Relations Among Linguistic and Cognitive Skills and Spoken Word Recognition in Adults With Cochlear Implants

Elizabeth A. Collison*
Benjamin Munson
Arlene Earley Carney
University of Minnesota,
Minneapolis

This study examined spoken word recognition in adults with cochlear implants (CIs) to determine the extent to which linguistic and cognitive abilities predict variability in speech-perception performance. Both a traditional consonant–vowel–consonant (CVC)-repetition measure and a gated-word recognition measure (F. Grosjean, 1996) were used. Stimuli in the gated-word-recognition task varied in neighborhood density. Adults with CIs repeated CVC words less accurately than did age-matched adults with normal hearing sensitivity (NH). In addition, adults with CIs required more acoustic information to recognize gated words than did adults with NH. Neighborhood density had a smaller influence on gated-word recognition by adults with CIs than on recognition by adults with NH. With the exception of 1 outlying participant, standardized, norm-referenced measures of cognitive and linguistic abilities were not correlated with word-recognition measures. Taken together, these results do not support the hypothesis that cognitive and linguistic abilities predict variability in speech-perception performance in a heterogeneous group of adults with CIs. Findings are discussed in light of the potential role of auditory perception in mediating relations among cognitive and linguistic skill and spoken word recognition.

KEY WORDS: cochlear implants, spoken word recognition, vocabulary size, nonverbal IQ, phonological neighborhood density

In the past 2 decades, the benefits of cochlear implants (CIs) for adults and children have been well established (e.g., Dowell, Clark, Seligman, & Brown, 1986; Fryauf-Bertschy, Tyler, Kelsay, Gantz, & Woodworth, 1997; Waltzman et al., 1997). Dramatic increases in open-set word and sentence recognition are typically noted postimplantation. However, researchers have reported large variability in speech-perception skills among recipients of CIs (e.g., Munson, Donaldson, Allen, Collison, & Nelson, 2003). Much research has sought to find factors that account for this variability, both to predict successful implant use and to assist in choosing postimplantation rehabilitation strategies. Studies have found that a large number of demographic and psychoacoustic variables are related to the speech-perception abilities of adults and children with CIs, including duration of deafness, etiology, type of device, length of implant use, frequency discrimination, gap-detection skills,

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*Currently affiliated with the Department of Otolaryngology–Head and Neck Surgery at the Indiana University School of Medicine, Indiana University–Purdue University Indianapolis.

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and place-pitch sensitivity (e.g., Blamey et al., 1992; Donaldson & Nelson, 2000; Miyamoto et al., 1994; Punch, Robbins, Myres, Pope, & Miyamoto, 1987). However, as much as half of the variance in speech-perception scores cannot be explained by these measures, suggesting that other predictors may exist.

Two possible predictors of speech-perception performance, which have received relatively little attention in the research literature, are cognitive and linguistic skills. In this article, we use the term *cognitive skills* broadly to encompass skills such as reasoning, memory, and nonverbal perception. We use the term *linguistic skills* similarly broadly to encompass both long-term linguistic knowledge and real-time language processing.

There are at least two reasons why variability in linguistic and cognitive skills may be predictive of variability in spoken word recognition. First, real-world word recognition requires people to parse a variable acoustic signal into abstract linguistic units like phonemes and syllables. In turn, these linguistic units are used to recognize words, which are used to understand sentences and ongoing discourse. The process of matching a variable acoustic signal to an invariant phonemic or syllabic representation requires individuals to make probabilistic matches between a variable input and relatively invariant representations in long-term memory. Moreover, ongoing word recognition requires individuals to hold acoustic information in working memory while these decisions are being made. It is reasonable to hypothesize, then, that measures of general cognitive ability, which also draw on the skills of memory and decision-making, would be correlated with measures of word recognition. Indeed, strong and robust relations between measures of cognitive skill and measures of other speech and language skills have been found. For example, one influential theory posits that variability in working memory underlies the variability in language-comprehension abilities of normal adults (Just & Carpenter, 1992). Adults with poorer working memory are able to retain less information during language-comprehension tasks and, therefore, experience greater difficulty parsing linguistic structures than do adults with better working memory.

