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Auditory-Cognitive Training Improves Language Performance in Prelingually Deafened Cochlear Implant Recipients

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Abstract

Objectives—Phonological and working memory skills have been shown to be important for the development of spoken language. Children who use a cochlear implant (CI) show performance deficits relative to normal hearing (NH) children on all constructs: phonological skills, working memory, and spoken language. Given that phonological skills and working memory have been shown to be important for spoken language development in NH children, we hypothesized that training these foundational skills would result in improved spoken language performance in CI-using children.

Design—Nineteen prelingually deafened CI-using children aged 4- to 7-years-old participated. All children had been using their implants for at least one year and were matched on pre-implant hearing thresholds, hearing thresholds at study enrollment, and non-verbal IQ. Children were assessed on expressive vocabulary, listening language, spoken language, and composite language. Ten children received four weeks of training on phonological skills including rhyme, sound blending, and sound discrimination and auditory working memory. The remaining nine children continued with their normal classroom activities for four weeks. Language assessments were repeated following the training/control period.

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Results—Children who received combined phonological-working memory training showed significant gains on expressive and composite language scores. Children who did not receive training showed no significant improvements at post-test. On average, trained children had gain scores of 6.35 points on expressive language and gain scores of 6.15 points whereas the untrained children had test-retest gain scores of 2.89 points for expressive language and 2.56 for composite language.

Conclusion—Our results suggest that training to improve the phonological and working memory skills in CI-using children may lead to improved language performance.

Keywords

cochlear implant; spoken language; training; phonological awareness; working memory

Introduction 1.1

Successful spoken language development depends on several underlying skill sets. Two constructs repeatedly shown to be fundamental for the development of spoken language are phonological awareness (PA) and verbal working memory (WM) [1]. Models of both constructs rely on auditory sensory processing as a first step, followed by phonological segmentation [2–5]. Given the importance of acoustic analysis for the development of both PA and WM, it is not surprising that children who have received a cochlear implant (CI) show delays in both constructs, as a result of their delays in hearing onset [6].

The constructs of PA and WM develop independently, but they are correlated [7–11], possibly because measures for both constructs involve phonological segmentation and storage [4]. Individually, they each support the development of spoken language. Typically developing PA and WM skills have been shown to predict typical spoken language development. Specifically, rhyme, phoneme identification, and phoneme detection abilities are predictive of later vocabulary development [8–10] and auditory discrimination abilities are predictive of future morphology development [12]. Nonword repetition span predicts later vocabulary size [13–17], the length and syntactic complexity of future utterances [18,19], and story-telling expressive language ability [20]. Conversely, when there are delays in PA and WM development, delays in spoken language development are also seen. For example, children with poor rhyme awareness make more speech production errors [21] and children who have poor sound blending skills tend to remain in the bottom quartile of language learners four years later [22]. Children with poor backward spans show reduced listening comprehension skills [23]. The fact that both typical and disordered spoken language can be predicted by assessments of PA and WM made at an earlier timepoint suggests that PA and WM skills provide a foundation for spoken language development [4,7,9,24]. If it is the case that PA and WM serve as a foundation for spoken language, efforts to improve spoken language should first improve the foundational skills. By training to improve PA and WM performance—with an emphasis on the skills that have been linked to language outcomes—we might expect to see greater gains in spoken language outcomes than would be seen by training on spoken language alone.

CI-using children provide a unique population in which to test the hypothesis that training spoken language's foundation—PA and WM skills—will result in spoken language gains. As a result of their delayed hearing onset, CI recipient children have deficits in their PA performance, including those specific skills that have been shown to serve as a foundation for spoken language outcomes. When matched to normal hearing (NH) children on language ability, CI-using children had poorer rhyme performance and phoneme identification than their NH counterparts, particularly when the phonology and orthography were incongruent, suggesting that the CI recipients were relying on the lexical knowledge to a greater degree than the NH children [25–28]. When matched on word knowledge, CI recipient children are poorer than their NH peers on measures of sound blending [29,30]. CI-using children are also poorer than listening-age matched NH children on auditory discrimination tasks [28,31].

In addition to their PA delays, CI recipient children also show WM deficits, presumably also as a result of their delayed hearing onset [32,33]. As with their PA deficits, CI-using children's deficits have been shown on the same tasks that have been demonstrated to serve as a foundation for spoken language learning. CI-using children are poorer than their NH peers on nonword repetition [34], backward span [35], and forward span [36].

Finally, CI recipient children show deficits in spoken language performance. As would be expected from their PA and WM deficits, they show spoken language performance deficits on those measures of spoken language that have been linked to PA and WM development. CI recipient children score lower than their NH peers on measures of receptive vocabulary [37–40], expressive vocabulary [41], receptive language [42–44], and expressive language [44–46]. Their utterances also tend to be shorter and less syntactically complex [47,48]. These spoken language deficits have been linked to their deficits in PA and WM [28,49–52]. As such, improvements in spoken language will likely depend on first making improvements to the foundational PA and WM skills.

