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Cochlear Implant Use by Prelingually Deafened Children: The Influences of Age at Implant and Length of Device Use

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This study focused on the long-term speech perception performances of 34 prelingually deafened children who received multichannel cochlear implants manufactured by Cochlear Corporation. The children were grouped by the age at which they received cochlear implants and were characterized by the amount of time they used their devices per day. A variety of speech perception tests were administered to the children at annual intervals following the connection of the external implant hardware. No significant differences in performance are evident for children implanted before age 5 compared to children implanted after age 5 on closed-set tests of speech perception ability. All children demonstrated an improvement in performance compared to the pre-operative condition. Open-set word recognition performance is significantly better for children implanted before age 5 compared to children implanted after age 5 at the 36-month test interval and the 48-month test interval. User status, defined by the amount of daily use of the implant, significantly affects all measures of speech perception performance except pattern perception.

KEY WORDS: cochlear implants, prelingually deafened children, age of implant, amount of use

The clinical use of cochlear implants has rekindled the historic controversy over the educational management and the social development of young deaf children (Lane, 1993; Tyler, 1993; Tyler, Davis, & Lansing, 1987). Philosophical differences are at the root of the controversy, with the primary issue being whether deaf children should be raised and educated as part of a Deaf community or integrated into hearing society. Advocates of cochlear implantation claim that the cochlear implant has had a dramatic impact on improving the acquisition and use of spoken language by deaf children, with positive ripple effects socially and psychologically (Osberger, 1993). Opponents of cochlear implants suggest that implanting a prelingually deafened child deprives that child of his or her Deaf culture and yet does not provide enough hearing to enable the child to become part of the hearing world (Lane, 1993). It is the viewpoint of some members of the Deaf community that the cochlear implant hinders parents of deaf children from accepting the deaf child and allowing him or her to become part of his or her natural community. The implant is viewed as " highly experimental…with unknown long-term consequences physiologically, psychologically, linguistically and socially" (Lane, 1993).

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Many studies have reported a wide range of speech perception performance by children with congenital and acquired profound hearing losses who have received multichannel cochlear implants. The results of studies published to date indicate congenitally deaf and other prelingually deafened children may not show measurable changes in speech perception performance until the cochlear implant has been used for two or more years (Fryauf-Bertschy, Tyler, Kelsay, & Gantz, 1992; Gantz, Tyler, Woodworth, Tye-Murray, & Fryauf-Bertschy, 1994; Miyamoto, Osberger, Robbins, Myres, & Kessler, 1993; Staller, Beiter, Brimacombe, Mecklenburg, & Arndt, 1991). Considerable variability in performance across children has been found and attributed to several factors, including the child's age at onset of deafness, the length of auditory deprivation experienced, and the age at which a child received the cochlear implant. Other factors, which are more difficult to quantify but may yield equal or greater influence on a child's performance with a cochlear implant, include the child's educational and home environment, the mode of communication used, and the amount and kind of rehabilitation training the child receives.

Several studies of subgroups of children from various cochlear implant centers have been published. Waltzman et al. (1994) reported on a group of prelingually deafened children who were implanted before 3 years of age and attained very high levels of speech perception performance after 2 years of implant use. The 14 children in this study received extensive aural/oral training and rehabilitation. Miyamoto et al. (1993) reported the mean scores on tests of speech perception ability for 8 children with congenital deafness and 11 children with prelingually acquired deafness with 1 to 4 years of implant experience. The results suggested no difference in speech perception performance of the two groups; roughly half of the children demonstrated open-set speech recognition. Shea, Domico, and Lupfer (1994) reported on 30 children with speech perception performance results up to 5 years post-implant. These results indicated that age at onset of deafness and age at implantation correlated with speech perception performance. However, the range of performance on tests was large, and number of participants tested at later test intervals was limited.

To date, few studies have documented speech perception performance of a large number of children who have used their cochlear implants for more than 2 years. The purpose of the present study is to analyze the longitudinal speech perception performance of prelingually deafened children who have 3 to 5 years of experience with their cochlear implants. Individual performance on selected tests of speech perception ability is presented as a function of (a) the duration of cochlear implant use, (b) the age at which the children received their cochlear implants, and (c) the amount of daily cochlear implant use. Providing the reader with individual results allows for appreciation of the variability among participants. The analysis of group data allows a view of trends in performance related to age at implant and patterns of cochlear implant use.

Method

Participants

Forty children who have received cochlear implants at the University of Iowa and have 3 or more years of cochlear implant experience were considered for this study. Data from 34 children are presented. Six children were excluded from the analysis for various reasons. Two children have Goldenhar Syndrome, which is characterized by craniofacial anomalies including an absent outer ear and malformed inner ear structure. These children, aged 5 and 6 at the time of cochlear implant surgery, were excluded because they received primarily stimulation of facial muscles from the cochlear implant and used fewer than 10 electrodes of the possible 22 implanted. One of these children stopped wearing the device after 2 years; the other child wears it consistently. It is believed to provide some auditory information as well as tactile input. Two children, ages 6 and 12 at the time of surgery, became non-users after 12 months of cochlear implant use. Another 12-year-old became a non-user after 18 months of implant use. Finally, one child, age 5 at surgery, was discounted from this study because of a malfunctioning device. The device failed completely after 3 years of use and was believed to have worked suboptimally before that time.

One other child among the group who was included in the study has also experienced an internal device failure. Child N14 experienced a sudden and complete failure after 2 years of implant use. He underwent surgery for a second cochlear implant within one month of the internal device failure and resumed using the cochlear implant one month later.

Demographic information for each of the 34 children is included in Table 1. The primary etiology of hearing loss among this group was from unknown congenital causes (17). Nine children had acquired deafness as a result of meningitis; one child had an acquired loss of unknown etiology. Hearing loss was identified in the children with suspected congenital losses by 2 years of age. Eight of the children with acquired hearing losses were identified as deaf by 20 months of age. These children clearly can be considered prelingually deafened. Two children, N6 and N27, with acquired hearing losses due to meningitis were identified at 30 months and 26 months of age. We chose to include these children in the study and to consider them prelingually deafened

Table 1. Biographical data for the children.

Subject	Etiology	Age at identification of profound Deafness (years:months)	Age at implantation (years: months)	User status
△ N1	meningitis	0:10	2:6	full time
⨹ N2	hereditary	1:1	2:11	full time
⛛ N3	unknown-congenital	1:7	2:11	full time
⊕ N4	unknown-congenital	0:6	3:0	full time
⊞ N5	unknown-congenital	0:7	3:4	full time
□ N6	meningitis	2:6	3:5	full time
◇ N7	cytomegalovirus	1:5	3:8	full time
▽ N8	unknown-congenital	0:6	3:9	full time
○ N9	unknown-congenital	0:9	3:10	full time
□ N10	meningitis	1:0	4:1	full time
◇ N11	unknown-congenital	1:2	4:3	full time
⊞ N12	unknown-congenital	0:9	4:5	full time
⊕ N13	meningitis	0:11	4:6	full time
◍ N14	unknown-congenital	0:6	4:8	minimal
△ N15	unknown-congenital	1:3	4:9	full time
▽ N16	unknown-congenital	1:6	4:9	full time
△ N17	unknown-acquired	1:8	5:0	full time
▲ N18	meningitis	0:11	5:1	non-user
⛛ N19	meningitis	0:1	5:2	full time
⟐ N20	unknown-other	1:6	5:2	full time
▽ N21	unknown-congenital	0:9	5:4	full time
◇ N22	unknown-congenital	0:11	5:6	full time
⊕ N23	unknown-congenital	1:1	5:8	full time
■ N24	Ushers syndrome	1:6	5:10	non-user
⊞ N25	unknown-congenital	2:0	6:8	full time
○ N26	unknown-congenital	0:4	7:4	full time
▼ N27	meningitis	2:2	9:6	non-user
⊕ N28	unknown-congenital	0:8	9:10	full time
▣ N29	meningitis	1:3	10:9	minimal
◈ N30	hereditary	1:1	11:0	minimal
△ N31	Mondini deformity	1:8	13:1	full time
■ N32	Mondini deformity	1:0	14:0	non-user
◍ N33	Mondini deformity	1:0	15:2	minimal
▲ N34	rubella	0:1	15:4	non-user

because they demonstrated limited verbal language skills at the time of cochlear implant surgery. Functional communication skills were not different from those exhibited by prelingually deafened children. All children were fit with conventional amplification before cochlear implant surgery. The children ranged in age from 2 to 15 years at the time of cochlear implant surgery. Nine children were between the ages of 2 and 3:11 (years:months); 7 children were between the ages of 4 and 4:11; 10 children were between the ages of 5 and 7:11; and 9 children were 8 years or older at the time of implantation. Pre-operative unaided pure tone thresholds and binaural aided thresholds are indicated for all the children in Table 2.

The children were determined to be appropriate candidates for cochlear implantation on the basis of an evaluation protocol used at the University of Iowa (Gantz, 1989; Tyler et al., 1987). This protocol includes medical and radiological evaluations, a psychological assessment, and audiological evaluations. The candidates exhibited good general health and had temporal bone computerized tomography scans that did not contraindicate placement of the electrode array because of bony growth or malformation of the cochlea. The candidates were judged by a clinical psychologist to possess no characteristics that would prevent participation in the study. Audiologically, the children were profoundly deaf. With conventional amplification, they either did not detect speech at 65 dB HL or greater, or they performed at levels below chance on selected tests of speech perception ability that are described later in this article.

