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Changes in children's speech discrimination and spatial release from masking between two and four years after sequential cochlear implantation

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ABSTRACT

Objective: To document changes in speech reception thresholds (SRTs) and spatial release from masking (SRM) for sequentially implanted children at two and four years after they received their second cochlear implant (CI_2).

Methods: Participants were 17 children who consistently used two sequentially implanted and optimally programmed cochlear implants. SRTs were measured monaurally in quiet and binaurally in noise using the adaptive McCormick Toy Discrimination Test. Speech signals were presented from 0° azimuth and noise from 0°, +90° or −90° azimuth. SRM was calculated from SRTs in noise. Measurements were made at two and four years post-CI_2.

Results: There were significant improvements over time in SRTs in quiet, SRTs in noise and SRM. SRTs in quiet improved more for CI_2 than for the first implant (CI_1). SRTs in noise and SRM improved more when noise was presented closest to CI_1 than when closest to CI_2. Performance became more symmetrical over time.

Discussion: Despite prolonged periods of unilateral auditory deprivation sequentially-implanted children exhibited continued improvement in SRT and SRM. These results are valuable in setting expectations for and counselling families of children considering sequential cochlear implants.

Keywords: Cochlear Implants; Bilateral; Spatial Release from Masking; Speech Discrimination; Sequential; Speech Reception Thresholds; Speech Intelligibility

INTRODUCTION

One advantage of binaural hearing is an increased ability to discriminate speech from background noise due to spatial release from masking (SRM). SRM refers to the improvement in speech discrimination obtained when speech and noise signals are spatially separated, and has been attributed to the head-shadow effect and binaural processing (e.g. Hawley *et al.*, 2004; Akeroyd, 2006). One aim of bilateral cochlear implantation in children is to realize this benefit for profoundly deaf children. Bilateral cochlear implantation can be performed simultaneously but is often performed sequentially (i.e. implantation occurs one ear at a time, with the second implant, CI_2, being implanted some time, often years, following the first, CI_1). As a result, sequentially-implanted children may experience prolonged and asymmetrical auditory deprivation compared to normally-hearing children, children who use bilateral hearing aids and children who undergo simultaneous cochlear implantation. As a consequence, the development of binaural listening skills for sequentially-implanted children is more likely to be limited by changes in plasticity in the maturing auditory system (Sharma *et al.*, 2007; Green *et al.*, 2011; Gordon *et al.*, 2013; Sparreboom, 2013).

Several studies have described changes in speech discrimination for sequentially-implanted children as a function of time up to two years post-CI_2 (Peters *et al.*, 2007; Sparreboom *et al.*, 2011; Strom-Roum *et al.*, 2012). In general, these studies show improvements in monaural and binaural speech reception thresholds (SRTs) in quiet and noise. Further, whilst children tend to perform better when listening via CI_1 alone compared to via CI_2 alone, the greatest improvements over time are seen for children listening via CI_2. To date, longitudinal data describing speech discrimination over a time period longer than two years post-CI_2 have not been reported in the literature. Even less is known regarding the development over time of

SRM for sequentially implanted children. A number of studies have shown that sequentially implanted children display asymmetrical SRM, i.e. greater SRM is available when the noise signal is closer to CI_2 compared to CI_1 (Litovsky *et al*., 2006; Van-Deun *et al*., 2010; Chadha *et al*., 2011). The durations of bilateral implant use in these studies vary from three months to five years, however no single study has reported changes in SRM over time for the same children.

Given the potential influence of auditory system plasticity, it is not straight-forward to predict the development trajectory of speech discrimination and SRM of sequentially-implanted children based on data obtained during the first two years post-CI_2. Knowledge of longer term outcomes would inform clinicians' management decisions for children with an existing single cochlear implant, as well as provide realistic expectations for families of such children. Therefore, this paper presents data from a small scale study conducted at our clinical centre that describes monaural SRTs in quiet, binaural SRTs in noise and SRM outcomes for sequentially implanted children at two and four years post-CI_2.

