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Changes in sound-source localization for children with bilateral severe to profound hearing loss following simultaneous bilateral cochlear implantation

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Abstract

Background: Sound localization is a valuable skill that children can develop to some extent via bilateral cochlear implants (biCIs). However, little is known regarding the change that can be expected in sound-source localization accuracy (SLA) pre- and post-biCI for children with bilateral, severe-to-profound hearing impairment who spent their early years listening via bilateral hearing aids (biHAs). This study therefore aimed to prospectively assess SLA in a group of children before, and at one year after, receiving simultaneous biCIs.

Methods: Ten children aged 5 to 18 years were tested. SLA was assessed using loudspeakers positioned at −60, −30, 0, +30 and +60 degrees azimuth. RMS errors and percentage correct scores were calculated. Changes in SLA were analysed via paired t-tests and potential relationships between hearing threshold levels (HTLs) and SLA via correlation analyses. Response distributions via biHAs and biCIs were examined via scatterplots.

Results: The mean within-subject changes in SLA were a significant improvement in RMS error of 11.9° ($p < 0.05$) and in percent correct by 21.5% ($p < 0.05$). Scatterplots demonstrated a trend toward better localization of sounds from 0° azimuth via biCIs compared to via biHAs. No significant associations were found between any measures of SLA and HTLs.

Conclusions: The findings of the present study demonstrate that simultaneous biCIs lead to improved sound localization in children with bilateral, severe to profound sensorineural hearing loss who previously used biHAs. SLA via biHAs or biCIs could not be predicted from children’s audiograms, and therefore should be measured directly.

Keywords: Localization; cochlear implants; hearing aids; child; hearing threshold levels; spatial hearing; bilateral; simultaneous.

Introduction

The ability to locate the sources of sound is valuable for children in their learning, socializing, play and for their safety. This importance was acknowledged in the decision to include sound-localization as a justification for providing bilateral cochlear implants (biCIs) to children in England and Wales (NICE, TA166, 2009). This guidance specifies that, on grounds of cost-effectiveness, biCIs must be implanted simultaneously, in one surgical procedure. It therefore follows that sound-source localization accuracy (SLA) should be measured routinely as part of a child's clinical care. This will allow clinical services to know what effect simultaneous biCIs has on the SLA of hearing-impaired children who had previously used bilateral hearing aids (biHAs).

To our knowledge, no previous data have been reported that provide a comparison of SLA via biHAs and simultaneously-implanted biCIs for the same children. Both Lovett et al (2015) and Dorman et al (2016) have reported SLA for different groups of listeners using either biHAs or biCIs. However, a limitation of the between-group design employed by these studies is that comparisons of SLA are complicated by other potentially influencing subject factors, e.g. differences in age or hearing loss. It is therefore not possible to make confident statements about the effect of biCIs on SLA in children who previously used biHAs based on the results of these two studies. The primary aim of this small-scale study was to share our clinical findings to provide a description of within-subject changes in SLA for ten children who previously used biHAs but subsequently received simultaneous biCIs.

SLA needs to be measured directly, as previously reported evidence indicates it cannot be predicted from a hearing impaired individual's hearing threshold levels (HTLs). This has been shown for unaided SLA in adults with mild to severe hearing loss (Noble et al, 1994) and for aided SLA in children with predominantly mild to severe hearing loss using biHAs (Lovett et al, 2015). No detailed description of associations between HTLs and SLA performance via biHAs is available for children with severe to profound hearing loss. Similarly, no previous reports have provided evidence to confirm whether a lack of an association between HTLs and SLA via biCIs also exists. Therefore, a secondary aim of this study was to test the extent to which SLA via biHAs and biCIs can be predicted by HTLs for children with severe to profound hearing loss.