The aim of the current study is to test the hypothesis that improving spoken language depends on improving the PA and WM skills on which spoken language depends in a group of CI-using children, who show deficits in PA, WM, and spoken language performance. We note that we are not the first to make this effort. Kronenberger and colleagues [53] provided CI recipient children aged 7 to 11 years-old with five weeks of WM training. Following training, children showed significant gains on sentence repetition [54], and gains were maintained for six months. However, it should be noted that the language measure, sentence repetition, itself has been used as a measure of WM performance [55,56], and it therefore remains unclear whether training will improve the spoken language skills suggested to rely on WM, which are also more distally related to WM. Kronenberger et al.'s training also did not address the CI-using children's PA deficits, which are likely also important for their spoken language abilities, leaving open the question as to how training to improve PA would impact spoken language outcomes.

The current effort addresses these remaining questions. The training paradigm will focus on those specific PA skills that have been shown to be important for spoken language development; it will also include training on verbal WM span. We hypothesize that training these foundational skills in CI-using children will result in improved performance on measures of spoken language. Because both constructs have been shown to be weak in CI-using children [25–27,35,36], both constructs have been shown to be important for language development [8–10,18– 20], both constructs are implicated in measures of PA and verbal WM [1,4,57], and because training on PA has been shown to transfer to verbal WM performance [1,58], for this initial effort we have opted against attempting to determine the precise mechanism of change by which training these foundational skills improves spoken language performance. Rather, we will focus on developing the foundational skills through training and examine spoken language performance as our outcome measure. Consequently, there may not be a one-to-one correspondence between a training task and a particular skill and, instead, several skills may be addressed within a single training task. This approach increases the efficiency of the training, making it more likely children will remain engaged throughout training; maintaining engagement with the training task increases the likelihood that children will develop the foundation of PA and WM skills that we hypothesize will result in improved spoken language performance.

Training was administered via Earobics (Houghton-Mifflin, Evanston, IL), which has been previously demonstrated to be effective for improving phonological awareness, general language abilities, and speech perception in noise in NH children [59–63]. Earobics also trains those same PA and WM skills—sound blending, phoneme identification, rhyme, and auditory discrimination—that have been shown to be weak in CI-using children [25–27,35,49]. Finally, Earobics has been specifically designed to appeal to young children, making it more likely to maintain their engagement, which in turn makes it more likely that they will development the PA and WM foundation needed.

Methods 1.2

Participants 1.2.1

Twenty-one children were recruited from Child’s Voice School in Wood Dale, Illinois, which provides children with hearing loss intensive listening and spoken language curriculum. Children were enrolled in a prospective study. Two children were excluded due to low performance IQ (<70 assessed on the Wechsler Preschool and Primary Intelligence Scale [46,64]); all remaining elementary-aged children enrolled at Child’s Voice were eligible to participate. All eligible children whose caregivers consented were enrolled in the study. The student population at Child’s Voice is not sufficiently large to match groups; we therefore randomly assigned children to either the trained or control groups. After random assignment, the two groups did not differ on age at test, duration of CI use, hearing thresholds prior to implantation, or hearing thresholds at test as discussed below.

All participants were prelingually deafened, aged between 4 and 7 years at test, and had been using their implants for at least one year. They were assigned to training or control group by the Child’s Voice principal, who did not participate in assessments or training. The first 10 children to enroll were assigned to the training group and the last 9 to enroll were assigned to the control group. Average participant demographics can be seen in Table 1 and individual demographics can be seen in the Appendix. On average, the children assigned to the control group were slightly younger (*M* = 62.7 months vs. *M* = 67.6 months) and had slightly less implant experience (*M* = 39.7 months vs. *M* = 45.7 months) but these differences were not significant. Despite their slight differences in CI experiences, children assigned to the control group had similar speech awareness thresholds to the trained group both prior to implantation (*M* = 74.4 dB HL vs. *M* = 74.5 dB HL) and immediately prior to training (*M* = 6.1 dB HL vs. 6.5 dB HL). Children with lower hearing thresholds prior to implantation tended to have been implanted later, but this correlation was not perfect (Pearson's *r* = .41). All children were on-track to graduate Child's Voice and attend the mainstream school in their home district by first grade. The test procedures were reviewed and approved by the Northwestern University institutional review board.