METHODS

Data were collected from 17 (eight male, nine female) children who had received sequential cochlear implants at our clinical service. For inclusion in this study we identified children who were over four years of age, developmentally able to participate and consistent users of both CI_1 and CI_2. We included only children with monaural aided thresholds of 35 dB HL or better at 0.25, 0.5, 1, 2, 4 and 6 kHz bilaterally. Data were collected for each child at two and four years post-CI_2 as part of their routine clinical management. Details regarding each participating child are given in Table 1. The age range of children at two years post-CI_2 was 62 to 156 months (median = 119 months) and at 4 years post-CI_2 was 85 to 182 months (median = 142 months). The time between CI_1 and CI_2 ranged from 19 to 95 months (median = 49 months). Based on information available in their medical records including audiological test results, correspondence and parental reports children were assumed to have congenital profound sensori-neural hearing loss. A number of children were notably older than others at CI_1 (i.e. ID 16, 17, 18, 19, 22 and 24) due to a range of non-audiological factors (e.g. repeated non-attendance at consultations, professional concern regarding family support). Table 1 also shows the internal implants, external speech processors and processing strategies used by each child in each ear at both test intervals. For the majority of participants these remained constant across the time interval. However, two participants (ID 5 and 8) with devices by Cochlear (Sydney, New South Wales, Australia) had changed from using Freedom™ to CP810™ speech processors between assessments and one other participant (ID19) with devices by MED-EL (Innsbruck, Austria) had changed speech processing strategy from HDCIS™ to FSP™ in one ear. Changes in speech processor hardware and processing strategy can influence speech discrimination (e.g. Kleine Punte *et al*., 2014, Mosnier *et al*., 2014.). However, the changes for these three children are considered to be relatively minor and as such will account for only small changes in speech discrimination performance. The effects of the other characteristics noted in Table 1 are effectively controlled for by the longitudinal design of this study.

Measurement of SRT in quiet and noise was achieved using the IHR Automated McCormick Toy Discrimination Test (Summerfield *et al.*, 1994) presented via the York Crescent of Sound (Kitterick *et al.*, 2011). The York Crescent of Sound consists of nine Canton Plus XS.2 loudspeakers (Niederlauken, Germany), each at a height of 1.1 metre, arranged in a horizontal semi-circle of radius 1.45 metres from +90º (90 º to the right of the child) to −90º azimuth (90º to the left of the child). Presentation of speech and noise signals was controlled via system software and routed to the loudspeakers via a MOTU UltraLite Mk3 (Cambridge, USA) audio interface and Alesis RA-150 dual-channel amplifiers (Cumberland, USA).

Speech signals were recorded by Summerfield et al. (1994) using a female voice. They consisted of the introductory phrase “Point to the” followed by the name of one of 10 to 14 toys (phonemically paired e.g. “key” and “tree”) selected at random by system software. The introductory phrase component of the speech signal had duration of 500 ms. The noise signal was a burst of broadband (pink) noise with duration of 1400 ms (linear rise-fall = 200 ms; steady-state = 1000 ms). The noise signal was presented 300 ms following the onset of the speech signal so that it was at steady-state for the duration of the toy name component of the speech signal.

All testing took place in a sound-attenuated room with the child seated so that their head was an equal distance from all loudspeakers. Children were asked to select which toy name they

