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# Speech Perception Performance of Nucleus Multichannel Cochlear Implant Users with Partial Electrode Insertions[1]

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## Abstract

Ossification of the cochlea need not pose a special problem in surgical implantation or in auditory performance of the cochlear implant candidate. The present investigation examines the speech perception performance of five children with ossified cochleas who received partial insertions of the Nucleus 22-channel cochlear implant. All the partial-insertion subjects were fit with their Nucleus cochlear implant between the ages of 2-5 years and used their device for at least 1.5 years; two of these subjects had used their device even longer, up to 4.5 years. The partial-insertion subjects' preimplant and 1.5 years postimplant performance on a battery of speech perception tests was compared to the average performance of age-matched control subjects who received full insertions of their electrode array. More extended comparisons were made for the two partial-insertion subjects who had used their cochlear implants for a longer period of time. The results revealed that the subjects with partial electrode insertions perform similarly to the control group at preimplant and 1.5 years postimplant. Furthermore, the partial-insertion subjects showed continued improvements in speech perception performance with increased device experience past 1.5 years, again similar to the full-insertion control group. The present results suggest that partial insertion of a multichannel implant device is an appropriate and feasible approach to the surgical management and auditory rehabilitation of children with complete ossification of the cochlea.

# Speech Perception Performance of Nucleus Multichannel Cochlear Implant Users with Partial Electrode Insertions

## Introduction

Meningitis is one of the most common etiologies of acquired hearing loss in childhood, causing severe-profound hearing loss (Becker, Eisenberg, Luxford, and House, 1984). Approximately half of the children fit with cochlear implants are deafened by meningitis, and as many as 70-80% will have some degree of cochlear ossification (Becker et al., 1984). For these children, cochlear implants are the mainstay of rehabilitation when the loss is so profound that no significant benefit from hearing aids can be obtained. Although it is easier to implant a single electrode device in an ossified cochlea, multichannel cochlear implants appear to offer greater potential for the development of speech and language skills in children (Miyamoto et al., 1994).

It is sometimes possible to fully insert a multichannel electrode array in an ossified cochlea. According to Green, Mitchell, Marion, and Hinojosa (1990), the basal turn of the scala tympani is the most frequent area of ossification regardless of etiology, and complete cochlear ossification is rare. Therefore, drilling out the basal turn may allow for complete insertion of a 22-electrode array, and the successful implantation of a postmeningitic child. However, Green, et al. (1990) also pointed out that a greater extent of ossification may be encountered in the apical and middle turns of the cochlea, making complete insertion difficult. In fact, it has been suggested that cochlear implantation is contraindicated in extensive ossification, either because of damage resulting from electrode insertion, or because of extensive neuronal destruction that may result from the ossification itself, leaving few surviving cells to stimulate (Balkany, Gantz, & Nadol, 1988; Nadol, Young, & Glynn, 1989).

What are the effects of partial electrode insertion on speech perception performance by patients with the Nucleus 22-channel cochlear implant? Presumably, because the same frequency range must be represented using fewer electrodes, it may be that partial insertion of the electrode array reduces the specificity of information available to the listener. If this is true, then reduced speech perception performance may result. Conversely, full electrode insertion might allow subjects to better detect the features of speech that the device has been engineered to extract. However, full electrode insertion would require a more extensive procedure, with the possibility of increased surgical risks. At present, the minimum number of active electrodes required for maximum performance is not known. To address this issue, Kileny, Zimmerman-Phillips, Zwolan, and Kemink (1992), used a within-subject design and found that subjects using a minimum of 10 active electrodes performed as well as when 20 channels were activated. Furthermore, very good speech understanding has been reported for some patients who use the Clarion multichannel cochlear implant, which employs only six active electrodes (Wilson, 1993).

The surgical approach in a child with an ossified cochlea is yet another area of uncertainty. Early approaches to the surgical implantation of children with ossified cochleas were conservative. Initially, the presence of cochlear ossification was considered a contraindication to implantation in children, because of concern over whether these children could use their devices to acquire good speech understanding. At the 1991 Medical and Surgical Issues panel discussion at the Third Symposium on Cochlear Implants in Children, the concern regarding implanting a child with an ossified cochlea was summarized by William M. Luxford, who stated that "the likelihood of that child benefiting from an implant is a lot less than if the cochlea is not ossified" (Miyamoto et al., 1991). The recommendation by Dr. Luxford at the time was to

implant as much as possible, if not all, of a multichannel device and hope for the best in speech perception performance.

A few limited approaches to drilling out the neo-ossified cochlea have been developed to permit partial insertion of the electrode array (Kemink, Zimmerman-Phillips, Kileny, Firszt, & Novak, 1992; Balkany, Luxford, Martinez, & Hough, 1988; Balkany, Cohen, Gantz, & Steenerson, 1994). Results with this approach were mixed. For example, Parisier and Chute (1993) described the speech perception performance of five children who received partial electrode insertions. Two children, with partial insertion of 15 and 20 electrodes, displayed some limited open-set speech understanding. However, three other children, who had 8-12 electrodes implanted, were only able to achieve some pattern perception even after two years of device use.

An alternative approach to implanting children with ossified cochleas was developed to permit full insertion of the Nucleus electrode array in patients with completely ossified cochleas (Gantz, McCabe & Tyler, 1988). Briefly, this procedure involves an initial facial recess approach to visualize the basal turn of the cochlea, combined with taking down the posterior canal wall and performing a radical mastoidectomy. In order to obtain complete access, the tympanic membrane, incus, and malleus are removed, the eustachian tube is obliterated, and the external canal is sewn closed. The remaining steps involve removal of the round window niche, drilling of the yellow-white bony growth, and creation of a modiolar trough with preservation of the modiolus. Obvious care is taken in drilling near the vicinity of the facial nerve and the carotid artery. The complete electrode array is then placed within the trough and secured by temporalis fascia.

In their first report, Gantz, et al. describe the speech perception performance of two adult subjects who underwent this procedure. Although one subject's speech perception abilities were characteristic of those of a typical non-ossified, postlingually deafened adult, the other subject was unable to be stimulated (Gantz et al., 1988). Balkany, Gantz and Nadol (1988) reported on a larger series of pre- and postlingually deafened patients with ossified cochleas in whom full electrode insertion was achieved. However, all 14 of these subjects had only partial cochlear ossification. After implantation, all 14 subjects had functional devices, and reportedly achieved results similar to non-ossified full insertion adult subjects.

The extensive procedure of Gantz et al. has also been successfully utilized in children with favorable results. Lambert, Ruth, and Hodges (1991) were the first to report on a single case of the first full drill-out in a prelingually deafened four year old child. The authors reported that postimplant, this child demonstrated improved lip reading and speech recognition skills. Steenerson and Gary (1994) utilized the Gantz method to achieve full insertion in three subjects, one prelingually deafened adult and two prelingually deafened children. This group supported the extensive implantation procedure of Gantz et al. after two of their partially-inserted subjects deteriorated to non-users within one year postimplant. Again, the subjects who received full electrode insertions were reported to have markedly improved performance.

In all of the above reports, the main goal was to achieve complete insertion of the full array of electrodes. However, very little speech perception data were reported and no direct comparisons between full-insertion and partial-insertion subjects were conducted. Thus, it is not clear whether a more extensive drill-out procedure to permit full insertion of the electrode array in fact yields better postimplant speech understanding in patients with cochlear ossification. It may be feasible to use such an approach if, in fact, subjects with full electrode insertions exhibit better speech perception abilities than subjects with only partial insertion of their electrode array. If this is not the case, then a partial approach, employing only minor changes in the typical surgical approach, might be preferred. Currently, only Kemink et al. (1992)

have compared the speech perception performance of postmeningitic children who received partial electrode insertions with that of non-ossified control subjects with full electrode insertion. The authors reported similar performance between the two groups. In light of their results, they questioned whether the use of an extensive surgical procedure to insert the full array was justified.

The purpose of the present investigation was to compare the speech perception performance of prelingually deafened children with Nucleus 22-channel cochlear implants who received partial insertion of their electrode array with the performance of children who had full electrode insertions. Because speech perception skills develop over time (Miyamoto, Kirk, Todd, Robbins, and Osberger, 1995), we employed a longitudinal analysis of performance in five children with 1.5 years of device experience, and two children with experience out to 4.5 years. This is the first study to examine any long-term follow-up, beyond the initial 18 month postimplant period, of partially inserted subjects and to compare them longitudinally with full-insertion cohorts. The present findings will further add credence to the Kemink et al. study if the preliminary results are able to show continued good speech performance on long-term follow-up. This is also the first report to use two separate age-appropriate test batteries to examine postimplant performance. This allows for the elimination of any age bias to test performance, i.e., children perform well because they are at an advanced age, allowing other factors besides speech perception abilities to confound the results and vice versa.

## Methods

### Subjects

Experimental subjects were selected from the pool of children with Nucleus multichannel cochlear implants currently followed at the Indiana University School of Medicine as part of a longitudinal study of sensory aids in children with profound hearing loss. Of the 12 children with partial insertion of the electrode array, 11 were noted either pre-operatively or at the time of surgery to have labyrinthitis ossificans. From this group of 12 potential subjects, we eliminated all children who had used their device for 6 months or less, because significant improvements in speech perception skills do not typically emerge before one year of device use (Fryauf-Bertschy, Tyler, Kelsay, & Gantz, 1992; Osberger, Miyamoto, Zimmerman-Phillips, et al., 1991; Staller, Dowell, Beiter, & Brimacombe, 1991). Three other potential subjects were eliminated for various reasons that may have later confounded the results: one for etiologic reasons (a Mondini malformation); one because of neurologic complications (microcephaly); and the third because the hearing loss was progressive, which made the classification of a prelingual profound hearing loss questionable. Thus, five prelingually deafened children, three with postmeningitic acquired bilateral profound hearing loss and two with idiopathic etiology, were left for inclusion as subjects in this investigation. Three were male and two were female. Subject characteristics are presented in Table 1.