Materials 1.2.2

Language Assessment—Pre- and post-test measures of vocabulary were done using the Expressive One Word Picture Vocabulary Test and the Receptive One Word Picture Vocabulary Test, Fourth Edition (EOWPVT/ROWPVT, [65]. Sentence-level language was assessed using the oral components of the Oral Written Language Scales, First Edition (OWLS, [66]. The Listening Comprehension subscale the OWLS measures the ability of the child to understand spoken sentence-level materials; it differs from the ROWPVT by asking the child to understand the semantics and syntax of a sentence beyond their lexical knowledge. In the Oral Expression subscale, children are asked to complete spoken sentences or speak whole sentences, depending on their ability. Both subscales assess children's lexical, syntactic, and semantic abilities, and the Oral Expression subscale has an additional pragmatic component. The OWLS also yields an Oral Composite score, representative of overall spoken language ability. The EOWPVT, ROWPVT, and OWLS all include published test-retest gains taken from a broad NH sample. These testretest gains provide a measure of reliability for the tests (EOWPVT: *r* = 0.97; ROWPVT: *r* = 0.91; Listening Comprehension: *r* = 0.80; Oral Expression: *r* = 0.86; Oral Composite: *r* = 0.89) as well as the amount of gain to be expected from repeated exposure. However, because these values were collected from NH children, we opted to utilize an untrained control group to ensure any trained gains in the CI sample were a result of training and not from repeated test exposure in that population.

The OWLS was developed for children ages 3;0 to 21;0 years. The two vocabulary tests were developed for children and adults ages 2;0 years or older. As such, all measures were appropriate for the current sample (aged 4 to 7 years at test). The tests have been shown to be reliable with repeated testing, including in the timeline used here. All language measures' raw scores can be converted to scaled scores that have been normed to the NH population, allowing for a comparison of performance across groups that is independent of developmental ability.

Training—Training emphasized the same PA and WM skills that have been shown to be difficult for CI recipient children through a series of short, computer-based, interactive exercises. PA skills included phoneme identification, rhyme, sound blending, and auditory discrimination. Additionally, as children worked through the difficulty levels, two of the games began to present their sounds in the presence of background noise, allowing children to practice their speech perception in noise as well. All skills were presented in the context of colorful computer games and children received feedback on each trial. The skills trained are listed in Table 2.

Training was completed on computers with speakers placed at approximately 0 degrees azimuth. Children seated themselves at a comfortable distance from the computer. Loudness settings were determined by a staff member at Child's Voice to ensure a comfortable loudness level for each child for each training session. Children who supplemented their CI with an FM system in the classroom continued to use the FM system during training.

There were six games total, emphasizing different skill sets. All children began training at the same point for all six games. The training algorithm then adjusted the difficulty level of each game independently for each child to ensure children were adequately challenged on each skill throughout training. Training was monitored by a staff member at Child's Voice to ensure the children remained on-task for the duration of training and to ensure all training sessions were completed.

Training was administered via Earobics (Houghton-Mifflin, Evanston, IL), which has been previously demonstrated to be effective for improving phonological awareness, general language abilities, and speech perception in noise [59–63]. Each game had its own training algorithm and trained a unique combination of auditory and cognitive skills. The listing of games, the tasks performed by the children, and the concepts trained by these tasks can be seen in Table 2. The criteria for advancement to more difficult stimuli were unique to each game (see Table 2). The unique advancement criteria for each game means that progress through the different games can vary as a function of a child's proficiency with the different skills emphasized in those games (e.g., a child may be better at phoneme matching than at sound blending, so progress would be more rapid through C. C. Coal Car than through Caterpillar Connection).

Procedure 1.2.3

Children completed the EOWPVT, ROWPVT, OWLS, and the Wechsler Preschool and Primary Scale of Intelligence [64] prior to training. The full battery was given across four days to minimize fatigue though all individual tests were completed in a single session. The first two days of assessment were devoted to the language outcome measures and the remaining two days were devoted to the IQ assessment. All assessments were given at Child's Voice School by an experimenter who had not participated in group assignments. Following the pre-training assessments, those children assigned to the training group completed four weeks of Earobics training. Children assigned to the control group continued their normal classroom activities during this time.

Training was administered at Child's Voice school by Child's Voice staff during the course of the normal school day. The children in the training group completed 75 minutes of training per week for four weeks; this training dosage is similar to other cognitive trainings given to this age range [67–70]. Flexibility in the arrangement of training minutes was permitted to accommodate class activities such as field trips, holidays, and school assemblies. Child's Voice staff administered the training to better accommodate class activities and to avoid daily interruptions by the experimenters. An individual training session was never longer than 25 minutes. Children were allowed to choose which games they wanted to perform on each training day with the constraint that no games could be repeated until all games had been completed. All games were completed within a two-training-day span and all games were played with equal frequency. The difficulty level of each game was determined by the training algorithms, described above, and varied across participants.