Table 1 Participants' characteristics

Identification code	First CI side	Aetiology	Age confirmed profoundly deaf *§	Age at first CI *	Age at second CI *	First CI model	Second CI model	Processors at 2 year assessment	Processors at 4 year assessment	1st CI strategy at 2 year assessment	1st CI strategy at 4 year assessment	2nd CI strategy at 2 year assessment	2nd CI strategy at 4 year assessment
5	R	Unknown	13	22	38	CI24 RE(CA)	CI24 R(CA)	Freedom	CP810	ACE, ADRO	ACE, ADRO	ACE, ADRO	ACE, ADRO
6	L	Unknown	0	29	55	Sonata ti100	Sonata ti100	Opus2	Opus2	FSP	FSP	FSP	FSP
8	R	Unknown	11	23	79	CI24R(CA)	CI24 RE(CA)	Freedom	CP810	ACE, ADRO	ACE, ADRO	ACE, ADRO	ACE, ADRO
10	L	Unknown	16	33	59	Pulsar ci 100	Sonata ti 100	Opus2	Opus2	FSP	FSP	FSP	FSP
11	R	Unknown	0	28	78	CI24RE(CA)	CI24RE(CA)	CP810	CP810	ACE	ACE	ACE	ACE
12	R	Unknown	0	17	63	CI24RE(CA)	CI24RE(CA)	CP810	CP810	ACE with ADRO	ACE, ADRO	ACE, ADRO	ACE, ADRO
16	R	Unknown	0	38	59	CI24RE(CA)	CI24RE(CA)	CP810	CP810	ACE, ADRO & auto-sensitivity	ACE, ADRO & auto-sensitivity	ACE, ADRO & auto-sensitivity	ACE, ADRO & auto-sensitivity
17	R	CMV	48	62	102	CI24RE(CA)	CI24RE(CA)	CP810	CP810	ACE, ADRO	ACE, ADRO	ACE, ADRO	ACE, ADRO
18	R	CMV	51	62	102	CI24RE(CA)	CI24RE(CA)	CP810	CP810	ACE, ADRO	ACE, ADRO	ACE, ADRO	ACE, ADRO
25	R	Unknown	17	22	118	C40+	Sonata ti 100	Opus2	Opus2	FSP	FSP	FSP	FSP
27	R	Usher's syndrome	0	34	129	C40+	Sonata ti 100	Opus2	Opus2	FSP	FSP	FSP	FSP
19	R	Unknown genetic	0	39	105	Pulsar ci 100	Sonata ti 100	Opus2	Opus2	HDCIS	FSP	FSP	FSP
26	L	Usher's syndrome	0	32	93	Pulsar ci 100	Sonata ti 100	Opus2	Opus2	FSP	FSP	FSP	FSP
22	L	Unknown	19	48	98	Pulsar ci 100	Sonata ti 100	Opus2	Opus2	FSP	FSP	FSP	FSP
31	L	Unknown	0	18	37	CI24RE Straight	CI24RE Straight	CP810	CP810	ACE, ADRO	ACE, ADRO	ACE, ADRO	ACE, ADRO
21	R	Unknown	0	33	114	C40+	Sonata ti 100	Opus2	Opus2	FSP	FSP	FSP	FSP
24	R	Unknown genetic	28	58	130	C40+	Sonata ti 100	Opus2	Opus2	FSP	FSP	FSP	FSP

*Ages given in months. §Where profound loss confirmed on immediate follow-up after failing neonatal hearing screen, age of diagnosis given as 0 months. Profound deafness defined as an unaided loss of 90 dB HL or worse at 2 kHz and 4 kHz bilaterally.

heard by pointing to a toy on a table in front of them, or selecting an image of the toy on a touch-screen.

Monaural SRTs in quiet were assessed first. Speech signals were presented from 0° azimuth at an initial level of 45 – 55 dB SPL whilst only one cochlear implant was activated. To encourage compliance with testing, the children were allowed to choose which speech processor to remove first. A one-down, one-up adaptive procedure with step sizes of 6 dB was used for the first two reversals, followed by six reversals using a two-down, one-up adaptive procedure with step sizes of 3 dB. The last six reversals were used to estimate SRT. The task was then repeated to measure SRT with only the other cochlear implant activated.

Binaural SRTs in noise were assessed next. First the speech signal and noise were presented from 0° azimuth (S_0N_0) to ensure that one standard outcome of listening in noise was obtained for each child should they withdraw co-operation before the end of the test session. Subsequently the speech signal remained at 0° azimuth and the noise was presented from −90° or +90° azimuth. Both −90° and +90° azimuth result in noise being closest to either CI_1 or CI_2. This is indicated within this paper by referring to these noise conditions as S_0N_{CI1} and S_0N_{CI2} respectively. The speech signal was fixed at 60 dB(A) SPL and the noise signal varied from an initial level of 30 to 38 dB SPL using an adaptive procedure. The first two reversals followed a one-down one-up procedure with step sizes of 6 dB. Six further reversals using a two-down one-up procedure with step sizes of 3 dB were used to establish SRT in noise, expressed as a signal to noise ratio (SNR). If the noise reached a maximum level of 60 dB SPL, i.e. a SNR of 0 dB, the speech signal was presented at adaptively quieter levels in order to adjust the SNR.

SRM was calculated for each participant by subtracting their SRT in noise for S_0N_{CI1} and S_0N_{CI2} from their SRT for S_0N_0. This resulted in two SRM measurements for each participant, i.e. SRM with noise located at CI_1 (SRM_{CI1}) and noise located at CI_2 (SRM_{CI2}).

