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Lexical Effects on Spoken Word Recognition by Pediatric Cochlear Implant Users[1]

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Abstract

This study examined lexical effects on word recognition by pediatric multichannel cochlear implant users. Based on computational analyses, word lists were constructed to allow systematic examination of the effects of word frequency, lexical density (i.e. the number of phonemically similar words, or neighbors), and word length. Performance on these new tests was compared with the PB-K test. The percent of words correctly identified was significantly higher for lexically "easy" words (high frequency words with few neighbors) than for "hard" words (low frequency words with many neighbors), but there was no lexical effect on phoneme recognition scores. Word recognition was better for multisyllabic than for monosyllabic stimuli. Word recognition performance was consistently higher on the lexically-controlled lists than on the PB-K, suggesting that the PB-K underestimates these subjects' spoken word recognition. These results demonstrate that pediatric cochlear implant users are sensitive to the acoustic-phonetic similarities among words, that they organize words into similarity neighborhoods in long-term lexical memory, and that they use this structural information in recognizing isolated words. The results also suggest that phoneme scores do not accurately reflect word recognition.

Lexical Effects on Spoken Word Recognition by Pediatric Cochlear Implant Users

The Nucleus multichannel cochlear implant provides substantial auditory information to children with profound hearing impairments who are unable to benefit from conventional amplification. However, children who use the Nucleus cochlear implant greatly vary in their spoken word recognition skills (Staller, Beiter, Brimacombe, Mecklenburg, and Arndt, 1991), depending in part on the age at onset and duration of their hearing loss (Fryauf-Bertschy, Tyler, Kelsay, and Gantz, 1992; Osberger, Todd, Berry, Robbins, and Miyamoto, 1991; Staller, Beiter et al., 1991; Staller, Dowell, Beiter, and Brimacombe, 1991), and on the length of cochlear implant use (Fryauf-Bertschy et al., 1992; Miyamoto et al., 1992; Miyamoto, Osberger, Todd et al., 1993; Osberger, Miyamoto, Zimmerman-Phillips et al., 1991; Waltzman, Cohen, and Shapiro, 1992; Waltzman, Cohen, and Spivak, et. al, 1990). Several different types of tests have been used to assess the perceptual benefits of cochlear implant use in children because of this variability in performance. Closed-set tests, which provide the listener with a limited number of response alternatives, have been used to measure the perception of prosodic cues, vowel and consonant identification, and word identification. According to Tyler (1993), approximately 50% of children with multichannel cochlear implants perform significantly above chance on closed set tests of word identification, and some obtain very high levels of performance (70-100% correct). For this latter group, more difficult open-set tests of spoken word recognition, wherein no response alternatives are provided, are needed to assess their perceptual capabilities.

Historically, spoken word recognition tests were adapted from articulation tests used to evaluate military communications equipment during World War II (Hudgins, Hawkins, Karlin, and Stevens, 1947). Several criteria were considered essential in selecting test items, including familiarity, homogeneity of audibility, and phonetic balancing (i.e. to have phonemes within a word list represented in the same proportion with which they occur in English). Phonetic balancing was included as a criterion because it was assumed that all speech sounds must be included to test hearing (Hudgins et al., 1947), and that phonetic balancing ensured homogeneity across different lists (Hirsh et al., 1952). Subsequent research demonstrated that phonetic balancing was not necessary to achieve equivalent word lists (Carhart, 1965; Hood and Poole, 1980; Tobias, 1964), and that other nonauditory factors, such as subject age or language level, also influence spoken word recognition (Hodgson, 1985; Jerger, 1984; Smith and Hodgson, 1970). Nonetheless, phonetically balanced word recognition tests still enjoy widespread use in both clinical and research settings because their psychometric properties have been well established (Hirsh et al, 1952; Hudgins et al., 1947). These tests also are widely used because recorded versions of the test materials are available, thereby facilitating comparison of results obtained at different test sites. Phonetically balanced word lists have been used to evaluate potential cochlear implant candidates, as well as to measure postimplant performance.

Spoken word recognition is often assessed in children using phonetically balanced materials such as the Phonetically Balanced Kindergarten word lists (PB-K) (Haskins, 1949). Children with multichannel cochlear implants generally perform poorly on these phonetically balanced tests (Fryauf-Bertschy et al., 1992; Miyamoto, Osberger, Robbins, Myres, and Kessler, 1993; Osberger, Miyamoto, et al., 1991; Staller, Beiter et al., 1991). For example, Osberger, Miyamoto, Zimmerman-Phillips et al. (1991) reported that the mean PB-K score for 28 subjects with approximately two years of cochlear implant use was 11% (range 0-36%). Only six of their subjects scored above 0% words correct. Similarly, Staller, Beiter et al. (1991) reported mean PB-K scores of approximately 9% words correct for 80 children who had one year of multichannel cochlear implant experience. It is difficult to distinguish among children with differing spoken word recognition skills with the PB-K test, or to measure changes with increased device experience because the scores of these subjects cluster in a restricted range near 0% correct. Furthermore, there is often a discrepancy between performance on these phonetically balanced word lists and communication abilities in more natural settings. That is, children may obtain very low scores on phonetically balanced word lists, but demonstrate relatively good performance during daily activities.

Implicit in the administration of most spoken word recognition tests is the assumption that the clinician is assessing the underlying perceptual processes employed in spoken word recognition (Lively, Pisoni, and Goldinger, 1991; Pisoni and Luce, 1986). Models of spoken word recognition generally propose an initial stage wherein the speech signal is converted to a phonetic representation, followed by a second stage wherein the phonetic representations are matched to the target words by discriminating among items stored in the mental lexicon (Luce, 1986; Luce, Pisoni, and Goldinger, 1990; Marslen-Wilson, 1987). Poor performance on phonetically balanced speech identification tests may result from difficulties at either stage. If the auditory signal presented via the cochlear implant is too degraded to allow accurate phonetic encoding, word recognition will be limited. The structure and organization of sound patterns in the mental lexicon can also influence word recognition (Pisoni, Nusbaum, Luce, and Slowiaczek, 1985). For example, when test item selection is constrained by phonetic balancing, the resulting lists may contain words that are unfamiliar to children with profound hearing losses, who typically have limited vocabularies (Dale, 1974; Lach, Ling, and Ling, 1970; Quigley & Paul, 1984). Obviously, words that are not within the mental lexicon of a listener cannot be recognized. In addition, lexical characteristics, such as the frequency with which words occur in the language (Andrews, 1989; Elliot, Clifton, and Servi, 1983) and the number of phonetically similar words in the language (Treisman, 1978a; 1978b) can affect the speed and accuracy of spoken word recognition (Luce, 1986; Luce et al., 1990). Phonetically balanced word recognition tests were not designed to assess the influence of these lexical factors on word recognition.