Methods

Data were collected from ten children (6 female) using biHAs who had been referred for assessment for, and subsequently received, simultaneous biCIs. All children received biHAs immediately following diagnosis. Each child had access to sound via biHAs sufficient to become users of spoken language. Children were aged 4 years or older and were developmentally able to participate in SLA assessment. Table 1 gives details of each child's relevant clinical history. All children used a full-length CI array in each ear and listened via CIs alone. Speech discrimination testing at one year post-biCIs showed that all children had an improvement in speech reception thresholds in noise, ranging from 5 to 45 dB speech-to-noise ratio. Data were collected at CI candidacy assessment (HTLs and SLA via biHAs) and at one year post-biCI activation (SLA via biCIs). Unaided HTLs were measured using standard, age-appropriate methods, via 3A inserts attached to either the child's hearing aid moulds or via foam tips. HTLs were measured in dB HL to the nearest 5 dB at 0.5, 1, 2 and 4 kHz. Due to the attention span of some of the younger children, HTLs at 250 Hz were not always measured and were therefore omitted from analysis. Our clinical protocol does not include testing at 750 Hz. Mean HTL was calculated from HTLs obtained at all four frequencies across both ears, i.e. $HTL_{(0.5\text{-}4)}$. Separate averages were also calculated for 0.5 and 1 kHz only and 2 and 4 kHz only i.e. $HTL_{(0.5\text{-}1)}$ and $HTL_{(2\text{-}4)}$ respectively. Where a child's HTL exceeded the maximum output of the audiometer (i.e. was greater than 120 dB HL) a value of 130 dB HL was assumed for that frequency for the purposes of calculating averages. HTL symmetry was defined as the absolute difference in $HTL_{(0.5\text{-}4)}$ between right and left ears. Symmetrical hearing loss was defined as a difference of 15 dB or less, in line with the "Belfast rule of thumb" (Smyth & Patterson, 1985). In all cases, normal middle ear function was confirmed by 226 Hz tympanometry.

Prior to measuring SLA, correct hearing aid and CI functioning was confirmed. SLA was assessed using the AB-York Crescent of Sound (Kitterick et al, 2011). This is an array of loudspeakers (Plus XS.2., Canton) arranged in a semi-circle of radius 1.45m. For this study, active loudspeaker locations were −60, −30, 0, +30 and +60° azimuth (negative angles denote locations to the left, positive angles denote locations to the right). Presentation of stimuli via the loudspeakers 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). Stimuli were the sentence “Hello, what’s this?” pre-recorded by five different female talkers. The talker used for each presentation was randomly selected by the system software and the average presentation level was 70 dB(A), randomly roved by ±5 dB in 1 dB steps. Six test stimuli were presented at random from each of the five loudspeakers so that there were 30 test trials in total. Children were seated equidistant from each loudspeaker at a chair of appropriate height and asked to face the central loudspeaker while listening for each trial, however head-movements were not restricted during stimulus presentation. Below each loudspeaker a video monitor displayed a number or object that could be used by the child to indicate their response (i.e. which speaker presented the stimuli) via a touch-screen. Other acceptable responses were saying the number or object aloud or pointing to the loudspeaker. Prior to testing, children were familiarized to the test by listening to stimuli from each loudspeaker and being told the location of each sound. During testing, children’s continuing participation was praised regardless of their accuracy and encouragement to listen was given as needed. Children were not given feedback regarding the actual location of any stimuli during testing.

SLA via biHAs and biCIs was estimated by root-mean-square (RMS) error and the percentage of correct responses. Zheng et al (2015) suggest that metrics averaged over the entire loudspeaker array (such as RMS error and percentage correct) are not sensitive to variations in SLA across the auditory space. They developed a novel analysis to quantify localization sensitivity by identifying regions in space that are more finely or coarsely perceptually mapped. However, as this method requires a greater number of more closely-spaced loudspeakers than were available in our clinical setting, it could not be used in the present study. In an attempt to address this limitation and provide more detailed information regarding the distribution of responses, this study generated scatterplots of stimulus location versus response location obtained via biHAs and biCIs for each child. Within-subject changes in RMS error and percentage correct scores were analysed using paired t-tests. Correlational analysis was used to investigate relationships between unaided HTL and RMS errors and percentage correct scores via biHAs and biCIs.

Results

Table 2 shows the three HTL averages ($HTL_{(0.5\text{-}4)}$, $HTL_{(0.5\text{-}1)}$ and $HTL_{(2\text{-}4)}$) calculated for each child. Values ranged from 74.4 to 107.5, 35.0 to 100.0 and 85 to 108.8 dB HL for $HTL_{(0.5\text{-}4)}$, $HTL_{(0.5\text{-}1)}$ and $HTL_{(2\text{-}4)}$ respectively. The narrower range of $HTL_{(2\text{-}4)}$ reflects the implant candidacy criteria followed in the UK which focuses on HTL at 2 and 4 kHz. Also shown is the absolute inter-aural difference, calculated from right and left Mean HTL. These are consistent with symmetrical hearing loss in nine out of the ten children.