Post-testing was administered within a week following the completion of training (or, in the case of the control participants, approximately four weeks following the completion of the pretests). Posttest assessments were administered by the same experimenter who administered the pretest assessments, not by the Child's Voice staff members who administered the training. In the posttest session, children completed the EOWPVT, ROWPVT, and the OWLS. Assessments were given at the homes of three control children because the four-week time-period ended during a school holiday; the remaining assessments were given at Child's Voice. Testing was done over two days to minimize fatigue though all single tests were completed in a single session. Thus, the trained and control children received equal exposure to the testing experimenters and were tested according to the same schedule though the control children received no exposure to the training task during the intervening four weeks.

Results 1.3

All analyses were performed on the standardized scores. Using the standardized scores removes differences across children due to developmental differences—in this sample, children were aged 4 to 7 years—that could mask differences resulting from training. Standardized scores were always calculated using the child's age at the pretest. Data were analyzed using 2 × 2 mixed-model ANOVAs, with session as the within-subjects factor. As hypothesized, we found a significant improvement of expressive oral language scores; we also found a significant improvement in overall oral language ability.

Language 1.3.1

There was no main effect of group on the three OWLS subtests: Listening Comprehension, $F(1,17) = 0.74$, $p = .40$; Oral Expression, $F(1,17) = 0.64$, $p = .44$; Oral Composite, $F(1,17) = 0.85$, $p = .37$. Shown in Figure 1, the trained and control groups did not differ in their language performance prior to training. Children's language performance was significantly lower than the published population mean at pretest for Oral Expression, $t(18) = 2.81$, $p = .01$, and Oral Composite, $t(18) = 3.00$, $p = .01$, measures, but not for Listening Comprehension, $t(18) = 2.14$, $p = .05$.

On the Oral Expression measure, there was a significant interaction of group and session, $F(1,17) = 7.54$, $p = .01$, $\eta^2_p = .31$. Shown in Figure 1, children in the training group showed a significant improvement on Oral Expression scores at posttest ($t(9) = 5.31$, $p < .001$, $d = 1.05$) whereas there was no change for the control group ($t(8) = 1.59$, $p = .15$). There was also a significant interaction for the Oral Composite score, $F(1,17) = 5.00$, $p = .04$, $\eta^2_p = .23$, where again there was a significant improvement by the trained group ($t(9) = 3.69$, $p = .005$, $d = 0.66$) but not the control group ($t(8) = 1.12$, $p = .27$). All children in the trained group improved on the Oral Expression measure whereas only 55% of control group children improved; 80% of trained children improved on the Oral Composite measure whereas only 55% of control children improved. The gains shown by the trained group for both the Oral Expression ($M = 6.35$) and Oral Composite ($M = 6.15$) exceed the published test-retest gain (M Oral Expression = 3.30, M Oral Composite = 5.70, [66], which in turn exceeded the test-retest gains made by the control group (M Oral Expression = 2.89, M Oral Expression = 2.56). Of the 10 trained children who improved on the Oral Expression measure, 5 showed gains of greater than 10 points; no control children showed Oral Expression gains of this magnitude. Of the 8 trained children who improved on the Oral Composite measure, 7 showed gains of greater than 10 points; 1 control child showed an Oral Composite gain of this magnitude. Overall, more trained than control children improved and the magnitude of this improvement was greater at both the group and individual level and was larger than would be expected from published test-retest assessments. We also found a main effect session on both Oral Expression and Oral Composite scores ($F(1,17) = 25.70$, $p < .001$, $\eta^2_p = .60$ and $F(1,17) = 13.90$, $p = .002$, $\eta^2_p = .45$, respectively), but these effects should be interpreted with an eye to the significant interactions.

For the Listening Comprehension component, there was no effect of session, $F(1,17) = 3.98$, $p = .06$, nor an interaction, $F(1,17) = 1.66$, $p = .21$, possibly because children's performance was not significantly different from published norms before training. However, we note that visual inspection of Figure 1 suggests the possibility of improvement by only the trained group that is masked by high variability in performance.

Because the control group was on average slightly younger and had slightly less CI experience prior to training—though these differences were not significant at the group level — we wanted to ensure the group × session interactions were a result of training and not of demographic differences. We therefore repeated the above analyses entering age at implant, age at test, and amount of CI experience as covariates. None of the covariates were found to be significant ($p > .05$). The group × session interactions for both the Oral Expression and Oral Composite scores remained significant. Correlating gain scores from the three OWLS subscales with age at implant, age at test, amount of CI experience, non-verbal IQ, hearing thresholds at time of implantation, and hearing thresholds at time of test also revealed no significant relationships ($p > .05$). Thus, the improvements in children's oral language scores appear to be a result of training and not differences in age or implant experience.