Statistical analysis was performed using two-level regression modelling (e.g. Goldstein, 2011; Snijders and Bosker, 2011) with the levels of the model being measurement (within-participant) and participant (between-participant). For each dependent variable (SRT in quiet, SRT in noise and SRM) a series of models were used to explore the effect of explanatory variables (i.e. time post-CI_2, implanted ear and noise location). An advantage of these models is their ability to incorporate the clustering of data inherent in repeated measures experimental designs, and avoid violating the assumption of independence of data that underpins single-level regression methods. Models were estimated by the maximum likelihood method via an iterative generalised least squares procedure (e.g. Goldstein, 1986). This allowed an estimate of model deviance to be made. The difference between the deviance of two models (that differ simply by the addition of explanatory variables) can be used as a test statistic to determine the effect of the explanatory variables on the dependent variable. This deviance statistic has a χ^2 distribution with degrees of freedom equal to the difference in number of variables included in the two models. In addition, regression coefficients can be tested for significance via the Wald test (see Snijders and Bosker, 2011).

RESULTS

Figure 1 shows the mean (n = 17) monaural SRTs measured in quiet for CI_1 and CI_2 ears (circles and squares respectively) at two and four years post-CI_2. A number of trends are clearly evident within the figure. CI_1 ears had lower mean SRT (i.e. better performance) than CI_2 ears at two years post-CI_2. In addition, SRT for both ears reduced (i.e. improved) as a function of time post-CI_2. These observations were confirmed by two-level regression modelling. Both the inclusion of ear ($\chi^2 = 5.46$, $df = 1$, $p < 0.05$) and time post-CI_2 ($\chi^2 = 37.84$, $df = 1$, $p < 0.0001$) caused significant reductions in model deviance. Inspection of the figure also suggests that the improvement in SRT over time was dependent on ear, with a greater change seen for CI_2 ears (8.1 dB) compared to the CI_1 ears (6.4 dB). However, after four years post-CI_2, CI_1 ears still had lower mean SRT than CI_2 ears. Statistical modelling including the interaction between ear and time post-second implant showed the difference in SRT improvement over time to be non-significant ($\chi^2 = 0.76$, $df = 1$, $p = 0.39$).[1]

[1] For this and all subsequent models reported here, greatest variation was seen at the measurement (within-participant) level, with only minimal variation seen at the participant (between-participant) level. This is in keeping with the longitudinal design of this study. For all models the residuals were confirmed as being normally distributed with mean of zero.

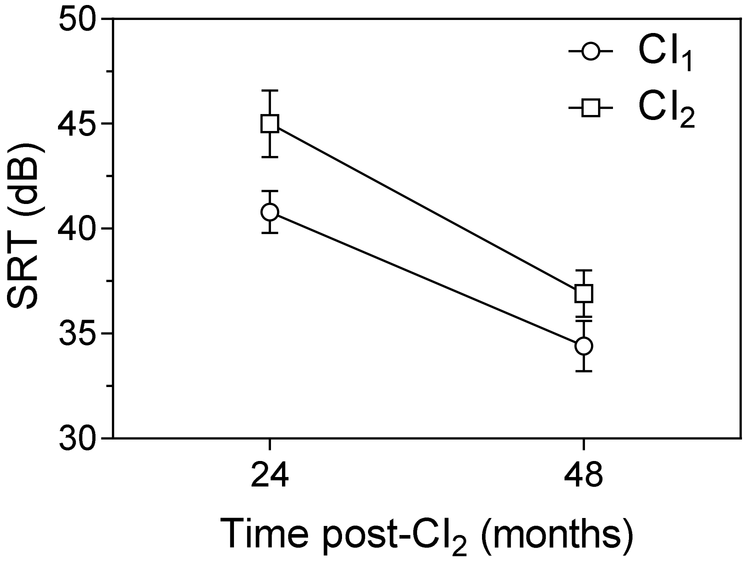

Figure 1 Mean monaural SRT in quiet for CI1 (circles) and CI2 (squares) ears as a function of time post-CI2. Error bars represent ± 1 standard error of the mean (SEM).