Figure 1 shows the RMS error (°) for each child obtained via biHAs and biCIs. RMS error ranged from 18.2° to 50.2° and 11.0° to 22.6° via biHAs and biCIs respectively. Most children showed only a small change in RMS error, though for some more substantial improvements were observed. A mean within-subject difference of 11.9° (95% CI: 2.7°, 21.1°), i.e. an improvement in accuracy for the biCIs condition, was observed. This was shown to be significant by a paired t-test ($t = 2.95$, $df = 9$, $p < 0.05$). Figure 2 shows the percent correct scores for each child. These ranged from 23.3 to 70.0% via biHAs and 51.3 to 93.3% for biCIs. Nine children had improved scores via biCIs, though one child was seen to decrease by 10%. The mean within-subject change from biHA to biCI was an improvement of 21.5% (95% CI: 5.4%, 37.5%) which was shown to be significant ($t = 3.03$, $df = 9$, $p < 0.05$). Individual RMS error and percentage correct scores via biHAs and biCIs are shown in Table 3.

Figures 3 to 6 show example scatterplots of response locations, as a function of loudspeaker location for four children. Scatterplots are shown for biHAs (panel A) and biCIs (panel B). The size of the datapoints represents the number of responses at that location with larger datapoints indicating a greater number of responses. Perfect performance would be indicated by five large datapoints lying along the dashed diagonal line, whereas chance performance would be represented by small datapoints randomly distributed throughout each quadrant. The four examples provided were chosen to illustrate trends identified within the group.

Figure 3 shows the scatterplots for a child (91) who exhibited the poorest SLA via biHAs (i.e. greatest RMS error and lowest percentage correct score). This is characterized by small datapoints distributed across all quadrants, consistent with multiple errors in lateralizing to the right or left and all stimuli presented from directly ahead perceived as coming from either the left or right. Comparison of the biHA and biCI scatterplots shows a marked improvement post-operatively, with fewer but larger data points clustered closer to the diagonal line via biCIs. A similar response pattern was seen for child 199. Figure 4 shows the response patterns for a child (155) who exhibited less poor SLA via biHAs. A similar pattern was also exhibited by child 181. In both cases a trait of perceiving stimuli to come disproportionately from the extreme right or left, including instances where sounds were presented from directly ahead was demonstrated. For child 155 all but one stimuli were correctly lateralized. Again, biCIs caused an improvement in SLA, with a greater proportion of stimuli from 0° azimuth correctly localized. The trend for improved ability to localize sounds from directly ahead via biCIs was shared by the remaining six participants (112, 129, 143, 157, 161 and 163) who had better SLA via biHAs than the four previous examples. None of these children made any lateralization errors via biHAs or biCIs. Figure 5 shows the scatterplots for one of these children (143). Across all ten children, whilst lateralization errors were made via biHAs, no children lateralized stimuli to the incorrect hemisphere via biCIs. Further, no children correctly localized all stimuli presented from 0° azimuth via biHAs, however four out of ten achieved this via biCIs. Figure 6 shows the scatterplots for child 112 who, unlike the other participants, gave a worse percentage correct score via biCIs. Whilst there were localization errors via biHAs, this child's responses tended to the diagonal line. In contrast, via biCIs, localization of sounds from ±60° azimuth was less accurate and accuracy for stimuli from 0° azimuth had improved. Consistent with the rest of the group, this child showed an improvement in RMS error via biCIs.

Finally, Table 4 shows the results of correlation analyses for RMS error and percentage correct scores for biHAs and biCIs with unaided HTLs. No significant associations were found. In addition, no significant relationships were observed between absolute inter-aural difference in HTL and RMS error or percentage correct scores via biHAs or biCIs.

Discussion

Despite the importance of knowing the effect of simultaneous biCIs on children who previously used biHAs, no directly relevant studies have been reported that examine within-subject changes in SLA for children with severe to profound hearing loss. To address this, the present study provides SLA findings measured as part of routine clinical care for ten such children. On average, our data show that biCIs resulted in small to substantial improvements in SLA, as measured by RMS error and percentage correct score. This was the case even though SLA via biHAs was comparable to that exhibited by some children using biCIs (Grieco-Calub & Litovsky, 2010; Van Deun et al., 2009; Zheng et al., 2015). Despite the improvement seen, biCIs did not lead to SLA equivalent to that seen in normally-hearing peers, who typically localize without error on this task (Lovett et al., 2012). Further, in the absence of test-retest reliability data for the methods of SLA assessment employed in this study, and information regarding just meaningful differences in SLA, it is difficult to define which of the ten children's SLA changed in a clinically significant way. For example, it is not yet known how improved localization of sounds from straight ahead but poorer accuracy at the periphery might affect a listener in real-life situations. The relationships between clinical measures of SLA and real-life experiences are a potential subject for future research.