Vocabulary 1.3.2

There was no main effect of group for expressive, $F(1,17) = 0.10$, $p = .76$, or receptive vocabulary, $F(1,17) = 0.44$, $p = .52$. Shown in Figure 2, the trained and control groups performed similarly well prior to training. Children's pretest performance was not significantly different from the published population mean [65] for receptive vocabulary, $t(18) = 0.11$, $p = .91$, but was significantly better than the published mean for expressive vocabulary, $t(18) = 2.33$, $p = .03$. Perhaps not surprisingly given their high pretest performance, there was no effect of session nor a significant interaction of group × session following training ($p > .05$).

Discussion 1.4

The aim of the current study was to test the hypothesis that providing CI recipient children with training on both PA and WM skills would result in improved performance on measures of spoken language. Our hypothesis was confirmed, and children who received combined PA-WM training showed significant improvements on oral expressive language and a spoken language composite score relative to untrained children. We note that training was administered by Child's Voice staff, not by the experimenters who did the testing, meaning that both control and trained children received the same amount of exposure to the experimenters who administered assessments. Additionally, assessments were given according to the same schedule for both control and trained children, meaning these effects cannot be attributed to increased familiarity with the assessments or the experimenters by the trained children. Additionally, age at test, age of implantation, and amount of CI experience were not found to be significant covariates, suggesting the improvements are a result of training.

Visual inspection of the data suggests the possibility of an improvement on the Listening Comprehension measure masked by high variability in a small population, but further research in a larger sample is needed. The current sample was small, and the small sample size may have masked training gains in receptive language (or, alternatively, inflated gains in expressive language). It is possible that a larger sample will reveal that training has little effect on receptive language and that many of the gains can be attributed to CI use [71–73]. Though there was no change in vocabulary performance following training, we note that this sample had vocabulary scores within the NH range prior to training. Training may prove to be effective for children with lower vocabulary scores. Alternatively, it is possible that children's high pre-training vocabulary performance provided a foundation for the development of the PA and WM skills developed during training, leading to their improved language performance [10,24–27,74]. Under this account, children with lower vocabularies would show a reduced benefit from pure PA-WM training. Further work is necessary to better understand what, if any, mediating effects vocabulary has on PA and WM development in CI recipient children and the effects of training on each.

Together with the findings of Kronenberger et al. [53], our results indicate a positive future for training to improve language in CI recipient children. Of course, we recognize we have only scratched the surface of the work that remains to truly understand how effective this paradigm could be. Kronenberger et al.'s study, along with earlier studies in NH children [70,75–77], provided evidence that training can lead to improvement on trained tasks and tasks that are proximally related to the training; the current study adds to the evidence that training can improve performance on distally related tasks, at least when transfer is assessed in tasks that depend on the on the trained skills. However, a limitation of all these studies, including the present one, is that there is no indication of which PA and WM skills are being improved via training. We used Earobics here because it emphasizes those same skills that have been shown to be weak in CI-using children. The improvement the trained children showed on expressive language adds to the literature that Earobics can improve PA performance [59–62], and does so in a younger population than has been previously trained. The structure of Earobics, however, limits our ability to determine the extent to which particular skills are improving and the relationship between skill improvement and language gains. A task for future work will be to identify the mechanism of change that is driving the improvement in spoken language performance, and determine precisely which skills are being improved in these training paradigms and how their improvement links to spoken language. As our understanding of training grows, it is becoming increasingly apparent that individual abilities pre-training influence training outcomes (for a review, see [78]. It is therefore likely that the precise skills that drive change will differ as a function of individual CI-using children's pre-training PA and WM aptitudes, and that training will need to be personalized to optimize outcomes [79,80].

As part of determining the mechanism of change, future work will need to verify that changes are a result of auditory-cognitive training and not an artifact of being in a training environment. This preliminary effort used a no-contact control group, and though we ensured that the two groups received equal exposure to the testers and were not performing differently due to familiarity, we cannot eliminate the possibility that the trained group's improved post-test performance was a result of leaving the classroom daily to engage in a training activity and not the training itself. As we work to identify precisely which PA and WM skills are being improved in training, and which PA and WM skills are driving improvements in spoken language, the use of active controls will be important.

A major limitation of our study is that we only assessed training outcomes immediately after training completion. Whether or not training gains are maintained appears to depend at least in part on the level of deficit seen prior to training: children with a greater degree of impairment maintain their gains longer whereas children who are more in line with a typical developmental trajectory see a loss of gains during the maintenance period [67,69,70,81]. This sample of children scored below 2 *SD* population means on the Oral Expression portion of the OWLS at pretest [66], and within the NH range at post-test, suggesting gains many have been large enough to be maintained, but an empirical test is clearly warranted. Along with the maintenance of gains comes the question of gains in academic settings. Though we saw significant improvement on a standardized measure of expressive language following training, it is unclear whether the trained children were able to transfer their improved language skills from the testing setting to the classroom setting, and whether these gains were maintained beyond the treatment period.

