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Importance of Age and Postimplantation Experience on Speech Perception Measures in Children With Sequential Bilateral Cochlear Implants

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Objectives: Clinical trials in which children received bilateral cochlear implants in sequential operations were conducted to analyze the extent to which bilateral implantation offers benefits on a number of measures. The present investigation was particularly focused on measuring the effects of age at implantation and experience after activation of the second implant on speech perception performance.

Study Design: Thirty children aged 3 to 13 years were recipients of 2 cochlear implants, received in sequential operations, a minimum of 6 months apart. All children received their first implant before 5 years of age and had acquired speech perception capabilities with the first device. They were divided into 3 age groups on the basis of age at time of second ear implantation: Group I, 3 to 5 years; Group II, 5.1 to 8 years; and Group III, 8.1 to 13 years. Speech perception measures in quiet included the Multisyllabic Lexical Neighborhood Test (MLNT) for Group I, the Lexical Neighborhood Test (LNT) for Groups II and III, and the Hearing In Noise Test for Children (HINT-C) sentences in quiet for Group III. Speech perception in noise was assessed using the Children's Realistic Intelligibility and Speech Perception (CRISP) test. Testing was performed preoperatively and again postactivation of the second implant at 3, 6, and 12 months (CRISP at 3 and 9 mo) in both the unilateral and bilateral conditions in a repeated-measures study design. Two-way repeated-measures analysis of variance was used to analyze statistical significance among device configurations and performance over time.

Setting: US Multicenter.

Results: Results for speech perception in quiet show that children implanted sequentially acquire open-set speech perception in the second ear relatively quickly (within 6 mo). However, children younger than 8 years do so more rapidly and to a higher level of speech perception ability at 12 months than older children (mean second ear MLNT/LNT scores at 12 months: Group I, 83.9%; range, 71–96%; Group II, 59.5%; range, 40–88%; Group III, 32%; range, 12–56%). The second-ear mean HINT-C score for Group III children remained far less than that of the first ear even after 12 months of device use (44 versus 89%; t, 6.48; $p < 0.001$; critical value, 0.025). Speech intelligibility for spondees in noise was significantly better under bilateral conditions than with either ear alone when all children were analyzed as a single group and for Group III children. At the 9-month test interval, performance in the bilateral configuration was significantly better for all noise conditions (13.2% better for noise at first cochlear implant, 6.8% better for the noise front and noise at second cochlear implant conditions, $t = 2.32$, $p = 0.024$, critical level = 0.05 for noise front; $t = 3.75$, $p < 0.0001$, critical level = 0.05 for noise at first implant; $t = 2.73$, $p = 0.008$, critical level = 0.05 for noise at second implant side). The bilateral benefit in noise increased with time from 3 to 9 months after activation of the second implant. This bilateral advantage is greatest when noise is directed toward the first implanted ear, indicating that the head shadow effect is the most effective binaural mechanism. The bilateral condition produced small improvements in speech perception in quiet and for individual Group I and Group II patient results in noise that, in view of the relatively small number of subjects tested, do not reach statistical significance.

Conclusion: Sequential bilateral cochlear implantation in children of diverse ages has the potential to improve speech perception abilities in the second implanted ear and to provide access to the use of binaural mechanisms such as the head shadow effect. The improvement unfolds over time and continues to grow during the 6 to 12 months after activation of the second implant. Younger children in this study achieved higher open-set speech perception scores in the second ear, but older children still demonstrate bilateral benefit in noise. Determining the long-term impact and cost-effectiveness that results from such potential capabilities in bilaterally implanted children requires additional study with larger groups of subjects and more prolonged monitoring. **Key Words:** Bilateral—Children—Cochlear implants—Sequential—Speech recognition.
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Binaural (two-ear) hearing enables optimal performance of the human auditory system. In normal-hearing subjects, binaural hearing is directly associated with improved speech understanding in quiet and in noise, as well as improved sound localization ability, when compared with listening with a single ear (1–4). Unilateral and/or bilateral hearing loss may deprive individuals of these binaural mechanisms. Because of the widely recognized binaural advantages, hearing professionals have for many years striven to provide effective binaural hearing to individuals with hearing impairment whenever technology has allowed (1,5–8). Because cochlear implants have been remarkably successful at launching many deaf people from a state of near-to-complete auditory deprivation to a state of hearing and being able to use auditory input successfully, little attention has been provided to the deficits unilateral cochlear implant recipients, especially children, might still experience by nature of being monaural listeners. In the past decade, there have been several studies demonstrating that most adult patients who receive bilateral cochlear implants may be able to realize significant benefits on measures of speech perception and sound localization under controlled experimental conditions (9–15). Initial reports also suggest that benefits from bilateral implants may be realized by prelingually deafened children (16–20).

Although it is medically feasible to provide bilateral implants in either sequential or simultaneous operations, most children with bilateral implants have been sequentially implanted, with months or years between the activation of the two devices. With regard to this population of children, several unique questions can be considered. First, how will the age of the patient (even if they are a high-performing unilateral implant recipient) at the time of second-ear implantation affect the hearing performance of the second-implanted ear and its performance relative to the first implanted ear? Second, is there an effect of second-implant experience on speech perception ability with the second ear alone? Third, if performance on speech perception measures with the second ear does not achieve that of the first ear, is it possible that a bilateral benefit might still be realized? This study was aimed at beginning to address these timely issues, with a focus on the age-related speech perception benefits of sequential bilateral implantation.