In addition to measuring SLA via RMS error and percentage correct score, we also characterized children's SLA performance by plotting their response patterns. This revealed a number of response pattern types which were comparable to those described by Zheng et al. (2015). In agreement with their study we found that each metric was sensitive to different aspects of SLA. Examples of this are the biHA results of children 112, 129 and 161 (Table 3) where RMS errors varied by less than two degrees but the proportion of correct responses ranged from 53% to 70%. Some children with similar RMS error or percent correct scores also had markedly different response distributions on inspection of the scatterplots. This suggests that children's abilities to perceptually map acoustic space differed in ways that were not captured by either RMS error or percentage correct alone. Therefore, to avoid missing important information, clinicians should measure SLA in a comprehensive manner, via each of the methods. One example from our data is child 112 whose RMS error improved whilst their percentage correct score decreased. It is not clear from this child's data why this was the case.

The secondary aim of the study was to explore associations between HTLs and SLA for both biHAs and biCIs. For biHAs, our data showed weak, non-significant correlations between HTL averages and RMS error and percent correct scores. This is broadly consistent with biHAs findings reported by Lovett et al. (2015) for children with predominantly mild to severe hearing loss, who found only a weak correlation between HTL averages in the better hearing ear and percentage correct scores. It should be noted that the present study was likely limited in its ability to detect strong associations due to the small sample size tested. It is interesting to note however, that whilst no significant correlations were found across the group, the four children (91, 155, 181 and 199) with the worst HTLs also had the worst SLA via biHAs and those with the best HTLs (143 and 161) were among those with the better SLA via biHAs Perhaps not surprisingly, we also found weak, non-significant correlations between average HTLs and SLA via biCIs. Again, those with the best HTLs were among those with the best SLA via biCIs. A lack of statistical power due to a small sample should be noted. However, other subject factors not measured in this study are also likely to confound any relationship between SLA via biCIs and HTLs. These include a child's age at the onset of hearing impairment (Nopp et al., 2004; Van Deun et al., 2009), age at intervention (Asp et al., 2011; Killan et al., 2015; Litovsky & Gordon, 2016; Van Deun et al., 2009) and the extent of their device use both prior to and following implantation (Asp et al., 2015; Godar & Litovsky, 2010). In the present study HTLs below 500 Hz were not included in the analysis. Future research could investigate whether the inclusion of lower frequency HTLs strengthens the relationship between hearing thresholds and SLA.

In conclusion, the findings of the present study demonstrate that simultaneous biCIs led to improved sound localization in a group of children with predominantly symmetrical, severe to profound sensorineural hearing loss that previously used biHAs. However, based on our findings of a child whose percentage correct score was worse for biCIs, and the lack of any association between HTLs and SLA performance, it is recommended that SLA be directly measured during baseline assessment and repeated post-operatively for each individual.

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Table 1 Participant Characteristics

Idno	Aetiology	Progression of hearing loss	HA	HA fitting targets	CI	CI strategy	Age at biHA test (months)	Age at biCI test (months)	Time post-CI (months)
91	unknown	progressive	Phonak Naida V SP	DSL v5	Cochlear	ACE	220	235	14
112	unknown	congenital	Widex P38	DSL i/o	Cochlear	ACE	215	230	14
129	unknown genetic	progressive	Phonak Nathos UP	DSL v5	Cochlear	ACE	124	140	13
143	unknown	congenital	Phonak Naida V SP	DSL v5	Cochlear	ACE	66	87	17
155	unknown	progressive	Phonak (not specified)	DSL i/o	Cochlear	ACE	115	129	13
157	Usher's Syndrome	congenital	Phonak Nathos UP	DSL v5	Cochlear	ACE	81	95	12
161	ANSD	fluctuating	Phonak Nathos SP	Not stated	Med-El	FSP	74	98	12
163	unknown genetic	progressive	Phonak PPCLP	DSL	Med-El	FSP	120	138	15
181	unknown	progressive	Phonak Power Maxx 411	DSL	Cochlear	ACE	74	92	12
199	unknown	progressive	Phonak Sky Q70-SP	DSL v5	Cochlear	ACE	197	216	15
						Mean	**128.6**	**146**	**13.7**
						St Dev	**60.48**	**59.22**	**1.63**