In this paper, we report on the development of two new word recognition tests in which lexical properties of the test items were carefully controlled; test development was motivated by several assumptions embodied in current theories of spoken word recognition discussed below. We also compare pediatric cochlear implant subjects' performance on these new tests with their performance on a phonetically balanced word recognition test.

Theoretical Framework for Test Development

Both word frequency and lexical similarity affect spoken word recognition performance. One measure of lexical similarity is the number of "neighbors," or words that differ by one phoneme from the target word (Greenberg and Jenkins, 1964; Landauer and Streeter, 1973). For example, the words <u>bat</u>, <u>cap</u>, <u>cut</u>, <u>scat</u> and <u>at</u> are all neighbors of the target word <u>cat</u>. Pisoni and his colleagues used phonetic transcriptions from a computer-readable version of Webster's Pocket Dictionary (Pisoni et al., 1985) to conduct a series of computational analyses of the acoustic-phonetic similarity of sound patterns of words. These analyses revealed that words could be organized into "similarity neighborhoods" based on both the frequency of occurrence of words in the language and density of words within the neighborhoods, as measured by one phoneme substitutions. Words with many lexical neighbors come from "dense" neighborhoods, whereas those with few neighbors come from "sparse" neighborhoods.

In a series of behavioral experiments with adult listeners, Luce (1986) and Luce et al. (1990) showed that these computational analyses have behavioral consequences, in that word frequency, neighborhood density, and the average frequency of words in the neighborhood all influence spoken word perception. Figure 1 illustrates the relationship between these three lexical characteristics. "Easy" words (high frequency words from sparse neighborhoods) were recognized faster and with greater accuracy than "hard" words (low frequency words from dense neighborhoods). Similar lexical effects on spoken word recognition have been shown by other investigators (Cluff and Luce, 1990; Luce, 1986; Luce, Pisoni, and Goldinger, 1990). The relationship between neighborhood density and word frequency has been formalized in the Neighborhood Activation Model (NAM) of Luce (1986).

Insert Figure 1 about here.

According to NAM, a stimulus input activates a set of similar acoustic-phonetic patterns in memory. These acoustic-phonetic representations are assumed to be activated in a multi-dimensional acoustic-phonetic space with activation levels proportional to the degree of similarity to the stimulus word. Over the course of processing, the pattern corresponding to the input receives successively higher levels of activation, while the activation levels of similar patterns become attenuated. This initial stage of activation is followed by a process of "lexical selection" among a large number of potential candidates that are consistent with the acoustic-phonetic input. Frequency is assumed to operate as a biasing factor by multiplicatively adjusting the activation levels of the acoustic-phonetic representations. In lexical selection, the activation levels are then summed and the probabilities of choosing each acoustic-phonetic representation are computed based on the overall activation level. Word recognition occurs when a given acoustic-phonetic representation is chosen based on the computed probabilities. Thus, NAM provides a two-stage account of how the structure and organization of the sound patterns of words in memory contributes to the perception of spoken words.

NAM has also provided a useful theoretical framework for examining the lexicons of children with normal hearing. Charles-Luce and Luce (1990) found that children aged 5-7 years had relatively small lexical neighborhoods when compared to those of adults. Children also exhibited more confusions among words, suggesting that their lexical representations are "coarser" and less fine-grained. More recently, Logan (1992) extended this work by applying the neighborhood similarity metric to language samples obtained from children between the ages of 18 months and 5 years. In Logan's analysis, word frequency and density referred, respectively, to the number of times each target word occurred, and to the number of neighbors within the corpus. Logan found that neighborhood density increased significantly until age 2 years, as new words were added to the lexicon, and thereafter remained relatively stable. He also found that neighborhood density in children was positively correlated with word frequency, paralleling the relationship found for these two variables in adults.

Little currently is known about the lexical representations of hearing-impaired children with multichannel cochlear implants. If the structural organization of words in their memory mirrors that of listeners with normal hearing, then word recognition performance should be influenced by word frequency and lexical density in a manner similar to that of normal-hearing children. Evidence of similar lexical organization would suggest that the perceptual processes underlying word recognition are similar in children with cochlear implants and listeners with normal hearing. The goal of this research was to develop several new measures that would allow us to examine the underlying perceptual processes influencing spoken word recognition by children with multichannel cochlear implants. Previous research with this group of subjects has provided descriptive information about their spoken word recognition; our intent was to examine the structural organization and access of words stored in these subjects' long-term lexical memory. If these subjects can encode specific acoustic-phonetic details, they should have narrow phonetic categories, resulting in better recognition of lexically "easy" than "hard" words. Conversely, if they are unable to encode fine phonetic details, the resulting broad phonetic categories should yield similar