MATERIALS AND METHODS

Subject Selection

This US multicenter protocol study had a repeated-measures design that evaluated sequential bilateral cochlear implantation in children and was sponsored by Cochlear Americas (Denver, CO, USA). Subjects were 30 children aged 3 to 13 years who received their first cochlear implant before 5 years and who possessed the necessary speech perception and cognitive skills to complete the designated speech perception tests. The prerequisites for enrolling in the study were based on speech measures obtained while the children were functioning with a single implant. These were 1) In the implanted ear, a score of 30% or greater on MLNT words (children $\leq$5 yr) or LNT words (children >5 yr) at 70dB sound pressure level; 2) In the ear to be implanted, severe to profound hearing loss based on pure-tone thresholds and score 30% or less aided on MLNT words (children $\leq$5 yr) or LNT words (children >5 yr) at 70 dB sound pressure level. In addition, before this testing, children who had not been wearing hearing aids (HAs) in the nonimplanted ear had to undergo a minimum 30-day HA trial before speech perception testing. 3) Children participated in a habilitation/educational setting, with emphasis on spoken language development. 4) Normal cochlear anatomy as determined by radiographic measures.

All children had either a Nucleus 22, a Nucleus 24, or a Nucleus 24 Contour in their first implanted ear and received a Nucleus 24 Contour or Nucleus 24 Contour Advance in their second ear (Cochlear). The children were divided into the following age categories on the basis of their age at the time of second-ear implantation: Group I, ages 3 to 5 years; Group II, ages 5 years 1 month to 8 years; and Group III, ages 8 years 1 month to 13 years.

Speech Perception in Quiet

Bilateral and unilateral (left and right ears) auditory performance was assessed preoperatively and again at 3, 6, and 12 months after the initial activation of the second device. The following speech perception measures were used: 1) MLNT words (Group I); 2) LNT words (Groups II and III); and 3) HINT-C sentences in quiet (Group III only).

Speech Perception in Noise

The primary speech perception measure used to evaluate bilateral enhancement in noise postoperatively was the CRISP test (21). The CRISP test was used to compare monaural (i.e., left and right ears alone) with bilateral performance in noise at 3 and 9 months postoperatively. For the CRISP test, the child was seated facing a loudspeaker placed approximately 5 feet away at 0 degrees front. Because this test is intended to evaluate speech intelligibility for known words, rather than vocabulary, the test was initiated by familiarizing the child with a series of 25 picture/sound combinations to ensure that the child correctly identified the picture and understood the target words. Testing was conducted under four conditions: 1) quiet; 2) target front and competing speech source in front; 3) target front and competing speech source on right; and 4) target front and competing speech source on left.

For each of these conditions, the child was tested bilaterally and with the first ear alone. The order of these conditions was randomized for each child. The CRISP test was administered at a fixed signal-to-noise ratio (SNR). The level of the noise was varied to avoid ceiling effects, but the individual SNRs were fixed across test conditions for each individual.

Statistical Analysis

Please refer to the online version.

RESULTS

Speech Perception in Quiet

Figures 1–3 illustrate the MLNT/LNT scores for subjects in Groups I to III, respectively, tested preoperatively and 3, 6, and 12 months postoperatively for each ear and the bilateral condition. The bilateral condition preoperatively refers to the children using the first-ear implant with a contralateral HA, whereas postoperatively, the bilateral condition refers to the use of two cochlear implants.

In Group I, the mean performance of the first ear did not significantly change during the 12-month period (preoperative was 69.6 versus 84.5% at 12 months; t = 1.928, p = 0.065, critical level = 0.017), whereas the mean performance of the second ear significantly increased with each time interval (preoperative to 3, 3–6, and 6–12 mo) during the same period (t = 10.56, p < 0.0001, critical level = 0.017; preoperative 2.4 versus 83.9% at 12 mo). The range of individual scores for the second ear in all Group I children at the 12-month evaluation was 71 to 96% compared with 0 to 17% preoperatively (only 1 child scored greater than 0% with an HA in the second ear preoperatively). For 6 of the 7 subjects, second-side scores were statistically indistinguishable from those for the first ear based on binomial comparisons (22) at the 12-month evaluation. It is important to note that Group I was the only group in which the second-ear mean performance (83.9%) eventually reached equivalent performance to that (84.5%) with the first-implanted ear (t = 0.09, p = 0.93, critical level = 0.05).

The mean bilateral score for Group I was not significantly different from that obtained for the first ear postoperatively (e.g., 92.3% bilateral versus 84.5% first ear at 12 mo; t = 2.29, p = 0.029, critical level = 0.025). By the 12-month evaluation, the second-ear mean (83.9%) was also not significantly different from the bilateral condition or the first ear (t = 2.50, p = 0.017, critical level = 0.017). However, the bilateral 12-month mean score was significantly better than that obtained preoperatively when the children were tested with the first ear and a contralateral HA (t = 3.24, p = 0.003, critical level = 0.017). The mean bilateral score at 12 months was 92.3% (range, 71–100%) compared with 67.3% (range, 38–100%) preoperatively with the children using an HA contralaterally in addition to the implant. Five of the 7 children scored 100% at 12 months, with only 1 of the 7 scoring 100% preoperatively. It is worth noting that the child scoring 100% preoperatively scored 95.8% in the second ear at 12 months compared with 0% preoperatively with an HA.