Table 2: Participant audiometric status

Idno	**Mean HTL$_{(0.5-4)}$ (dB HL)**	**Mean HTL$_{(0.5-1)}$ (dB HL)**	**Mean HTL$_{(2-4)}$ (dB HL)**	**Absolute inter-aural difference in HTL$_{(0.5-4)}$ (dB)**
91	96.25	77.50	108.75	12.50
112	107.50	96.25	110.00	5.00
129	91.25	83.75	93.75	7.50
143	74.38	35.00	105.00	13.75
155	100.00	87.50	107.50	12.50
157	91.25	86.25	92.50	10.00
161	77.50	63.75	85.00	17.50
163	96.25	93.75	97.50	7.50
181	100.63	88.75	101.25	3.75
199	102.50	100.00	100.00	2.50
Mean	**93.751**	**81.25**	**100.125**	**9.25**
St Dev	**10.63**	**19.20**	**8.07**	**4.83**

Table 3 RMS error and percentage correct scores via biHAs and biCIs.

Idno	**Baseline assessment via BiHAs**		**Assessment one year post-CI via BiCIs**	
	RMS error (degrees)	**Percent correct (%)**	**RMS error (degrees)**	**Percent correct (%)**
91	50.20	23.33	22.58	51.33
112	21.21	70.00	18.97	60.00
129	20.49	63.33	18.97	70.00
143	18.17	63.33	16.43	70.00
155	32.40	40.00	15.49	93.33
157	18.97	70.00	10.95	86.67
161	20.49	53.33	16.43	70.00
163	16.43	70.00	14.49	76.67
181	33.32	43.33	16.43	70.00
199	49.30	23.33	10.95	86.67
Mean (SD)	**28.10 (12.76)**	**52.00 (18.54)**	**16.17 (3.57)**	**73.47 (12.79)**

Table 4: Associations between SLA measures and HTL averages

		$\mathrm{HTL}_{(0.5\text{-}4)}$	**$\mathrm{HTL}_{(0.5\text{-}1)}$**	**$\mathrm{HTL}_{(2\text{-}4)}$**
RMS error biHAs	Pearson Correlation	0.441	0.299	0.403
	Sig. (2-tailed)	0.203	0.401	0.249
RMS error biCIs	Pearson Correlation	-0.003	-0.225	0.396
	Sig. (2-tailed)	0.994	0.532	0.258
Percent correct biHAs	Pearson Correlation	-0.270	-0.157	-0.287
	Sig. (2-tailed)	0.450	0.664	0.422
Percent correct biCIs	Pearson Correlation	0.067	0.247	-0.252
	Sig. (2-tailed)	0.853	0.492	0.482

