pádraig Kitterick, personal communication.

Data points are clustered around 1, 2 and 4 years post-CI2, as these were standard assessment intervals. Although trends are difficult to discern from subjective inspection of the figure regression analysis, controlling for the other variables, found a significant reduction of 0.13 degrees per month post-CI2 ($p < 0.05$). Significant differences were obtained between the manufacturers. Med-El systems were associated with more accurate localization, with RMS error 5.79 degrees smaller than Cochlear ($p < 0.01$) and 9.19 degrees smaller than Advanced Bionics ($p < 0.05$). As all Advanced Bionics users were simultaneously-implanted, a second model exploring the effect of CI manufacturer using only data from simultaneously implanted children was performed. This gave similar results to the first model, suggesting that the differences in localization seen between CI systems was not materially affected by whether a child received their implant simultaneously or sequentially (Table 5).

DISCUSSION

Previous research is limited in its ability to provide information on potential influencing factors on sound-source localization ability. Limitations include small sample size, inability to differentiate between the effects of time-based factors and comparisons across different populations. The present study therefore aimed to investigate the effects of factors that influence localization ability, namely inter-implant interval and onset of profound deafness, whilst controlling for CI manufacturer, age and time since CI2, for simultaneously and sequentially implanted children. This was achieved via multiple regression analysis of routinely collected clinical data from a large number of children. This allowed analysis of the independent effects of a number of explanatory variables on localization accuracy (measured via RMS error).

We found a broad range of localization accuracy, consistent with other studies of bilaterally implanted children. Our whole group mean RMS error was 25.4 degrees, ranging from 0.0 to 62.7 degrees. Zheng et al (2015) reported mean RMS errors of 19 children, 4 of whom had some acoustic experience prior to BiCI and 8 of whom had less than one year inter-implant interval. When first assessed with mean BiCI experience of 29.8 months, mean RMS error was 31.3 degrees, falling to 26.2 degrees for the same children at a later assessment interval. This is comparable to the present study. Grieco-Calub and Litovsky (2010) report mean RMS error of 37.4 degrees (range 19 to 56 degrees) for 19 sequentially implanted children, around half of whom were congenitally deaf. Van Deun et al. (2010) report a very similar mean RMS error of 38 degrees from 30 children who were all implanted sequentially and two thirds of whom were congenitally deaf. Compared to Grieco-Calub & Litovsky (2010) and Van Deun et al. (2010) our children localized with smaller RMS error on average. This may be due to the relatively longer duration of BiCI experience of the children in our study, the larger proportions of children with acquired and progressive losses and simultaneous implantation, and likely methodological differences also. Asp et al. (2011) reported bilaterally implanted children's localization in terms of Error Index. Outcomes also varied from perfect accuracy to chance performance for a five loudspeaker array localization task. We found greater mean RMS error than that of normally-hearing children, who typically perform the task with perfect accuracy (Lovett et al. 2012).

Inter-implant interval was shown to have a significant influence on sound-source localization ability. This adds to the arguments in support of minimizing inter-implant interval where possible for children with bilateral profound hearing loss. It is interesting to note that the effect of inter-implant interval was still significant in this group who had received their second implant up to 6 years ago. Thus, despite being experienced users of bilateral CIs, children did not fully overcome the detriment caused by prolonged inter-implant interval. This is consistent with theories of long-lasting cortical reorganization in response to unilateral auditory deprivation, which suggest a critical period of 18 months (e.g. Gordon et al. 2013; 2015).

Our data showed age at onset of bilateral profound hearing loss also had a significant effect on sound-source localization, with better performance seen for children with longer experience of bilateral acoustic sound prior to BiCIs. This is consistent with previous studies that indirectly explored the effect of auditory experience during the early years. For example, Grieco-Calub & Litovsky (2010) showed that children reported by parents to be benefiting from hearing aids were more likely to have better sound-source localization via CIs than peers who had not benefitted from hearing aid use. Previously, Killan et al. (2015) showed that type of hearing loss (categorized as acquired/progressive or congenital) influenced sound-source localization, with children with acquired/progressive loss performing better than those with congenital hearing loss. Their study was limited due to children with acquired/progressive loss being older than children in the congenitally deaf group. The present data adds to the evidence for the effect of age at onset of profound hearing loss by quantifying and directly exploring this variable.