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Insert Table 1 about here

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### Device Characteristics

Device characteristics for each of the subjects are also shown in Table 1. Each of the test subjects was fit with the Nucleus 22-channel device, with only partial insertion of the electrode array secondary to extensive cochlear ossification. Across subjects, the number of partially inserted electrode rings ranged from 9 to 13. One subject used the Wearable Speech Processor (WSP) programmed in the F0/F1/F2 processor strategy. This strategy encodes fundamental frequency (F0) and the frequency and amplitude of the first two formant frequencies (F1, F2). For voiced sounds, the stimulation rate of the two electrodes

# Table 1

Subject characteristics and device characteristics of partial-insertion users.

| Name | S1 | S2 | S3 | S4 | S5 |
|---|---|---|---|---|---|
| Etiology | UNK | UNK | MEN | MEN | MEN |
| Age @ Onset(yrs) | 0.0 | 0.0 | 1.9 | 2.1 | 1.6 |
| Age @ Implant(yrs) | 5.8 | 4.9 | 5.4 | 2.6 | 3.3 |
| Yrs of Dep | 5.8 | 4.9 | 3.5 | 0.5 | 1.7 |
| Comm Mode | Oral | Total | Oral | Oral | Total |
| Device Brand | NUC 22 | NUC 22 | NUC 22 | NUC 22 | NUC 22 |
| Processor | MSP | WSP | MSP | MSP | MSP |
| Proc. Strategy | MPEAK | F0F1F2 | F0F1F2 | MPEAK | F0F1F2 |
| Stim. Mode | CG | CG | CG | CG | BP |
| Active Electrodes | 10 | 13 | 09 | 12 | 11 |

representing F1 and F2 is equal to F0. For unvoiced sounds, the pulse rate varies at an average of 100 Hz. The remaining subjects used the Mini Speech Processor (MSP). Two of these subjects used the MSP programmed in the F0/F1/F2 strategy described above. The remaining two subjects used the MSP processor strategy programmed in the Multipeak (MPEAK) processor strategy (McKay & McDermott, 1993; Skinner, Holden, Holden, et al., 1991). In addition to estimating F0, F1, and F2, the MPEAK strategy estimates amplitudes in three additional frequency bands (Bands 3, 4, and 5) encompassing the frequency range from 2.0 to 6.0 kHz. During voiced signals, electrodes representing F1 and F2, and Bands 3 and 4 are stimulated at a pulse rate equal to the fundamental frequency. For unvoiced sounds, a nonperiodic pulse rate varying between 200 and 300 Hz is used to stimulate electrodes representing F2 and Bands 3, 4, and 5.

**Training**

Because many of the subjects in our longitudinal study live a great distance from the Indiana University School of Medicine, neither the experimental nor the control subjects received ongoing auditory rehabilitation at our center. However, it is a requirement of our study that all subjects of school age be enrolled in educational programs that are supportive of auditory and speech development. The emphasis is on auditory, speech and language needs for each individual child. Therefore, auditory development with their cochlear implants was guided by the subjects' school personnel and parents.

**Stimulus Materials**

Depending on their age at time of testing, children in our longitudinal study are administered one of two speech perception assessment batteries. Our original "School-Age" battery is intended to assess performance in children aged 6-9 years. More recently, as younger children have been implanted, we have developed a "Baby" battery intended for children aged 2-5 years. Both batteries assess discrimination and recognition skills with speech materials ranging from phonemes to sentences, using either a closed- or open-set response format.

**School-Age Battery.** The speech perception measures included in this battery have been described in detail by Osberger, Robbins, Miyamoto, et al. (1991). They will be presented briefly here. *The Screening Inventory of Perceptual Skills* (SCIPS) was developed at Indiana University to assess speech discrimination skills using a closed-set format. The SCIPS is presented in the auditory-only modality and has two levels of difficulty. In the first level, pairs of words are distinguished from one another by syllable number (3 vs. 1; 3 vs. 2). The second, more difficult level, holds syllable number constant while contrasting words by phonetic features. The SCIPS employs the "go/no-go" paradigm, wherein the child responds only when the target word is spoken by the examiner ("go"). If any other word is spoken, the child is not supposed to respond ("no-go"). This task, then allows the child to concentrate on only one key word at a time. Responses are scored as correct if the child either picks up an object representing the spoken word, or is able to imitate the word. Chance performance on the SCIPS is 50%.

The *Minimal Pairs Test*, also developed at Indiana University, is a closed-set test that assesses discrimination of 80 pairs of words differing by a single vowel or consonant feature. Stimulus items are presented in the auditory-only modality, and the child responds by pointing to the picture that was named. Children's responses are scored by the percent of consonant features (voicing, manner, and place) or vowel features (vowel height and vowel place) that are correctly recognized. An overall composite score is also obtained. Chance performance is again 50%.

The *Common Phrases Test*, also developed at Indiana University, is an open-set measure that assesses the recognition of ten common everyday phrases (e.g., "What do you like to eat?"; "It is cold

outside.") There are six different lists of 10 phrases. This test is administered in both an auditory-only and an auditory-plus-visual modality. The child may respond by repeating the entire phrase or sentence correctly, or by answering correctly if the stimulus is a question.

**Baby Battery.** The object identification subtest of the *Grammatical Analysis of Elicited Language-Pre Sentence Level* (GAEL-P; Moog & Geers, 1983) has been adapted for utilization as a speech perception measure to assess closed-set speech recognition skills. The test consists of 30 different objects representative of simple one- and two-syllable words within the vocabulary of the children between 2-5 years. Test items are presented in the auditory-only modality; subjects respond by selecting one of the four alternative objects. Thus, chance performance is 25%.

The Mr. Potato Head measure (Indiana University, 1994) assesses the child's recognition of simple words and sentences using a common children's game. This test, presented auditory-only, requires that the child manipulate the toy pieces in response to the examiner's instructions ("Make Mr. Potato Head go to sleep."; "Put the black hat on Mr. Potato Head.") This is considered a modified open-set task because there are a finite set of possible distractors, but they number in the thirties. The child's responses are scored as the percent of key words (out of 20) and sentences (out of 10) correctly identified. Because the Mr. Potato Head test is a modified open-set task and there is a remote chance that the child would be able to correctly guess the target word but not the complete sentence, chance performance is scored 5% for words and 0% for sentences.

The *Pediatric Speech Intelligibility Test* (PSI), (Jerger & Jerger, 1984) consists of 20 words and 20 sentences, separately presented in a closed-set. As administered in our protocol, subjects are shown four different story boards (two for words and two for sentences), each containing six pictures. The items are presented in an auditory-only and an auditory-plus-visual modality. Subjects respond by pointing to the picture described by the target word or sentence. Responses for words and sentences are scores separately; chance performance for both is 17%.

**Procedures**

All test items in both batteries were administered via live-voice using the procedures employed in our research protocol. A team of five examiners (two audiologists and three speech-language pathologists), who had extensive experience in live-voice testing, evaluated the subjects. Subjects were seated facing the examiner approximately 1.5 feet away. Test instructions were presented orally or in Total Communication mode, depending on each subject's communication modality. Signing was not included when the test items themselves were administered. The stimuli were articulated clearly and concisely in a manner described by Picheny, Braida, and Durlach (1985), and presented at levels that ranged roughly from 70 to 75 dB SPL (loud conversational speech). The test items were presented one time only; missed items were not repeated. For auditory-only test administration, the examiner covered her face with a mesh screen so that speechreading cues were not available to the subject.

The partial-insertion subjects were divided into two groups according to which speech perception battery was administered. There were three subjects each in the "School-Age" battery and "Baby" battery groups (data from subject 1 were used in both batteries, because he had data at each interval utilized in this study, and was still under six years of age when the "baby" battery was developed).

Subjects in our longitudinal study are typically evaluated prior to receiving a cochlear implant, and then again every six months or annually. We selected two intervals to examine speech perception performance: preimplant, and 1.5 years postimplant, which was the longest interval of device use at which

all five partial insertion subjects had been tested. Their performance was compared to the average performance of all full-insertion control subjects with similar ages at onset of hearing loss and similar ages at time of implant, who were tested at both intervals. However, because two of the measures in the "Baby" battery were only recently developed (GAEL-P and Mr. Potato Head) we have relatively few children with data at both the preimplant and 1.5 postimplant intervals on these two measures. For these two measures, a cross-sectional comparison was carried out, wherein performance of the "Baby" battery partial-insertion group was compared to the average performance of all full-insertion subjects who had been assessed on the same measures at either the preimplant or 1.5 year postimplant interval and were of similar age at onset, age at time of implant, and age at time of testing.

Two of the partial-insertion subjects in the "School-Age" battery had used their cochlear implant for 4.5 years or more. Their long-term performance also was compared to that of a group of full-insertion control subjects who were similar in terms of age at onset of hearing loss, age at time of implant, and length of device use. The performance of the long-term partial-insertion subjects was compared to that of all appropriate control subjects at three intervals: 2.5 years, 3.0 years, and $\geq$ 3.5 years. At the $\geq$ 3.5 interval, data from each control subject's most recent interval were selected (3.5-5.0 years) to compare with the partial insertion subject's performance at 4.5 years post-implant

## Results

A separate comparison of the subject characteristics and performance data for the partial insertion and full-insertion control subjects will be presented below for children tested with the "School-Age" and "Baby" batteries. The cross-sectional comparison of subject characteristics and performance for longer periods of device use follows.

### "School-Age" Battery

Table 2 presents the average characteristics of the "School-Age" battery for the three partial insertion and 10 full insertion control subjects. The mean age at onset of deafness for both groups was less than 1 year of age. On average, both groups of subjects were fitted with their device at about 5 years of age. One partial-insertion subject used Total Communication (S2) and the remaining two used Oral Communication. For the full-insertion group, eight used Total Communication and two used Oral Communication.