Results for the Group II children were similar to those of Group I in that no statistically significant changes in mean scores were observed for the first ear over time (preoperative was 74 versus 68% at 12 months for the 8 subjects with data at both intervals; t = 1.18, p = 0.26, critical level = 0.05). In addition, significant changes between test intervals were observed for the second ear (preoperative was 0 versus 59.5% at 12 mo; t = 9.91, p < 0.001, critical level = 0.05) preoperative to 12 months, except between 6 and 12 months (t = 0.71, p = 0.48, critical level = 0.05). For the second ear, all the children in Group II scored 0% preoperatively with an HA but had scores ranging 40 to 88% at 12 months (9 mo for 1 child). Again, the bilateral mean scores were not significantly better than the first ear at any postoperative time point. However, it is important to note that by the 12-month evaluation, the mean scores for the first and second ears also were not significantly different (68% first ear and 60% second ear; t = 1.37, p = 0.19, critical level = 0.05). As with the younger children, the performance for the second ear had caught up with the first side. In contrast to Group I, the mean 12-month bilateral implant score for Group II (81% for the 8 subjects with 12-mo data) was not significantly better than the mean score obtained preoperatively (71% for the 8 subjects with 12-mo data) when

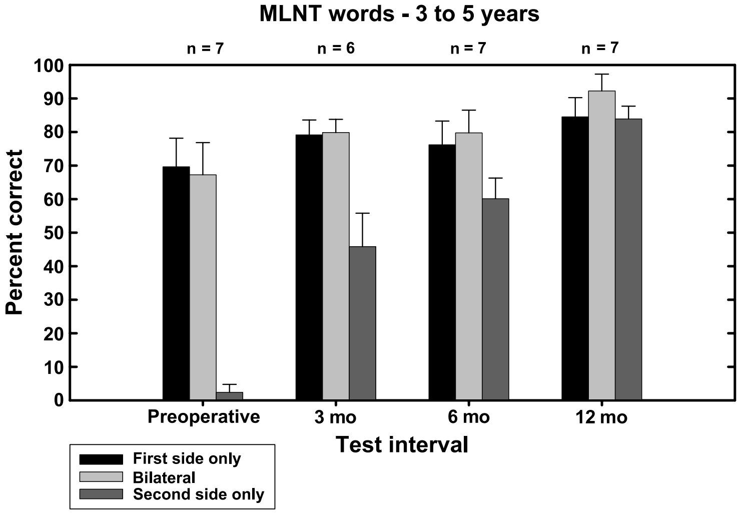

FIG. 1. Multisyllabic Lexical Neighborhood Test word scores for children 3 to 5 years old at the time of second-ear implantation. Error bars are standard errors of the means. MLNT, Multisyllabic Lexical Neighborhood Test.

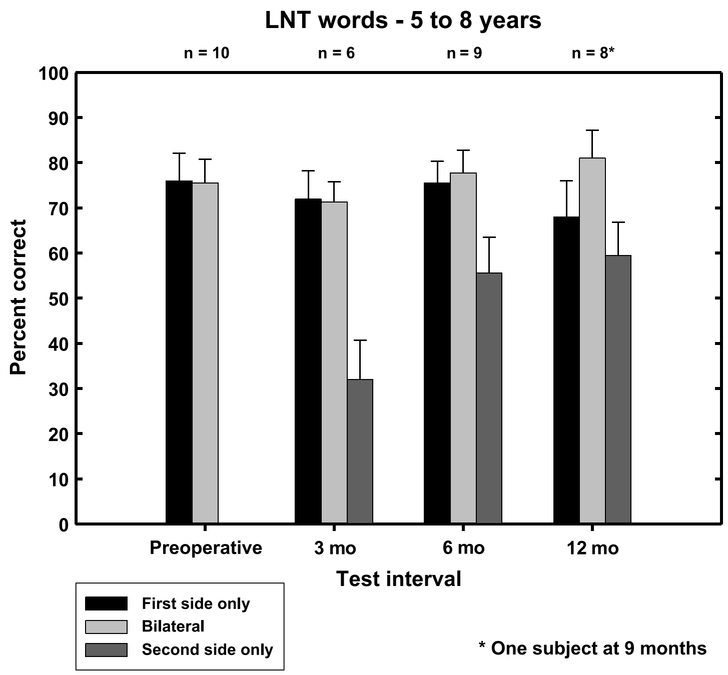

FIG. 2. Lexical Neighborhood Test word scores for children 5 to 8 years old at the time of second-ear implantation. Error bars are standard errors of the means. LNT, Lexical Neighborhood Test.

using an implant and an HA ($t = 1.45$, $p = 0.176$, critical level = 0.05). However, 7 of the 8 subjects with 12-month data scored 80% or greater with bilateral implants at 12 months, whereas of the same 8 subjects, only 4 scored 80% or greater preoperatively.