All children received the feature-extraction multichannel cochlear implant manufactured by Cochlear Corporation (Clark & Tong, 1982). In every case all 22 active electrodes were placed in the cochlea and medical follow-up was uneventful. The first 10 prelingually deafened children implanted at the University of Iowa (participants N9, N10, N14, N17, N21, N22, N24, N26, N33, and N34) initially used the Wearable Speech Processor (WSP-III) (Blamey, Dowell, Clark, & Seligman, 1987). This processor employs a feature-extraction strategy that extracts amplitude and frequency estimates for the fundamental frequency (F0) and the first (F1) and second (F2) formant frequencies from the incoming signal. In all but two cases, participants N9 and N33, the WSPs were subsequently replaced with the Mini Speech processor (MSP) (Skinner et al., 1991), which can be programmed to code three high frequency bands of spectral energy in addition to F0F1F2 (MPEAK). All 24 of the remaining children were initially fit with the Mini Speech processor utilizing the MPEAK strategy. For each child the electrical stimulation of the implant electrodes and the speech processor parameters were configured on an individual basis.

All of the children in this study were trained in Total Communication. Their communication skills varied greatly, however; some children depended primarily on the aural component of communication, whereas others primarily used the manual or sign language component to communicate. The educational settings were also unique to each child. All of the children attended home-community educational programs in Iowa, Illinois, Wisconsin, and Minnesota; none were in residential

Table 2. Preimplant audiometric thresholds under earphones for the left (LE) and right (RE) ears and best-aided audiometric thresholds in the sound field with hearing aids and/or tactile aids are indicated in dB HL. Implanted ear is shown in parentheses for each child. No response due to the upper limits of the audiometer is indicated by NR.

		Frequency (kHz)				
Participant		**.250**	**.500**	**1**	**2**	**4**
N1	(RE)	75	90	105	100	95
	LE	80	95	110	115	NR
	Hearing Aid	60	70	75	65	60
N2	(RE)	100	100	115	NR	NR
	LE	100	110	120	NR	NR
	Hearing Aid	70	85	NR	NR	NR
N3	RE	80	85	95	NR	NR
	(LE)	NR	95	NR	NR	NR
	Hearing Aid	50	50	65	70	NR
N4	RE	NR	NR	NR	NR	NR
	(LE)	NR	NR	NR	NR	NR
	Hearing Aid	60	80	NR	NR	NR
N5	(RE)	100	110	NR	NR	NR
	LE	100	105	NR	NR	NR
	Hearing Aid	65	60	75	NR	NR
N6	RE	NR	NR	NR	NR	NR
	(LE)	NR	NR	NR	NR	NR
	Hearing Aid	65	NR	NR	NR	NR
N7	RE	NR	NR	NR	NR	NR
	(LE)	NR	NR	NR	NR	NR
	Hearing Aid	65	NR	NR	NR	NR
N8	RE	95	105	NR	NR	NR
	(LE)	85	115	NR	NR	NR
	Hearing Aid	65	65	NR	NR	NR
N9	(RE)	90	90	NR	NR	NR
	LE	90	NR	NR	NR	NR
	Hearing Aid	70	NR	NR	NR	NR
N10	RE	75	100	NR	NR	NR
	(LE)	80	105	NR	NR	NR
	Hearing Aid	55	65	85	NR	NR
N11	RE	NR	NR	NR	NR	NR
	(LE)	100	110	120	NR	NR
	Hearing Aid	70	70	85	NR	NR
N12	RE	80	100	105	NR	NR
	(LE)	85	95	100	NR	NR
	Hearing Aid	40	50	50	85	NR
N13	(RE)	NR	NR	NR	NR	NR
	LE	NR	NR	NR	NR	NR
	Hearing Aid	70	NR	NR	NR	NR
N14	RE	90	NR	NR	NR	NR
	(LE)	90	NR	NR	NR	NR
	Hearing Aid	70	85	NR	NR	NR
N15	(RE)	90	100	110	110	120
	LE	90	110	115	110	NR
	Hearing Aid	65	65	75	80	NR
N16	RE	90	100	115	NR	NR
	(LE)	90	100	110	NR	NR
	Hearing Aid	55	55	60	NR	NR
N17	(RE)	90	110	NR	NR	NR
	LE	NR	NR	NR	NR	NR
	Hearing Aid	70	85	NR	NR	NR
	Tactile Aid	50	50	65	65	65
N18	RE	90	NR	NR	NR	NR
	(LE)	85	100	NR	NR	NR
	Hearing Aid	50	70	NR	NR	NR
N19	RE	105	115	NR	NR	NR
	(LE)	100	NR	NR	NR	NR
	Hearing Aid	60	75	NR	NR	NR
N20	(RE)	105	NR	NR	NR	NR
	LE	100	NR	NR	NR	NR
	Hearing Aid	70	NR	NR	NR	NR
N21	(RE)	90	100	110	115	NR
	LE	110	115	NR	NR	NR
	Hearing Aid	60	80	85	NR	NR
	Tactile Aid	35	45	50	55	65
N22	RE	85	95	NR	NR	NR
	(LE)	85	95	NR	NR	NR
	Hearing Aid	70	80	85	85	NR
N23	RE	80	100	110	NR	NR
	(LE)	80	105	110	NR	NR
	Hearing Aid	50	55	60	80	NR
N24	RE	80	90	NR	NR	NR
	(LE)	100	NR	NR	NR	NR
	Hearing Aid	65	85	NR	NR	NR
N25	(RE)	80	75	110	NR	NR
	LE	90	NR	NR	NR	NR
	Hearing Aid	60	55	70	NR	NR
N26	RE	80	90	110	NR	NR
	(LE)	80	95	110	NR	NR
	Hearing Aid	60	60	70	NR	NR
	Tactile Aid	50	50	55	60	65
N27	RE	90	NR	NR	NR	NR
	(LE)	NR	NR	NR	NR	NR
	Hearing Aid	70	85	NR	NR	NR
N28	(RE)	100	105	NR	115	NR
	LE	75	85	110	110	NR
	Hearing Aid	45	50	65	85	NR
N29	(RE)	85	90	115	115	115
	LE	90	100	NR	NR	NR
	Hearing Aid	55	60	75	75	NR
N30	RE	90	85	110	NR	NR
	(LE)	90	90	115	NR	NR
	Hearing Aid	45	55	60	NR	NR
N31	(RE)	NR	115	120	120	NR
	LE	NR	115	115	105	NR
	Hearing Aid	70	80	75	70	NR
N32	RE	100	105	NR	NR	NR
	(LE)	90	95	115	NR	NR
	Hearing Aid	45	40	60	60	NR
N33	(RE)	90	95	100	100	105
	LE	100	100	100	105	110
	Hearing Aid	60	55	55	60	NR
N34	RE	85	85	100	110	NR
	(LE)	80	105	NR	NR	NR
	Hearing Aid	50	50	70	NR	NR

programs. The children received different kinds and quantities of auditory stimulation and training at home and at school.

One variable thought to affect a child's speech perception performance is the amount of time the implant device is used on a daily basis. To estimate the amount of time each child used his or her device per day, parents completed a questionnaire, the Parent Monthly Diary (Fryauf-Bertschy, Tye-Murray, & Tyler, 1991), that was developed at the University of Iowa. Parents responded to a set of 30 statements, using a scale from 1 to 10 to reflect the truthfulness of a statement. A rating of 1 means the statement is never true and a rating of 10 indicates the statement is always true. The responses to the statement "My child wears the cochlear implant all waking hours" were collected each time a child was tested. These ratings were then averaged for each child. Children with ratings of 8 or above were considered full-time users. Those with ratings of 7 and below were considered minimal users. Children with averaged values below 7 typically used the device only at school and did not wear it on weekends. Five children included in this study have subsequently become non-users of the implant. After several years of minimal implant use, they stopped wearing the device completely (see Table 1). Results from children who were considered minimal users and eventual non-users are represented with shaded symbols and filled symbols, respectively, in all figures. All of the children in the youngest age group, 2–3:11, were full-time cochlear implant users. One child implanted at age 4:8 is considered a minimal user. For the 5–7:11 age group, two children eventually stopped wearing the cochlear implant after several years of minimal use. The highest incidence of minimal and eventual non-use of the cochlear implant occurred in children implanted after the age of 8 years. In this age group, three children became non-users; three others are considered minimal users.

Procedures

The children were tested pre-operatively and at annual intervals after the connection of their external implant hardware. The speech perception tests used to evaluate performance were the Monosyllable, Trochee, Spondee test (MTS; Erber & Alencewicz, 1972), the Four-Choice Spondee test from the Early Speech Perception test battery (Geers & Moog, 1990), the Word Intelligibility by Picture Identification test (WIPI; Ross & Lerman, 1971), the Vowel Perception Test (Tyler, Fryauf-Bertschy, & Kelsay, 1991), and the Phonetically Balanced Kindergarten Word Lists (PB-K, list 1A; Haskins, 1949). The Vowel Perception Test and the Early Speech Perception test battery were developed after several children in this study underwent cochlear implant surgery; therefore these results are not available for some children at early test intervals. All of the tests with the exception of the PB-K test are closed-set tests that measure pattern or word recognition. The PB-K is an open-set test of word and phoneme recognition.

The Monosyllable, Trochee, Spondee test consists of two presentations of 12 pictured words: four monosyllables, four trochees, and four spondees. Two scores are obtained that reflect the number of times the correct stress pattern was recognized and the number of words correctly identified. The Four Choice Spondee test includes four words that are represented by pictures or objects. Each word is presented three times in random order. Typically the words were *baseball*, *hotdog*, *airplane*, and *popcorn*. The Vowel Perception Test consists of five plates of four pictured consonant-vowel-consonant words. On each plate the words are contrasted by medial vowel only, for example *bite*, *boot*, *boat*, and *bat*. Each word is presented in the sound-only condition twice for a total of 40 test items. See Appendix A for a copy of the test plates. The Word Intelligibility by Picture Identification test (WIPI) is a 25-item, 6-choice closed-set test of phonetically similar words represented by pictures. In this study, the results of sound-only testing are presented. If a child did not demonstrate knowledge of all of the vocabulary in the WIPI test, a reduced set of WIPI test plates was used. A copy of the reduced-set WIPI test and a correlation of the full- and reduced-set tests appears in Appendix B. The PB-K test is an open-set test of 50 words presented in the sound-only condition. Responses were scored for correct word and correct phoneme recognition. In some cases a reduced set of 20 words was used for younger children who did not demonstrate knowledge of the vocabulary in the full list (see Appendix C). The children were asked to repeat words and to sign their responses. For instances when a child could not offer a sign but could provide a verbal response, the production was phonetically transcribed. No corrections were made for phonemic substitutions any child may have made.