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Insert Table 2 about here

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Figures 1a and 1b present individual scores for the partial-insertion subjects on the SCIPS closed-set word recognition task at the preimplant and 1.5 years postimplant intervals. In these figures, the average preimplant and 1.5 year postimplant performances of the age-matched control group are represented by dashed horizontal lines. Recall that performance on Level 1 of the SCIPS (Figure 1a) represents the subjects' ability to discriminate between pairs of words on the basis of syllable number, and Level 2 represents discrimination on the basis of vowel and consonant distinctions. At the preimplant interval, two of the three partial insertion subjects, (S1 and S3) demonstrated pattern-perception skills that were superior to those of the full-insertion group, who performed at about chance levels (50% correct). After 1.5 years of device use, all three of the partial insertion subjects were able to identify words from a two-alternative closed-set at performance levels significantly greater than chance performance, with

# Table 2

Subject characteristics of longitudinal "School Aged" battery.

| | PARTIAL INSERTION | | FULL INSERTION | |
|---|---|---|---|---|
| | Mean | Std. Dev | Mean | Std. Dev. |
| Age onset | 0.7yrs | 0.93 | 0.9yrs | 1.40 |
| Age fit | 5.2yrs | 0.35 | 5.0yrs | 0.41 |
| Yrs. dep. | 4.6yrs | 0.86 | 4.1yrs | 1.50 |
| C.A. | 5.15yrs | 0.5 | 4.9yrs | 0.45 |
| Comm mode | 66%(oral)33%(TC) | | 20%(oral) 80%(TC) | |
| Number | Three | | Ten | |

increases ranging from 10-50%. Overall, their postimplant performance was equal to or superior to that of the full-insertion control group.

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Insert Figure 1 about here

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Figure 2 illustrates the subjects' preimplant and 1.5 years postimplant performance on the Minimal Pairs Test. This test assesses the ability to use differences in a single consonant or vowel feature to accurately identify words. Subjects' identification of words based on vowel information is presented in the left panel; scores based on consonant recognition are presented in the right panel. The average performances for the full-insertion subjects are represented as in Figure 1 by a dashed line. At the preimplant interval, all three of the partial-insertion subjects performed at chance levels for discrimination based on either vowel or consonant information. In this respect, they were similar to the full-insertion group. At the 1.5 years postimplant interval all three partial insertion subjects showed large improvements, (increases ranged from 25-50%) in their recognition of words on the basis of vowel cues. In this respect, their performance was equal to or better than the full-insertion subjects. Both the partial-insertion and control groups demonstrated less improvement for consonant cues. Nonetheless, two of the three partial-insertion subjects (S1 and S2) demonstrated skills that were similar to those of the full-insertion group (percent correct ranged from 55-70% for the partial insertion subjects and 60% on average, for the full insertion group at the postimplant interval). The third partial insertion subject, S3, demonstrated essentially no change in consonant recognition abilities after 1.5 years of device use.

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Insert Figure 2 about here

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Figure 3 presents the partial insertion subjects' performance on the open-set Common Phrases Test administered in the auditory-plus-visual modality (3a) and the auditory-only modality (3b) at the pre- and 1.5 years postimplant intervals. The average performances for the full-insertion group are represented as before by dashed lines. In Figure 3a, it can be seen that two of the partial insertion subjects (S1 and S3) were able to correctly respond to approximately 30-50% of the simple phrases or sentences at the preimplant interval. This level of performance is superior to that of the average preimplant performance of the full-insertion group. The results indicate that these two partial-insertion subjects were able to use minimal auditory information combined with visual stimuli to aid in word recognition. Figure 3a illustrates that at 1.5 years postimplant all three partial-insertion subjects had made large gains in their ability to identify common phrases using both auditory and visual information (some as large as 70%). At the postimplant interval, their performance ranged from approximately 80-100%, which was much better than the average of about 30% sentences correct demonstrated by the full-insertion subjects. This pattern of results suggests that the partial-insertion subjects were integrating the auditory information available through their device with the visual information they have always had available to improve their speech perception abilities.

An examination of the partial-insertion subjects' identification of sentences using only auditory information yields somewhat similar results (Fig. 3b). Here it can be seen that both the partial-insertion and full-insertion subjects performed poorly at the preimplant interval. Only one of the partial-insertion subjects, S1, was able to identify even one sentence correctly. This was slightly better than the average performance of the full-insertion group. At the 1.5 years postimplant interval, the full-insertion group

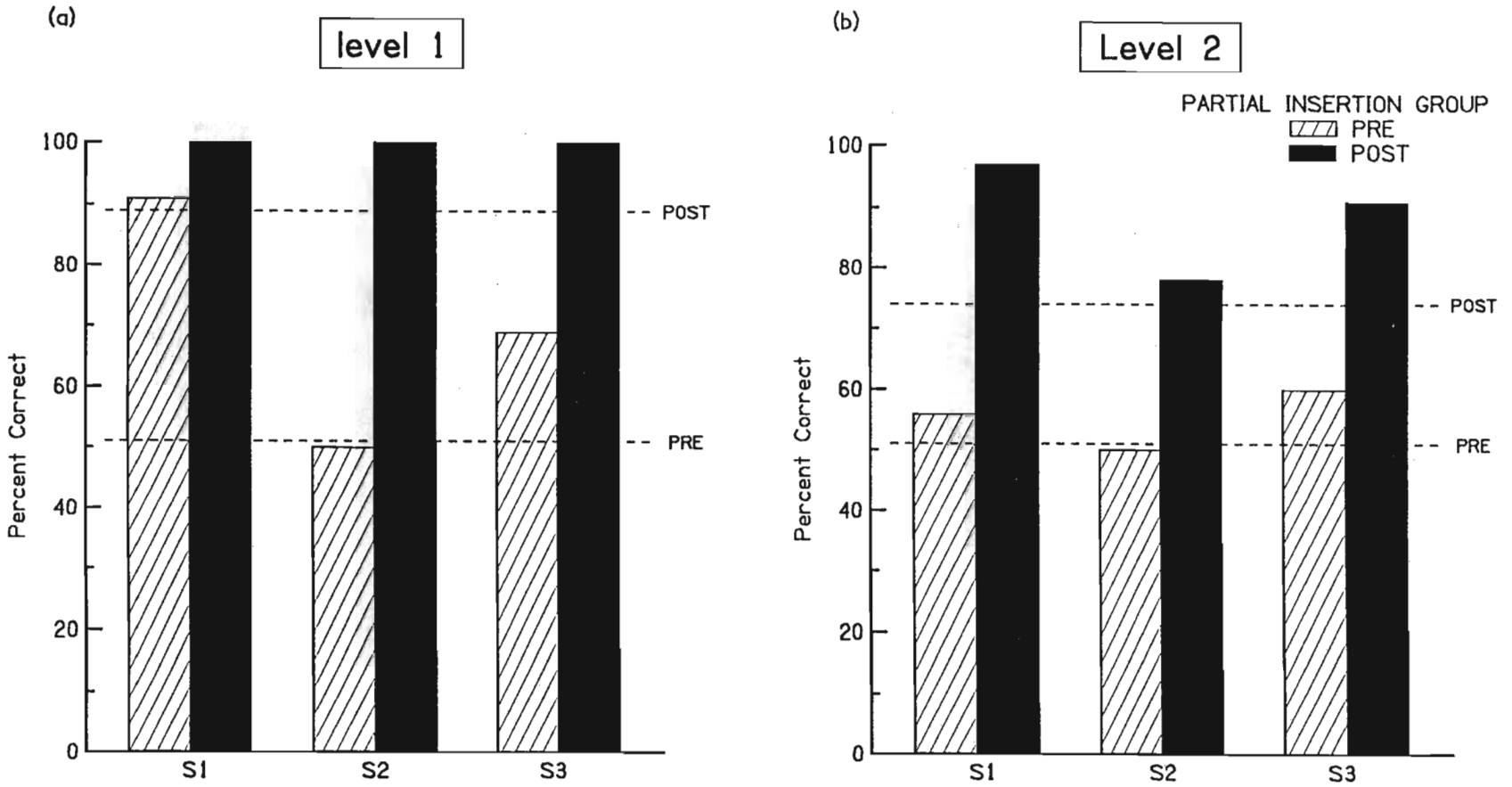


**Figure 1.** Comparison of three "School Aged" partial-insertion cochlear implant subjects' performance on a closed-set test of word discrimination at two levels of difficulty (level 1, words distinguished by syllable number; level 2, words distinguished by contrasting phonetic features), with the average performance of ten age-matched longitudinal full insertion cohorts, as represented by the horizontal lines labeled "pre" and "post." The post interval is equivalent to 1.5 years after date of implantation.