All children whose unaided hearing thresholds were outside NICE CI criteria (NICE, 2009) up to at least approximately 48 months of age localized with better accuracy than the group average in the present study. This is broadly consistent with reports by Sharma et al., (2007a, 2007b) who showed that congenitally deaf children need to receive CIs in both ears by the age of 42 months to give symmetrical electrophysiological responses to sound. Other behavioural studies of localization ability in children have also noted a benefit of binaural listening during the early years (Steffens et al., 2008; Grieco-Calub & Litovsky, 2010; Van Deun et al., 2010). It should be noted however that in the present study, pre-operative hearing thresholds below 2 kHz were not used in our definition of profound hearing loss. As a consequence it is possible that the present study may underestimate the effect of pre-operative hearing levels due to unknown variability in low-frequency hearing.

CI manufacturer had a significant effect on sound-source localization ability, with Med-El implants being associated with the most accurate localization ability, followed by Cochlear and then Advanced Bionics. Interpretation of this effect based on modelling the whole group was potentially complicated since all users of Advanced Bionics devices were simultaneously implanted, whilst Med-El and Cochlear users were either simultaneously or sequentially implanted. It was therefore possible that the effect of manufacturer seen might have been influenced by inter-implant interval effects. To explore this, an additional model including data from only simultaneously implanted children (regardless of CI manufacturer) was calculated and compared with the original model. Similar differences between the three manufacturers were evident in both models, indicating that CI manufacturer had a similar effect on localization accuracy for both simultaneously and sequentially implanted children and that this effect was independent of inter-implant interval. Our study was not designed to explore reasons for differences between systems however, one plausible explanation may be differences in automatic gain control, which can influence outcomes for speech discrimination (Spahr et al. 2007). The range of stimulus intensity used in the present study, from 65 to 75 dB(A), is toward the higher levels for speech, equivalent to e.g. a team-mate calling during a sports game or raised voices during a group meal. Input sounds from 65 to 75 dB SPL may result in CI stimulation at levels at, or close to, maximum stimulation amplitude for Cochlear and Advanced Bionics patients, hence ILDs for sounds in this range may be difficult to perceive. For Med-El recipients these intensities are mapped to a lower portion of the patients' dynamic range and will produce CI stimulation over a wider range of electrical amplitude (Vaerenberg et al. 2014). Localization via CIs is thought to be dominated by ILDs (Seeber & Fastl 2008), even in children where fine structure strategies facilitate some degree of ITD sensitivity (Eklöf & Tideholm, 2018). Since Med-El systems apply less compression to sounds louder than 65 dB SPL compared to Cochlear or Advanced Bionics, ILD cues may have been better preserved for children using Med-El systems in the present study. It is therefore possible that repeating this study using quieter stimuli would not find the same difference between manufacturers. Age at CI1 and CI2 is not likely to account for the difference in localization across CI manufacturers. On average, for congenitally deaf children, Med-El users were older at CI1 and CI2. This is a detrimental influence on sound-source localization, not advantageous, and so cannot explain the results.

Consistent with previous studies (Asp et al., 2011; Kühn et al. 2013; Asp et al. 2015), time post-CI2 was shown to influence localization ability, with a longer time associated with improved performance. It should be noted, however, that actual binaural listening time varies from child to child dependent on how consistently they use their devices. Inconsistent device use has been shown to be a particular issue for sequentially implanted children (Galvin & Hughes. 2012; Fitzgerald et al. 2013). A limitation of the present study was that it was not possible to determine or control for how much time each child had spent listening via both CIs together.