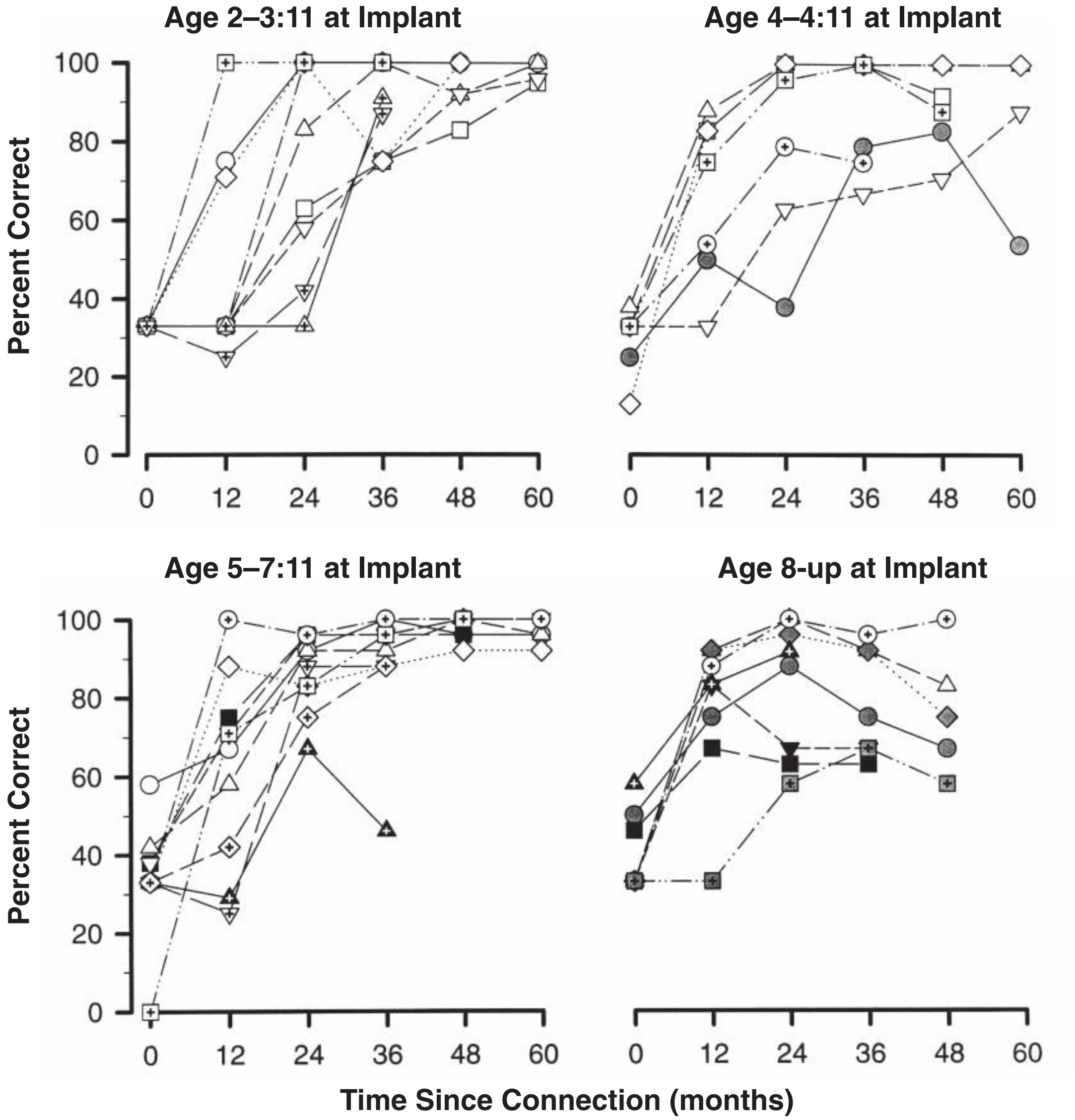
All tests were administered either via monitored live voice (female) at about 60 dB HL or via a personal computer that presented recorded (female voice) randomizations of a test at approximately 60 dB HL. In general, live voice testing was used with the younger children to maintain their attention to the task. Some children were tested in a live-voice mode at early test intervals and then, when appropriate, they were tested with recorded materials at later test intervals. Not all of the children were able to complete each test at each test interval, either because of their age or because the test was not yet developed. Pre-operatively, the children used their personal hearing aids or tactile aids to complete the tests. Following cochlear implantation, they used their cochlear implant devices only for all tests.

Results

The results of all tests are displayed in Figures 1 through 7. Participants were divided by the age at which they received their cochlear implants, and individual performance is plotted over time. Open symbols represent children who are full-time cochlear implant users. Shaded symbols represent children who do not wear their cochlear implants most waking hours. Filled symbols indicate children who eventually become non-users of the cochlear implant (see Table 1). Children who were unable to consistently detect sound pre-operatively, but were able to identify the test vocabulary and complete the test task, were assigned a chance score. If a child was unable to identify the vocabulary or complete the test task in an audiovisual mode (using sign and lipreading in addition to sound) at any test interval, then the child was not tested. Occasionally, there are missing data because a child missed an appointment, equipment malfunctioned, or because the test had not yet been developed.

Figures 1 and 2 present the results of the MTS test, which measures stress or pattern recognition and word identification, respectively. For stress recognition, Figure 1, chance performance is 33%. Scores above 50% are significantly different from chance ($p < 0.05$; one- tailed test) using the binomial model (Thorton & Raffin, 1978) with 0 variance associated with chance. A trend of improving performance over time is evident in each age

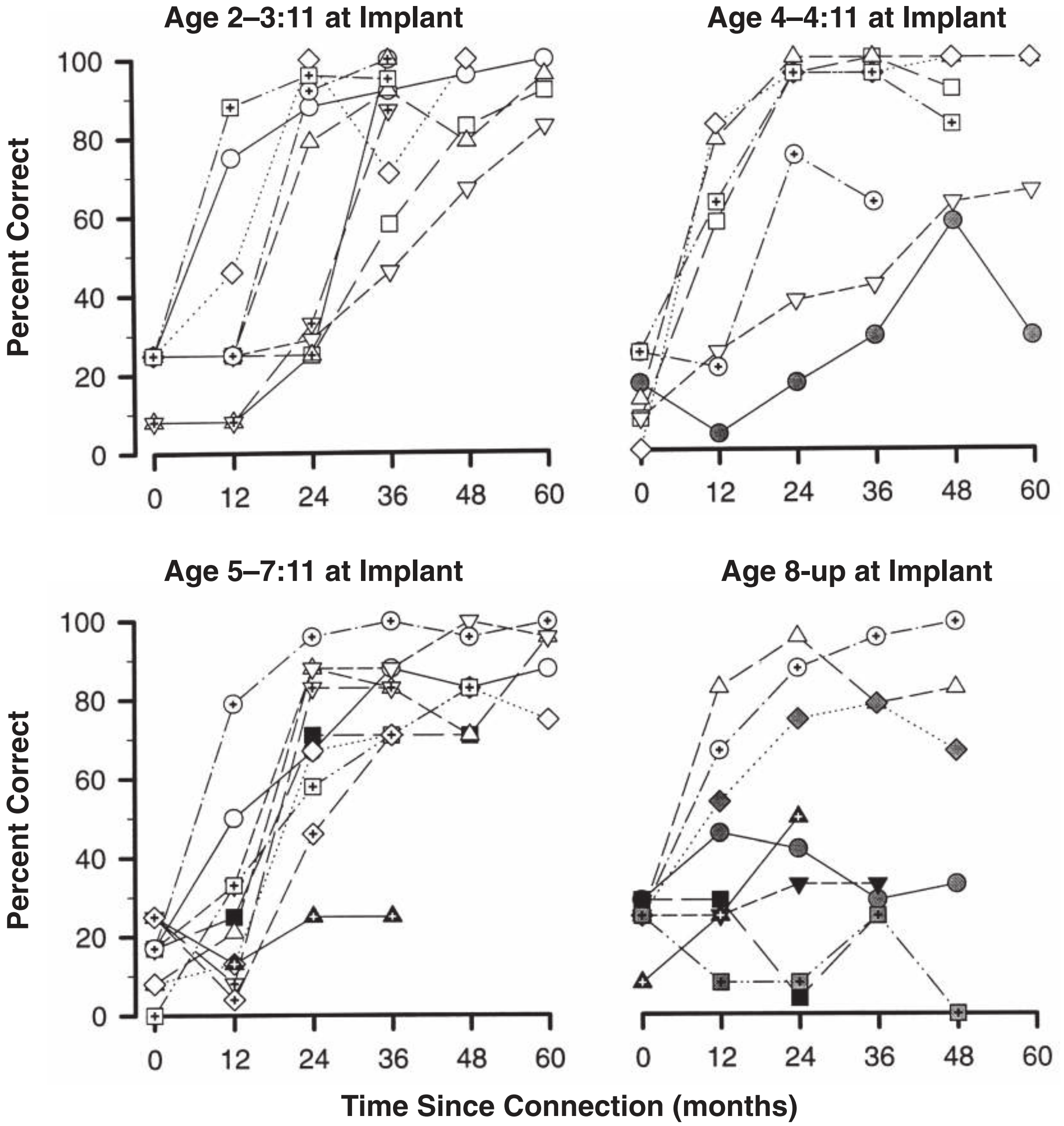
Figure 1. Individual results of the MTS Stress test over time. Chance performance is 33% correct. Children are grouped by age at implantation. Shaded symbols represent children whose parents assigned an average score of 7 or less to the statement "My child wears the cochlear implant all waking hours." Children who eventually became non-users of the implant are indicated by filled symbols.



group. After 24 months of cochlear implant use, all but one child in this study, N24, scored above 50%, demonstrating that use of the cochlear implant provides significant improvement in closed-set pattern recognition. No significant differences in performance existed between children implanted before 5 years of age and children implanted after 5 years of age for any of the test intervals. In general, minimal and eventual non-users had the lower scores in each age group compared to full-time users. *T* tests reveal a statistically significant difference in performance at the 36-month [$t(7.8) = -3.71$, $p = 0.0062$] and 48-month [$t(4.7) = -2.63$, $p = 0.0497$] test intervals for minimal and eventual non-users compared to full-time users.