Another limitation is the relatively high auditory ability of all the children enrolled in the study. As previously noted, the children's expressive and composite language scores were more than 2 *SD* below the NH mean at pretest, but expressive and receptive vocabulary were both within the NH range. Despite their young age, all the children were able to understand the oral instructions of the experimenters and complete the auditory-only training. It remains to be seen if children who score more poorly on language measures and/or who have more difficulty understanding spoken language will show as much benefit from auditory-only training or if training will need to be modified to accommodate their particular needs. Conversely, it is worth highlighting the fact that the training was accessible for children as young as 4-years-old. Training young children is more likely to have an impact on their language development [82]. Moving forward, we will need to balance the auditory accessibility of the training for children with weak auditory skills and the current accessibility of the training for very young children.

Conclusions 1.5

CI recipient children show deficits in both their PA and WM abilities, the same abilities that have been shown to support language learning. It therefore stands to reason that improving the functioning of those underlying skills would result in improved language performance. We tested this hypothesis by providing prelingually deafened CI recipient children with combined PA-WM training. We saw a significant improvement in their oral expressive and overall spoken language outcomes following training. We look forward to the development of additional training paradigms to further improve language abilities in this population.

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Appendix A

Trained participant characteristics.

Participant	Age	Age at Implant	CI Duration	Pre-Implantation Speech Awareness Threshold	Speech Awareness Threshold at Pretest		Performance IQ	Bilateral Implant	Simultaneous Bilateral Implant	Gender
T1	78	49	29	70	R: 35		82			F
T2	72	33	39	80		L: 10	121			F
T3	54	7	47	85	R: 20	L: 25	108	X		M
T4	72	46	26	55	R: 30	L: 20	103	X		M
T5	73	9	64	85	R: 15	L: 10	99	X		M
T6	75	18	57	55	R: 25	L: 25	110	X		F
T7	66	9	57	70	R: 20	L: 20	105	X		M
T8	57	14	43	80	R: 30	L: 20	93	X		F
T9	53	20	33	85	R: 0	L: −10	100	X	X	M
T10	57	14	43	80	R: 30	L: 20	79	X		F

Note. All ages are given in months, as is duration of CI use.

Appendix B

Control participant characteristics.

Participant	Age	Age at Implant	CI Duration	Pre-Implantation Speech Awareness Threshold	Speech Awareness Threshold at Pretest		Performance IQ	Bilateral Implant	Simultaneous Bilateral Implant	Gender
C1	51	42	9	35		L: 35	101			F
C2	95	18	77	85	R: 25	L: 15	125	X		M
C3	50	30	20	90		L: 20	114			M
C4	95	17	78	85	R: 20	L: 20	101	X		M
C5	53	21	32	55		L: 45	114			F
C6	55	38	17		R: 25	L: 25	82	X		M
C7	68	9	59	80	R: 15	L: 15	110	X		M

Participant	Age	Age at Implant	CI Duration	Pre-Implantation Speech Awareness Threshold	Speech Awareness Threshold at Pretest		Performance IQ	Bilateral Implant	Simultaneous Bilateral Implant	Gender
C8	48	20	28	80	R: 15		123			F
C9	50	10	40	75	R: 30	L: 20	77	X	X	M

Note. All ages are given in months, as is duration of CI use.