As can be observed from Figure 3, speech perception scores in Group III subjects in the second ear remained far less than the first implanted ear even after 12 months. The mean scores for the first ear did not significantly change during the 12-month period (preoperative was 73 versus 81% at 12 mo for the 12 children with data at both intervals; $t = 1.19$, $p = 0.24$, critical level = 0.025). Although more modest for the Group III children compared with the younger children, there was a statistically significant improvement in mean scores for the 12 children with data at both intervals from 0 (all subjects

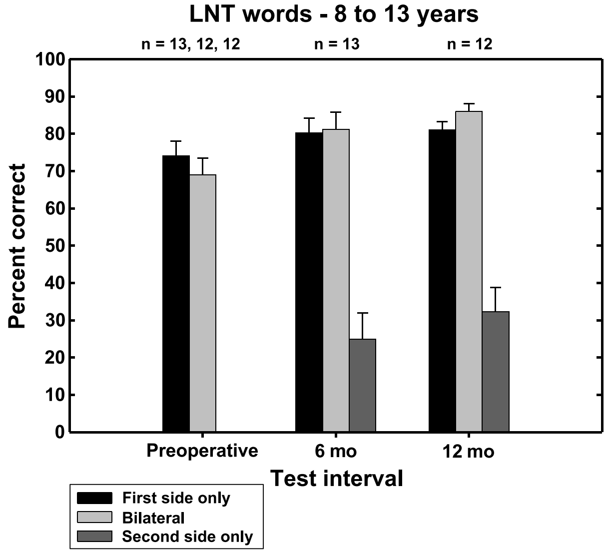

FIG. 3. Lexical Neighborhood Test word scores for children 8 to 13 years old at the time of second-ear implantation. Error bars are standard errors of the means. LNT, Lexical Neighborhood Test.

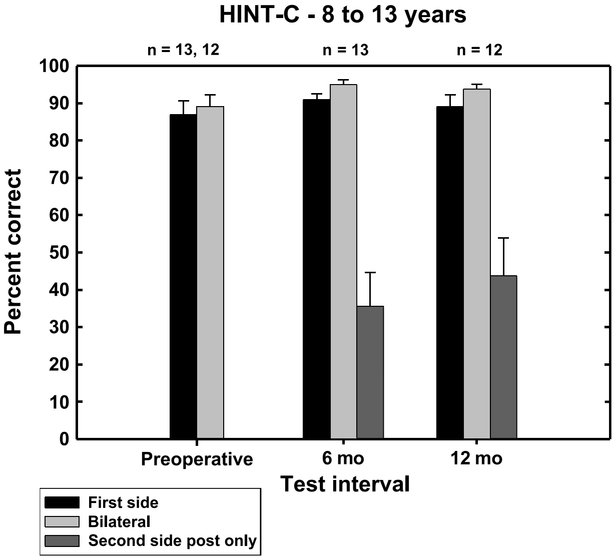

FIG. 4. Hearing in Noise Test for Children sentences for children 8 to 13 years old at the time of second-ear implantation. Error bars are standard errors of the means. HINT-C, Hearing in Noise Test for Children.

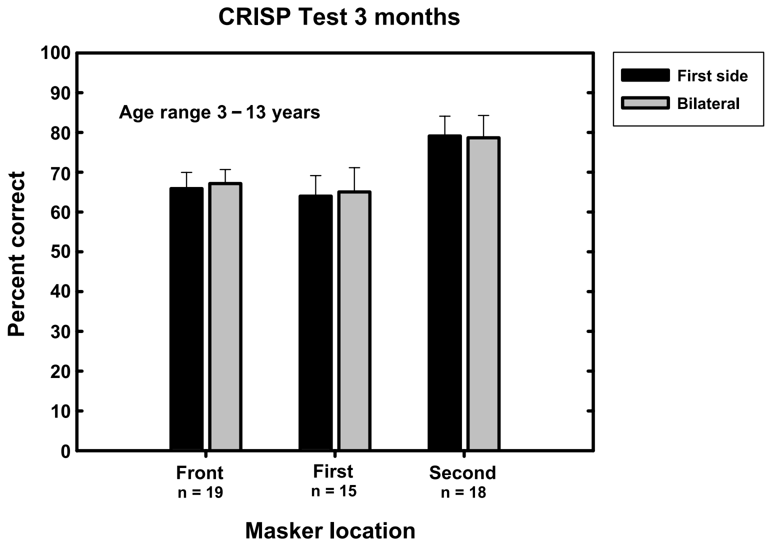

FIG. 5. Children's Realistic Intelligibility and Speech Perception scores for all age groups tested at 3 months after second-ear implantation. Error bars are standard errors of the means. CRISP, Children's Realistic Intelligibility and Speech Perception.

scored 0% preoperatively with an HA) to 26.7% (t = 4.69, p < 0.0001, critical level = 0.05) at 6 months with the second implant. Although the mean improved to 32% for the second ear at 12 months, this was not a significant change during the 6-month mean (t = 1.56, p = 0.12, critical value = 0.05). The range of individual scores for the second ear at the 12-month evaluation was 12 to 56% compared with 0% preoperatively for all children in Group III. Interestingly, despite the relatively small improvement the second ear made in mean word recognition, the bilateral score at 12 months (86%) was significantly better (t = 3.02, p = 0.004, critical level = 0.017) than the mean score for the Group 3 children when using the first-ear implant and an HA preoperatively (69%).