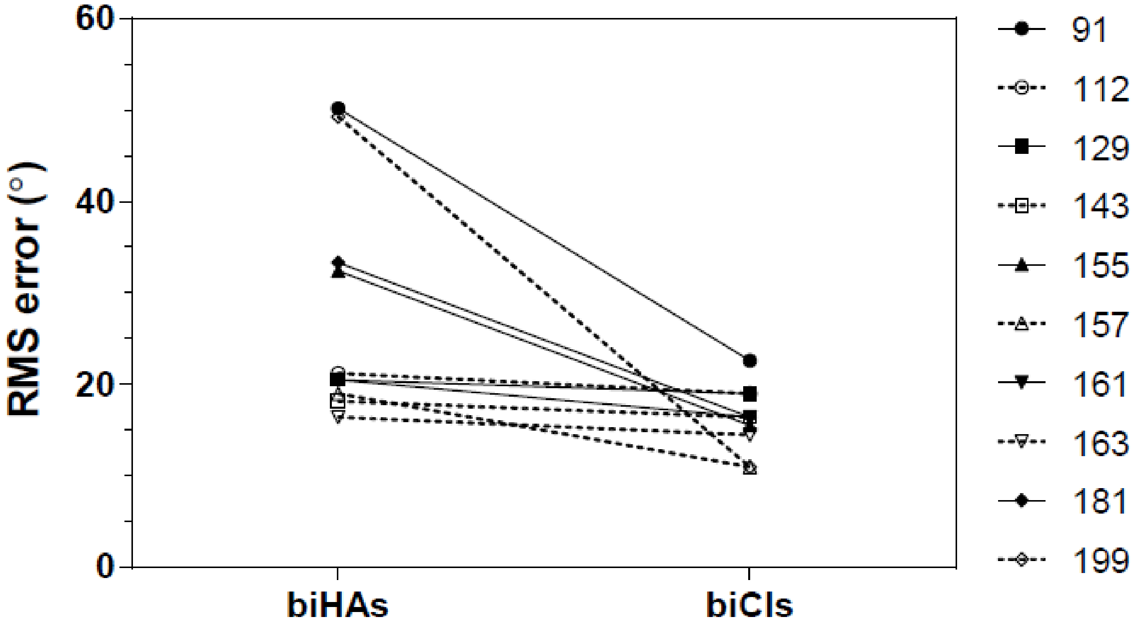

Figure 1. RMS error (°) for each child obtained via biHAs and biCIs.

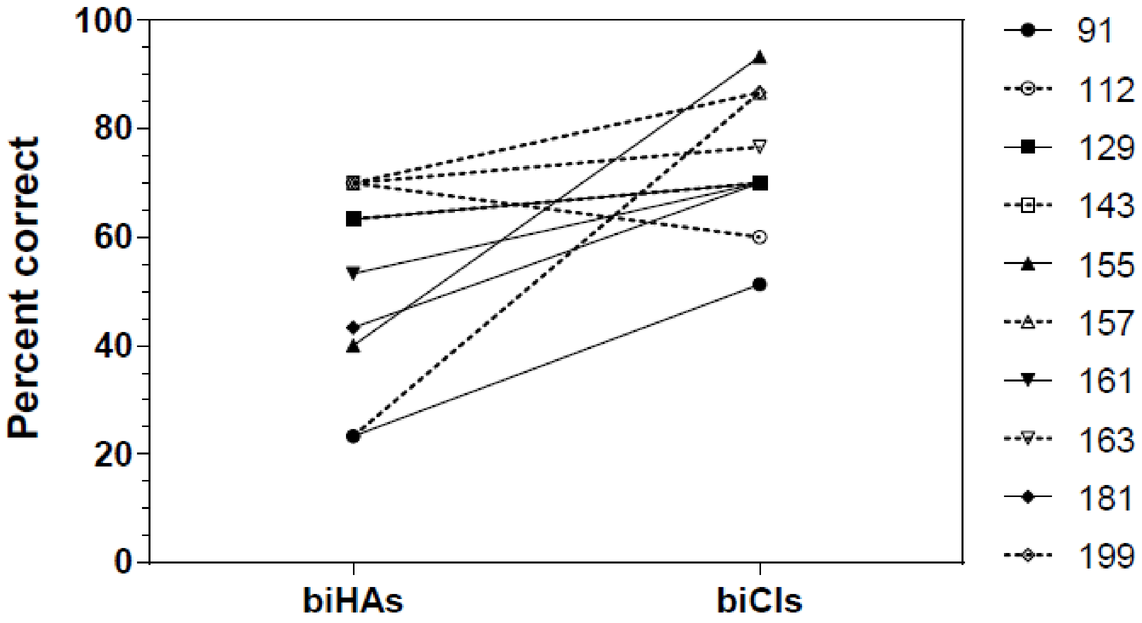

Figure 2. Percentage correct score for each child obtained via biHAs and biCIs.