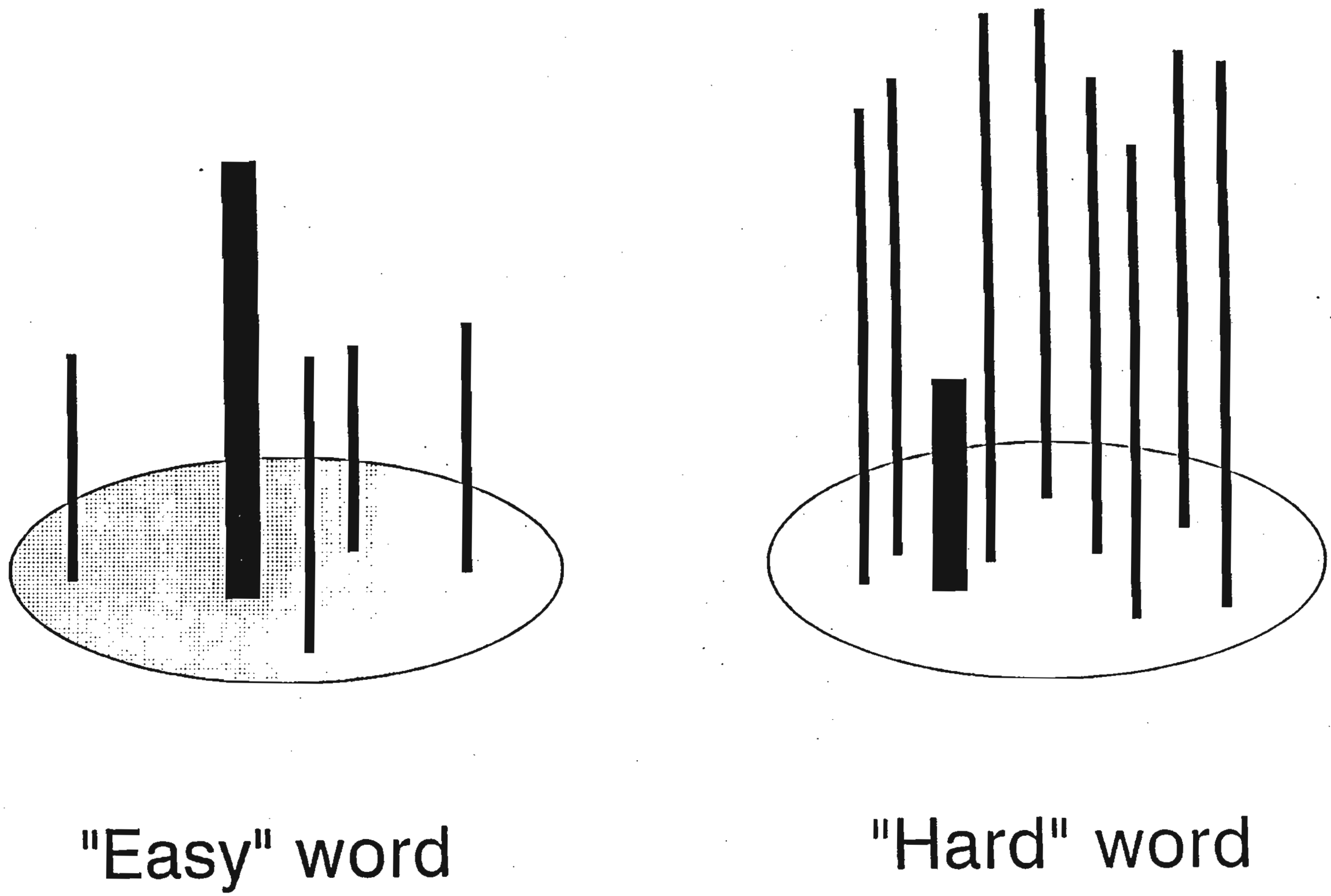

Figure 1. Lexical neighborhood for "easy" words and "hard" words based on computational analyses.

performance for "easy" and "hard" words because both "easy" and "hard" words would have many words with which they could be confused.

The present investigation consisted of three phases. First, new lexically-controlled stimulus materials were developed and computational analyses were used to compare their lexical characteristics with those of the PB-K word lists. Second, we used behavioral measures to compare word recognition of lexically controlled words with phonetically balanced monosyllabic word lists. Third, we examined the effects of word length and lexical characteristics on spoken word recognition. Our goal was to examine whether performance improved for multisyllabic stimuli compared with monosyllables, and to see if lexical characteristics of the stimulus items influences multisyllabic word recognition.

EXPERIMENT I

Method

Speech Materials. The first challenge in developing new perceptual tests was to find vocabulary items that would be appropriate for children with a profound hearing impairment. The vocabulary items needed to be familiar to children with limited lexicons, and yet meet certain lexical criteria. Most of the previous research concerning lexical effects of word recognition has been carried out with adult subjects, and this vocabulary was not suitable for the subjects in the present investigation. Logan's (1992) analyses of samples of child language obtained from the CHILDES (Child Language Data Exchange System) database (MacWhinney and Snow, 1985) is one of the few studies specifically concerned with lexical effects on spoken word recognition by young children. The CHILDES database contains data from published studies carried out by child language researchers (e.g. Brown, 1973), and consists of transcripts of verbal exchanges between a child or children and a caregiver or another child in the environment. Logan analyzed a large number of utterances obtained at regular intervals from several young children (1 to 5 years of age). The children were in the early stages of language development, and therefore it seemed likely that the words in Logan's corpus would be familiar to children with limited vocabularies. Also, based on his computational analyses, the lexical properties of the words were known. Therefore, we selected test items using data from Logan's computational analyses of the CHILDES database.

The subset of Logan's corpus containing words produced by children aged 3 to 5 years was used to generate stimulus items for two new tests. A monosyllabic word test, the Lexical Neighborhood test (LNT), was developed using two "easy" and two "hard" 25-item word lists. Monosyllabic test items for the LNT were selected from Logan's analyses. All multisyllabic words, proper nouns, possessives, contractions, plurals, and inflected forms of words were eliminated from the corpus. Next, the median value of these words was determined for word frequency and neighborhood density. In Logan's analysis, word frequency refers the number of occurrences of a given word within the corpus that he analyzed, and neighborhood density refers to the number of neighbors for a target word that could be found in the corpus by adding, substituting, or deleting one phoneme from the target word (Logan, 1992). The median word frequency was 4 occurrences, with a range from 1-519 occurrences. Neighborhood density ranged from 0-19 neighbors, with a median of four neighbors per target word. "Easy" words were selected from those above the median for word frequency and below the median for neighborhood density, whereas "hard" words had the opposite characteristics. For example, old was classified as an "easy" word (frequency = 38 occurrences, density = 3 neighbors) and bed was classified as a "hard" word (frequency = 2 occurrences, density = 7 neighbors).

To quantify the differences between lexically controlled word lists and the PB-K, it was necessary to obtain lexical statistics (e.g. word frequency and neighborhood density) for the individual PB-K words. Unfortunately, lexical statistics for the PB-K words could not be obtained from Logan's computational analyses of the CHILDES database because less than 24% of the PB-K test items were contained within his corpus. Thus additional computational analyses were required based on a larger corpus, as described below.

Computational analyses. New computational analyses were performed on the four PB-K the two LNT "easy" and the two LNT "hard" lists using lexical statistics obtained from a computerized version of Webster's Pocket Dictionary (see Pisoni et al., 1985). The lexical characteristics of interest were word frequency, neighborhood density, neighborhood frequency, and familiarity. Word frequency counts stored in the Webster's Pocket Dictionary database were obtained from Kucera and Francis (1967), an index to the number of occurrences of the target word per one million words of printed text. The frequency counts from Kucera and Francis (1967) are assumed to reflect the frequency of occurrence of words in the language (i.e. the frequency of occurrence for the adult lexicon). Here neighborhood frequency refers to the number of neighbors for a target that are found within the 20,000 word database by adding, substituting, or deleting one phoneme from the target word. Neighborhood frequency refers to the average word frequency of all the lexical neighbors of a target word. The familiarity ratings contained in this database were obtained from adult listeners with normal hearing (Nusbaum, Pisoni, & Davis, 1984). Familiarity was rated using a scale varying from 1 to 7. A rating of 1 indicates an unfamiliar word, and 7 indicates a highly familiar word.