For the MTS word test, Figure 2, chance performance is 8% if all 12 words are considered. If a child uses envelope cues to eliminate alternatives that differ in syllable number and pattern, chance performance is 25%. Scores above 41% are significantly different from chance ($p < 0.05$; one-tailed test) using the binomial model (Thorton & Raffin, 1978) with 0 variance associated with chance. Results from the MTS word recognition test showed a pattern of improving scores over time, with the exception of children who are minimal and eventual non-users of the cochlear implant. No significant differences in performance existed between children implanted before 5 years of age and children implanted after 5 years of age for any of the test intervals. At the

Figure 2. Individual results of the MTS Word test over time. Chance performance is 8% correct if all words are considered and 25% correct if envelope cues are used to eliminate alternatives differing in syllable pattern and number. Shaded symbols represent children whose parents assigned an average score of 7 or less to the statement "My child wears the cochlear implant all waking hours." Children who eventually became non-users of the implant are indicated by filled symbols.



12-month test interval, approximately half of the children in each age group scored significantly above chance. By the 36-month test interval, all full-time users in every age group scored significantly above chance. Minimal and eventual non-users demonstrated the lower scores in each age group compared to full-time users. *T* tests revealed that this difference is statistically significant at the 24-month [$t(11.6) = -3.63$, $p = 0.0036$], the 36-month [$t(8.7) = -5.82$, $p = 0.0003$], and the 48-month [$t(4.4) = -3.03$, $p = 0.0349$] test intervals. Subject number was not adequate for analysis at the 60-month test interval.

Figure 3 presents the results of the Four Choice Spondee test. Chance performance is 25%; scores above 41% are significantly different from chance ($p < 0.05$; one-tailed test) using the binomial model (Thorton & Raffin, 1978) with 0 variance associated with chance. This test was added to the test battery after some children were implanted; therefore, several data points are missing at early test intervals. Many children mastered this relatively easy task by the 12-month test interval. With the exception of the children who were minimal and eventual non-users, all children demonstrated improved performance with time. There are no significant differences in performance at any test interval when comparing children implanted before age 5 to children implanted after age 5. The greatest variability in performance is seen in children implanted after age 8 and

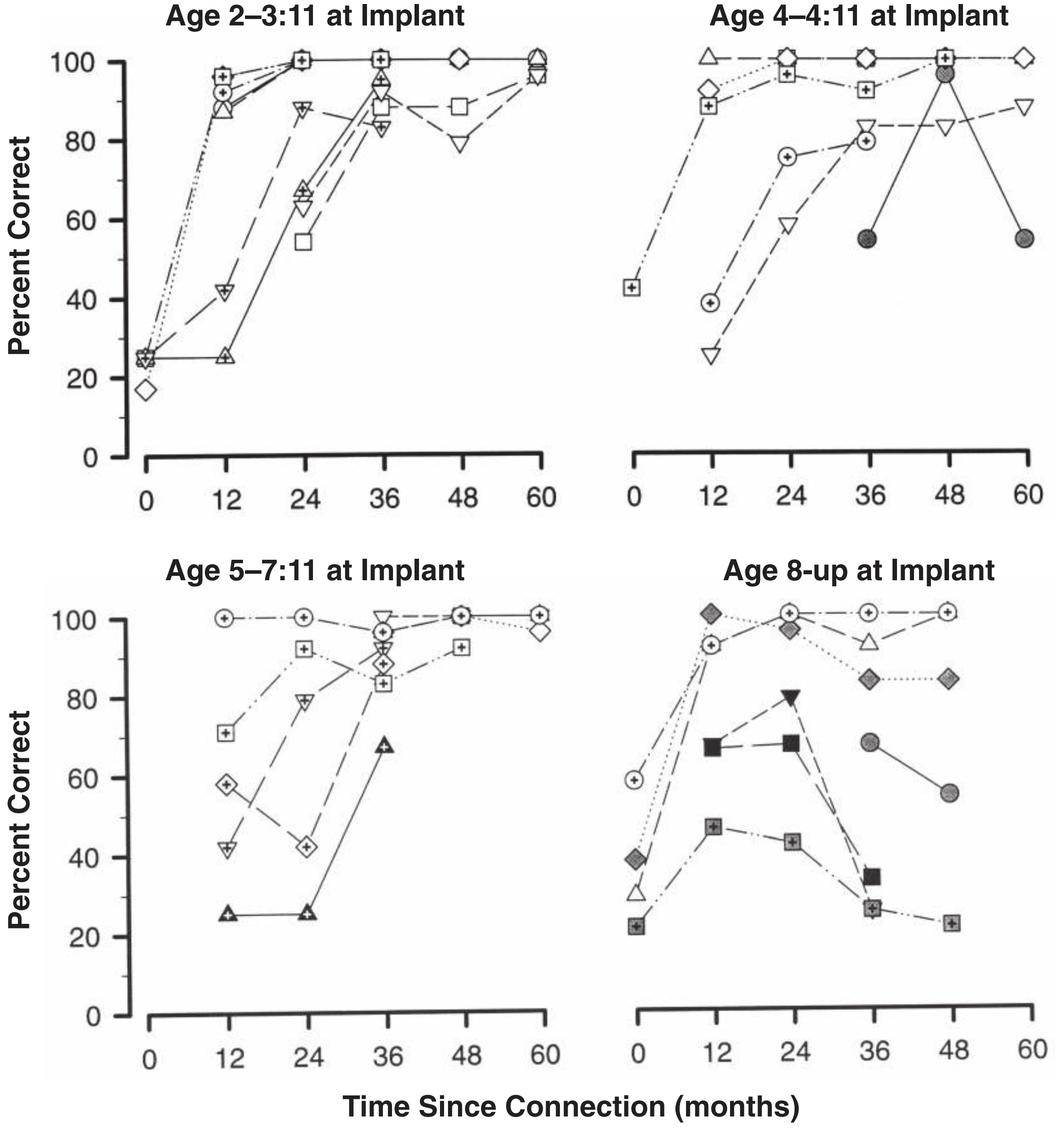


Figure 3. Individual results of the Four-Choice Spondee test over time. Chance performance is 25% correct. Shaded symbols represent children whose parents assigned an average score of 7 or less to the statement "My child wears the cochlear implant all waking hours." Children who eventually became non-users of the implant are indicated by filled symbols.

can be attributed to children who are minimal and eventual non-users. Full-time users performed significantly better than minimal users at the 36-month test interval [$t(6.5) = –4.73$, $p = 0.0027$]. A decrease in subject number and ceiling effects may account for the lack of significant differences in performance between the younger children versus older children and between the full-time users versus minimal users at later test intervals.

Figure 4 shows the results of the Vowel Perception Test. Chance performance is 25%; scores above 38% are significantly different from chance ($p < 0.05$; one-tailed test) using the binomial model (Thorton & Raffin, 1978) with 0 variance associated with chance. The same trend of improving scores over time is evident, with the exception of children implanted at an older age who are minimal users. A significant difference in performance between children implanted before 5 years of age and children implanted after 5 years is evident at the 36-month test interval only [$t(27.7) = 2.80$, $p = 0.009$]. Significant differences exist between full-time users and minimal users at 24 months and subsequent test intervals: 24 months [$t(17.6) = –4.04$, $p = 0.0008$]; 36 months [$t(10.7) = –4.60$, $p = 0.0008$]; 48 months [$t(4.2) = –2.30$, $p = 0.008$]. The analysis could not be performed for the 60 months test intervals because of a decrease in number of subjects.

Figure 5 combines results of the reduced- and full-set tests of the Word Intelligibility by Picture Identification test (WIPI). When a child lacked the vocabulary

Figure 4. Individual results of the Vowel Perception test over time. Chance performance is 25% correct. Shaded symbols represent children whose parents assigned an average score of 7 or less to the statement "My child wears the cochlear implant all waking hours." Children who eventually became non-users of the implant are indicated by filled symbols.