Figure 4 illustrates the HINT-C scores obtained for subjects in Group III in each test condition at the designated test intervals. Results were similar to the LNT scores for Group III in that first-ear (preoperative was 86 versus 89% at 12 mo for the 12 children with data at both intervals; t = 0.30, p = 0.77, critical level = 0.025) and bilateral (preoperative was 88% versus 94% at 12 mo for the 11 children with data at both intervals; t = 0.92, p = 0.36, critical level = 0.025) scores did not change significantly during the 12-month test interval, nor were they significantly different from each other (first-ear mean was 89 versus 94% bilateral at 12 mo; t = 0.79, p = 0.43, critical level = 0.05). The second-ear mean score remained far less than that of the first ear even after 12 months of device use (44 versus 89%; t =

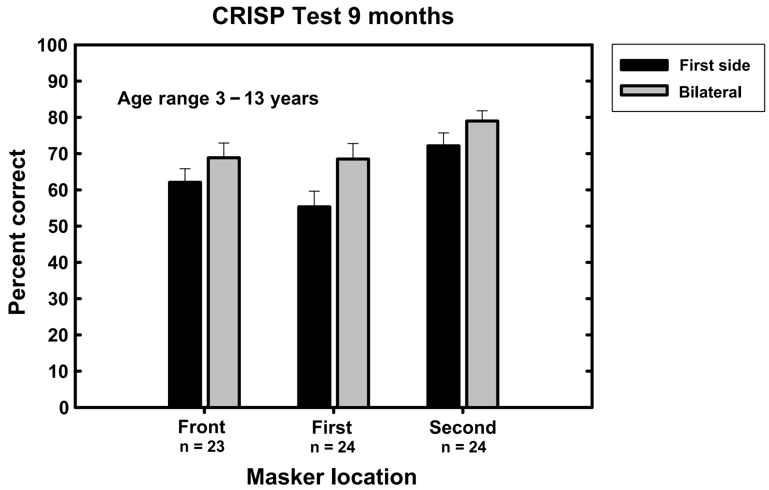

FIG. 6. Children's Realistic Intelligibility and Speech Perception scores for all age groups tested at 9 months after second-ear implantation. Error bars are standard errors of the means. CRISP, Children's Realistic Intelligibility and Speech Perception.

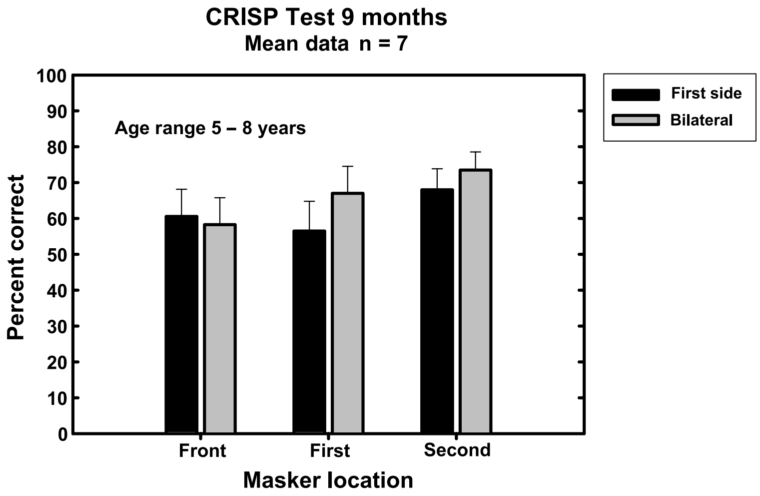

FIG. 7. Children's Realistic Intelligibility and Speech Perception scores for children 5 to 8 years old tested at 9 months after second-ear implantation. Error bars are standard errors of the means. CRISP, Children's Realistic Intelligibility and Speech Perception.

6.48, $p < 0.001$, critical value = 0.025), although individual scores varied considerably from 0 to 96%.

Speech Perception in Noise

Children's Realistic Intelligibility and Speech Perception test results for bilateral benefit in noise are illustrated for all subjects together at the 3- and 9-month test intervals in Figures 5 and 6. In each figure, percent correct scores are shown according to the spatial location of the masker. At the 3-month test interval, there were no statistically significant differences between the bilateral and first ear, only configuration for any masker location. However, at the 9-month test interval, performance in the bilateral configuration was significantly better for all noise conditions ($t = 2.43$, $p = 0.018$, critical level = 0.05 for noise front; $t = 4.295$, $p < 0.0001$, critical level = 0.05 for noise at first implant; $t = 2.43$, $p = 0.018$, critical level = 0.05 for noise at second implant side), particularly when noise was directed toward the first cochlear implant (CI) on the basis of the differences in mean scores shown in Figure 6. Adding the second CI with the better SNR resulted in improved performance (by 13.2%; 68.5 from 55.3% noise at first CI). The bilateral configuration was 6.8% better for the noise front (62.1–68.9%) and noise at second CI (72.2% to 79%) conditions. However, the results do show an increasing advantage of the bilateral condition over the first ear alone with the additional 6 months of experience regardless of masker location. The 9-month CRISP results are broken down by age. In Group I, only 4 of these young subjects were able to complete the test due to attention limitations, difficulty understanding the task, and/or fatigue. In each age group, the difference between the scores for the bilateral

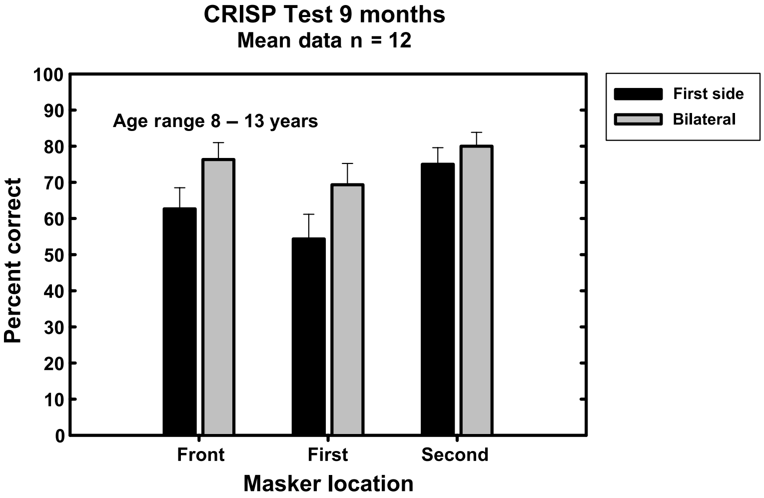

FIG. 8. Children's Realistic Intelligibility and Speech Perception scores for children 8 to 13 years old tested at 9 months after second-ear implantation. Error bars are standard errors of the means. CRISP, Children's Realistic Intelligibility and Speech Perception.