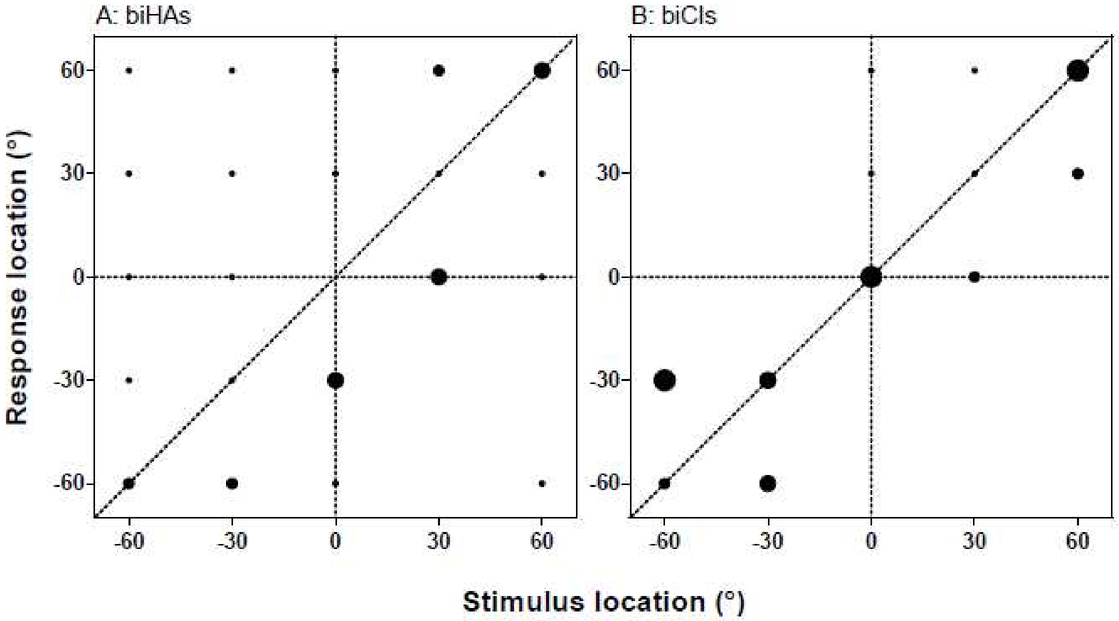

Figure 3. Scatterplots of response locations as a function of loudspeaker location for child 91. Panel A and B show biHAs and biCIs results respectively. The diagonal dashed line represents perfect performance. The size of the datapoints represent the number of responses at that location.

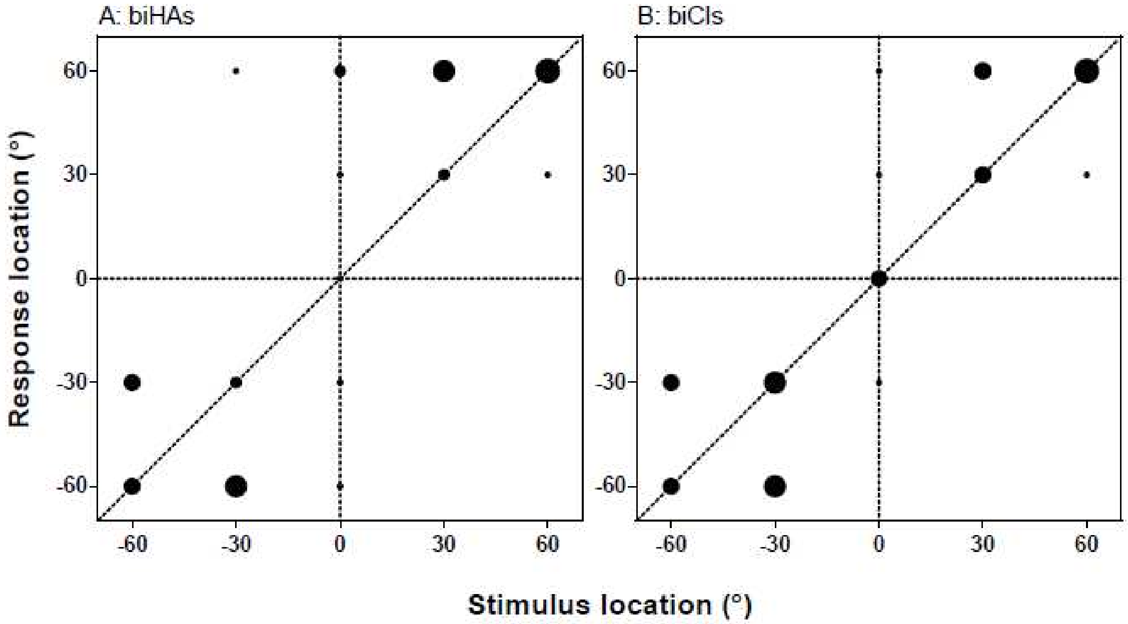

Figure 4. Scatterplots of response locations as a function of loudspeaker location for child 155. The format is the same as for Figure 3.