Second, relations between vocabulary size and spoken word recognition may be related to the indirect effect that lexicon size has on phonological detail in lexical representations. Beckman and Edwards (2000) proposed that children's ability to represent phonemes in long-term memory separately from the words in which they occur is related to their vocabulary development. As children learn more words, the degree of phonemic and syllabic detail in these words' representations in long-term memory increases. This increased detail allows children to recognize spoken words more quickly, particularly when they are presented in degraded conditions (i.e., when information is removed or masked; Garlock, Walley, & Metsala, 2001; Metsala, 1997). Beckman and Edwards's proposal is consistent with other research in the development of phonology, spoken word recognition, and phonological awareness, which has converged on the notion that phonological detail in long-term memory is related to vocabulary size (for a review of these studies, see Metsala & Walley, 1998). A recent study by Frisch (2001) extended the idea that variability in vocabulary size can predict variability in phonological processing in adults.

In this report, we further explore the variability in spoken word recognition in adults and evaluate whether this variance is related to variability in linguistic or cognitive skills. Because people with CIs rely on degraded information to recognize words, it is reasonable to hypothesize that those people with larger vocabularies would be more successful than those with smaller vocabularies. Moreover, given that people with CIs must hold information in working memory and make a probabilistic match between a signal and representation in long-term memory, it is reasonable to hypothesize that people with better cognitive skills would be more successful than those with poorer cognitive skills.

Some past research has examined relations between cognitive skill, linguistic skill, and speech-perception abilities by people with CIs. A number of early studies of CI use (e.g., Punch et al., 1987) found that one cognitive measure, IQ, predicted variance in speech-perception measures. More recent studies have used finer-grained measures of cognitive skills. Gantz, Woodworth, Abbas, Knutson, and Tyler (1993) conducted an exploratory study on demographic, audiological, physiological, and psychological predictors of success in 48 adults with CIs. Part of this study examined relations among "a wide variety of attributes, including intelligence, cognitive abilities, and personality attributes" (p. 910) and speech perception in adults with CIs. Gantz et al. found that participants' abilities to use nonverbal communication strategies, as well as their abilities to monitor rapidly changing visual stimuli, predicted postoperative speech-perception outcomes. Other measures, including participation in health care and speech-reading ability, also predicted variance in speech-perception abilities. Gantz et al. hypothesized that the relation between visual monitoring and speech perception drew on participants' abilities to extract sequentially presented information and process it rapidly. In another study, Lyxell et al. (1998) found a small but significant relation between reading-span measures and speech-perception abilities in adults with CIs. In contrast, van Dijk et al. (1999) did not find a significant relation between a different cognitive measure, a psychological self-report measure, and speech-perception ability.

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Considerably more work has been done that examines cognitive and linguistic measures as predictors of speech-perception performance by children with CIs. Blamey et al. (2001) examined the relation between standardized, norm-referenced measures of linguistic abilities and speech-perception skills in 87 children with CIs and/or hearing aids. Analyses indicated that receptive vocabulary measures accounted for a significant proportion of the variance in speech-perception measures. Cleary, Pisoni, and Kirk (2000) found that speech perception by children with CIs was related to measures of memory span. Similarly, Cleary, Dillon, and Pisoni (2002) found that a measure of linguistic skill, nonword repetition, was correlated significantly with both open-set word repetition and closed-set word identification. The relation between linguistic and speech-perception skills in children may be reciprocal: Evidence supporting this reciprocity comes from Sarant, Blamey, Cowan, and Clark (1997), who found that language habilitation improved speech-perception scores in a small sample of children.

Previous research on the relations among linguistic, cognitive, and speech-perception ability has been limited in two ways. First, the majority of this research has been conducted with children, rather than with adults. Children evidence great variability in language skills. Although one might assume greater homogeneity of abilities in adults, there is actually great variability in their linguistic and cognitive skills when fine-grained measures of processing are considered (e.g., Gernsbacher, 1997). This variability may be predictive of variability in spoken word recognition.