RESULTS

Table 1 presents a comparison of the average lexical characteristics for the three word lists. The mean familiarity rating was near 7.0 for each list, indicating that all test words were highly familiar to adults with normal hearing. On average, the PB-K words were higher in frequency of occurrence and had higher neighborhood frequencies when compared to the LNT word lists. An analysis of variance (ANOVA) was computed for each lexical characteristic with word list as the independent variable. There was a significant difference in neighborhood density among the three word lists ($F[2,240]=17.33$, $p<.0001$). Post hoc Scheffe tests indicated that the LNT "hard" words had significantly more neighbors than either the LNT "easy" words or the PB-K words ($p<.01$); there was no difference in density between the LNT "easy" words and the PB-K words. For mean neighborhood frequency, the effect of word list was marginally significant ($F[2,240]=2.93$, $p<.055$). The average neighborhood frequency was much higher for the PB-K word lists than for either of the LNT word lists.

Insert Table 1 about here.

DISCUSSION

The results of our computational analyses revealed that there were significant differences in the lexical characteristics of the three word lists. Neighborhood density was significantly greater for the LNT "hard" words than for either of the remaining lists. Neighborhood frequency differed marginally across the three word lists, but there were no significant differences in word frequency. However, the variability in word frequency and neighborhood frequency was much greater for the PB-K than either LNT word list. This is not surprising, as the LNT items were chosen to meet certain lexical criteria. According to NAM,

Table 1.

Mean Lexical Characteristics for the Monosyllabic Word Tests.

	LNT easy		LNT hard		PB-K	
	Mean	(s.d.)	Mean	(s.d.)	Mean	(s.d.)
Familiarity[a]	7.0	(0.2)	7.0	(0.0)	6.9	(0.2)
Word frequency[b]	275.9	(400.6)	144.7	(214.8)	568.2	(1642.9)
Neighborhood density[c]	10.4	(6.0)	18.9	(5.7)	13.7	(7.6)
Neighborhood frequency[d]	97.5	(181.8)	416.0	(823.5)	522.9	(3014.9)

[a]Familiarity was rated from 1-7, with 1 indicating an unfamiliar word, and 7 indicating a highly familiar word (Nusbaum, Pisoni, and Davis, 1984)
[b]Word frequency refers to the number of occurrences per one million words of printed text (Kucera and Francis, 1967).
[c]Neighborhood density refers to the number of lexical neighbors that could be found in the Webster's Pocket Dictionary database by deleting, adding, or substituting one phoneme of the target word (Pisoni et al., 1985).
[d]Neighborhood frequency refers to the average word frequency of a target word's lexical neighbors.

word frequency should act as a biasing factor in favor of recognition. Thus, the extreme variability in word frequency and neighborhood frequency suggests that some PB-K words should be rather difficult to identify, such as those that have many lexical neighbors that are high in word frequency thus competing during the lexical selection process. All three of the word lists contained words that were rated as highly familiar by adult listeners. However, only 24% of the PB-K words were contained within the corpus analyzed by Logan (1992). This finding strongly suggests that many of the PB-K words simply may be unfamiliar to children with limited vocabulary skills, such as children who are very young, or who have a profound hearing impairment. With this structural information we can now turn to the behavioral tests of spoken word recognition.

EXPERIMENT II

The purpose of Experiment II was to determine whether differences in the lexical characteristics of word lists influence spoken word recognition by children with multichannel cochlear implants, and to compare spoken word recognition of lexically controlled and phonetically balanced word lists.

Method

Subjects. The subjects were pediatric Nucleus cochlear implant users who were seen at Indiana University Medical Center as part of their regularly scheduled postimplant appointments. Children were included as subjects if they demonstrated some spoken word recognition, even if only in a closed-set format. Children who did not demonstrate some evidence of word recognition were excluded. This eliminated very young children and some children who had used their device for less than one year, as word recognition usually does not emerge prior to one year of cochlear implant experience. Twenty eight children who were evaluated as part of our research protocol met the criterion for inclusion in the study. Subject information is presented in Table 2.

Insert Table 2 about here.

Table 3 presents processor and programming strategy information for each subject. Two subjects used the WSP speech processor programmed in the F0/F1/F2 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 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) programmed in the MultiPeak (MPEAK) strategy (McKay and McDermott, 1993; Skinner 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 F1, F2 and Bands 3, 4 and 5.

Insert Table 3 about here.

Table 2.

Subject characteristics for Experiment I (N=28).

Subject	Mean (years)	Standard deviation (years)
Age at onset	1.4	2.3
Length of auditory deprivation	5.9	3.0
Age at implant	7.3	2.7
Length of implant use	3.0	1.6
Age at time of testing	10.2	2.4

Table 3.

Processor Information for Subjects in Experiment I (N=28).

Subject	Processor	Strategy	Stimulation Mode	Active Electrodes
SEE	MSP	MPEAK	CG	18
SDV	MSP	MPEAK	BP+1	20
SJZ	MSP	MEAK	BP+2	19
SJN	MSP	MPEAK	BP+1	20
SDR	MSP	MPEAK	BP+1	19
SFV	MSP	MPEAK	BP	15
SJA	MSP	MPEAK	BP+1	18
SJI	MSP	MPEAK	CG	22
SFR	MSP	MPEAK	BP+1	19
SKA	MSP	MPEAK	BP+2	19
SEU	MSP	MPEAK	BP+1	16
SJJ	MSP	MPEAK	BP	18
SEF	MSP	MPEAK	BP	20
SEQ	MSP	MPEAK	BP+1	20
SCA	MSP	MPEAK	CG	17
SJQ	MSP	MPEAK	BP+1	20
SDJ	MSP	MPEAK	BP+1	21
SJH	WSP	F0F1F2	BP+1	20
SEH	MSP	MPEAK	BP+2	17
SGN	MSP	MPEAK	BP+1	19
SFN	MSP	MPEAK	BP+1	20
SJY	MSP	MPEAK	BP+1	21
SJP	MSP	MPEAK	BP+3	13
SAD	MSP	MPEAK	BP	11
SFY	MSP	MPEAK	BP+4	19
SDC	WSP	F0F1F2	CG	18
SJV	MSP	MPEAK	BP+1	20
SGQ	MSP	MPEAK	CG	17