One limitation of this study is the use of RMS error alone to measure sound localization, as it does not capture more subtle aspects of a person's localization ability (Grieco-Calub & Litovsky, 2010; Zheng et al., 2015; Killan et al., 2018). A further potential limitation is the 30 degrees spacing between loudspeakers, which does not allow localization accuracy to be measured with the fine spatial resolution achieved in some other studies (e.g. Zheng et al., 2015). However, as the mean RMS error found in the present study (25.4 degrees) is comparable to those reported by Zheng et al. (2015) (31.3 and 26.2 degrees at first and second test intervals respectively) it is likely that loudspeaker separation did not substantially impact our findings. Indeed, the spatial resolution achieved in our study is similar to other previous research (e.g. Asp et al., 2011; Killan et al., 2015; Murphy et al., 2011). A loudspeaker array with large separations between speakers may lead to ceiling effects, where children find the test too easy. As only one out of the 127 children completed the test with perfect accuracy, it is considered unlikely that ceiling effects limited our findings. Similarly, Asp et al (2011) reported only two out of sixty-six bilaterally implanted children perfectly completed a localization task that used five loudspeakers separated by 45 degrees.

Importantly, the loudspeaker spacing in the present study is representative of situations a hearing impaired child might encounter in day to day life, at mealtimes, during lessons or playing sport. For example, a child might be writing while sat around a table with friends doing group work at school when another child begins to speak.

Our regression model accounted for 26% of variance in the data. A number of factors not measured in our study potentially account for some of the remaining variance. One such factor is asymmetric loudness growth caused by, for example, avoidance of facial nerve stimulation or recent re-programming. A second possible influence is the effect of children moving their head following stimulus onset. Whilst asked to face ahead for the onset of each presentation, some children moved their heads more than others during the sentence and some leaned forward when they were concentrating, effectively moving the loudspeaker array out of the horizontal plane. Finally, variation in children’s concentration during the task could account for some variance in the data. Data were excluded from analysis if the tester deemed a child had been uncooperative or distracted such that their responses were clearly unreliable. However the analysed group will have included children with varying levels of attention, fatigue and motivation, potentially influencing their responses in more subtle ways that are difficult to quantify.

Our findings provide further evidence that the unilateral auditory deprivation experienced while waiting between a first and second CI causes a long-term detriment in subsequent sound-source localization. Therefore inter-implant interval should be minimized for children with bilateral severe-to-profound hearing loss. The significant effect of age at onset of profound deafness means that clinicians can expect children with acquired or progressive hearing loss to localize comparatively well via BiCIs. This knowledge is useful for patient selection for BiCIs, counselling and targeting rehabilitation for children where progress is not seen. Another implication is that it is important to monitor a child's localization accuracy over several years following BiCIs so that failure to develop localization skills can be identified. Where this is found, appropriate measures can be taken to initiate targeted rehabilitation, including reviewing BiCI use, addressing any programming issues, or recommending localization listening practice. The family can be counselled regarding their child's speech processor use to ensure that both processors are worn simultaneously for most of the day, rather than alternating, and also to ensure that processor microphones are not positioned side-by-side on the top of the child's head rather than over the ears. Listening practice can include games where the child closes their eyes and family members play an instrument from differing, unknown locations in the room, then the child guesses where the sound came from; or where a noise-making toy or phone is hidden in the room and the child is encouraged to listen to help them find it.

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Author Contribution Statements:

C.F.K. contributed to the conception and design of the work, collected the data, contributed to the interpretation of data analysis, drafted the article, contributed to the article’s revision and gave final approval of the submission. A.J.S. conducted the data analyses, contributed to the writing of the results section of the manuscript, and gave final approval of the submission. E.C.K. provided substantial critical revision of the manuscript, including presentation and interpretive analysis of the results, and gave final approval of the submission. C.L.T contributed to the design of the work, revision of the draft article and gave final approval of the submission. C.H.R. contributed to the conception of the work, revision of the draft article and gave final approval of the submission.