A second limitation of previous research is that these studies have examined a limited number of speech-perception measures. For example, van Dijk et al. (1999) and Blamey et al. (2001) both used repetition accuracy for sentences and consonant–vowel–consonant (CVC) words as their sole measures of speech perception. Although these test materials have linguistic content, the task of repeating the stimuli involves minimal linguistic and cognitive processing and may not use the same cognitive and linguistic skills involved in real-world spoken language comprehension. In daily communication, speech perception is used as the “front end” for higher-level language comprehension. Research suggests that the relations between speech perception and language comprehension are both strong and reciprocal; that is, intact speech perception is necessary for language comprehension, and expectations based on linguistic knowledge bias speech perception (e.g., Pitt & McQueen, 1998). Tasks in which the language-processing component of speech perception is reduced or removed may not be related to measures of cognitive and linguistic skills. The latter skills may be predictive of performance only on tasks that actively engage language-comprehension processes. This predictive relationship may not be evident in the normal-hearing adult population’s perception of speech in quiet. Adults with normal hearing (NH) show relatively little variability in speech perception in quiet, as people tend to perform uniformly at ceiling levels. Predictive relations may only be evident in adults with CIs, who show great variability in speech perception.

Gated-word recognition (Grosjean, 1996) is an example of a speech-perception task that engages aspects of higher-level language comprehension. This paradigm requires listeners to identify words that have had acoustic–phonetic information systematically removed. Only a portion of the word is presented initially, with gradually greater amounts of information presented on successive trials. For example, the first gated presentation of a 250-ms word might only include the first 100 ms of information. Subsequent presentations of the word would present gradually more information (i.e., the initial 125 ms of the word, the initial 150 ms of the word, etc.) until the entire word has been presented. In gating tasks, listeners attempt to identify words based only on partial acoustic information. This requires listeners to search their lexicons and to determine the most probable response to an uncertain stimulus. The act of searching the lexicon and formulating a probable response requires listeners to have a large lexicon and intact cognitive skills to search that lexicon. Moreover, the gating task has a level of ecological validity not offered by traditional CVC-repetition tasks—specifically, in many real-word listening tasks, people are required to identify words from which information has been removed through masking by transient environmental noises. Dependent variables in gating tasks are the *isolation point* of a word (i.e., the earliest gate at which the target word is accurately identified) and *confidence ratings* for the listeners’ responses.

The gating paradigm has been used in a number of studies of spoken word recognition in children and adults with NH (Edwards, Fox, & Rogers, 2002; Elliot, Hammer, & Evan, 1987; Garlock et al., 2001; Marslen-Wilson & Warren, 1994; Metsala, 1997; Munson, 2001; Walley, Michela, & Wood, 1995). These studies have found that children and older adults require more acoustic information than adults with NH to identify words accurately. Moreover, two studies found that gated-word recognition is related to vocabulary size: Munson (2001) found that two clinical estimates of vocabulary size, raw scores on the Peabody Picture Vocabulary Test–III (PPVT-III; Dunn & Dunn, 1997) and the Expressive Vocabulary Test (EVT; Williams, 1997), were better predictors of gated-word recognition than was age in a group of 61 children aged 3–7. Subsequently, Edwards, Fox, and Rogers (2002) found that vocabulary size predicted children’s ability to discriminate pairs of

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gated words. In both studies, children with larger-sized vocabularies evidenced better speech-perception abilities than did those with smaller-sized vocabularies.

The present study expands on past research by examining the influence of linguistic and cognitive abilities on speech-perception skills of adults with CIs, using both gated-word recognition and CVC-repetition tasks. We examine this relation in two ways. First, we examined correlations among clinical measures of cognitive and linguistic abilities and measures of spoken word recognition. A finding of strong, consistent relations among these measures would suggest that these skills are related.