One participant (ID5) had incomplete SRT in noise data and was therefore not included in subsequent analysis. The mean (n = 16) binaural SRTs measured in noise (expressed as SNR in dB) at two and four years post-CI_2 are shown in Figure 2. The figure shows the SNRs obtained for the three locations of noise: S_0N_0 (circles), S_0N_{CI1} (squares) and S_0N_{CI2} (triangles). At two and four years post-CI_2, lowest mean SNRs (i.e. better performance) were measured at S_0N_{CI2} with highest SNRs measured at S_0N_0. For all three noise locations SNRs reduced (i.e. improved) as a function of time post-CI_2. The largest improvement was seen at S_0N_{CI1} (7.2 dB) followed by S_0N_{CI2} (5.7 dB), with a smaller improvement (2.7 dB) seen at S_0N_0. As a result, mean SRT in noise at S_0N_{CI1} was most similar to that obtained at S_0N_0 at two years but was closest to S_0N_{CI2} at four years. These observations are confirmed by the results of statistical modelling. Both noise location (χ^2 = 25.91, df = 2, p < 0.0001) and time post-CI_2 (χ^2 = 51.30, df = 1, p < 0.0001) caused highly significant reductions in model deviance. The interaction between noise location and time post-CI_2 was also shown to be significant (χ^2 = 10.05, *df* = 2, $p < 0.01$) confirming the difference in improvements seen across the three conditions. The model also confirms the convergence of SRT in noise for S_0N_{CI1} and S_0N_{CI2} as a result of the greater improvement seen for S_0N_{CI1}. Whilst SRT at S_0N_{CI1} and S_0N_{CI2} were significantly different at two years post-CI_2 (t = 3.27, $p < 0.001$), the difference was not significant at four years post-CI_2 (t = 1.81, p = 0.04).[2]

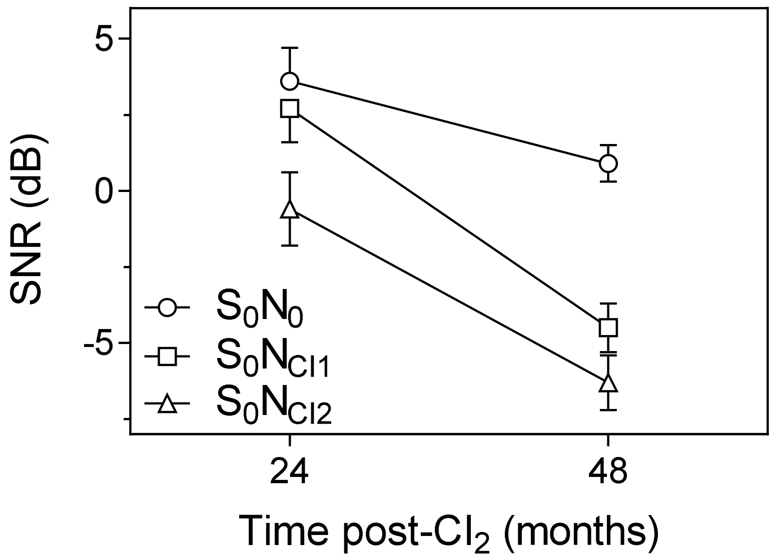

Figure 2 Mean binaural SRT in noise measured for S0N0 (circles), S0NCI1 (squares) and S0NCI2 (triangles) as a function of time post-CI2. Error bars represent ± 1 SEM.

Finally, Figure 3 shows the mean (n = 16) SRM values obtained as a function of time post-CI_2. SRM values are shown for both noise locations, i.e. SRM_{CI1} and SRM_{CI2}. A clear trend for both SRM_{CI1} and SRM_{CI2} to increase (improve) as a function of time post-CI_2 is evident. In addition, a notable difference exists between SRM_{CI1} and SRM_{CI2}, with SRM_{CI2} having larger values (i.e. more advantage) than SRM_{CI1} at two and four years. However, this difference becomes smaller as a function of time post-CI_2 from 3.3 dB at two years to 1.8 dB at four years. That is, SRM_{CI1} shows a greater improvement than SRM_{CI2}, and as a result,

[2] For multiple hypotheses testing a Bonferroni-corrected significance level of $p < 0.01$ was used.

SRM across ears is observed to become more symmetrical over time. Statistical modelling confirmed both noise location (χ^2 = 6.34, *df* = 1, $p < 0.05$) and time post-CI_2 (χ^2 = 17.00, *df* = 1, $p < 0.0001$) had a significant effect on SRM. The interaction between noise location and time was not significant (χ^2 = 0.73, *df* = 1, p = 0.39), indicating that the time-dependent improvements in SRM_{CI1} and SRM_{CI2} were not significantly different.