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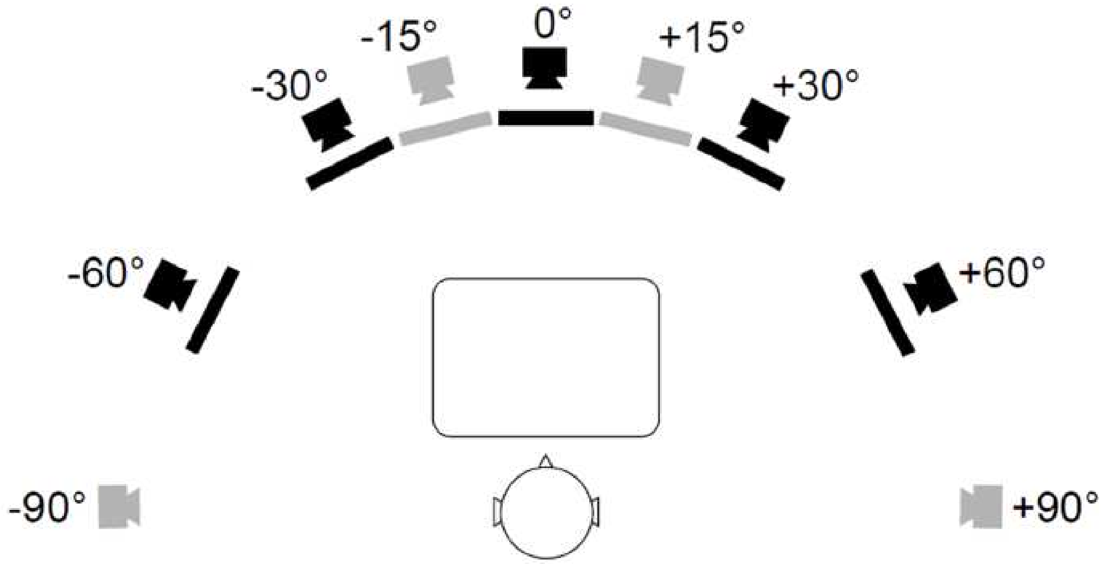

Figure 1

The child is shown seated in front of a table and facing the centre of the arc of loudspeakers. Loudspeaker positions are shown in degrees azimuth, negative angles denote locations to the left and positive angles denote locations to the right of centre. Inactive video monitors and loudspeakers are shown in grey. Active video monitors and loudspeakers are shown in black.

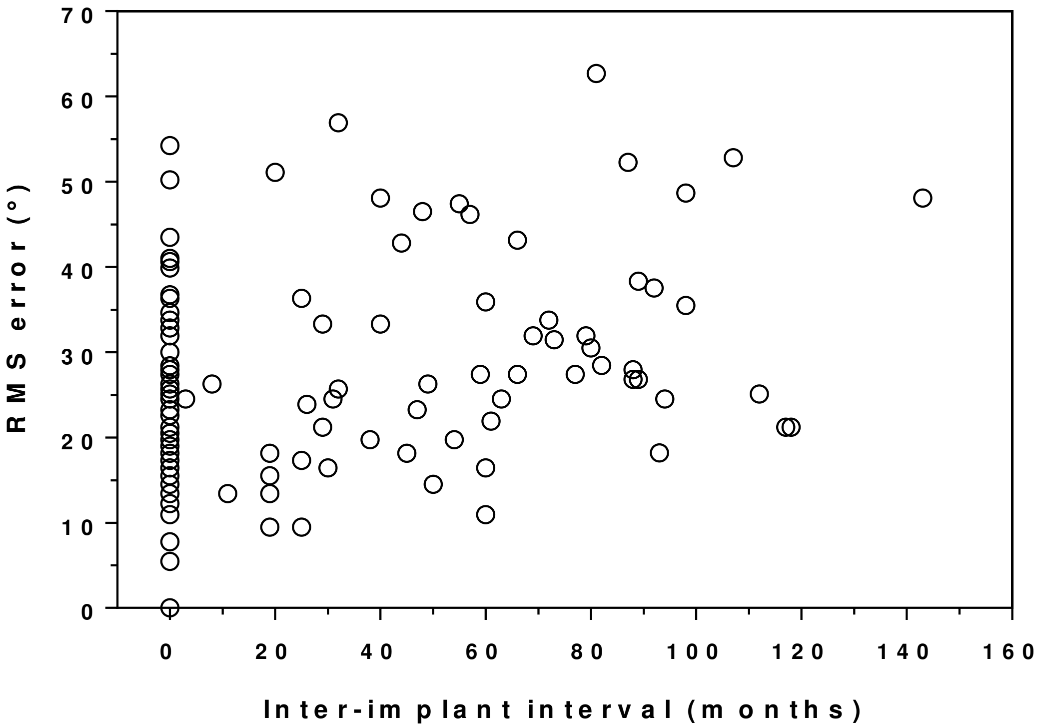

Figure 2

RMS errors are plotted for each child against the duration of their inter-implant interval in months.