Second, we examined the influence of linguistic ability on spoken word recognition by examining the perception of words varying in neighborhood density (Pisoni, Nusbaum, Luce, & Slowiaczek, 1985). Neighborhood density is a measure of how similar a word is to other words in the lexicon and is determined by counting the number of words that can be created by adding, deleting, or substituting a phoneme in any position of a target word. For example, the words *pen, tin, pit, spin,* and *in* are all neighbors of the word *pin*. Neighborhood density has been shown to influence speech perception in adults with NH (e.g., Pisoni et al., 1985; Vitevitch & Luce, 1999), gated-word recognition in children (Garlock et al., 2001; Metsala, 1997), CVC-repetition accuracy in children and adults with CIs and adults with sensorineural hearing loss (Kirk, 1999; Kirk, Pisoni, & Miyamoto, 1997; Kirk, Pisoni, & Osberger, 1995), and nonword repetitions in adults with CIs (Vitevitch, Pisoni, Kirk, Hay-McCutcheon, & Yount, 2002). The fact that neighborhood density affects spoken word recognition in children and adults with hearing loss suggests that there is a link between linguistic knowledge and speech perception in this population. A finding that neighborhood density also influences speech-perception abilities in adults would provide additional support for the hypothesis that linguistic skills influence speech-perception skills in that population.

The objectives of this study were threefold. First, we wanted to measure the ranges of performance of adults with CIs on three standardized clinical tests of cognitive processing, vocabulary size, and vocabulary knowledge. Our purpose was to establish whether adults with CIs show approximately the same ranges of variation in linguistic and cognitive skills as those ranges found in the normal-hearing adult population. Second, we examined the influence of neighborhood density on gated-word recognition in adults with CIs and age-matched adults with NH. As in previous research, we reasoned that the effect of neighborhood density on speech perception is evidence for a relation between speech-perception ability and lexical knowledge. Accordingly, group differences in the application of linguistic skills in speech-perception performance should emerge as a Group × Difficulty interaction, with the listeners with CIs showing a larger influence of neighborhood density on performance than the listeners with NH. Finally, we examined whether measures of cognitive and linguistic abilities were related to measures of spoken word recognition. Specifically, our aim was to determine whether predictive power exists among these measures in adults with CIs as it does in children. We were particularly interested in establishing relations among cognitive and linguistic measures and the more complex gated-word recognition measure, and whether those relations were stronger than those with the less complex CVC-repetition measure.

Method

Participants

Listeners With CIs

Fifteen postlingually deafened adults (7 men and 8 women) participated in the experiment. These listeners were recruited from a larger cohort of people who had received CIs in the Department of Otolaryngology at the University of Minnesota. All participants were taking part in a larger study on histological, physiological, psychophysical, and perceptual aspects of electrical hearing. The participant identification codes used throughout the present experiment are taken from the codes in the larger study so that they may be compared with other published studies of this cohort (e.g., Munson et al., 2003). The only criterion that was used to select listeners for this study from among the larger cohort was that their speech be sufficiently intelligible for the audiologist to provide a reliable response for scoring open-set speech-perception tests.

The participants ranged in age from 34 to 68 years, with a mean age of 55 years (*SD* = 9.1). The duration of severe-to-profound sensorineural hearing loss among the CI users ranged from 0 to 35 years, with a mean of 11.7 years (*SD* = 2.2). All participants were native speakers of American English. The range of CI experience was from 9 months to 12 years (*M* = 5.7, *SD* = 3.6). Six participants used the Nucleus 22 (N22) device, 2 participants used the Nucleus 24 (N24) device, 6 participants used the Clarion device, and 1 participant used the Clarion II (C II) device. All of the listeners with N22 devices used the spectral peak (SPEAK) processing strategy. One of the N24 users used the SPEAK strategy, and the other used the advanced combination encoder (ACE) strategy. Of the 7 participants with Clarion devices, 3 used the continuous interleaved sampling (CIS) strategy and 4 used the paired pulsatile stimulation (PPS) strategy. One participant, P04, was bilaterally implanted, with an N22 on the right ear and an N24 on

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the left ear. To maintain consistency across participants, this participant used only her N24 CI during testing. A second participant, C16, was originally implanted with a Clarion CI. She was later explanted and then re-implanted with a second Clarion device.

Table 1 provides individual participant demographics for age at testing, sex, etiology of deafness, duration of profound deafness, duration of implant use, and type of cochlear implant device and strategy. Demographic information on duration of deafness and length of CI experience for participants P04 and C16 refers to when they were first implanted. Participants were paid on an hourly basis for their involvement in the experiment.