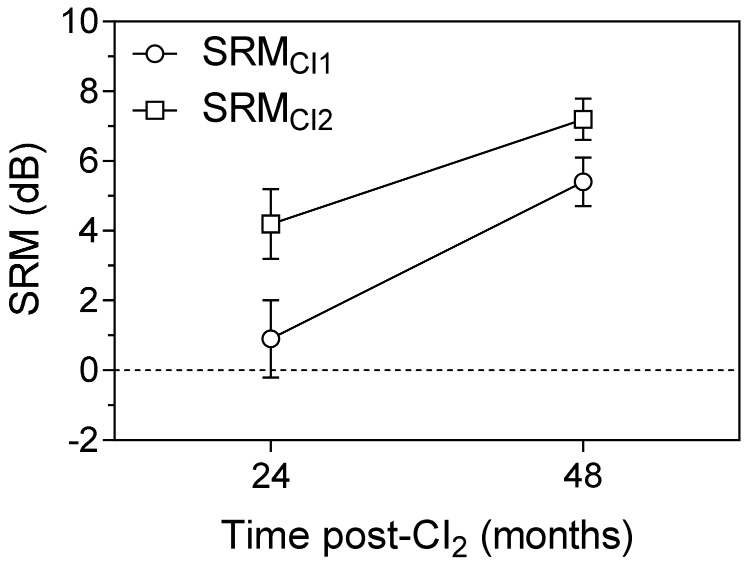

Figure 3 Mean SRMCI1 (circles) and SRMCI2 (squares) as a function of time post-CI2. Error bars represent ± 1 SEM.

DISCUSSION

To date, no longitudinal data have been reported that describe changes in SRM over time for sequentially-implanted children. Previous investigators (Peters *et al*., 2007, Sparreboom *et al*., 2011 and Strom-Roum *et al*., 2012) have described longitudinal changes in speech discrimination abilities for this group of children, but these are limited to the first two years post-CI_2. The small scale longitudinal study described in this paper is the first to provide a description of changes in speech discrimination in quiet and noise as well as SRM for sequentially-implanted children at four years post-CI_2.

Our findings demonstrate that the trajectory of improvement in speech discrimination performance previously reported for up to two years post-CI_2 (Peters *et al*., 2007; Sparreboom *et al*., 2011; Strom-Roum *et al*., 2012) continues during the next two years. That is, SRT in both quiet and noise continue to improve for both CI_1 and CI_2. Whilst better performance is seen for CI_1, CI_2 shows the greatest improvement over time. This results in more symmetrical performance across ears.

Similar findings were also obtained for SRM. Whilst our mean values measured at two years post-CI_2 were similar to those reported at the same time point by Litovsky *et al*. (2006) and Sparreboom *et al*. (2011), substantial improvements in SRM for noise presented 90° towards CI_1 and CI_2 were observed at four years post-CI_2. The present data also shows that the notable asymmetry in SRM evident at two years post-CI_2 (Litovsky *et al*, 2006; Van-Deun *et al*, 2010; Chadha *et al*, 2011) becomes less marked by four years post-CI_2. However, this group of sequentially-implanted children did not gain the same symmetrical SRM reported for simultaneously implanted children at two years post-CI_2 (Chadha *et al*., 2011).

In summary, the present findings show that sequentially-implanted children who are consistent users of two cochlear implants that provide access to sounds at 35 dB HL or better bilaterally continue to experience substantial improvements in discriminating speech in noise up to four years post-CI_2, despite the extended period of auditory deprivation in their second-implanted ear. These findings, along with other evidence (e.g. Smulders *et al.*, 2011) support the recommendation that children with an existing single implant should be considered for assessment for a second implant. As a tentative indication of the window of opportunity for providing a second implant, children in this study who had used a single cochlear implant for up to 95 months before receiving a second implant still experienced significant improvement in speech discrimination abilities.

The increased knowledge of the development of speech discrimination provided by this paper is useful when counselling families of children considering sequential implantation. As part of managing expectations families can be made aware of the long time-scale over which benefits may be obtained. Similarly, some children who have already received a second, sequential implant struggle to establish consistent use of both devices (Galvin and Hughes, 2012; Fitzgerald *et al.*, 2013). For these families the knowledge that these improvements can continue beyond two years post-CI_2 may serve as motivation to persevere with using the second cochlear implant and the associated rehabilitation.

Finally, in order to determine the trajectory of any further changes in speech discrimination beyond four years post-CI_2, it is recommended that further studies are undertaken with the aim of measuring speech discrimination performance at longer intervals post-CI_2.

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