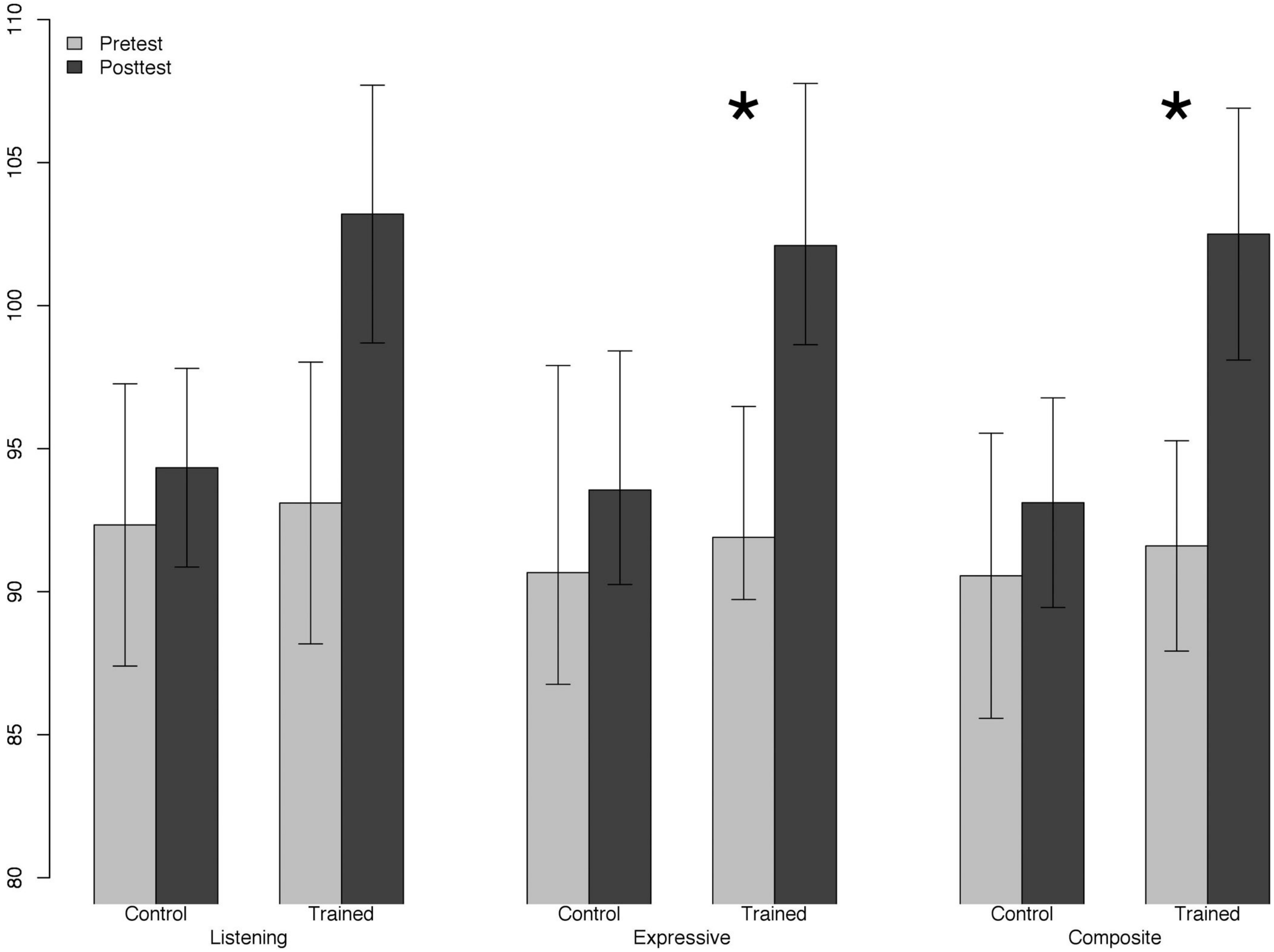

Figure 1.

Performance on listening, expressive, and composite portions of the language test (OWLS) at pre- and post-test by the trained and control groups. Error bars are standard error of the mean. Data were analyzed using group (trained vs. control) × session (pre- vs. post-test) mixed ANOVAs, where group was the between-subjects factor. There was a significant improvement by the trained group on the expressive and composite language scores, indicated by a significant group×session interaction ($p < .05$). The significant change from pre- to post-test for the trained group is indicated in the figure.