Listeners With NH

Fifteen adults with NH participated in the experiments. These adults did not have an identified hearing loss and had passed an air-conduction hearing screening at 0.5, 1, 2, and 4 kHz bilaterally. There were 3 men and 12 women in this group. The average age for listeners with NH was 54 years (*SD* = 8.4 years). The adults with NH did not complete the cognitive and linguistic measures; however, we wanted to minimize the chance that the group differences in spoken-word-recognition measures were attributable to group differences in cognitive or linguistic skills. Therefore, we matched the listeners with NH to the listeners with CIs on the highest level of education attained, which we expected would be correlated with cognitive and linguistic skills. Both groups included 4 participants who had completed high school, 2 who had completed a 2-year college degree, 7 who had completed a 4-year university degree, and 1 who had completed a graduate degree. Participants with NH were paid for their participation.

Standardized Tests

Participants with CIs were given three standardized tests to assess language and cognitive abilities: the EVT, the Test of Nonverbal Intelligence–3 (TONI-3; Brown, Sherbenou, & Johnsen, 1997), and the Woodcock-Johnson III Tests of Cognitive Abilities: Verbal Comprehension section (WJ-III VCS; Woodcock, McGrew, & Mather, 2001). The EVT assesses expressive vocabulary and provides normative data for children and adults aged 2.5 to 90 years. In this test, the participant is provided with a picture and a name for the picture and is asked to provide a synonym for the same picture.

The WJ-III is a test of higher-level cognitive–linguistic ability for individuals ranging in age from 2 to 90 years. In the present study, only the Verbal Comprehension section was administered. The Verbal Comprehension section is made up of four subtests: Picture Vocabulary, Synonyms, Antonyms, and Verbal Analogies, with the combined score reflecting high-level verbal knowledge and processing.

The TONI-3 measures nonlinguistic cognitive abilities. Normative scores are provided for 5- through 86-year-old people. The TONI-3 does not use listening, speaking, reading, or writing by either the examiner or

Table 1. Demographic information for the participants with cochlear implants.

Participant	Age at testing (years; months)	Sex	Etiology	Years of profound deafness	Duration of implant use (years;months)	Device	Strategy
N28	63;0	M	Meningitis	0	5;11	N22	SPEAK
C05	46;11	M	Unknown	0	3;11	Clarion	CIS
N12	52;11	M	Progressive	8	10;11	N22	SPEAK
N32	34;10	M	Rubella	24	4;11	N22	SPEAK
P04	63;4	F	Otosclerosis	8	4;11	N24	SPEAK
N13	64;5	M	Progressive	2	11;11	N22	SPEAK
N14	58;2	M	Progressive	0	8;7	N22	SPEAK
C16	48;11	F	Progressive	13	5;11	Clarion	PPS
C03	53;6	F	Progressive	27	4;5	Clarion	PPS
C20	60;3	M	Progressive	31	1;11	Clarion	CIS
C07	62;2	F	Progressive	35	3;5	Clarion	CIS
D02	52;6	F	Unknown	1	0;9	C II	PPS
N34	56;7	F	Mumps	16	12;0	N22	SPEAK
P07	68;7	F	Unknown	3	3;2	N24	ACE
C15	43;0	F	Unknown	7	2;5	Clarion	PPS

Note. N22 = Nucleus 22; N24 = Nucleus 24; C II = Clarion II; SPEAK = spectral peak; CIS = continuous interleaved sampling; PPS = paired pulsatile stimulation; ACE = advanced combination encoder.

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the examinee. The examiner pantomimes all directions, and the participant responds by pointing to pictures. Thus, this test examines purely nonverbal cognitive skill, in contrast to the language-based EVT and WJ-III VCS. In the TONI-3, participants identify relations among abstract figures and solve problems following manipulation of these figures. A sample item might examine a matching task in which the participant is shown a picture of three identical black and white line drawings (e.g., three squares) and then is prompted to point to the matching shape among a set of either four or six choices.

Stimuli

Two sets of word-recognition stimuli were used in this study: isophonemic CVC words from Boothroyd (1968) and gated CVC words. Eight lists of 10 words were used to measure CVC-word-repetition accuracy. Each list contained the same 10 vowels and 20 consonants in different combinations. The 30 phonemes used in each list were chosen because they occur commonly in CVC words.