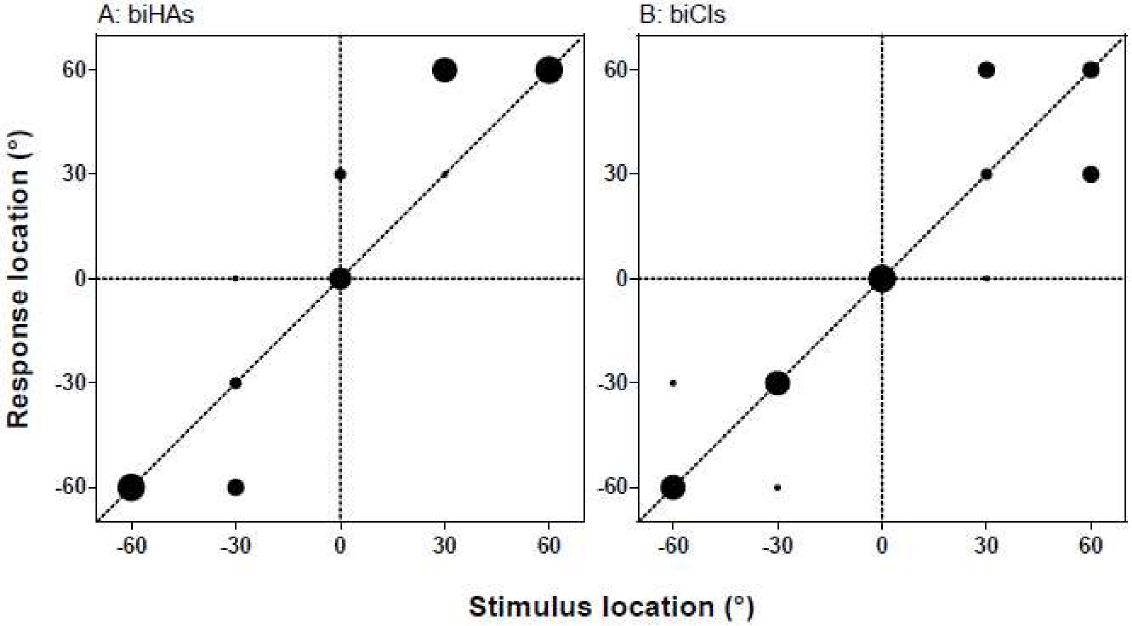

Figure 5. Scatterplots of response locations as a function of loudspeaker location for child 143. The format is the same as for Figure 3.

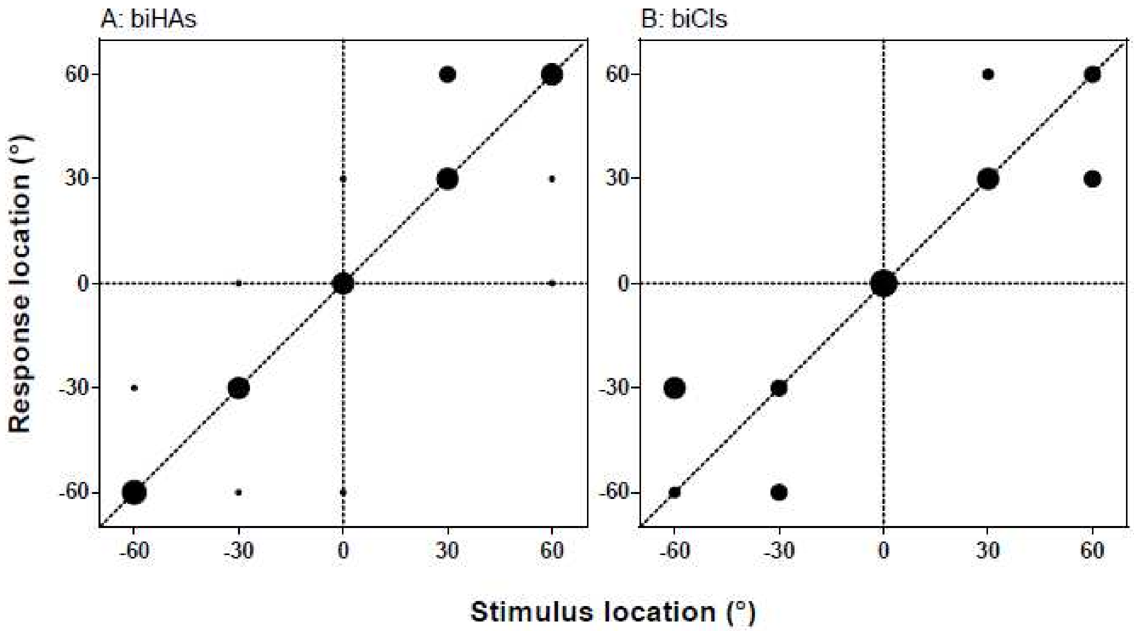

Figure 6. Scatterplots of response locations as a function of loudspeaker location for child 112. The format is the same as for Figure 3.