and first CI configuration is largest when noise is directed at the first CI. Comparing mean scores for first implant ear and the bilateral condition, there were no statistically significant differences for the 2 younger groups. Figure 7 shows results for Group II children that are very similar to those obtained for Group I. The small subject numbers in each group was likely a factor in the failure of the differences to reach statistical significance (Group I, n = 4; Group II, n = 7). However, for the older group (Figure 8; n = 12) the mean bilateral scores were significantly better than scores with the first ear alone for conditions with the noise at front (76.3–62.7%; $t = 3.75$, $p = 0.001$, critical level = 0.05) and noise at first implant ear (69.3 versus 54.3%; $t = 3.57$; $p = 0.001$, critical level = 0.05) (for an expanded "Results" section, please refer to the online version).

DISCUSSION

The current study provides speech perception performance data for 30 children who all received their first cochlear implant when they were younger than 4 years of age, had acquired speech perception capability with the first ear, but received their second implant at various ages.

There seem to be intricate and complicated interactions between first-ear, second-ear, and bilateral performance levels. Overall, the work suggests that if sequential bilateral implantation is being considered in a child, doing so earlier in life might produce better results on measures such as those used here. However, 11 of the 13 Group III children also achieved some level of open-set word recognition by 6 to 12 months postactivation, and all children grouped as a whole show a statistically significant binaural advantage in noise by 9 months. Thus, the notion that an upper limit might be placed on the age of second-ear implantation needs to be avoided while additional data are produced that can support decisions at the clinical level more definitively. Because selection criteria are being made, it is also important to consider that children participating in this study had to meet a minimum requirement for speech perception with the first implanted ear; thus, extension of these findings to children with poorer first-ear outcome needs to be made with caution.

The effect of auditory experience on the speech perception abilities of a sequentially implanted second ear in children has yet to be reported. In this study, all 3 groups showed statistically significant mean improvements in speech perception with the second ear up through the 6-month testing. The second ear of children in Group I continued to improve and equaled the speech perception performance of the first ear by the 12-month test interval. What is not known from this study is whether additional experience past the 12-month testing would result in better second-ear performance for the children in Groups II and III.

Litovsky et al. (19,20) measured two aspects of spatial hearing abilities in children with sequential bilateral CIs: the minimum audible angle (MAA) and the effect of spatially separating target and masking speech using the CRISP test. The first study (19) included 13 children with bilateral CIs (CI + CI) and 6 children with 1 CI and an HA in the nonimplanted ear (CI + HA). Approximately 70% (9/13) of children in the CI + CI group had MAA thresholds (discriminated left/right source separations) of less than 20 degrees. Of those children, 77% (7 of 9) performed better when listening bilaterally than with either CI alone. The improved performance in the bilateral conditions was observed primarily after an extensive period of bilateral stimulation, which is consistent with the data reported here, which show that the emergence of bilateral benefits can occur during a lengthy period in an auditory system that was not initially activated in a bilateral mode. The second study (20) measured both MAA and CRISP performance with 10 children in each group (CI + CI or CI + HA) but used an adaptive SNR to measure speech reception thresholds, rather than the fixed-SNR approach used here. On the MAA task, only the CI + CI group performed significantly better when listening bilaterally than monaurally, although the large intersubject variation in the CI + HA group suggested that some children with bimodal hearing are able to perform fairly well on the MAA task. Measures of speech in quiet and in noise showed that, on average, bilateral implants provide a benefit of several decibel reduction in speech reception thresholds. In contrast, in the CI + HA group, the addition of the HA in the nonimplanted ear often resulted in binaural "disruption," or reduced performance compared with the monaural condition.

The age range and age at bilateral implantation of children studied by Litovsky et al. (19,20) was similar overall to the range used here (4–14 yr) and is a byproduct of the age at which children have been, to date, receiving bilateral CIs clinically. Taken together, these studies suggest that, on average, children with bilateral CIs are able to combine the inputs to the two ears in ways that provide most of the children at least some benefits on tasks related to spatial hearing. In quiet, the benefit can be thought of as resulting from binaural summation. In noise, for the most part, these abilities involve having access to the ear with the best SNR, but to some extent, there are also small benefits due to the squelch effect. Similar effects have been reported in adults (9,10,23).

There are several possible explanations, which cannot be distinguished by this study, with regard to why the second implanted ear of the older children did not acquire the speech perception ability achieved by the younger children. First, the older children had a greater time interval between first- and second-ear implantation. This may have resulted in more ingrained reliance and attention to the first ear input than possibly exists in children with a shorter interval between implantation. The more prolonged dependency on the first implanted ear may create reluctance on the part of these older children to focus on the second ear input in a way necessary for optimal progress. This may be accentuated by the greater need for the most optimal hearing with increasing age. The daily demands placed on the older child's hearing may make them less able to tolerate a period of adjustment

Another possible explanation for the poorer performance of the second ear in older children is complicating social and personal factors. These children were high-performing unilateral implant recipients with normal or near normal language and speech who had long since "graduated" from auditory-verbal therapy at the time of their second implant. In addition, many of the children were preteens or teens and were going through a great deal of emotional adjustment to life itself. For some of these older children, the prospect of surgery and resumption of auditory-verbal therapy was not welcomed by the child. It is possible that this created emotional resistance with decreased motivation on the part of the child to work with the second implant.