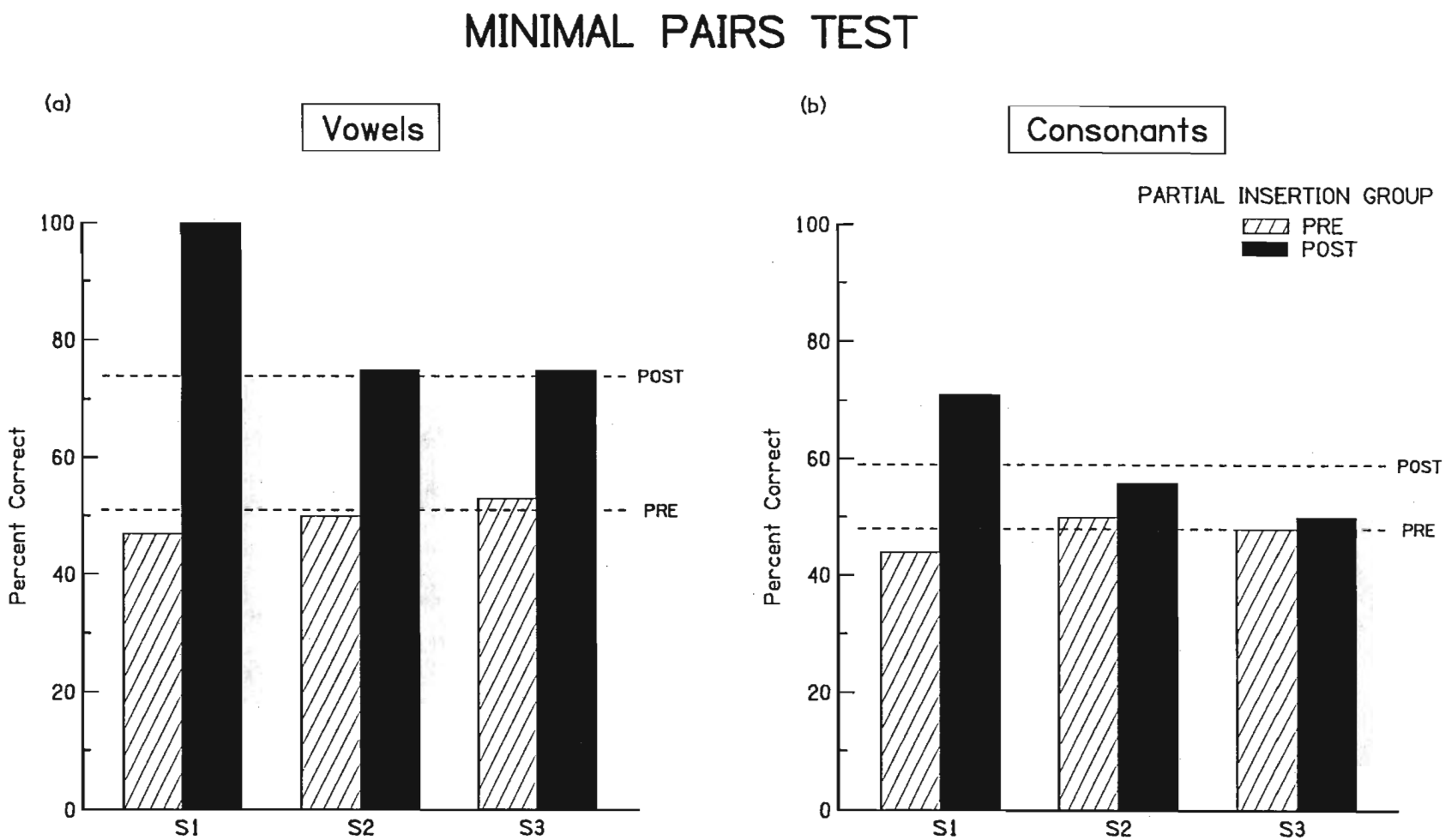


**Figure 2.** Comparison of three "School Aged" partial-insertion cochlear implant subjects' performance on a closed-set test of word discrimination differing by either a single vowel or consonant feature (see text for full explanation), with the average performance of ten matched longitudinal full-insertion control group at preimplant and 1.5 years postimplant, as represented by the horizontal dashed lines.

recognized an average of only about 10% of the sentences. In contrast, two of the partial-insertion subjects demonstrated large improvements (to 70% and 30% for S1 and S3, respectively).

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Insert Figure 3 about here

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In summary, the partial-insertion subjects tested with the "School-Age" battery demonstrated closed-set word recognition skills that were similar or in some cases, superior to those of the full-insertion control group. Even more encouraging, with one exception, the open-set speech perception skills in these children were far superior to their age-matched full-insertion peers who had used their device for a similar length of time. The results suggest that subjects with partial electrode insertions can obtain substantial speech perception benefit from a Nucleus multichannel cochlear implant.

**"Baby" Battery**

Subject characteristics for the longitudinal "baby" battery are presented in Table 3. The partial-insertion subjects' speech perception performance was compared with that of eight age-matched full-insertion subjects who were tested at both the preimplant and 1.5 years postimplant intervals. The partial-insertion group had a slightly later age at onset of deafness, approximately 1.2 years as compared to 0.4 years for the full-insertion group. However, both groups received their cochlear implants at an average age of almost 4 years. Two of the partial-insertion subjects used Total Communication and one used Oral Communication. In the full-insertion group, seven children used Total Communication and one used Oral Communication.

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Insert Table 3 about here

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The partial-insertion subjects' ability to identify words and sentences on the closed-set PSI are illustrated in Figures 4 and 5, respectively. As in the previous figures, the average performance of the full-insertion control group is represented by dashed horizontal lines. In Figure 4a, performance in the auditory-plus-visual modality is presented, and in the auditory-only modality in 4b. At the preimplant interval, two of the partial-insertion subjects (S4 and S5) identified words presented in either the auditory-plus-visual or auditory-only modality at approximately chance levels (17%) just as the full-insertion subjects did. Following 1.5 years of device use, both of the subject groups demonstrated substantial improvements in their understanding of words presented in a closed set. Postimplant word recognition scores for the partial-insertion subjects ranged from about 60-100% correct in the auditory-plus-visual modality, and from about 30-90% correct in the auditory-only modality. One partial-insertion subject, S1, demonstrated preimplant performance in both modalities that was superior to the average performance of the full-insertion group at 1.5 years postimplant (approximately 85-100% correct). The postimplant performance of S4 and S5 approached but did not equal the average performance of the full-insertion group in the auditory-plus-visual modality. However, in the auditory-only modality only one partial-insertion subject did not demonstrate performance that equaled or exceeded the average postimplant performance of the control group.

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Insert Figure 4 about here

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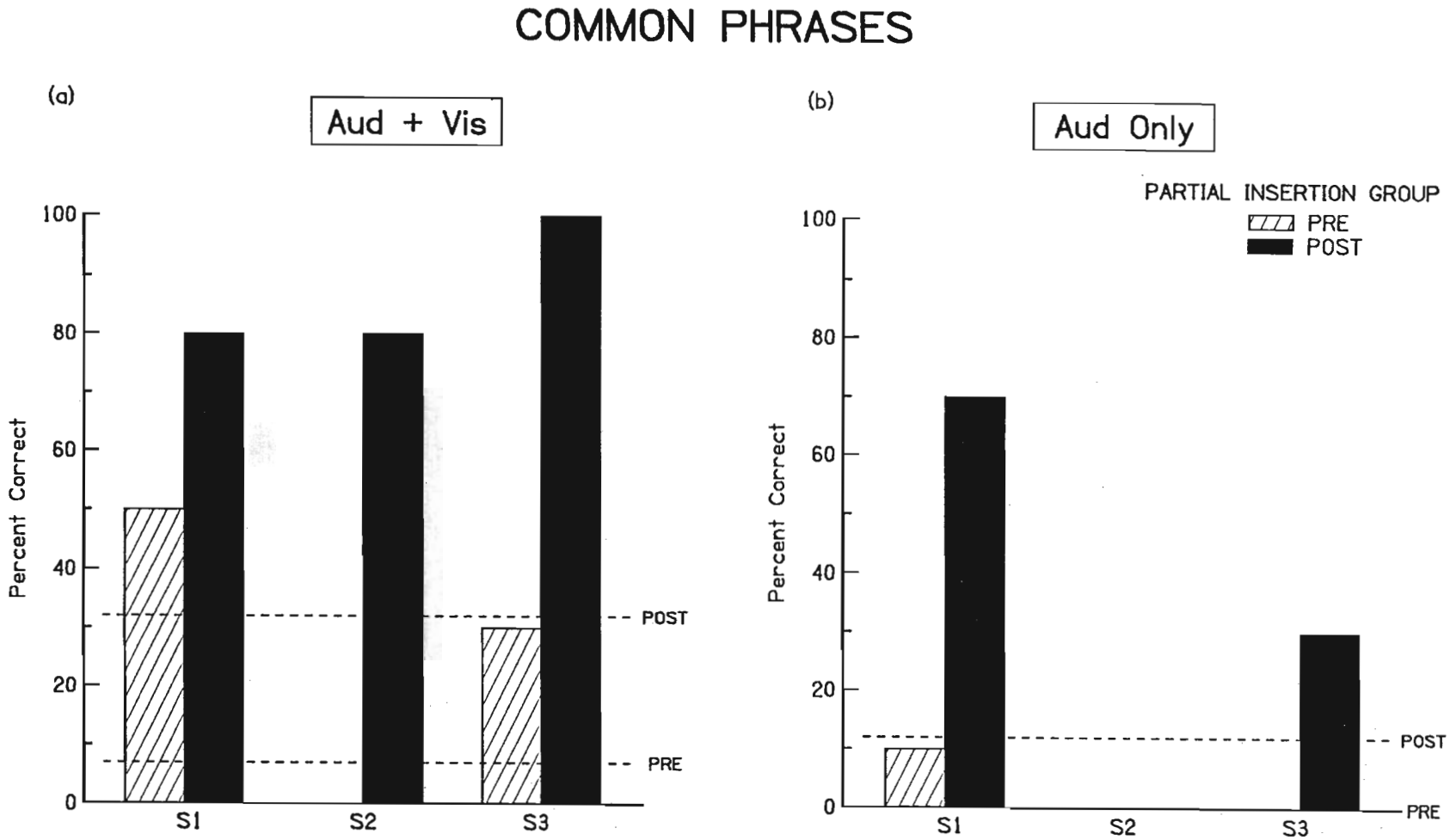


**Figure 3.** Comparison of three "School Aged" partial-insertion cochlear implant subjects' performance on an open-set measure of 10 common everyday phrases in both the auditory-only and combined auditory and visual mode (see text for explanation), with the average performance of ten matched longitudinal full insertion control group at preimplant and 1.5 years postimplant, as represented by the horizontal dashed lines.