Stimulus Materials and Procedures. The three word lists analyzed in Experiment I were used to assess spoken word recognition. Order of test presentation (LNT "easy" word list, LNT "hard" word list, and PB-K) was counterbalanced across subjects. Half of the items on a PB-K list were administered so that the number of items would be consistent across tests. The tests were administered live voice with the subjects seated facing an examiner approximately 1.5 feet away. The method of stimulus presentation was the same as that used for all live voice tests in our research protocol (Miyamoto, Osberger, Todd, et al. 1993). The examiner held a mesh-covered screen in front of her face so that speech-reading cues were not available to the subjects. A team of five examiners (two audiologists and three speech-language pathologists), who had extensive experience with live-voice testing evaluated the children. The stimuli were articulated clearly and precisely in a manner described by Picheny, Durlach and Braida (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. Subjects responded by repeating the word, which the examiner entered on a response sheet. Subjects who used total communication were asked to sign and say their response. Subjects who used oral communication were asked to spell or write their response if their speech was not intelligible. If the subject was unable to sign or write a response, it was transcribed phonemically by the examiner. Responses were scored as the percent of words and phonemes correctly identified.

RESULTS

Table 4 presents the mean percent of words and phonemes correctly identified on each monosyllabic word list. Nine of the 28 subjects scored less than 20% correct on both the LNT "easy" and the PB-K word lists (range = 0-12% for both tests). These subjects were excluded from further analyses because there was no potential to measure lexical effects in subjects with such limited spoken word recognition.

Insert Table 4 about here.

Figure 2 shows the percent of words and phonemes correctly identified on the three lists for the remaining 19 subjects. Individual differences in word recognition were present. The percent of words correctly identified by the 19 subjects ranged from 20-72% on the LNT "easy" word list, from 12-72% on the LNT "hard" list, and from 4-54% on the PB-K word lists. Fourteen of the subjects showed decrements in performance on the LNT "hard" lists compared to the LNT "easy" lists, ranging from 4-24% words correct. Of the remaining five subjects, four had similar scores on both lists of the LNT (increases on the LNT "hard" list ranged from 0-4%) and one showed an increase of 28%. Those subjects for whom lexical effects were not evident were those with poorer performance on the LNT "easy" condition (e.g. their scores ranged from 20-28% words correct). Individual phoneme recognition scores ranged from 31-82% correct on the LNT "easy", 36-87% on the LNT "hard", and 4-54% on the PB-K word lists. Differences between the "easy" and "hard" word lists were less for phoneme scores than for the word scores. When compared to phoneme recognition on the LNT "easy" list, performance on the LNT "hard" list increased for seven subjects (range 2-21% higher), decreased for 11 subjects (range 3-15% higher) and remained unchanged for one subject. PB-K phoneme scores were lower than those on the LNT "easy" list for all 19 subjects, with decrements in scores ranging from 1-28%. PB-K phoneme scores were lower than LNT "hard" phoneme scores for 16 subjects, with decrements ranging from 2-27%.

One-way repeated measures analyses of variance (RMANOVA) were computed separately for the word and phoneme scores with word list as a dependent variable. Results indicated that word identification

Table 4.

Mean percent correct scores for the three monosyllabic word tests (N=28).

	LNT easy	LNT hard	PB-K
Mean % words correct (standard deviation)	29.6 (22.1)	23.4 (18.9)	13.9 (15.1)
Mean % phonemes correct (standard deviation)	44.8 (24.9)	45.8 (23.4)	36.9 (22.6)

differed significantly across the three lists ($F[2,18] = 31.62$, $p<.0001$). Scheffe post hoc tests indicated that "easy" LNT words were identified most accurately, followed by "hard" LNT words, and then the PB-K words ($p<.01$). A significant effect of word list was also found for the phoneme scores ($F[2,18] = 14.84$, $p<.0001$). Although post hoc analyses revealed that phoneme identification did not differ significantly between the "easy" and "hard" LNT word lists, phoneme recognition was significantly poorer for the PB-K test than for the LNT word lists ($p<.01$).

Insert Figure 2 about here.

DISCUSSION

The results of Experiment II revealed that pediatric cochlear implant users do use lexical knowledge in their word recognition tasks. That is, their spoken word recognition was significantly better on the "easy" word list than on the "hard" word list of the LNT. However, performance on the two LNT word lists did not differ when the tests were scored by the percent of phonemes correctly identified. Thus, it appears that phoneme recognition performance does not predict word recognition abilities. Phoneme recognition scores do not assess the perceptual processes underlying word recognition, such as the way in which the lexical items are organized selected in long-term memory.

Despite their hearing loss and the degraded sensory input provided via the cochlear implant, these subjects did display sensitivity to the acoustic-phonetic similarity among the test words. The results suggest that even though these children have limited vocabularies, they appear to organize words into similarity neighborhoods in long-term memory, and use this structural information in recognizing isolated words. This observation is further supported by the finding that word recognition performance differs between the two levels of the LNT, but that phoneme recognition does not. If words were simply recognized as an isolated sequence of speech sounds, then similar phoneme scores would lead to similar word recognition scores. Instead, the present findings demonstrate that pediatric cochlear implant users recognize words in the context of other words in their lexicons (i.e. similarity neighborhoods) in much the same way as do children with normal hearing (Charles-Luce and Luce, 1990; Logan, 1992).

Word recognition was best on the LNT "easy" words, followed by performance on the LNT "hard" and PB-K lists respectively. The computational analyses carried out earlier provide a principled explanation for these results. According to NAM, word recognition is influenced by the number of phonetically similar words in the lexicon and by word frequency. Neighborhood density was significantly higher for the LNT "hard" words than for the other two lists. That is, there were more phonetically similar words with which the LNT "hard" words could be confused. Of course, this does not explain why the PB-K words were identified less accurately than the LNT "easy" words. It appears that the differences in neighborhood frequency (i.e. the average word frequency of a target word's lexical neighbors) among the three lists might have contributed to poor performance on the PB-K word lists. The average neighborhood frequency for the PB-K words was much higher than for the LNT "easy" words. According to NAM, this indicates that there was more competition for selection from the lexical neighbors of the PB-K target words than from the lexical neighbors of the LNT target words. It has been demonstrated by Goldinger, Luce, and Pisoni (1989) that lexical competition influences spoken word recognition.

A second reason for the improved word recognition performance on the LNT lists might relate to the distribution of speech sounds within each test. The LNT word lists are not phonetically balanced.