Additionally, the concept that a decrease in central auditory neural plasticity may occur with increasing age can be theorized to be at work in these older subjects. In implanted children, auditory plasticity and the role of experience have been identified as a key factor in cortical auditory evoked potentials (24,25) and in the ability to acquire language postimplantation (26–28) Such studies have supported the existence of a "sensitive" or "critical" period corresponding to an age of transient maximal neural plasticity in the central auditory system (25,29) and have been used to justify clinical decisions to lower the age of candidacy for unilateral implantation to optimize outcomes. Taken together, data support the idea of a critical period for auditory development. However, any interpretation or prediction must be approached with caution because any direct effect on speech perception performance of a second ear in sequentially implanted children or on binaural sensitivity in children with bilateral implants remains to be more fully documented. A reduced capacity for the development of the central auditory pathways serving the second ear with increasing age can explain some of the age-related differences observed in this study.

Some important caveats to this work are noted here. First, children who today have bilateral implants are typically from families with higher than average awareness, education, and desire to be on the edge of new medical approaches. In addition, our selection criteria required that subjects must have acquired open-set speech perception capability with their first cochlear implant. This introduces some degree of bias such that the outcomes in the children tested here may actually overestimate what would be measured in the overall population. In addition, the small n size in some of the groups, which was most significant in the youngest age group during CRISP testing, and which was related mostly to attention limitations and difficulty of these young children completing the task, may have also produced some biases in the data that are hard to control. It is unclear whether these biases may have overestimated or underestimated the benefit of bilateral implantation. Until larger numbers of subjects are studied from a more variable array of backgrounds, this issue will not be fully understood. It should be kept in mind that the bilateral comparisons used in this study represent a very limited analysis of the potential benefit of bilateral cochlear implantation in real-world conditions. However, the data as they stand represent the first study of its kind, and the results, although interpreted with caution, can be informative regarding the possible outcomes in children who are bilaterally implanted (for an expanded "Discussion," please refer to the online version).

CONCLUSION

Bilateral sequentially implanted children who are successful users of their first device are able to obtain open-set speech discrimination in their second ear even when receiving their second implant as late as 13 years of age.

The speech perception scores in the second ear of children in this study improved with experience during the first 6 months of implant use. Scores continued to improve for up to 12 months in children younger than 8 years. Further experience from 6 to 12 months did not improve the mean scores of the 8- to 13-year-old children.

Speech perception scores in the second ear improved at a faster rate and achieved a higher final level at 12 months (near that of the first implanted ear) in the youngest children (younger than 8 yr). Second-ear mean scores remained significantly less than those of the first implanted ear in the oldest age group (older than 8 yr).

Sequentially implanted children in this study have better mean speech perception scores in background noise in the bilateral condition than with a single implant. The performance in quiet may also be greater for the bilateral condition but did not reach statistical significance in this study due to the small measured differences and relatively small number of subjects.

Although this study adds to the understanding of how sequentially implanted children adjust to and benefit from a second device, determining the long-term impact on the life of the child and the resulting cost-effectiveness of bilateral cochlear implantation in children requires further study with larger groups of subjects and longer periods of monitoring.

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SUPPLEMENTARY INFORMATION

MATERIALS AND METHODS

Statistical Analysis: To address statistical significance grouped results were first analyzed using a Two-Way Repeated Measures Analysis of Variance (ANOVA) with test interval and Device Configuration (i.e., First CI, Second CI, Bilateral CIs) as the two factors and speech test (MLNT, LNT, HINT-C or CRISP) score as the dependent variable. Prior to subjecting percentage data to the ANOVA procedure, the data were subjected to an arcsin transformation (arcsin $\sqrt{x}$) so that the percentage values more closely followed a normal distribution. Pairwise comparisons, based on the Holm-Sidak method (SigmaStat, 2004) were then used to address differences among device configuration and performance over time. The Holm-Sidak test, involves computing and ordering the *p* values of all comparisons from smallest to largest. Each *p* value is then compared to a critical level that depends upon the significance level of the test, the rank of the *p* value, and the total number of comparisons to be made. *P* values less than the critical level indicate significant differences among the various groups being tested.

RESULTS

The ANOVA analyses indicated significant interaction between test interval and device configuration (first ear, second ear, and bilateral) for all speech perception measures when significant effects occurred, with the exception of the CRISP test at 9 months. Since the main interest is progression over time for the different device configurations the results that follow will focus on the results obtained in the post-hoc analyses, rather than present the various ANOVA main effects. There were occasions when a child did not complete a test due to attention limitations or fatigue, as indicated by the subject numbers for each test condition at each interval in each of the relevant figures discussed below. To minimize the effects of such omissions every available data point was used for the post-hoc comparisons such that the statistical results were based on matched data (i.e., comparisons were made within the same subjects across test conditions) on as many subjects as possible.

HINT C: Note that this test was assessed preoperatively only for the first ear and bilateral conditions with the intent of making comparison postoperatively between the speech perception scores of the first ear, second ear, and bilateral conditions over time. Statistical comparisons with preoperative performance for the second ear with a hearing aid are not made.