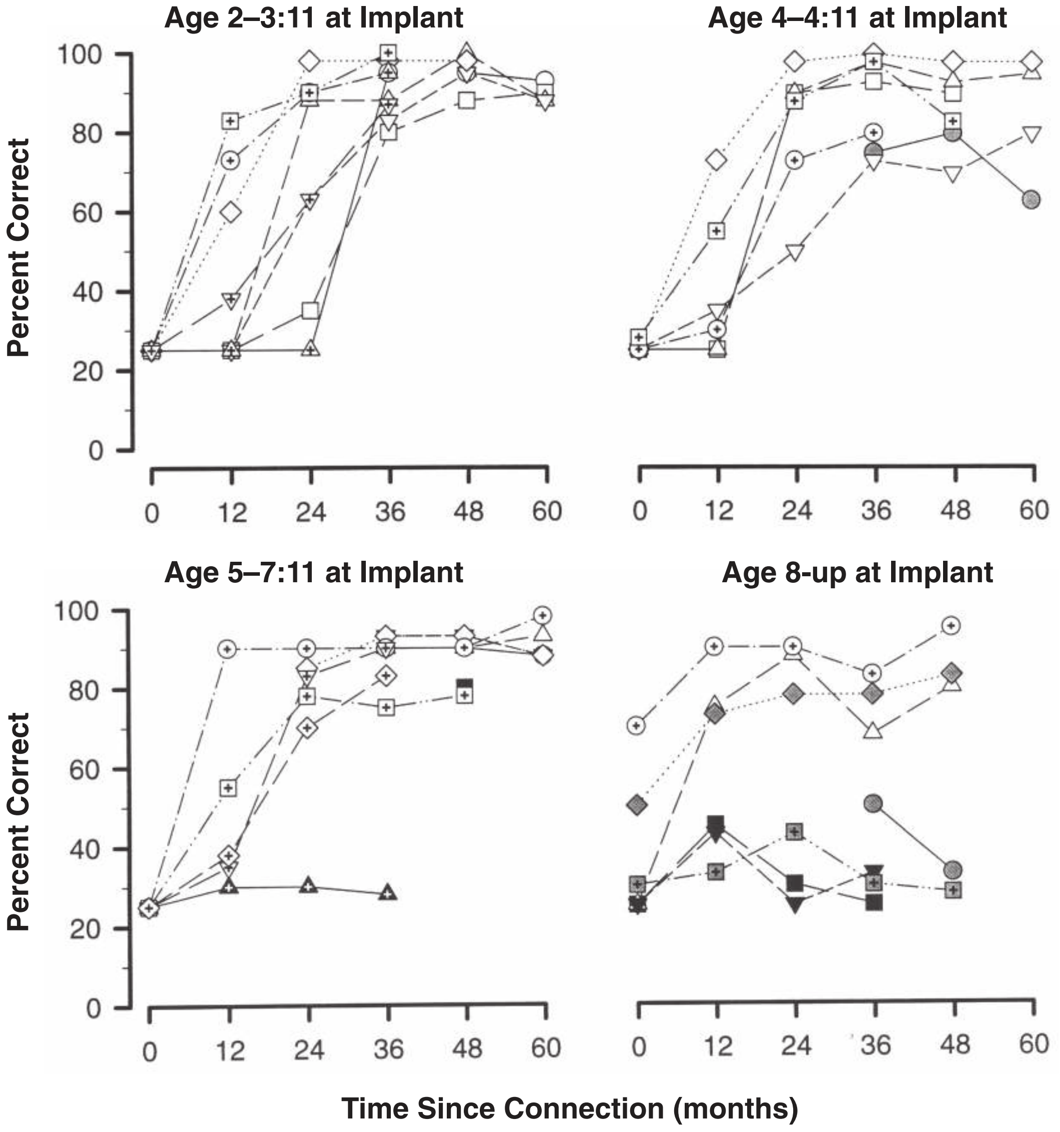
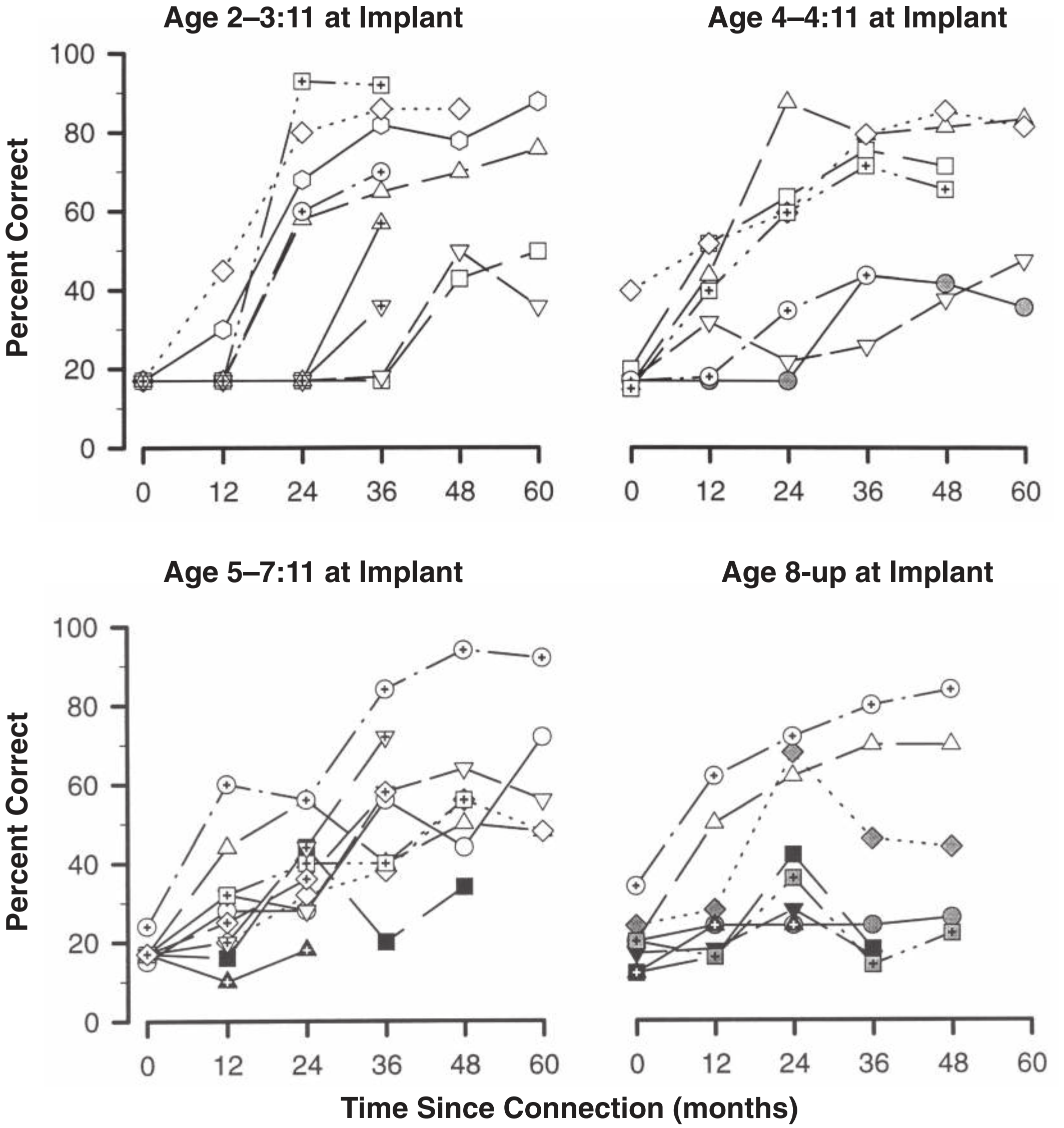


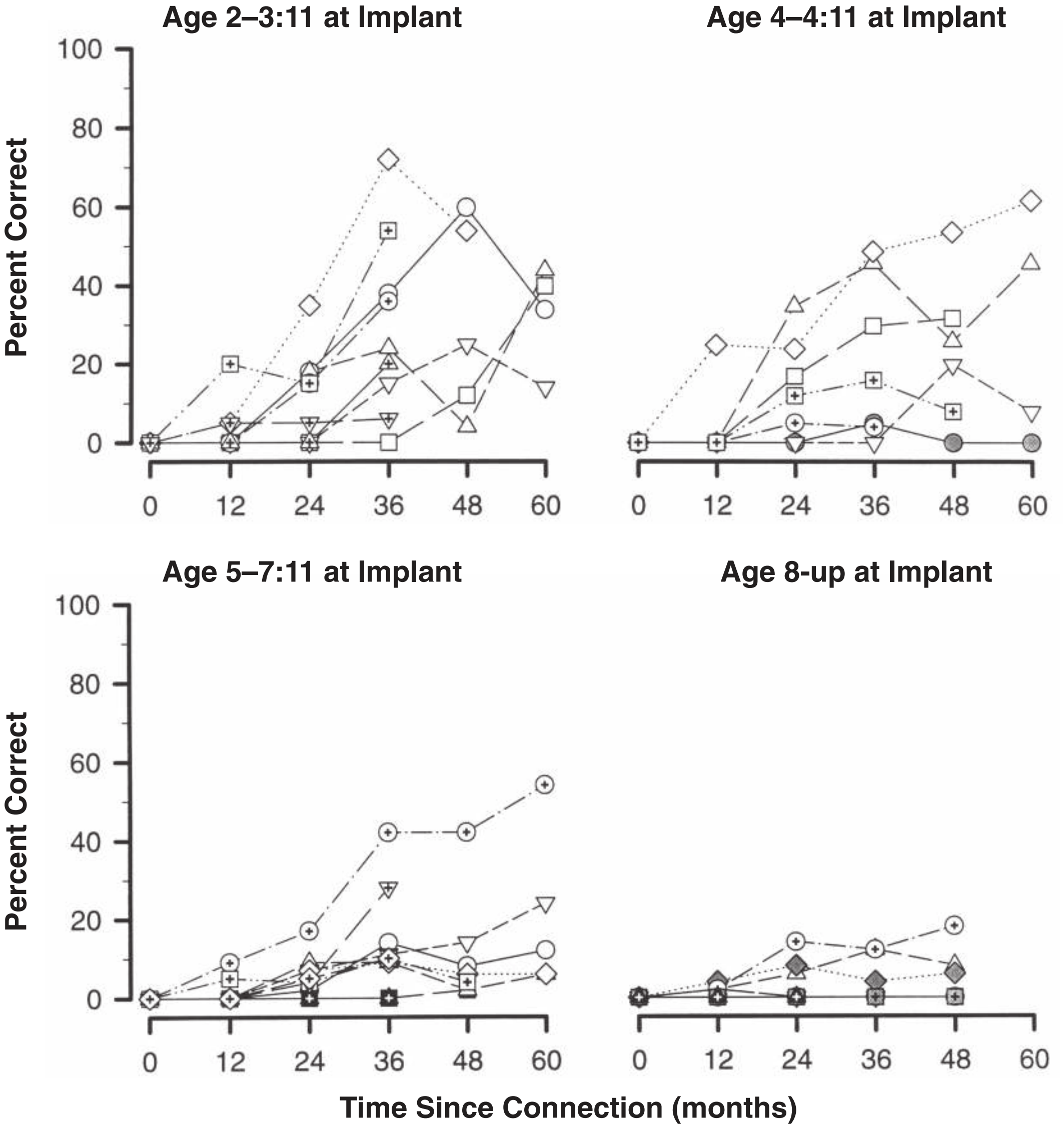
Figure 5. Individual results of the WIPI test over time. Chance performance is 17% correct. Shaded symbols represent children whose parents assigned an average score of 7 or less to the statement "My child wears the cochlear implant all waking hours." Children who eventually became non-users of the implant are indicated by filled symbols.