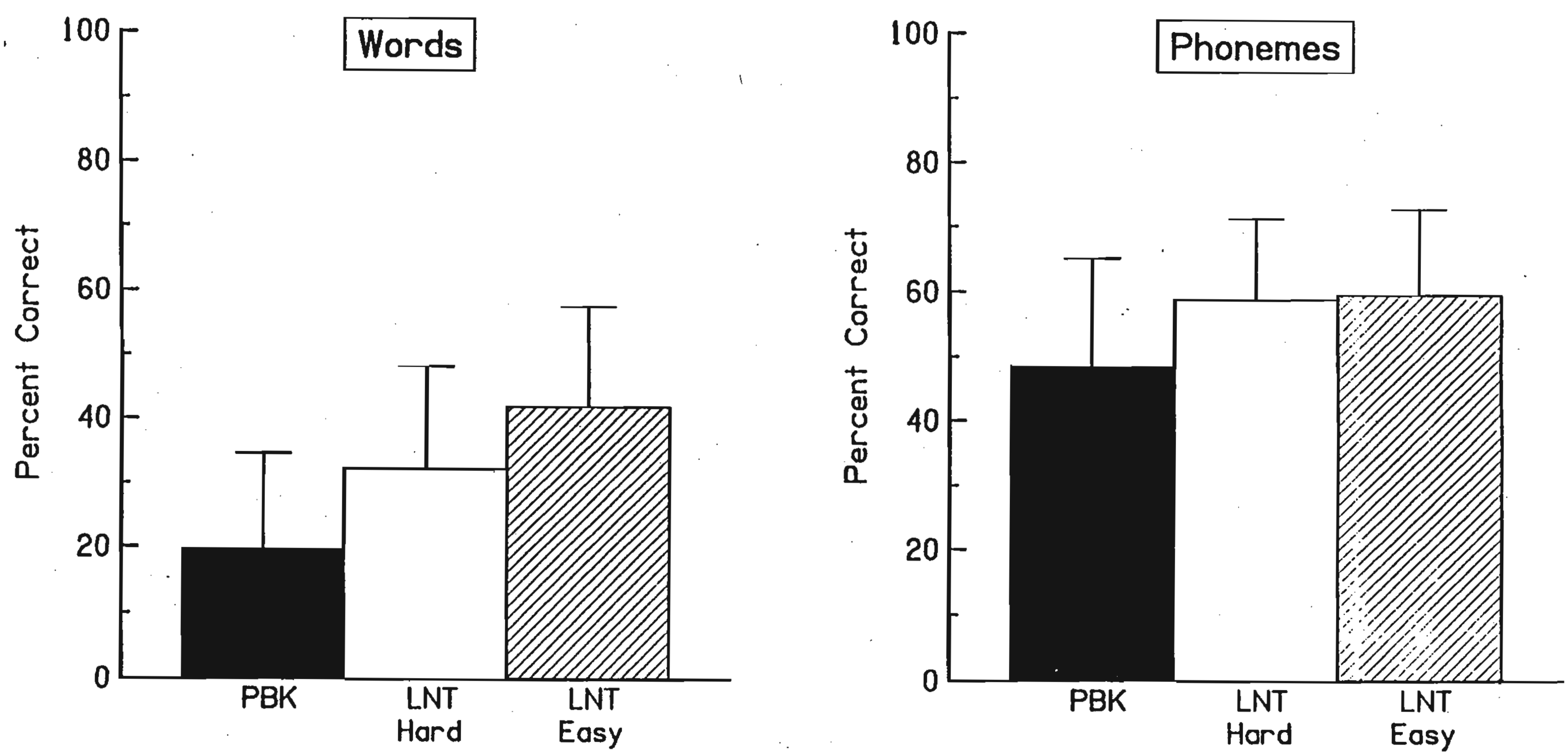

Figure 2. Percent of words and phonemes correctly produced on the three monosyllabic word lists.

Therefore, they may contain more phonemes that are well conveyed via a cochlear implant, such as stop or nasal consonants, than do the PB-K word lists. Table 5 presents the average occurrence of consonants per 25 words by manner and voicing categories. The distribution of phonemes is similar across the three tests, suggesting that the phonemic content of the tests did not account for the observed variation in word recognition in the data.

Insert Table 5 about here.

There is also another reason why performance on the PB-K words was significantly poorer than on the LNT word lists. All test items were classified as highly familiar by adults with normal hearing. However, word familiarity varies with age (Walley, 1993), and therefore the PB-K items may not have been equally familiar to children as to they were to adults. Only 24% of the words on the PB-K were contained within the CHILDES database, suggesting that the PB-K test contains a high proportion of words that are not familiar to young children or to children with profound hearing impairments.

Another important finding was that although word recognition performance was better overall on the LNT word lists than on the PB-K, there were still a number of children who received scores in a restricted range near 0% words correct on all three tests. These children differed from those who achieved scores of at least 20% on the LNT "easy" word lists in that they had a greater period of auditory deprivation prior to receiving a cochlear implant (8.6 years vs. 4.6 years), and they had a shorter period of device use (3.5 years vs. 1.7 years). This pattern of performance is consistent with examinations of word recognition scores in children with cochlear implants (Fryauf-Bertschy et al., 1992; Miyamoto et al., 1992; Miyamoto, Osberger, Todd, et al. 1993; Osberger, Miyamoto, Zimmerman-Phillips, et al., 1991; Waltzman, Cohen, and Shapiro, 1992; Waltzman, Cohen, and Spivak, et. al, 1990). Because of their poor performance on monosyllabic word tests, it was not possible to examine whether the lexical properties of the stimulus items influenced their word recognition performance in any systematic way.

EXPERIMENT III

This study was conducted to determine whether the use of multisyllabic test items would yield higher word recognition scores than monosyllabic stimuli, and to determine whether multisyllabic word recognition is influenced by the lexical properties of the stimulus words. Monosyllabic word are particularly difficult to identify because the redundant linguistic and contextual cues typically present in multisyllabic words and in sentences are unavailable. The use of multisyllabic stimuli in spoken word identification test should yield higher recognition scores, because these items are less easily confused with other words than monosyllabic stimuli. However, lexical characteristics may not influence multisyllabic word recognition because these words have fewer lexical neighbors with which they must compete for recognition. In Experiment III we compare word and phoneme recognition between mono- and multisyllabic word lists, and examine the effects of word frequency and neighborhood density on the recognition of mono- and multisyllabic words.

METHODS

Subjects. The subjects were 19 pediatric Nucleus cochlear implant users who were seen at Indiana University Medical Center as part of their regularly scheduled postimplant appointments. Subject information is presented in Table 6. All of the subjects used the MSP processor programmed in the

Table 5.