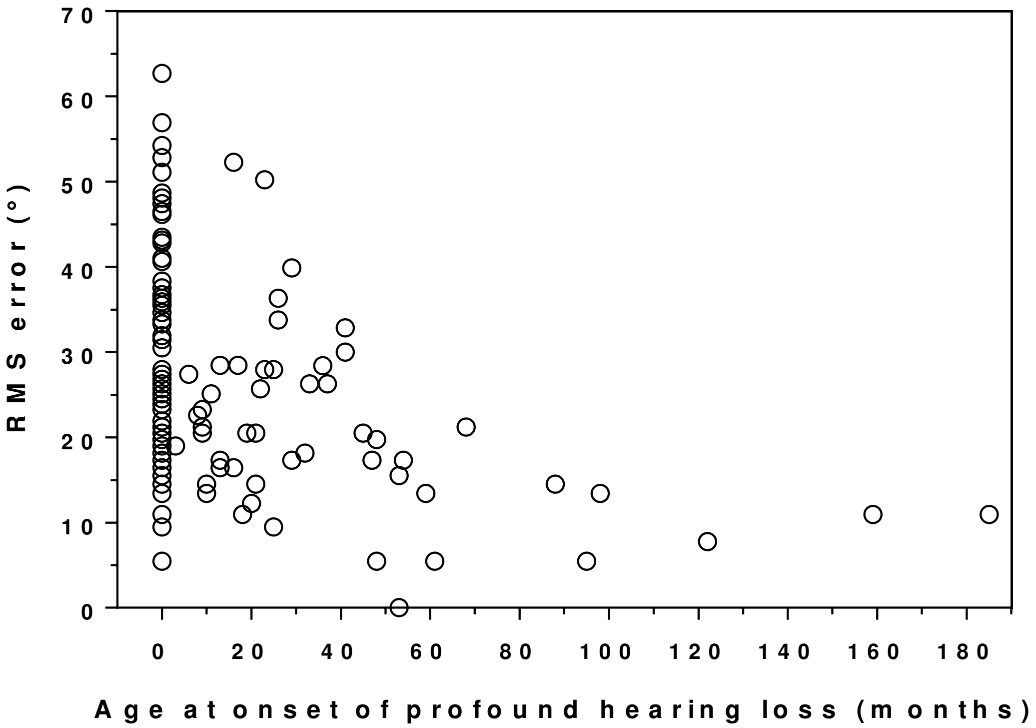

Figure 3

RMS errors are plotted for each child against the age at which their hearing loss was first confirmed to be profound at 2 and 4 kHz in at least one ear. Children whose hearing impairment was detected by newborn hearing screening and confirmed to fall within this range on immediate follow-up are plotted as having met this criterion from birth and are clustered at the far left.