skills to complete the full-set WIPI, a reduced set consisting of the most familiar words was administered. In general, the younger children were administered the reduced-set test until they demonstrated knowledge of the full-set vocabulary at later test intervals. Two lists of 25 pictured items were presented, for a total of 50 items on the full-set test. Four lists of 10 pictured items were presented, for a total of 40 items on the reduced-set test. Chance performance is 17% correct; scores above 28% are significantly different from chance ($p < 0.05$; one-tailed test) using the binomial model (Thorton & Raffin, 1978) with 0 variance associated with chance. Use of the reduced-set WIPI introduces no bias in analysis of data; see Appendix B for reliability of the reduced-set WIPI scores relative to the full-set scores. The results of the WIPI showed great variability in performance in all age groups. Most children show a slow rate of improvement over time. Although the percentage of children who eventually score significantly better than chance is greater for the younger group (implanted before age 5) than for the older group (implanted after age 5), the difference in performance at any one test interval between older and younger children is not significant. A significant difference in performance between full-time users and minimal users is apparent at the 36-month test interval [$t(16.3) = -5.04$, $p = 0.0001$] and the 48-month test interval [$t(11.8) = -5.51$, $p = 0.0001$].

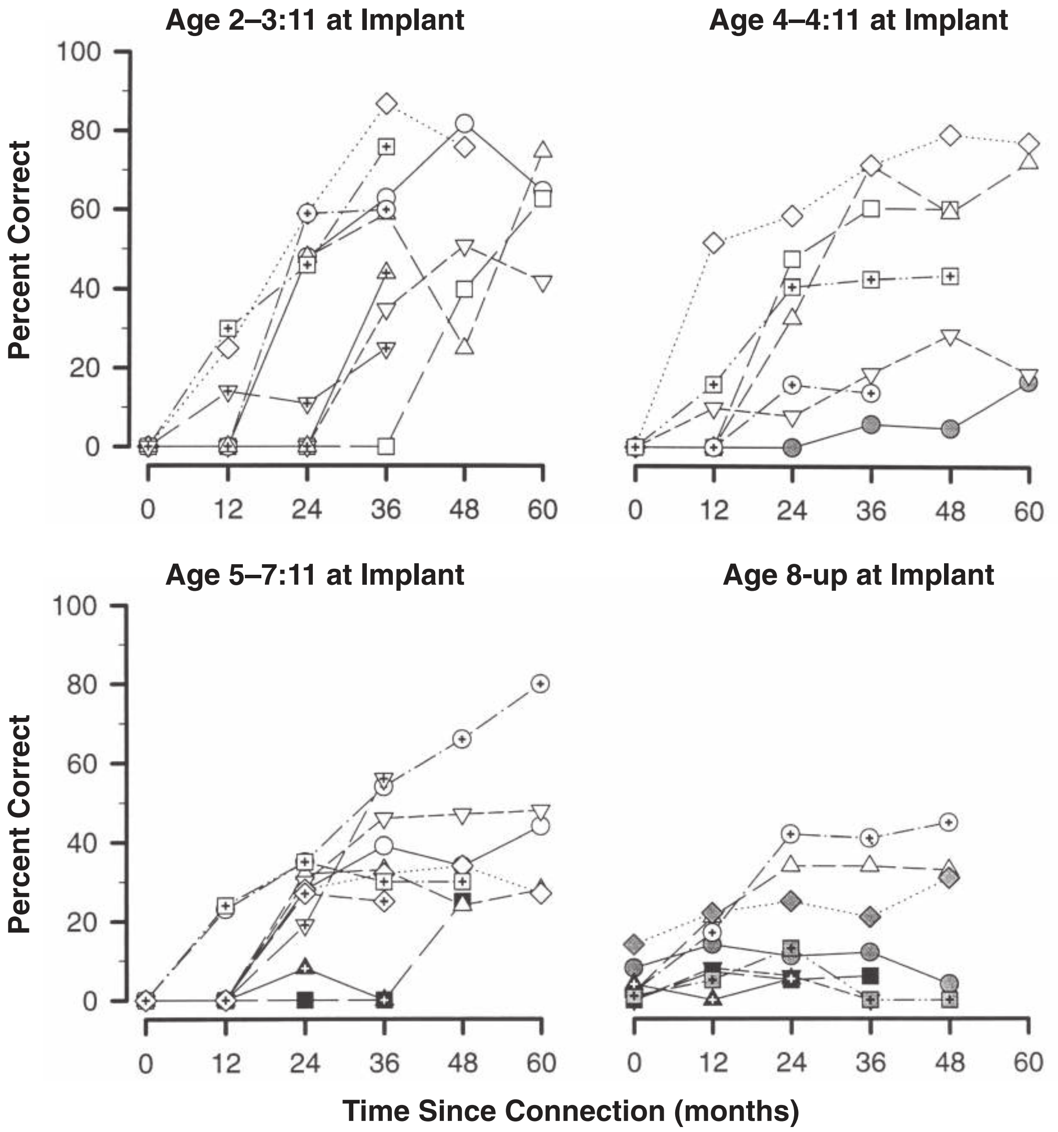
Figure 6 combines results of the reduced- and full-set tests of the open-set PB-K word test, list 1A. Combined

Figure 6. Individual results of the PB-K Word test over time. This is an open-set task; chance performance is 0%. Shaded symbols represent children whose parents assigned an average score of 7 or less to the statement "My child wears the cochlear implant all waking hours." Children who eventually became non-users of the implant are indicated by filled symbols.



phoneme scores are shown in Figure 7. Chance performance on both measures is 0%. In general, the younger children were administered the reduced-set test until they demonstrated knowledge of the full-set vocabulary at later test intervals. Use of the reduced-set PB-K list tended to elevate scores slightly. A quadratic equation was developed and applied to correct for full-list and reduced-list differences. See Appendix C and Appendix D for reliability of the reduced-set PB-K words and phoneme scores relative to the full-set scores. In all age groups in Figure 6, no child achieved greater than 20% word recognition at 12 months post-implant. However, by the 24-month test interval there is a greater spread of scores, ranging up to 35% for children in the younger age groups. Several children implanted before age 5 realized relatively high performance at later test intervals on this difficult task. One child implanted after age 5 demonstrated 54% word recognition at 60 months post-implant; the remaining 17 children implanted after age 5 scored below 30% at any test interval. The difference in performance between children implanted before age 5 and children implanted after age 5 is significant at the 36-month test interval [$t(21.8) = 2.47$, $p = 0.0217$] and the 48-month test interval [$t(15.0) = 2.14$, $p = 0.0488$]. Full-time users and minimal users demonstrated significantly different performance at these test intervals as well as at the 24-month test interval (p 0.0003). Subject number was not adequate for analysis at the 60-month test interval.

Figure 7. Individual results of the PB-K phoneme test over time. Chance performance is 0% correct. Shaded symbols represent children whose parents assigned an average score of 7 or less to the statement "My child wears the cochlear implant all waking hours." Children who eventually became non-users of the implant are indicated by filled symbols.


Age 2–3:11 at Implant

Age 4–4:11 at Implant

Age 5–7:11 at Implant

Age 8-up at Implant

The PB-K phoneme scores are shown in Figure 7. For all age groups, there is a wide range of performance after the 12-month test interval, ranging from 0 to 85% correct. For at least one test interval, 10 of 16 children implanted before age 5 scored greater than 50%. In contrast, only 2 of 18 children implanted after age 5 scored greater than 50%. Children implanted before age 5 scored better than children implanted after age 5 at all test intervals, but the difference is significant at the 36-month test interval only [$t(26.6) = 2.34, p = 0.0266$]. The majority of full-time users eventually scored above 30% on this test. In contrast, all of the minimal and eventual non-users scored below 32%. Full-time users scored significantly better than minimal and eventual non-users at the 24-month, 36-month, and 48-month test interval (p 0.002). A small number of participants did not allow analysis at the 60-month test interval.

Discussion

This study focused on the long-term performance of 34 prelingually deafened children who received feature-extraction multichannel cochlear implants. The children were grouped by the age at which they received cochlear implants and were characterized by the amount of time they used their devices per day. A variety of speech perception tests was administered to the children at annual intervals following the connection of the external implant hardware. We examined individual performance, age group trends, and the effects of daily use time up to 5-years post-implant.