Mean Number of Consonant Occurrences per 25 Stimulus Words for the Monosyllabic Word Tests.

	LNT easy	LNT hard	PB-K
Voiced stops	11.0	8.5	9.4
Unvoiced stops	11.5	15.5	13.7
Voiced sibilants	0.0	1.0	2.0
Unvoiced sibilants	5.0	2.5	7.4
Voiced fricatives	1.5	0.0	1.0
Unvoiced fricatives	6.0	4.0	5.0
Voiced affricates	2.0	0.0	0.5
Unvoiced affricates	2.0	0.0	0.8
Nasals	9.5	10.0	5.4
Liquids	10.0	6.5	10.9

MPEAK strategy. The stimulation mode was common ground for two subjects, bipolar for three, bipolar+1 for eight children, and bipolar+2 for one subject. The number of active electrodes programmed into their processor strategy ranged from 15-21 electrodes.

Insert Table 6 about here.

Stimulus Materials and Procedures. The LNT "easy" and "hard" word lists were used to assess monosyllabic word recognition. A new set of words, the Multisyllabic Lexical Neighborhood Test (MLNT), was developed to assess how listeners use information about word length and syllable structure in word identification tasks. The MLNT consists of an "easy" and a "hard" list each containing 15 items varying from two to three syllables in length. Multisyllabic test items were selected from Logan's corpus using similar procedures as in Experiment I, except that monosyllabic words were excluded from the analyses. That is, all words were highly familiar to young children, and were divided into "easy" and "hard" lists by word frequency and neighborhood density. Word frequency for the multisyllabic words within Logan's corpus ranged from 1 to 100 occurrences, with a median value of 2 occurrences. Neighborhood density ranged from 0-7 with a median of 0 neighbors. The MLNT "easy" list contained words that had word frequencies greater than two and neighborhood densities of 0; the MLNT "hard" word list contained words with frequencies less than 2 occurrences and neighborhood densities greater than 0 neighbors.

Order of test presentation and list difficulty were counterbalanced across subjects. All other procedures were the same as those used in Experiment II.

RESULTS

As in Experiment II, data from subject's who did not score at least 20% words correct on the LNT "easy" word lists were excluded from the data analyses. Four subjects were eliminated using this criterion. Figure 3 presents the percent of words and phonemes correctly identified on the "Easy" and "Hard" lists according to syllable structure. On average, multisyllabic word recognition performance was higher than monosyllabic word recognition for both "easy" and "hard" word lists. However, the differences between recognition scores for the multi- and monosyllabic stimulus items were much smaller for phoneme recognition than for word recognition.

Individual word recognition scores varied from 20-72% correct on the LNT "easy" lists, 12-72% correct on the LNT "hard lists, 20-93% on the MLNT "easy" lists, and 13-87% on the MLNT "hard" lists. For the monosyllabic stimuli, 11 subjects had worse performance on the "hard" than the "easy" list, with decrements ranging from 4-28%. For the MLNT the same number of subjects had poorer performance on the "hard" than the "easy" list, with decrements ranging from 6-67%. On the LNT, phoneme recognition varied from 39-82% correct on the "easy" lists and from 39-87% correct on the "hard" list. Eleven subjects had poorer phoneme recognition on the LNT "hard" list than the "easy" list, with decrements ranging from 3-15%. On the MLNT, phoneme recognition scores varied from 38-92% correct on the "easy" list and from 25-97% correct on the "hard" list. Only five subjects had poorer phoneme recognition on the MLNT "hard" list compared with the "easy" list, with decrements ranging from 2-46%. The remaining 9 subjects had better phoneme recognition MLNT "hard" list than the MLNT "easy" list, with increases ranging from 1-12%.

Table 6.

Subject Characteristics for Experiment III (N=19).

	Mean (years)	Standard deviation (years)
Age at onset	1.94	2.58
Length of auditory deprivation	5.63	3.37
Age at implant	7.57	2.94
Length of implant use	3.10	1.56
Age at time of testing	7.57	2.94

A split-plot factorial design was employed contrasting syllable structure (mono- vs. multisyllabic word lists) and score type (word vs. phoneme) with list difficulty ("easy" vs. "hard") as the independent variable. Identification of "easy" and "hard" words did not differ when scores were collapsed across syllable structure and score type. However, performance was significantly better on the multisyllabic lists than on the monosyllabic word lists ($F[1] = 18.21$, $p<.0001$), and word scores were significantly poorer than phoneme scores ($F[1] = 76.03$, $p<.0001$). There was also a significant interaction between score type and list difficulty ($F[3] = 32.97$, $p<.02$). Word scores decreased with increasing list difficulty, whereas phoneme recognition remained relatively stable.

Insert Figure 3 about here.

DISCUSSION

The results of Experiment III demonstrated that pediatric cochlear implant subjects use word length cues to assist them in word recognition. These subjects were significantly better at recognizing multisyllabic than monosyllabic words, probably because multisyllabic words have few neighbors, minimizing competition in lexical selection.

For both the monosyllabic and multisyllabic word lists, word recognition was significantly better on the "easy" than the "hard" lists. This pattern replicates the findings obtained in Experiment II, and also demonstrates that lexical properties influence the recognition of multisyllabic words. It seems likely that word frequency is the important factor contributing to lexical effects of multisyllabic word recognition, as the variability in neighborhood density is small.

On both the LNT and MLNT, word recognition was significantly poorer than phoneme recognition. Furthermore, word recognition decreased with increasing list difficulty, but phoneme recognition did not. These findings support the assertion that phoneme recognition cannot be used to predict word recognition abilities.

GENERAL DISCUSSION

The results of this investigation demonstrate that pediatric cochlear implant users' word recognition performance is influenced by the lexical properties of the stimulus words. That is, words that are high in frequency and low in neighborhood density were identified with greater accuracy than those with the opposite characteristics. Improved word recognition on the lexically "easy" word lists was observed for both monosyllabic and multisyllabic stimulus words. Thus, these subjects appear to organize words into similarity neighborhoods in long-term memory, and use this structural information in word recognition, just as do listeners with normal hearing (Charles-Luce and Luce, 1990; Cluff and Luce, 1990; Luce, 1986; and Luce et al. 1990; Luce, 1986; Luce, Pisoni, and Goldinger, 1990).