CRISP: Test-time constraints meant that many children were not assessed on the CRISP test in the second ear. To maximize a balanced design with the largest number of subjects, results for the first ear and the bilateral condition are presented. Because the 3 and 9 month testing for each subject may have been performed at different SNRs, the absolute scores are not comparable between test intervals.

DISCUSSION

Group I patients (age 3–5 years at time of second implant) were the only ones in which the second ear speech perception performance consistently achieved that of the first ear. By the 12 month evaluation, for 6 of the 7 subjects, second-side scores were statistically indistinguishable from those for the first ear. One child from Group I scored 21% poorer (significant) with the second ear compared with the first. In this latter case, the child had shown substantial and steady improvement over the 12 months of second implant use. At this child's 3 month evaluation the difference was 58% between first and second ears in favor of the first side, and 30% at the 6 month evaluation.

Group II patients (age 5.1–8 years) also showed large improvements in speech perception ability in the second ear after 6 months of implant use, but mean scores remained below that of the first ear. Two of the 8 children obtained a second-ear score significantly poorer than the first ear after 9 to 12 months of device use with 6 children scoring no different statistically. The range of scores for the second ear at the 12 month evaluation (9 months for one child) was 40 to 71%, compared to 71 to 96 % for Group I.

The speech perception data for Group III patients (age 8.1–13 years) showed significantly reduced performance in the second ear despite early first ear implantation. Although substantially improved over preoperative scores with a hearing aid (all Group 3 children scored 0% preoperatively) the range of scores obtained for the second implant ear was reduced compared with the younger children at the 12 month evaluation, being 12 to 56%. Only 2 of the 12 children with data at the 12 month evaluation achieved scores comparable with their first implant ear. The other 10 children scored 28 to 92 % poorer with the second ear compared with the first ear, two of whom continued to score 0% after 12 months of second ear experience.

In addition to evaluating the development of speech perception ability of a sequentially implanted second ear, this study also sought to determine if speech perception scores are better in quiet and in noise when both ears are used together compared to either ear alone. Bilateral improvement reached statistical significance when all children were analyzed as a single group (N = 24) and for Group III children (N = 12) tested in background noise (CRISP) at 9 months. This bilateral advantage is greatest when noise is directed towards the first implant ear (in this case the head-shadow effect mitigates the effect of the noise at the second ear allowing access to an ear receiving a better signal-to-noise ratio). This is particularly interesting for patients in Group III who attained more limited second ear speech perception ability. This suggests that even when second ear open set speech perception is minimal certain auditory cues are still made available that are utilized by the listener for greater overall speech understanding in the bilateral condition. In quiet conditions (MLNT, LNT, HINT-C), although bilateral mean scores are greater than those of the first implanted ear for each age group, the difference does not reach statistical significance. This is also true when CRISP scores in noise are broken down for children in Group I (N = 4) and II (N = 7). Several of the younger subjects in these two groups found it difficult to complete the CRISP test, leading to a small N. The small differences measured in these conditions would require greater numbers of subjects than exists in this study in order to determine statistical significance.

To date, there have been a handful of studies published on bilateral cochlear implantation in children. Some of the focus has been on whether children overall can realize aspects of hearing attributed to binaural mechanisms, regardless of age of first and second ear implantation, or the level of speech perception and language already acquired by the child with the first implanted ear. In the largest series reported to date, Kuhn-Inacker et al reported results of 39 bilaterally implanted children who were heterogeneous with regard to age at onset of hearing loss, age at first ear implantation, speech perception competence with their first device, and time lag between implants.[1] Fourteen of the 39 patients had no significant speech perception ability with their first implanted ear. Postoperative speech perception testing in quiet and in noise was reported comparing the bilateral condition with the best performing unilateral ear only. The mean bilateral benefit in speech perception scores in noise (SNR +15dB) compared to the best monaural condition was 18.4 +8.2%. No statistically significant influence of age at first implantation or time gap between implantations on bilateral benefit in noise was reported. In addition, from that study it was difficult to surmise where there are differences between the first and second implanted ears, or effect of age on second ear performance.

In non-human species there is literature that illustrates how early experience shapes the development of the central auditory pathways. In these studies, manipulation of the auditory environment can induce abnormal auditory physiology, either at the level of a single neuron (Seidl & Grothe, 2005) or population of neurons (Zhang et al., 2002).[2,3] Examples of auditory plasticity are observed in barn owls, primarily in juvenile animals, and generally not in adults (Knudsen, 2002; but see Linkenhoker & Knudsen, 2002).[4,5] Data also show that, in congenitally deafened cats fit with a unilateral cochlear implant and then exposed to controlled acoustic stimuli, the largest responses were obtained in cats that were implanted at a younger age and that had longer auditory experience (Kral et al., 2002).[6]

It is important to mention the relative difficulties encountered by subjects in these 3 groups adjusting to their second device. Subjects in Group I, on average, accepted their second device with very little difficulty. At the other extreme were the subjects in Group III. The stimulation of their second ear was at first a very unpleasant experience to the child and subjectively seemed to interfere with the hearing they enjoyed with the first device. In several cases a battle ensued between the child and the parent/audiologist team over use of the device. It became necessary, as is now our custom for all older children, to reinstitute Auditory-Verbal therapy for the second ear, for fear of potential non-use of that device. Ultimately all Group III patients adjusted and use their second implant either all or most of the time. Patients in Group II varied in difficulty of adjustment, but anecdotally did not have on average as much difficulty as subjects in Group III.

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