The tests used to evaluate the children were selected to assess a range of speech perception skills, from pattern recognition to word and phoneme identification. The MTS stress recognition test represents the easiest task in the battery of tests presented. At the time these children were entered into the implant program, the typical candidates possessed so little residual hearing that they were unable to perceive differences in duration and envelope cues in a limited set of words. With time, children in all age groups realized improved performance on this task, including those who eventually became non-users of the device. Regardless of age at implant and amount of daily device use, cochlear implant use affords improved pattern perception. The results of the MTS Word test, the Four Choice Spondee test, the Vowel Perception test, and the WIPI also indicate continued improvement in performance over time for full-time users of the cochlear implant. However, most children who do not wear their devices consistently do not demonstrate improvement on these tasks of closed-set word identification. These results suggest that children with cochlear implants, including those who are not consistent users of the device, may benefit by perceiving envelope cues of speech that may provide lipreading enhancement. This improvement alone, however, may not be sufficient benefit to encourage young adolescents to continue wearing the device. Children who are consistent users of their cochlear implant devices show improvement over time in their abilities to recognize words from a closed set. This suggests prelingually deafened children can develop improved understanding of speech with consistent cochlear implant use.

In order to have sufficient numbers to examine the effects of age at implant, the children were divided into two groups: those implanted before age 5 and those implanted after age of 5. With the exception of the results from the Vowel Perception Test at the 36-month test interval, no significant differences in performance were evident on any of the closed-set speech perception tests at any test interval in terms of age at implant. There is a trend of higher scores for children implanted before age 5 on the WIPI test, but the differences were not significant.

The results of open-set word recognition tests more clearly indicate differences in performance that may be attributed to age at implant. The results of the PB-K words tests shown in Figure 6 indicate that most children receiving cochlear implants before age 5 will ultimately be able to use audition only to repeat some words; it is the exceptional child implanted after age 5 who will score greater than 20% on this task. Open-set word understanding is a measure frequently used to assess the benefit of cochlear implantation in adult cochlear implant users, but it must be interpreted somewhat differently in children. Unlike postlingually deafened adults, prelingually deafened children do not have the auditory memory of spoken language to help them interpret the electrical signal of the cochlear implant. Open-set word testing can help us understand what elements of speech can be processed and delivered electrically to a congenitally deaf ear. We must realize, however, that interpretation of speech depends upon the child's linguistic skills, his or her willingness to guess, and his or her ability to fill in missing bits of auditory information. Children in this study did not communicate in auditory-only modes during the majority of their waking hours. They relied upon a combination of visual and auditory information. Using only audition without the benefit of context is a very difficult task to ask them to undertake. Therefore, the results of this testing must be interpreted with some caution. A child may be able to repeat all the phonemes of a given word, but he may not be able to recognize that word. This may slightly elevate test scores. Alternately, some children may be able to repeat a word phonetically, but when they access their lexicon, they change their response to match the sounds of the closest word with which they are familiar. This could depress test scores. A particular child may use a different strategy in this task at different times depending upon his or her age and experience. Percent-correct results on the phoneme recognition test are higher than those for the word recognition test. Almost all children, regardless of when they received their cochlear implants, can repeat some phonemes from a list of presented words. Paired with lipreading, this could be a significant contribution to communication.

Characterizing the children by amount of daily use explains much of the variability in performance on all tests. With few exceptions, those who diverge from the trend of gradually improved scores over time are minimal and eventual non-users. The differences in performance between the full-time users and the minimal users was significant for all tests at most test intervals. We can speculate as to whether poor performance with the cochlear implant is the cause or the result of minimal use. Most of the children in this study who are designated as minimal users displayed inconsistent patterns of cochlear implant use from the time of the initial stimulation. Despite counseling regarding the slow development of auditory skills, some children and their parents could not sustain interest in and support for wearing the cochlear implant hardware when benefit was minimal. Less than full-time use of cochlear implants by children in this study occurred primarily in children implanted after the age of 5 years. This supports the notion that longer duration of deafness in a prelingually deafened child may result in less functional benefit and more difficulty adjusting to a cochlear implant.

The results of this study indicate that most children derive benefit from their cochlear implants for speech perception tasks. Some perform very well, and others demonstrate limited use of their hearing. These results do not directly address how prelingually deafened children with cochlear implants use auditory skills in natural settings. Children who do not achieve high test scores may still benefit from cochlear implants by demonstrating pragmatic use of audition, such as recognition of their names, awareness of communication by others, and awareness of environmental sounds. Conversely, children who demonstrate good performances on tests may not show functional use of hearing in natural settings. Each child's functional use of a cochlear implant depends upon his or her social and educational environment. A child may choose not to wear a cochlear implant for reasons unrelated to hearing ability; for example, he or she may be self-conscious about the appearance of the device.

The population of children with cochlear implants is highly heterogenous, as is the population of deaf children as a whole. Some authors have suggested that some studies of cochlear implant use by children may not represent the entire population of implanted children (Lane, 1995; Rose, 1994; Tyler, 1993). Non-users may not be included in studies, and there is a tendency for poorer performers to drop out of test protocols. The group means may present a skewed picture of what is typical. These critics assert that children who are not likely to perform above chance may not be tested. When the results of only those children who can perform the tests are presented, the average scores overstate the abilities of the complete group. Results for both pre- and postlingually deafened children are sometimes averaged, resulting in mean scores that are heavily influenced by the better scores of the postlingually deafened children. Presenting mean scores of groups of children may not allow the reader to appreciate the considerable variability in performance across children.

The results of this study alone may not convince the opponents of cochlear implants to view them as a potential asset to prelingually deafened children. However, the data are presented in such a way that the interested reader can see individual performance of a particular child over time. The long-term impact of the use of cochlear implants upon prelingually deafened children as a group is yet to be determined. The results of this study support the premise that cochlear implants improve speech perception abilities in deaf children when the devices are used consistently.

Acknowledgments

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References

Blamey, P. J., Dowell, R. C., Clark, G. M., & Seligman, P. M. (1987). Acoustic parameters measured by a formant-estimating speech processor for a multiple-channel cochlear implant. *Journal of the Acoustical Society of America*, *82*, 38–47.

Clark, G. M., & Tong, Y. C. (1982). A multiple-channel cochlear implant: A summary of results for two patients. *Archives of Otolaryngology-Head & Neck Surgery*, *108*, 214–217.

Erber, N. P., & Alencewicz, C. (1972). Audiologic evaluation of deaf children. *Journal of Speech Hearing Disorders*, *41*, 256–267.

Fryauf-Bertschy, H., Tye-Murray, N., & Tyler, R. S. (1991) . *Parent monthly diary.* Iowa City: University of Iowa.

Fryauf-Bertschy, H., Tyler, R. S., Kelsay, D., & Gantz, B. J. (1992). Performance over time of congenitally deaf and postlingually deafened children using a multi-channel cochlear implant. *Journal of Speech and Hearing Research*, *35*, 913–920.

Gantz, B. J. (1989). Issues of candidate selection for a cochlear implant. *Otolaryngology Clinics of North America*, *22*, 239–247.

Gantz, B. J., Tyler, R. S., Woodworth, G. P., Tye-Murray, N., & Fryauf-Bertschy, H. (1994). Results of multichannel cochlear implants in congenital and acquired prelingual deafness in children: Five-year follow-up. *American Journal of Otology*, *15*(Suppl.), 1–7.

Geers, A. E., & Moog, J. S. (1990). *Early Speech Perception Test Battery.* St. Louis:Central Institute for the Deaf.

Haskins, H. A. (1949). *A phonetically balanced test of speech discrimination for children* (masters thesis). Evanston, IL: Northwestern University.

Lane, H. (1990). Cultural and infirmity models of deaf Americans. *Journal of the Academy of Rehabilitative Audiology*, *23*, 11–26.

Lane, H. (1993, February/March). Cochlear implants: Boon for some—bane for others. *Hearing Health*, 19–23.

Lane, H. (1995). Letter to the editor. *American Journal of Otology*, *16*, 393–399.

Miyamoto, R. T., Osberger, M. J., Robbins, A. M., Myres, W. A., & Kessler, K. (1993). Prelingually deafened children's performance with the Nucleus multichannel cochlear implant. *American Journal of Otology*, *14*, 437–445.

Osberger, M. J. (1993, February/March). Children with cochlear implants: Proven winners. *Hearing Health*, 19–23.

Rose, D. E. (1994) Cochlear implants in children with prelingual deafness: Another side of the coin. *American Journal of Audiology*, *3*(1), 6.

Ross, M., & Lerman, J. (1971). *Word Intelligibility by Picture Identification.* Pittsburgh, PA: Stanwix House, Inc.

Shea, J. J., Domico, E. H., & Lupfer, M. (1994). Speech perception after multichannel cochlear implantation in the pediatric patient. *American Journal of Otology*, *15*, 66–70.

Skinner, M. W., Holden, L. K., Holden, T. A., Dowell, R. C., Seligman, P. M., Brimacombe, J. A., & Beiter, A. L. (1991). Performance of postlinguistically deaf adults with the wearable speech processor (WSP III) and Mini Speech Processor (MSP) of the Nucleus multi-electrode cochlear implant. *Ear and Hearing*, *12*, 3–22.

Staller, S. J., Beiter, A. L., Brimacombe, J. A., Mecklenburg, D. J., & Arndt, P. (1991). Pediatric performance with the Nucleus 22-channel cochlear implant system. *American Journal of Otology*, *12*, 126–136.

Thornton, A. R., & Raffin, M. J. M. (1978). Speech discrimination scores modeled as a binomial variable. *Journal of Speech and Hearing Research*, *21*, 507–518.

Tyler, R. S. (1993). Cochlear implants and the Deaf culture. *American Journal of Audiology*, *2*(1), 26–32.

Tyler, R. S., Davis, J., & Lansing, C. R. (1987). Cochlear implants in young children. *Asha*, *29*, 41–49.

Tyler, R. S., Fryauf-Bertschy, H., & Kelsay, D. (1991). *Childrens Vowel Perception Test.* Iowa City: University of Iowa.