## Table 3

Subject characteristics of longitudinal "Baby" battery.

| | Partial Insertion | | Full Insertion | |
|---|---|---|---|---|
| | Mean | Std. Dev. | Mean | Std. Dev. |
| Age onset | 1.20yrs | 0.94 | 0.40yrs | 0.71 |
| Age fit | 3.90yrs | 1.44 | 3.80yrs | 0.76 |
| Yrs. Dep. | 2.70yrs | 2.40 | 3.30yrs | 1.05 |
| C.A. | 4.70yrs | 1.60 | 4.5yrs | 1.20 |
| Comm mode | 66%(oral)34%(TC) | | 12%(oral)88%(TC) | |
| Number | Three | | eight | |

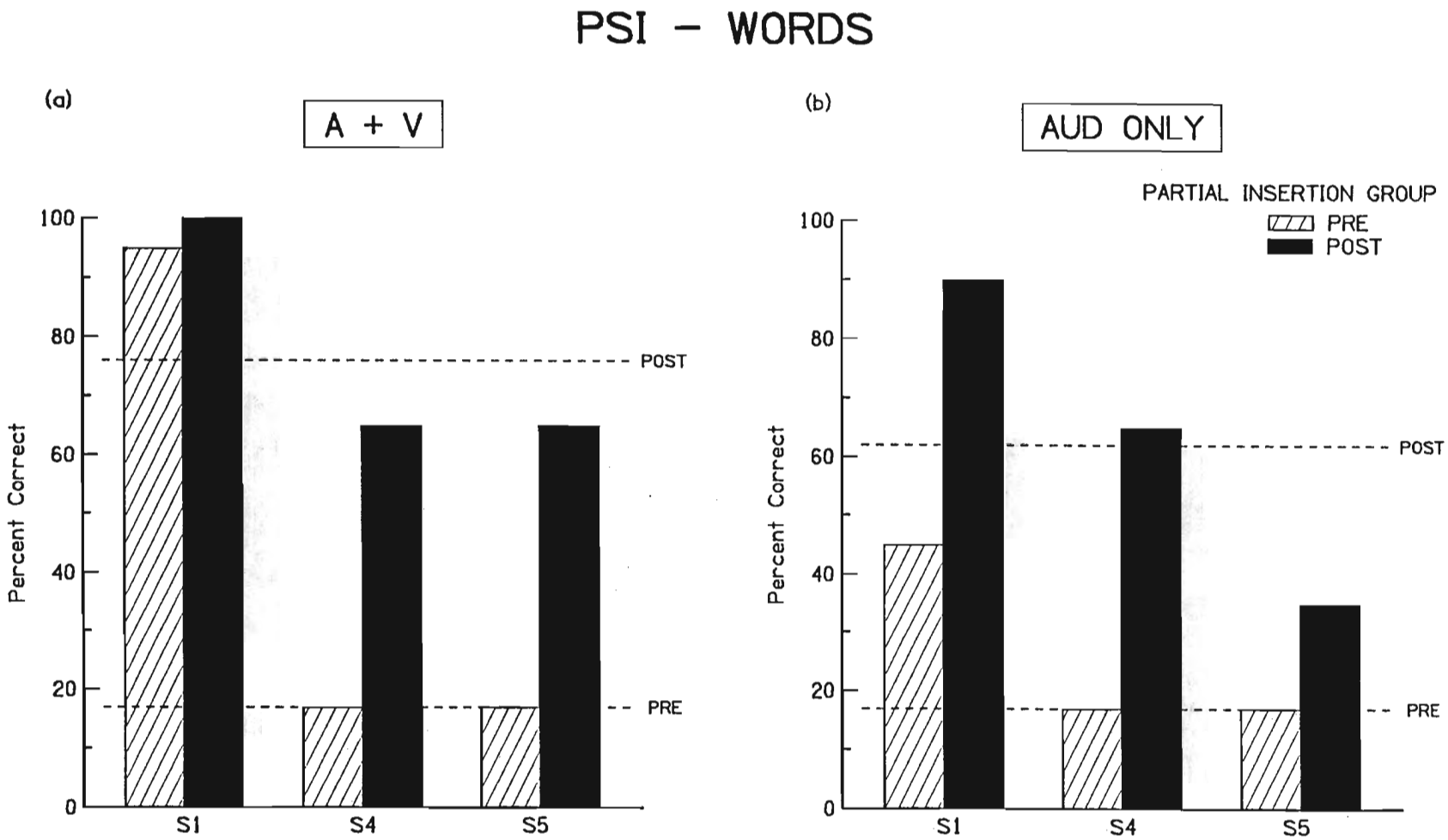


**Figure 4.** Comparison of three "Baby" partial-insertion cochlear implant subjects' performance on a closed-set test of 20 words, administered in both the auditory-only and combined auditory and visual mode (see text for explanation), with the average performance of eight longitudinally matched full-insertion cohorts at their respective pre- and postimplant intervals as represented by the dashed horizontal line.

Figures 5a and 5b illustrate similar results for sentence recognition on the PSI. Once again, subject S1 demonstrated superior recognition in the auditory-plus-visual modality at both preimplant and 1.5 years postimplant, whereas the remaining two partial-insertion subjects performed at chance levels preimplant. After 1.5 years of implant experience, the recognition of sentences presented in the auditory-plus-visual modality exceeded the average performance of the control group (50%) for all three partial-insertion subjects (100%, 60% and 60% for S1, S4, and S5 respectively.) For sentences presented in the auditory-only modality, S4 again displayed superior skills preimplant compared to the control group, whereas the remaining two partial-insertion subjects were performing at chance. At the postimplant interval, only the performance of S5 (about 40%) approached that of the average for the control group (about 48%), whereas the performance of S4 (about 70%) exceeded that of the control group. The remaining partial-insertion subject, S5, correctly identified about 30% of the items at 1.5 years postimplant.

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Insert Figure 5 about here

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For the remaining two tests in the "Baby" battery (GAEL-P and Mr. Potato Head), the performance of the partial-insertion subjects were compared to two different full-insertion control groups: those that were tested at preimplant, and those that were tested at 1.5 years postimplant. Table 4 presents the subject characteristics of the partial-insertion subjects compared to the two control groups. The mean age at onset for the preimplant control group was slightly different from the mean of the partial-insertion group. A slightly larger difference in age of onset was evident for the four postimplant control subjects (1.2 yrs vs. 0.3 yrs). All three groups had a similar mean age at time of implant, approximately 3.5 years. Again, the mode of communication differed somewhat in the control groups versus the partial-insertion group. The partial-insertion group had a higher percent of subjects who were oral, whereas the percentage was almost reversed in the two control groups for Total Communication.

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Insert Table 4 about here

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Figure 6 presents the subject performance for the GAEL-P. Preimplant data were not available for S1, as the GAEL-P was not part of our assessment battery at the time of preimplant testing. It can be seen that remaining subjects in both groups recognized words at levels slightly lower than the chance score of 25% at the preimplant interval. Following 1.5 years of device use, the three partial-insertion subjects demonstrated word recognition scores ranging from approximately 70-90% correct. Thus, their word recognition skills were similar to or exceeded the average performance of the full-insertion group on this more difficult assessment measure. It appears that overall, these partial-insertion subjects were able to perform as well or better than their full-insertion cohorts on closed-set measures of isolated word recognition.

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Insert Figure 6 about here

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Figure 7 demonstrates the subjects' open-set speech recognition abilities as measured by the Mr. Potato Head task. Word recognition is presented in Figure 7a and sentence recognition in 7b. Again, preimplant data were not available for S1. The data for the two remaining partial-insertion subjects

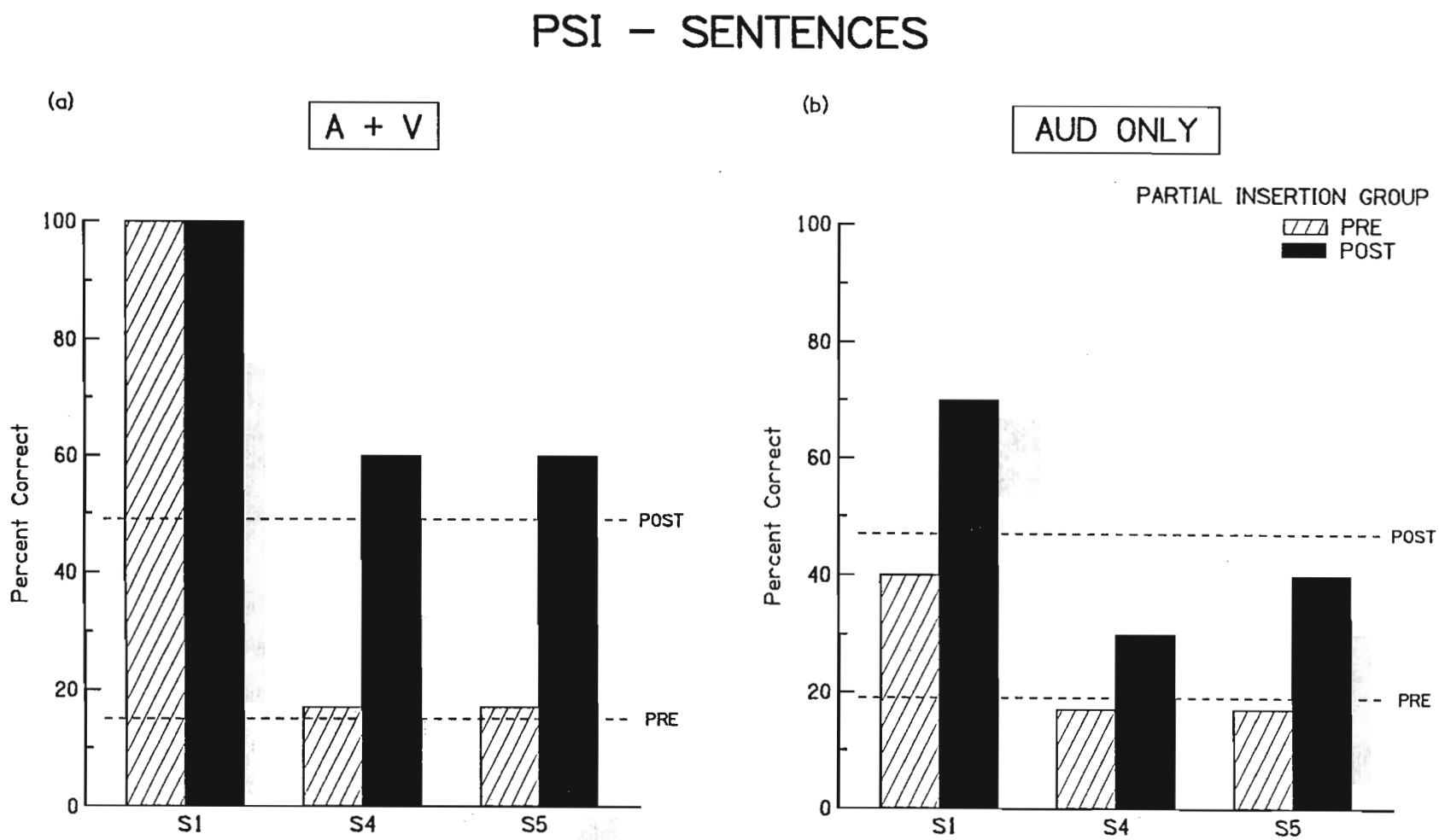


**Figure 5.** Comparison of three "Baby" partial-insertion cochlear implant subjects' performance on a closed-set test of 20 sentences, administered in both the auditory-only and combined auditory and visual mode (see text for explanation), with the average performance of eight longitudinally matched full insertion cohorts represented by the "pre" and "post" horizontal dashed lines.