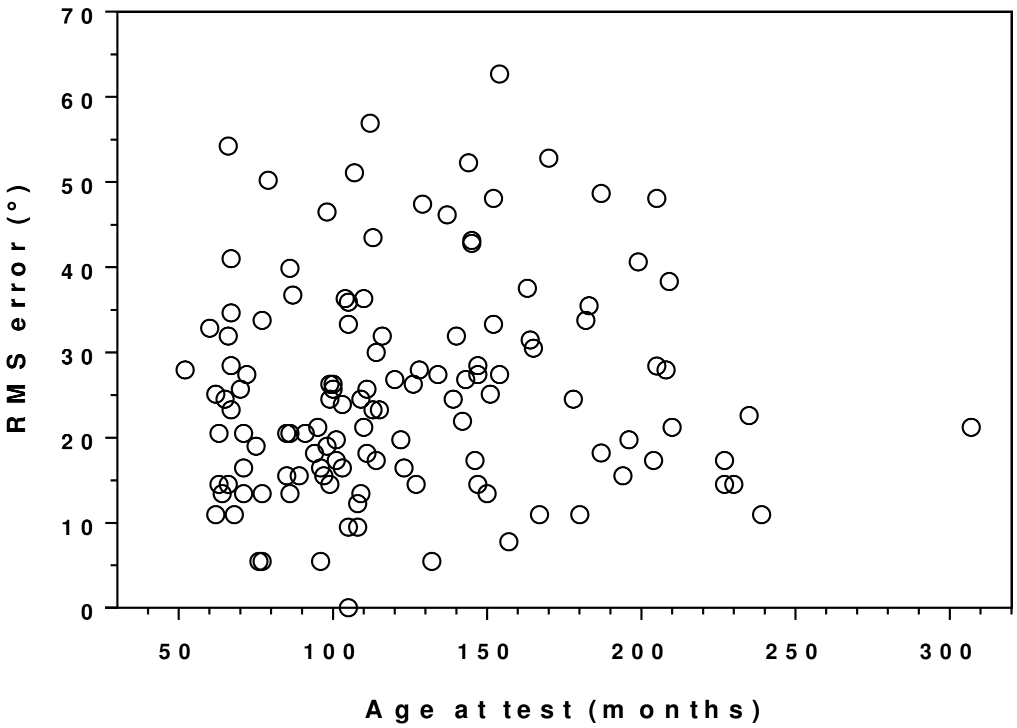

Figure 4

RMS errors are plotted for each child against their age at test in months.

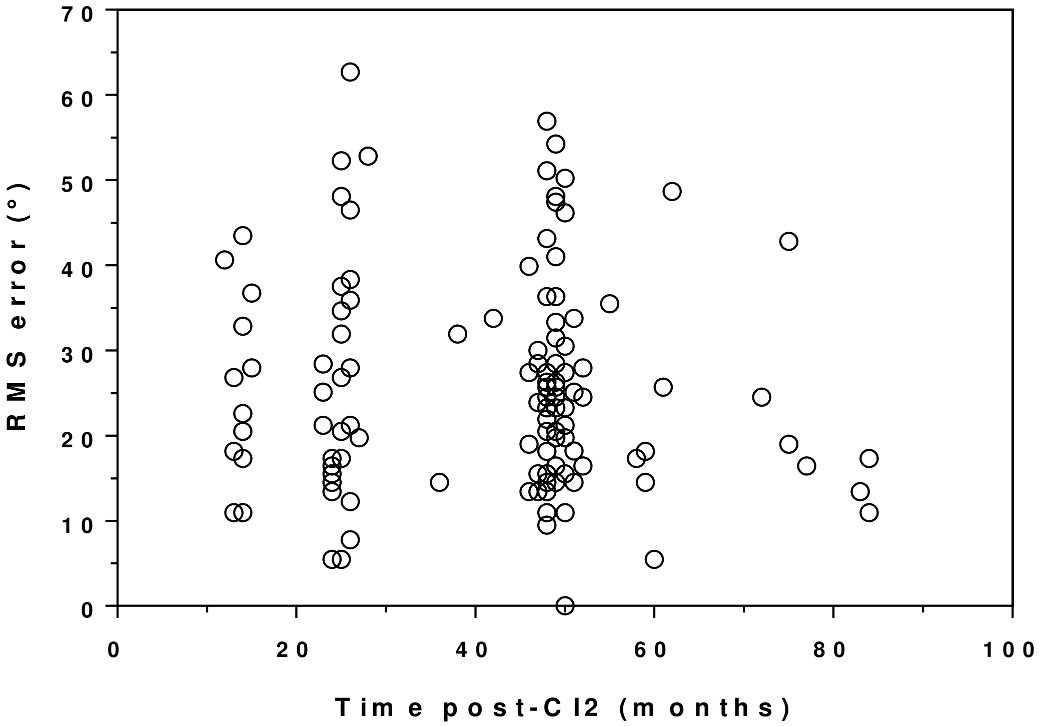

Figure 5

RMS errors are plotted for each child against the number of months since they received their second CI.