Waltzman, S. B., Cohen, N. L., Gomolin, R. H., Shapiro, W. H., Ozdamar, S. R., & Hoffman, R. A. (1994). Long-term results of early cochlear implantation in congenitally and prelingually deafened children. *American Journal of Otology*, *15*(Suppl.), 9–13.

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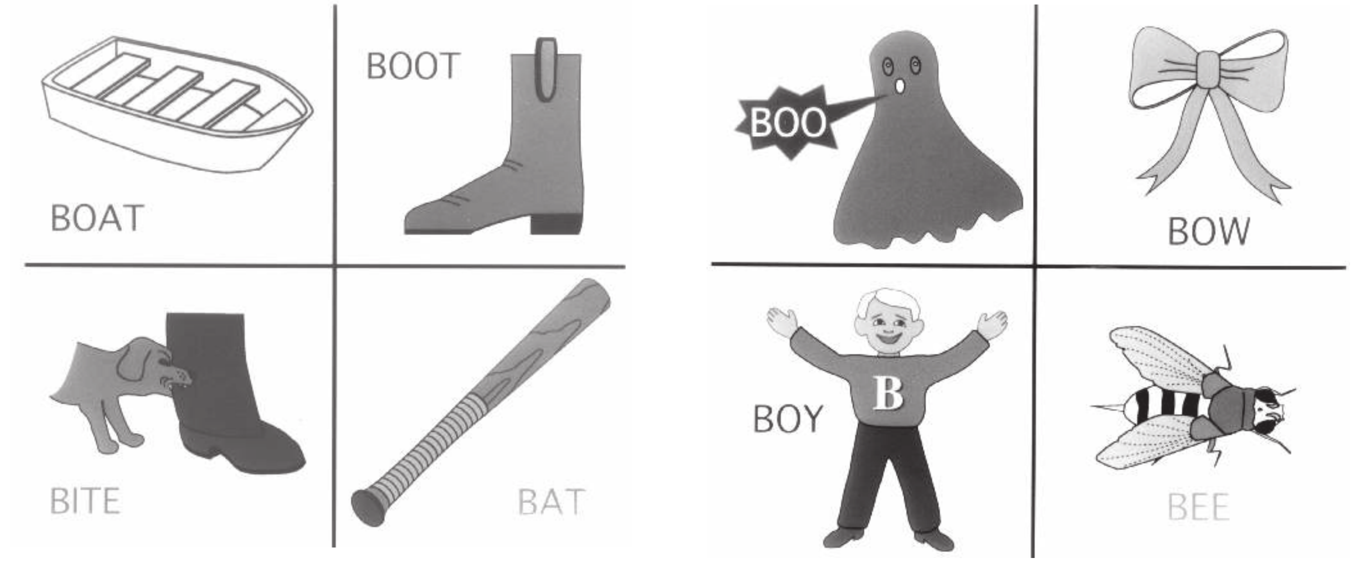
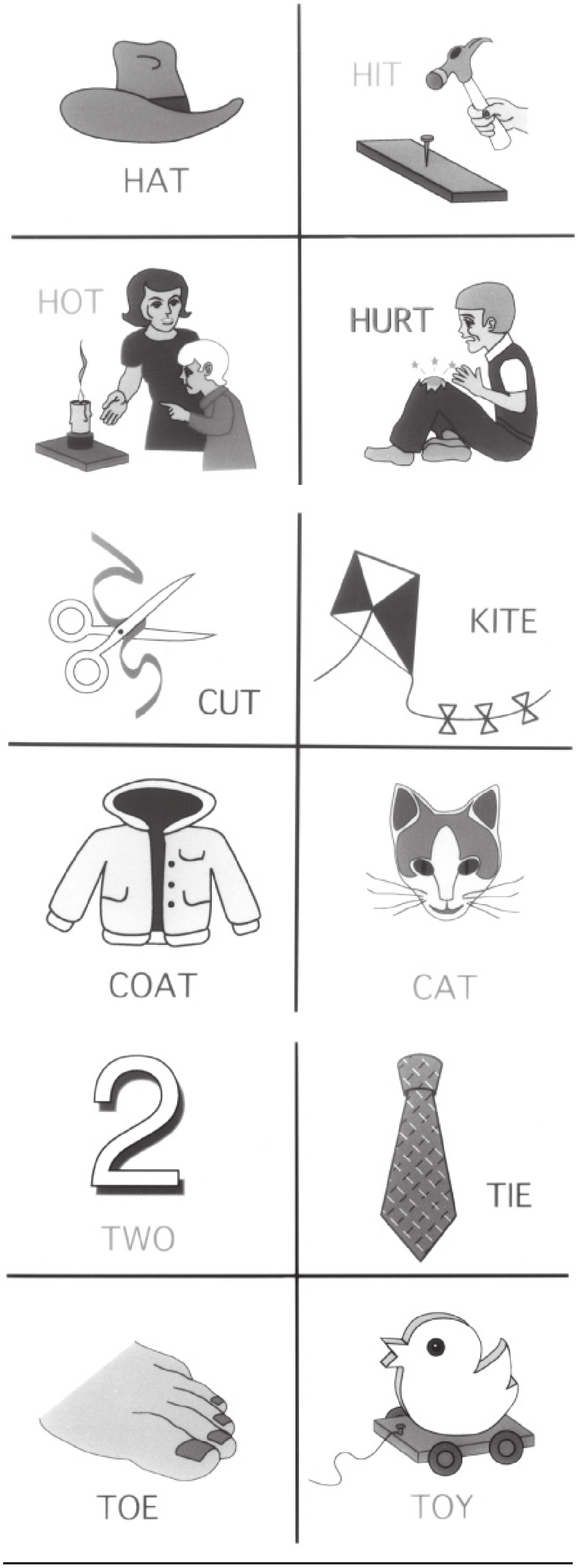
Appendix A. The Vowel Perception Test

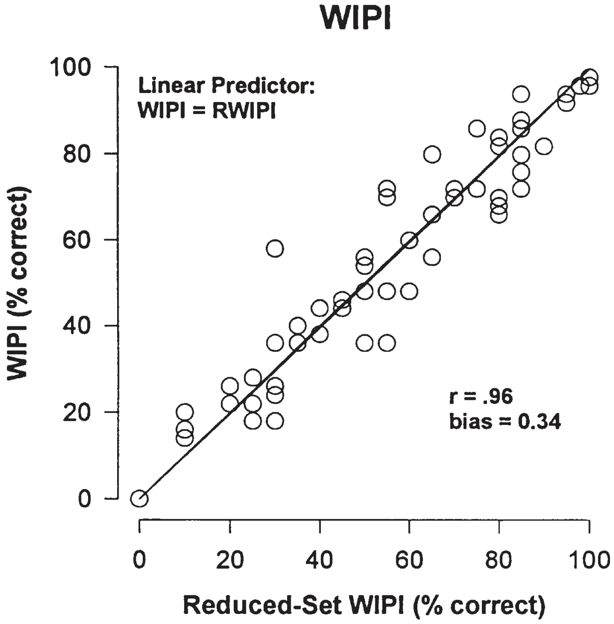




Appendix B. Reliability of reduced-set WIPI score. Values of the full-set WIPI are plotted against the reduced-set WIPI for 71 administrations to 38 subjects. Reduced-set WIPI predicts WIPI with less than 1 percentage point bias and with correlation of .96.

Reduced-set WIPI

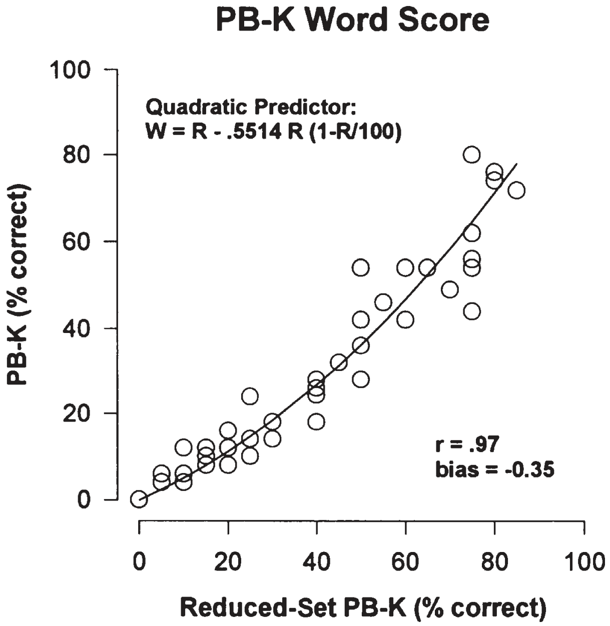
school	broom	moon	spoon
ball	bowl	bell	bow
fox	socks	box	blocks
hat	flag	bag	black
pan	fan	can	man
neck	desk	nest	dress
stair	bear	chair	pear
eye	pie	fly	tie
gun	thumb	sun	gum
straw	dog	saw	frog



Appendix C. Reliability of the reduced-set PB-K word score. Values of the full-set PB-K word score (W) are plotted against the reduced-set PB-K word score (R) for 58 administrations to 34 subjects. The quadratic predictor has bias less than 1 percentage point and correlation of .97 with the full score.

Reduced-set PB-K

1. please
2. bath
3. pants
4. bad
5. take
6. bus
7. five
8. mouth
9. dish
10. put
11. no
12. box
13. teach
14. tree
15. me
16. hit
17. neck
18. ride
19. hot
20. pink



Appendix D. Reliability of the reduced-set PB-K phoneme score. Values of the full-set PB-K phoneme score (P) are plotted against the reduced-set PB-K phoneme score (R) for 58 administrations to 34 subjects. The quadratic predictor is practically unbiased and has correlation of .98 with the full score