In both Experiments II and III lexical effects were observed for word recognition, but not for phoneme recognition. That is, phoneme perception was similar on the "easy" and "hard" lists, whereas word recognition was affected by the properties of the test items. This finding demonstrates that these listeners perceive words in the context of other phonetically similar words in their lexicon, rather than as merely a sequence of unrelated phonemes. Furthermore, the present results demonstrate that phoneme perception cannot be used to predict word recognition performance on tests of this kind.

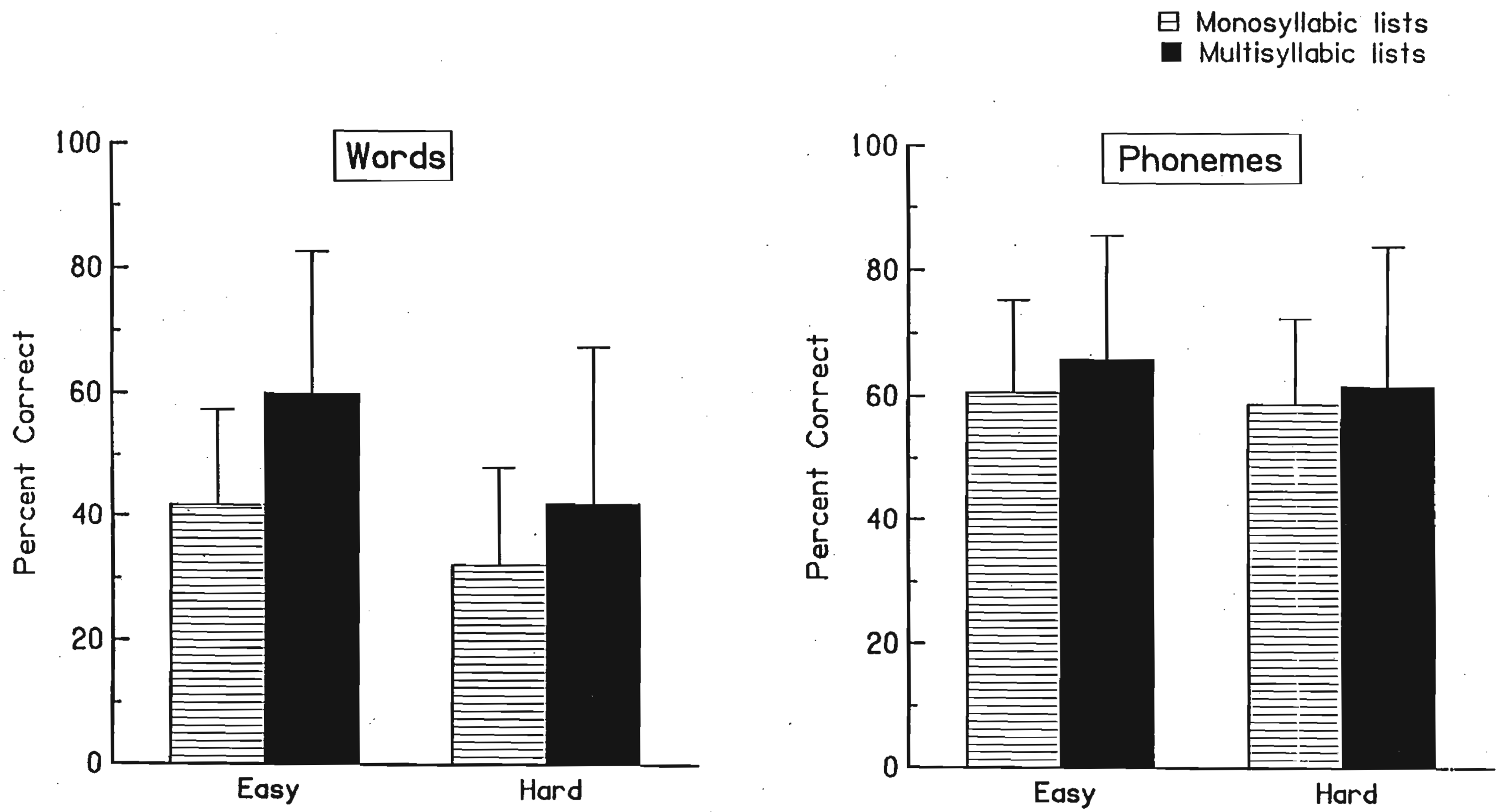

Figure 3. Percent of words and phonemes correctly produced on the monosyllabic and multisyllabic word lists.

Multisyllabic word recognition was significantly better than monosyllabic word recognition suggesting that our subjects used length cues as well as spectral information in recognizing words (Charles-Luce, Luce, and Cluff, 1990; Cluff and Luce, 1990). Again, these findings replicate previous research with listeners with normal hearing (Cluff and Luce, 1990). As a group, the children who performed very poorly on the monosyllabic word recognition tests (i.e., less than 20% words correct on the LNT "easy" lists) were those who had longer periods of auditory deprivation prior to receiving a cochlear implant, and who had used their device for a much shorter period. It may be that word recognition skills will emerge in this population with increased device experience. The present results indicate that multisyllabic tests are useful in assessing the underlying perceptual processes in children with limited auditory perception skills.

The results of Experiment II revealed that some words were particularly easy for the subjects to identify (e.g. the LNT "easy" lists), and some were particularly difficult (e.g. the PB-K words lists). The computational analyses of the stimulus items on these tests carried out in Experiment I provide a principled theoretical basis for accounting for these word recognition differences. In addition, the vocabulary on the PB-K may not be familiar to children with profound hearing losses because only 24% of the PB-K words were found in the CHILDES corpus of young children's productions analyzed by Logan (1992). The vocabulary on phonetically balanced tests may be constrained by this criterion, and thus unfamiliar words may be included.

The observed differences in word recognition performance on these tests can accounted for by NAM, which assumes that <u>both</u> word frequency and lexical density influenced word recognition. The computational analyses revealed that the PB-K lists had intermediate values for lexical density, but that the average neighborhood frequency of these lexical items was high. Thus the poor word recognition displayed on the PB-K may be due to the presence of unfamiliar words and lexical competition from similar sounding words in the lexicon.

The new perceptual tests developed for this investigation appear to be very useful for measuring word recognition in children with multichannel cochlear implants who exhibit varying speech perception abilities. The new tests appear to be more sensitive to changes in word recognition that occur over time because they yield a wider range of scores within and across children. In addition, these tests allow an examination of the perceptual processes underlying spoken word recognition, and they provide a framework for accounting for differences between tests and stimulus words. More importantly, these new tests may be used to gain further knowledge about the organization of sound patterns of words in young children's memory and the processes used to access these patterns in traditional speech identification tests.

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