Table 1
Participant Characteristics

		Simultaneous (N = 65)	Sequential (N = 62)
Age (months)	Median	91	136
	Youngest	52	85
	Oldest	235	307
Onset of profound hearing loss categorized	Congenital	N = 28 (43%)	N = 48 (77%)
	Acquired / Progressive	N = 37 (57%)	N = 14 (23%)
Age at onset of profound deafness at 2kHz and 4 kHz in at least one ear (months)	Median	10	0
	Youngest	0	0
	Oldest	185	68
Age at CI1 (months)	Median	50	31
	Youngest	6	14
	Oldest	220	165
Age at CI2 (months)	Median	50	88
	Youngest	6	26
	Oldest	220	283
Inter-implant Interval (months)	Median	0	58
	Least	0	3
	Greatest	0	143
Time since CI2 (months)	Median	47	48
	Least	12	13
	Greatest	77	84
Manufacturer	Med-El	N = 27 (42%)	N = 38 (61%)
	Cochlear	N = 31 (48%)	N = 24 (39%)
	Advanced Bionics	N = 7 (11%)	N = 0 (0%)
Children with differing CI models in right and left ears		N = 1 (1%)	N = 48 (77%)

Table 2
Characteristics of the children's cochlear implant systems

	Advanced Bionics (N=7)	Cochlear (N=55)	Med-El (N=65)
Speech processor	Naida (N=2) Harmony (N=5)	CP910 (N=5) CP810 (N=52) Freedom (N=1)	Opus 2
Processing strategy	HiRes Optima S (N=2) HiRes-S w/Fidelity 120 (N=5)	ACE	FSP
Microphone	Processor, omnidirectional	Standard, omnidirectional	Standard, omnidirectional
Active electrodes	Up to 16	Up to 22	Up to 12
Electrode array length	15 mm	15 to 20 mm	23 to 26 mm

Table 3
Ages at CI1 and CI2 by manufacturer for the congenitally deaf children

	Age at CI1 (months)		Age at CI2 (months)	
	Median	**(range)**	**Median**	**(range)**
Advanced Bionics (N=4)	20	(13 to 67)	20	(13 to 67)
Cochlear (N=29)	26	(12 to 186)	63	(12 to 186)
Med-El (N=43)	32	(6 to 216)	91	(6 to 216)

Table 4
Results of regression analysis for both simultaneously and sequentially implanted children.

No = 127
Adj. R^2 = 0.259

Variable		**Coefficient**	***p***	**95% Confidence Interval**	
Inter-Implant Interval (months)		0.14	<0.001	0.07	0.22
Onset of Deafness: Age when HTLs ≥90 dB HL at 2 and 4 kHz in at least one ear first measured (months)		-0.11	0.004	-0.19	-0.04
Time since CI2 (months)		-0.13	0.035	-0.26	-0.01
Age at Test (per month of life)		-0.02	0.466	-0.07	0.03
Manufacturer (relative to Med-El)	**Cochlear**	5.79	0.006	1.65	9.93
	Advanced Bionics	9.19	0.043	0.31	18.06

A positive coefficient indicates an association between the variable and greater, i.e. less accurate SLA.

Table 5

Results of regression analysis for simultaneously implanted children only.

No = 65
Adj. R^2 = 0.220

Variable		**Coefficient**	***p***	**95% Confidence Interval**	
Onset of Deafness: Age when HTLs ≥90 dB HL at 2 and 4 kHz in at least one ear first measured (months)		-0.10	0.007	-0.17	-0.03
Time since CI2 (months)		-0.17	0.033	-0.33	-0.01
Age at Test (Per month of life)		-0.03	0.213	-0.09	0.02
Manufacturer (relative to Med-el)	**Cochlear**	7.48	0.008	2.03	12.93
	Advanced Bionics	10.66	0.017	1.97	19.36

A positive coefficient indicates an association between the variable and greater, i.e. less accurate SLA.