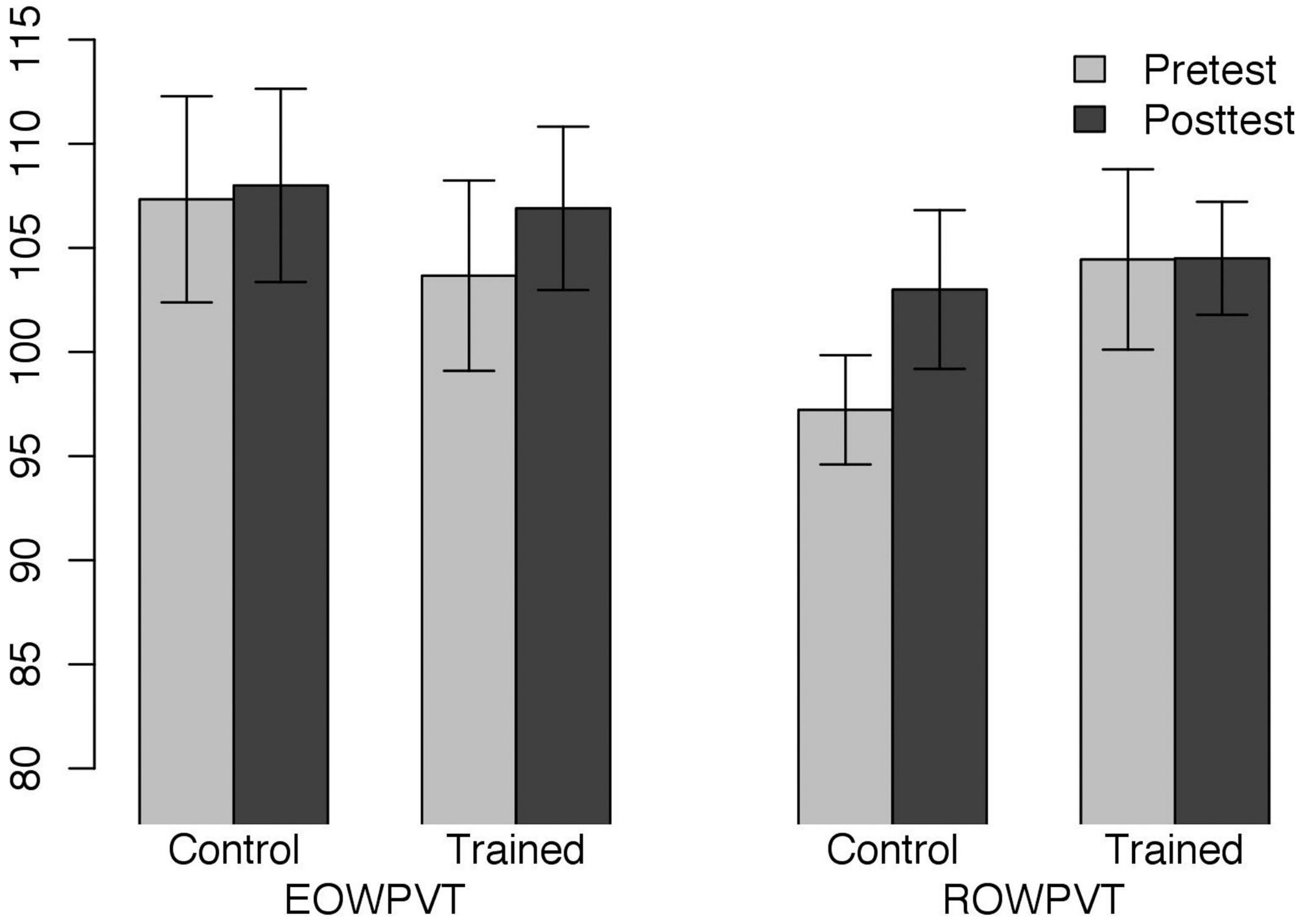

Figure 2.

Performance on expressive and receptive portions of the vocabulary test (EOWPVT/ROWPVT) at pre- and post-test by the trained and control groups. Error bars are standard error of the mean. Data were analyzed using group (trained vs. control) × session (pre-vs. post-test) mixed ANOVAs, where group was the between-subjects factor. There was no change in performance by either group (*p* > .05), though both groups performed at or better than NH norms at pretest.

Table 1

Participant characteristics.

	Trained			Control			!!	!!
	M	*SD*	Range	*M*	*SD*	Range	*t*(17)	*p*
Age	67.6	9.8	55 – 79	62.7	19.2	48 – 95	0.72	0.48
Age at Implant	21.9	15.4	7 – 49	23.0	10.3	10 – 39	0.18	0.86
CI Duration	45.7	13.2	28 – 70	39.7	24.8	12 – 78	0.67	0.51
Pre-Implantation Speech Awareness Threshold	74.5	11.7	55 – 85	74.4	17.9	35 – 90	0.01	0.99
Speech Awareness Threshold at Pretest	6.5	5.8	0 – 15	6.1	5.5	0 – 15	0.15	0.88
Performance IQ	100.0	12.7	79 – 121	105.2	16.8	77 – 125	0.77	0.45
Number Bilateral (Simultaneous)	7 (1)			5 (1)				
Number of Females	5			3				

Note. All ages are given in months, as is duration of CI use. (Simultaneous) refers to the number of children who received simultaneous bilateral implants.

Table 2

Earobics Step 1 Games, Targeted Concepts, and Criteria for Advancement

Game Title	Task	Concept	Criterion for Advancement
Karloon's Balloons	recalling and sequencing environmental and speech sounds in quiet and noise	auditory working memory (C); sound identification (A); phoneme identification (A); speech perception in noise (A)	three consecutive correct
C. C. Coal Car	matching phonemes to graphemes; identifying target phonemes as initial, medial or final	phoneme matching (A); phoneme identification (A)	four consecutive correct
Rap-a-Tap-Tap	recalling a sequence of drumbeats, speech sounds, syllables, and phonemes	auditory working memory (C); syllables (A)	80% accuracy in a block
Caterpillar Connection	blending 2 words into a compound word; blending 2 or 3 syllables into a word; blending 2, 3, or 4 phonemes into a word	auditory working memory (C); sound blending (A)	three consecutive correct
Rhyme Time	find the non-rhyme; find the non-rhyme in noise	auditory working memory (C); rhyme (A); speech perception in noise (A)	three consecutive correct
Basket Full of Eggs	discrimination of pairs of phonemes, syllables	auditory discrimination (A)	85% accuracy in a block

Note: (C) refers to a primarily cognitive concept and (A) refers to a primarily auditory concept