## Table 4

Subject characteristics for the cross-sectional "Baby" battery.

| | Pre-Implant | | | | 1.5yrs PostImplant | |
|---|---|---|---|---|---|---|
| | PARTIAL INSERTION | | FULL INSERTION (cross-sectional) | | | |
| | Mean | Std Dev | Mean | Std Dev | Mean | Std Dev |
| Age onset | 1.2yrs | 0.94 | 0.75yrs | 0.91 | 0.3yr | 0.52 |
| Age fit | 3.9yrs | 1.44 | 3.6yrs | 0.89 | 3.5yr | 0.65 |
| Yrs. dep. | 2.7yrs | 2.40 | 2.9yrs | 1.50 | 3.2yr | 1.10 |
| C.A. | 4.7yrs | 1.6 | 3.5yrs | 0.91 | 5.1yr | 0.68 |
| Comm mode | 66%(oral)34%(TC) | | 37%(oral) 63%(TC) | | 75%TC 25%O | |
| Number | Three | | Sixteen | | Four | |

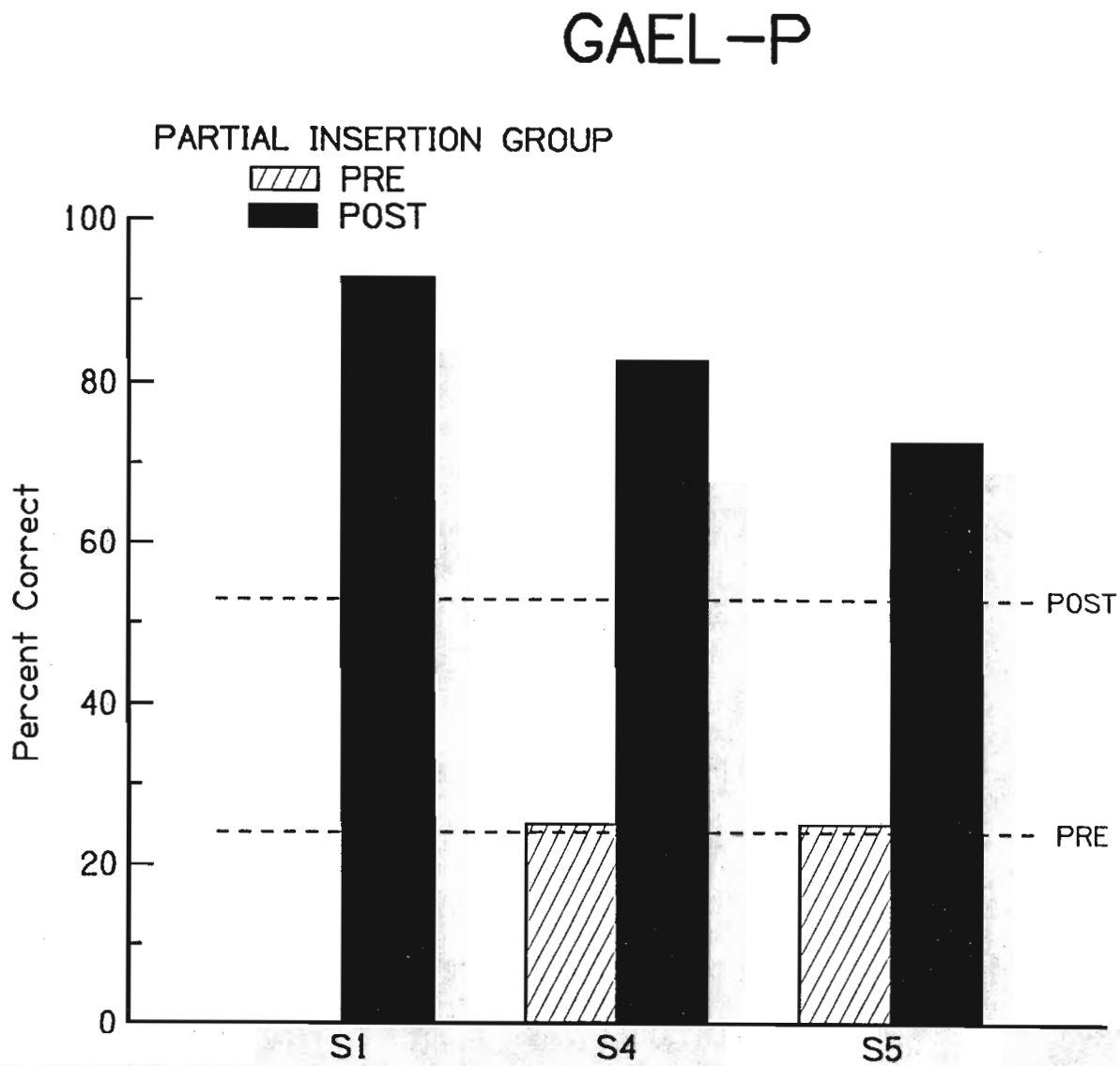


**Figure 6.** Comparison of three "Baby" partial-insertion cochlear implant subjects' performance on a closed-set speech recognition task, presented in the auditory-only modality (see text for explanation), with a cross-sectionally matched group of full-insertion controls ("pre" n=16; "post" n=4) as represented by the horizontal dashed lines.

illustrates that they could correctly identify about 10% of the words and none of the sentences in the preimplant condition. This level of performance is approximately the same as that of the full-insertion control group. At the 1.5 years postimplant interval, all three partial-insertion subjects demonstrated improvements in their word and sentence recognition. S1 had the largest improvements, to 60% correct for both words and sentences. S4 and S5 both demonstrated postimplant open-set skills that were similar to or better than their full-insertion peers: about 40-50% for word recognition, and about 20% for sentence recognition. Clearly there were individual differences in performance, but overall, the three subjects performed very close to, if not better than, the full-insertion averages at both the pre- and postimplant points. This was true, even across both closed- and open-set formats for the "Baby Battery."

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Insert Figure 7 about here

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**Long-Term Results**

To examine how partial-insertion subjects perform on long-term postimplantation intervals, we compared two of the "School-Age" battery partial-insertion subjects who had used their device for at least 4.5 years with a cross-sectional group of full-insertion long-term cochlear implant users. Subject characteristics for the two partial-insertion subjects and the cross-sectional controls are presented in Table 5. Thirteen of these subjects were used for comparison at 2.5 years postimplant; nine at the 3.0 years postimplant, and seven at the >3.5 years postimplant interval. Overall, the control groups were matched very closely to the two partial-insertion subjects on all the variables presented, with only a slight difference in age at time of implant (5.2 vs. 4.2 yrs) and the age at time of testing (8.7 vs. 7.7 yrs). In the partial-insertion group, one of the subjects used Total Communication and one used Oral Communication. For the full-insertion groups, there was only a slight difference in mode of communication between the cohorts and the experimental group.

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Insert Table 5 about here

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The long-term performance of the two partial-insertion subjects are presented in Figures 8 and 9. Closed-set performance was measured with the Minimal Pairs Test (Figure 8) and open-set speech recognition with the Common Phrases Test (Figure 9). The average performance of the control groups at each interval is represented by the cross-hatched bars in both Figures 8 and 9. Figure 8 demonstrates the results of improved closed-set performance over time for both the control and experimental groups, for the recognition of both vowel and consonant features. Both groups continued to demonstrate better vowel recognition than consonant recognition, even with longer periods of device use. Performance from 2.5 years postimplant to >3.5 years postimplant on consonant recognition showed slight long-term improvement for both the partial-insertion and control subjects. In Figure 8a, a similar result is demonstrated for vowel recognition, in that only slight improvements were noted over these long-term intervals (scores were in the range of 80-100%); however, improvements were seen from the earlier 1.5 postimplant interval. Overall, the partial-insertion subjects' performance on the long-term follow-up of the Minimal Pairs test was equal to or better than the full-insertion subjects' performance.

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Insert Figure 8 about here

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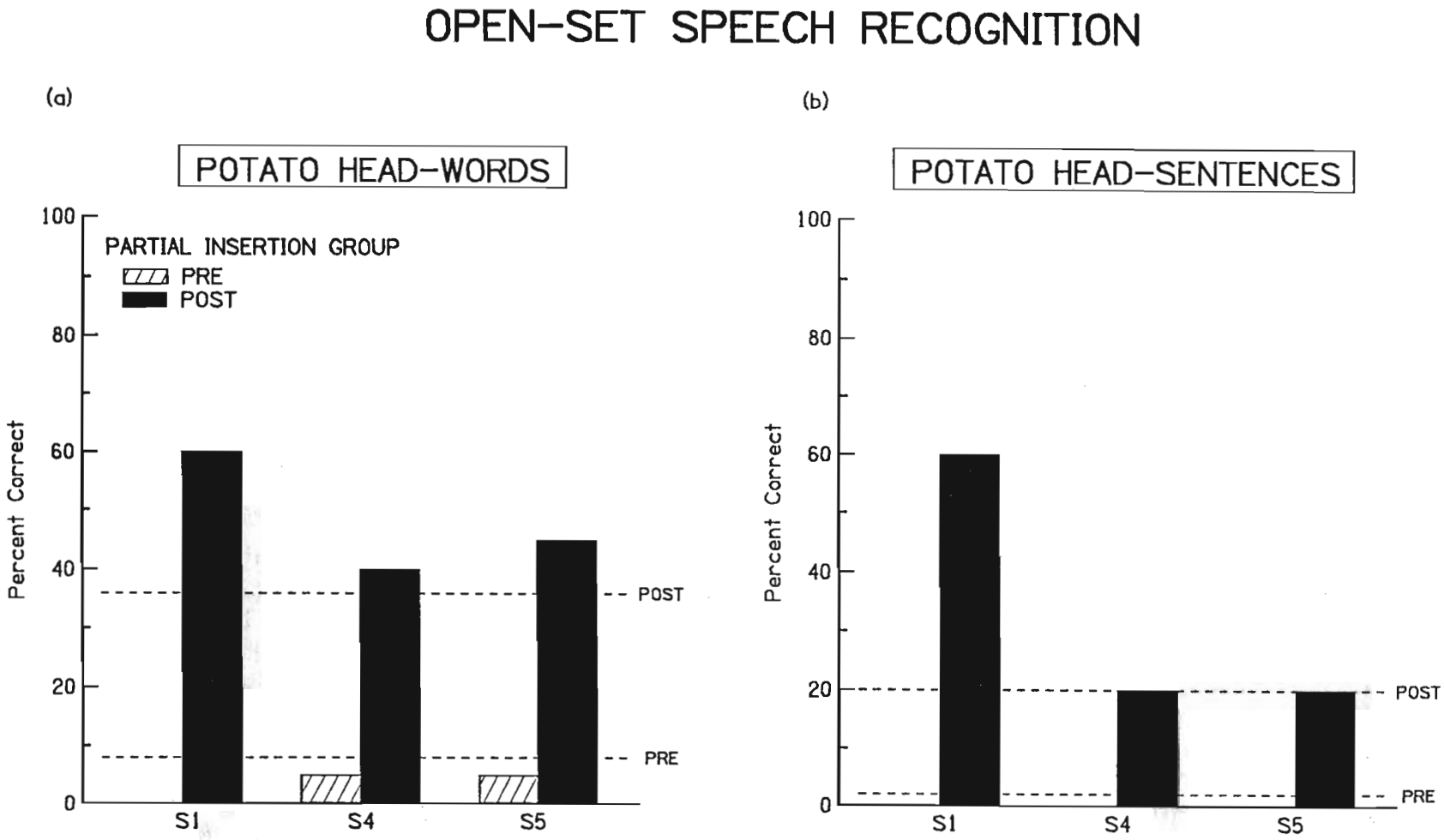


**Figure 7.** Comparison of three "Baby" partial-insertion cochlear implant subjects' performance on a modified open-set task of speech recognition of simple words and sentences (see text for explanation), with a cross-sectional group ("pre" n=16; "post" n=4) of matched full-insertion controls represented by the dashed horizontal lines.

# Table 5

Subject characteristics of long-term follow-up results.

| Partial Insertion | | | Full Insertion | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2.5/3.0/>3.5 yrs | | 2.5 yrs PI. | | 3.0yrs PI. | | >3.5yrs PI | |
| | Mean (yrs) | S D. (yrs) | Mean (yrs) | S D. (yrs) | Mean (yrs) | S D. (yrs) | Mean (yrs) | S D. (yrs) |
| Age onset | 0.95 | 0.95 | 0.8 | 1.1 | 0.73 | 1.1 | 0.7 | 1.1 |
| Age fit | 5.20 | 0.25 | 4.5 | 0.9 | 4.4 | 0.8 | 4.2 | 0.7 |
| Yrs. Dep. | 4.20 | 0.70 | 3.6 | 1.1 | 3.6 | 0.9 | 3.5 | 0.9 |
| C.A. | 7.70 | 0.33 | 7.1 | 0.9 | 7.4 | 0.8 | 8.7 | 0.7 |
| Number | Two | | thirteen | | nine | | seven | |

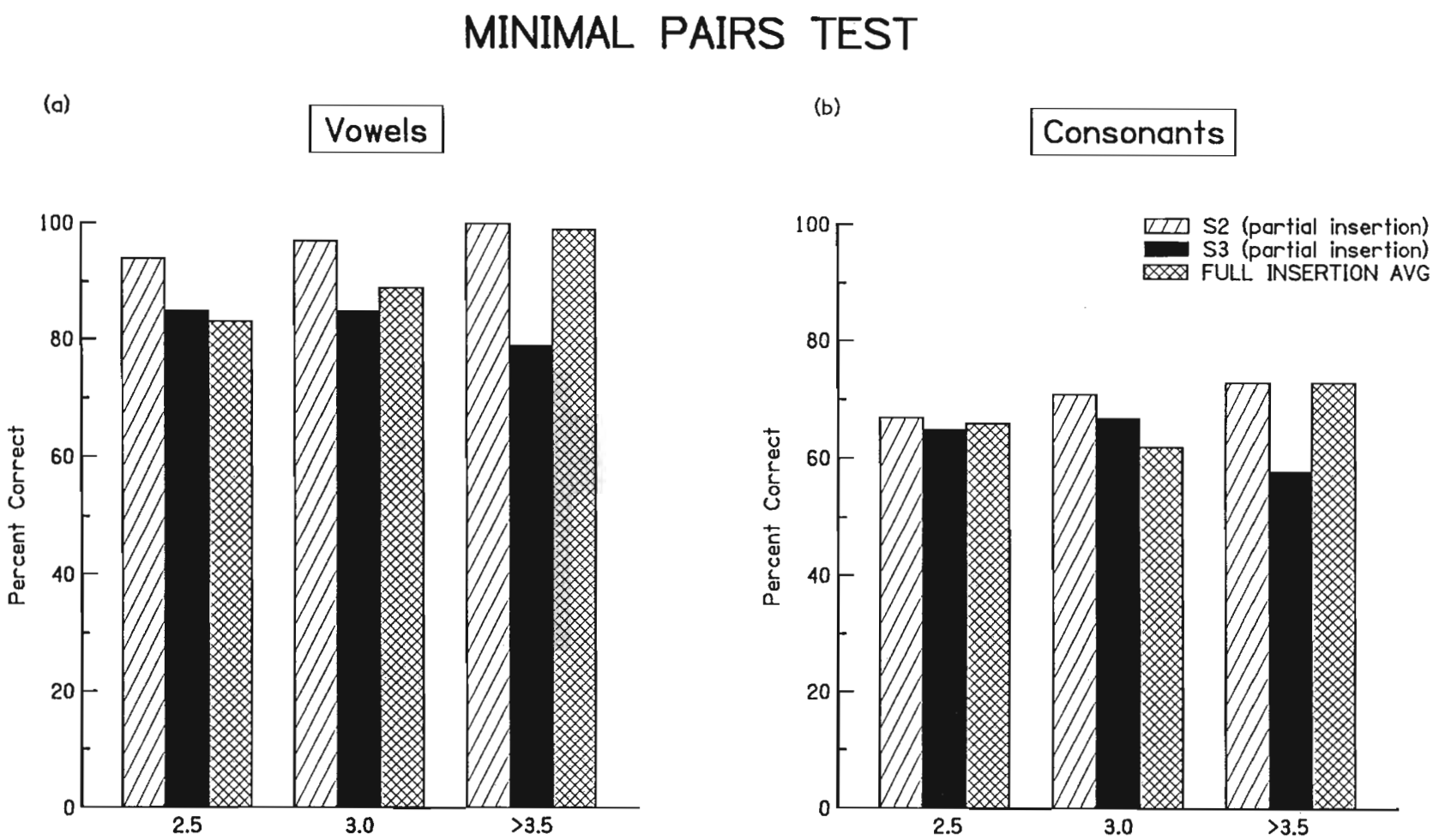


**Figure 8.** Comparison of two long-term follow-up "School Aged" partial-insertion cochlear implant subjects' performance on a closed-set test of word discrimination differing by either a vowel or consonant feature (diagonal & black filled bars), with a cross-sectional group of matched full-insertion controls represented by the hatched bar at the 2.5 (n=13), 3.0 (n=9), and >3.5 (n=7) year intervals.

In Figure 9, the long-term performance of the partial-insertion subjects on the open-set Common Phrases Test is presented. In Figure 9b, it can be seen that S2's performance increased approximately 10%, from the 1.5 year postimplant data for the auditory and visual mode. Subject S3 had already achieved ceiling level scores at the 1.5 year postimplant interval on the auditory and visual mode that little change was noted. It appears from these preliminary data that ceiling level scores on this measure occur at the >3.5 year postimplant interval, yet due to individual variability, these levels may be achieved as early as 18 months postimplant. At the 2.5 and 3.0 years postimplant interval, both the partial-insertion subjects outperformed their full-insertion cohorts. At the >3.5 interval both groups were performing similarly (90-100%).

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Insert Figure 9 about here

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In Figure 9a, the auditory-only format of the Common Phrases is presented for the long-term follow-up. Improvement over time with device use is evident here in comparison to Figure 3. At the 1.5 year postimplant interval, Subject 2 was unable to perform above zero at the pre- and postimplant interval for the auditory-only condition, yet he showed vast improvement over the next two years, with scores of 30-60% correct. Subject 3 did not have data to report at the 2.5 year interval, but in the last interval achieved auditory-only sentence recognition scores of 40%. These results are encouraging because they represent the most difficult testing format for the profoundly deafened patient. Again, although there is some individual variability, both subjects performed at levels consistent with the controls on the auditory-plus-visual mode and at least one of the two subjects (S2) performed similarly to the control subjects on the auditory-only format of sentence recognition.

Overall, the long-term postimplant results remain consistent with the earlier interval data. The partial-insertion group performance is at levels consistent with, or better than, the full-insertion group across both closed- and open-set formats.

## Discussion

The purpose of this study was to compare the performance of subjects with partial electrode insertion, implanted at Indiana University, with age-matched longitudinal controls with full insertion of their electrodes. Our results revealed that the subjects were able to achieve substantial improvements in speech perception performance despite only having partial insertion of their Nucleus multichannel device. The three subjects in the "Baby" battery demonstrated the largest gains on closed-set word recognition tasks (GAEL-P & PSI-W), with 1.5 year postimplant increases ranging from 40-50%. That is, all three partial-insertion subjects tested with the "Baby" battery demonstrated at the postimplant interval improved closed-set discrimination of words based on gross segmental differences. Although improvements were noted for both the auditory-only and auditory-plus-visual presentation modes, they were largest in the latter modality. These results are similar to those for the control subjects. The present findings are encouraging, because they suggest that children with partial electrode insertions integrate the auditory information from their implant with visual cues to aid in speech identification. Furthermore, this approximates/approaches the stimulus conditions faced in natural listening situations.

The most difficult speech perception task for the cochlear implant users is to identify words or sentences when no response alternatives are provided (i.e., open-set). The present results revealed that all three "Baby" battery partial-insertion subjects achieved at least some open-set speech understanding at the

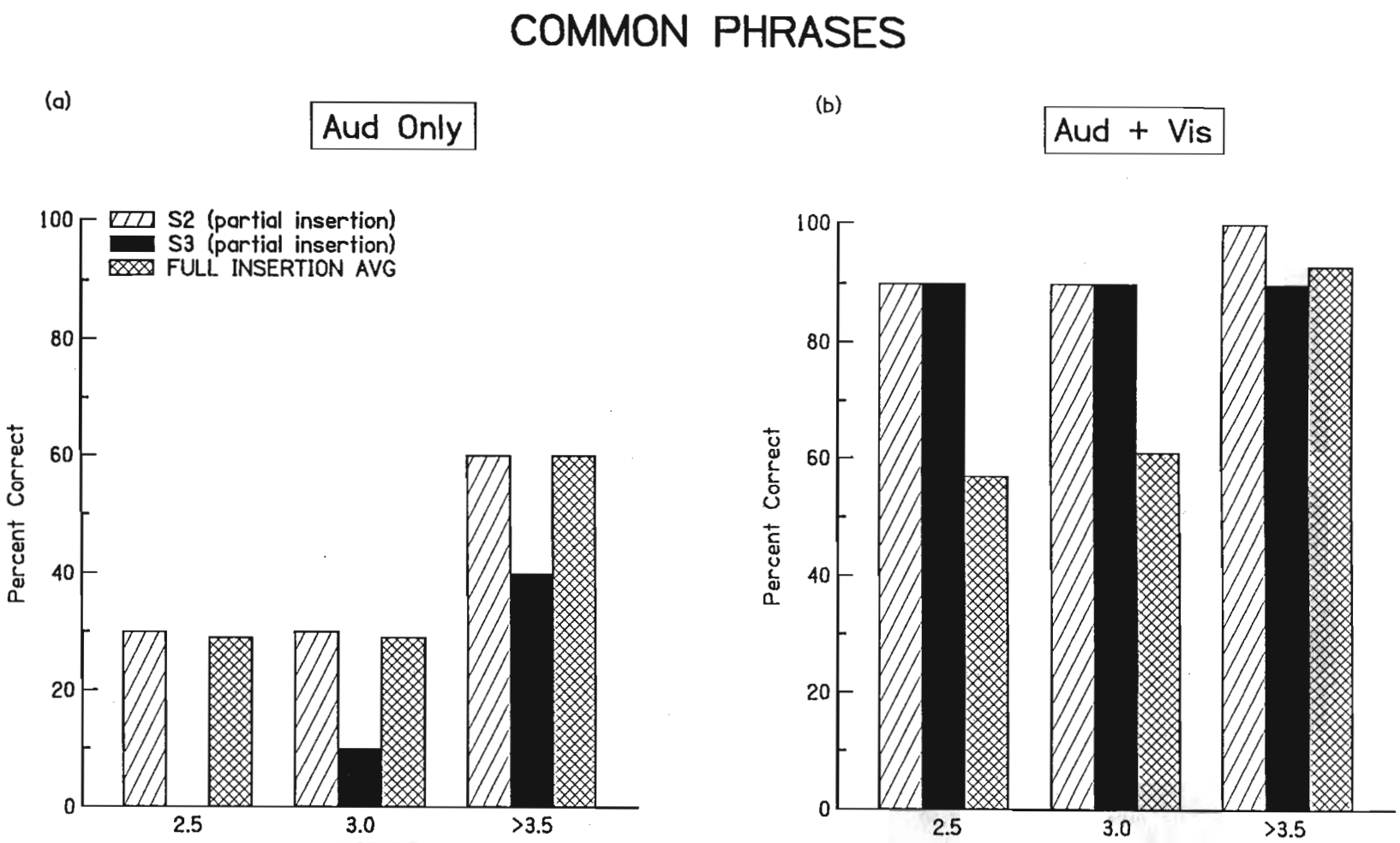


**Figure 9.** Comparison of two long-term follow-up "School Aged" partial-insertion cochlear implant subjects' performance on an open-set measure of recognition of 10 common everyday phrases, (administered in both the auditory-only and combined auditory and visual modality), with a cross-sectional group of matched full-insertion controls as represented by the hatched bar at the 2.5 (n=13), 3.0 (n=9), and >3.5 (n=7) year intervals.

postimplant interval (ranging from 20% for sentence to 45% for key words in sentences). Our preliminary "Baby" battery speech perception results obtained across several modalities and speech perception formats collected during the first 18 months postimplant show negligible speech performance differences between those with a partial insertion of their electrodes and those with full insertion of electrodes and no ossification.

The results for the partial-insertion subjects tested with the "School Age" battery were very similar to those from the "Baby" battery subjects. That is, these partial-insertion subjects were able to achieve substantial gains in speech perception after receiving a cochlear implant. After 1.5 years of cochlear implant use, these subjects were obtaining near-maximum scores on closed-set tests of pattern perception and vowel recognition. Improvements in consonant recognition were smaller and more variable, from very minimal 3-7% (S2 & S3) to 25% (S1) improvement. Improvements for consonant recognition were similar to the average increase of 10% over the same interval seen for the control group. These results are also consistent with previous reports in the literature (Miyamoto et al., 1995). Results for the partial insertion subjects tested with the "School Age" battery also show substantial improvements in open-set speech recognition following 1.5 years of device use. Again, the largest increases (ranging from 30-70%) were seen for stimuli presented in the auditory-plus-visual modality. The "School Age" subjects demonstrated larger improvements in their open-set speech understanding through listening alone at the postimplant interval than did the control subjects, suggesting that the partial insertion of electrodes does not seem to impede the ability to achieve auditory-only, open-set sentence recognition.

Why might a partial-insertion subject outperform the average scores of full-insertion subjects, as was demonstrated in our results? Several recent reports have shown that the mode of communication used by the child affects speech perception performance (Osberger, Miyamoto et al., 1991; Somers, 1991). These investigators suggest that children with cochlear implants who use the oral mode of communication may achieve better speech and language skills than those who use total communication. On the "Baby" battery S4, an oral communicator, achieved performance levels well above both the other partial-insertion subjects and the controls. Yet, of the two remaining partial-insertion subjects who performed similarly to each other, one is an oral communicator and the other is a total communicator. This pattern supports the findings of Osberger, Miyamoto et al. (1991); and Staller et al. (1991), that not all oral children exhibit superior speech perception performance compared to children who use other communication modalities. Still, the mode of communication cannot be ruled out as a contributing factor to the performance levels seen, and may indeed explain some of the better performance data over that of the controls who used primarily the total communication mode.

Speech perception data from the two partial-insertion subjects with more than four years of cochlear implant use revealed similar trends. The results indicated that perception skills of subjects with partial insertion do not regress. Instead, the present data revealed that these subjects' auditory skills continued to progress. At each postimplant interval, the two long-term partial-insertion subjects displayed speech perception skills that were similar to their full-insertion peers. Although more long-term follow-up subjects are needed, these preliminary results add support to the notion of utilizing partial insertion of the electrode array in the ossified cochlea.

In summary, our preliminary results of both early interval (18 months postimplant) and long term (4.5 years postimplant) speech perception performance demonstrated that partial insertion of the Nucleus cochlear implant electrode array does not appear to limit the auditory capabilities of subjects with labyrinthitis ossificans. The speech perception performance of children with partial insertion of their

devices was generally similar to or in some cases even better than the performance of the non-ossified full-insertion control subjects on both closed- and open-set speech perception measures.

Our results are consistent with those reported earlier by Kemink et al. (1992), who also examined the performance of patients with partial electrode insertions. All of our partial-insertion subjects demonstrated improved speech perception results postimplant compared to their preimplant intervals. However, the present findings extended those of Kemink et al., because we were able to examine performance over a longer time course. Although others have reported limited success with partial-insertion subjects (Parisier & Chute, 1993) or diminished performance over time (Steenerson & Gary, 1994), the present results do not support this finding. Taken together, the current results and those of Kemink et al., suggest that partial insertion of at least 8 electrodes provides enough auditory information for children to obtain substantial benefits from their cochlear implants.

Others have advocated an alternative approach to the surgical management of patients with ossified cochleas who are candidates for a cochlear implant (Gantz et al., 1989; Steenerson et al., 1994; Balkany et al., 1988; and Lambert et al., 1991). These authors have all been proponents of implanting the full electrode array in the ossified cochlea. Their reported postimplant speech perception results were comparable to those of the average performance of patients with non-ossified cochleas implanted at their respective institutions. The present results appear to be similar to those of Gantz et al. in that our patients with ossified cochleas perform at levels similar to non-ossified subjects. They differ in that the present subjects had partial insertion of their device, whereas Gantz et al.'s had full insertion. We cannot state definitively that our subjects would not have done better with full insertion of their electrodes. However, the fact that they, like the subjects with ossified cochleas in whom full insertion was achieved, perform similarly to full-insertion cochlear implant subjects is encouraging.

The partial-insertion procedure employed at Indiana University minimizes the inherent risks to the facial nerve and carotid artery that may result from a more extensive drill-out of the cochlea to insert a full array. The present results seem to support the use of a more conservative approach to implanting some children with ossified cochleas. An additional factor should be considered when weighing the advantages or disadvantages of the two surgical approaches. In the current study all partial-insertion subjects had at least 8 electrodes implanted (range 8-13). Kileny et al. (1992) found similar speech perception results were achieved when subjects with full electrode insertion were tested using either the 10 most basal electrodes or the full array. However, it may be that implanting fewer electrodes would yield poorer levels of performance.

In summary, the preliminary data reported in this paper indicates that partial insertion of 8-13 electrodes yields substantial improvements in the speech perception of prelingually deafened children and that these results are maintained over time. Perhaps the extensive procedure described by Gantz et al. (1988) could be reserved for those special cases where ossification is so extensive that insertion of eight or more electrodes is prohibited. We will continue to follow the remaining partial-insertion children to see if their results are similar to these preliminary observations.

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