Twenty monosyllabic CVC words from the Hoosier Mental Lexicon (Pisoni et al., 1985) were used as stimuli in the gating task. Ten low-neighborhood-density words (i.e., less than three neighbors) and 10 high-neighborhood-density words (i.e., more than three neighbors) were used. We controlled for phonetic content by balancing the place, manner, and voicing of the consonants in our CVC stimuli.

An adult male speaker of American English was recorded producing each of the stimulus words three times. The speaker used a head-mounted Micro-mic (AKG model C420; AKG Acoustics, Vienna, Austria) placed approximately 7 cm from the lips. The stimuli were recorded in a double-walled sound booth on a digital studio workstation (Roland, model VS890; Roland Corp., Los Angeles, CA). They were sampled at 44.1 kHz, and low-pass filtered at 22.05 kHz, using 16-bit quantization. Stimuli were normalized for overall root-mean-square (RMS) amplitude, and token durations were measured using Cool Edit Pro software (version 1.2; Syntrillium, 1996). The average durations for isophonemic words and gated words were 625.7 ms (SD = 87.2) and 596.65 ms (SD = 77.4), respectively. The tokens that were closest to the mean duration for the three lists were selected for use in the experiment to minimize token-to-token variability in duration.

The duration of the shortest gated stimulus for each word was 100 ms. This condition was designated as stimulus 0. In subsequent presentations, acoustic information was added in 50-ms increments. That is, each gate was 50 ms longer than the previous gate. The exception to this stimulus scheme was the difference between the second-to-last gated stimulus and the entire word; this difference depended on the duration of the whole word. The number of gates per stimulus ranged from 8 to 13. A one-factor ANOVA revealed that the number of gates did not differ as a function of neighborhood density, $F(1, 18) < 1, p > .05$.

Procedure

Participants were tested individually in a double-walled sound-treated booth. Stimuli were presented at 60 dB SPL in sound field through two speakers (Audix model PH5, Wilsonville, OR) attached to a personal computer. This presentation level was chosen because Skinner, Holden, Holden, Demorest, and Fourakis (1997) have suggested that 60 dB SPL simulates everyday listening levels. Before each session, sound pressure level was calibrated using a portable sound-level meter for a concatenated file containing a representative sample of stimuli. Participants set the sensitivity level of their cochlear implant at the default setting and then adjusted the volume of their implants to a comfortable level. Sequence of the five tasks (EVT, TONI-3, WJS-III, CVC-word repetition, and gated-word recognition) was randomized across participants.

In the gating task, participants were told that they would hear a list of one-syllable words from which acoustic information had been removed. Participants were told to guess what they heard and to provide a confidence rating for their guess on a seven-point scale. On the response scale, 1 represented “not at all sure,” 4 represented “somewhat sure,” and 7 represented “completely sure.” Gated stimuli were presented in a duration-blocked format, in which participants heard all of the tokens at the shortest duration (i.e., 100 ms), then all of the tokens in the next duration category (i.e., 150 ms), and so on, until the complete word had been presented. The duration-blocked format was employed rather than the successive format (i.e., presenting all segments of each stimulus sequentially) because of the finding that participants tend to perseverate on incorrect responses in successive gating tasks (Walley et al., 1995). Stimuli were randomized within blocks. Two monosyllabic words were used as practice stimuli.

In the isophonemic CVC-repetition task, participants were told that they would be hearing one-syllable words and they were to repeat what they heard. Participants were encouraged to guess, even if they were not sure about their answer. Two lists of 10 words each were used as practice lists. The experimental items consisted of eight lists of 10 words. List order was randomized across participants.

For both word-recognition tasks, an experimenter (the first author) listened to each participant’s responses

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outside of the booth and recorded the responses. Participants also were tape recorded during the session, and a second coder (the second author) listened to 10 responses from each of the participants to assess reliability. Interrater reliability on the accuracy of these responses was 98.3%. For the five responses on which there was disagreement, the first coder's response was used. The high rate of interrater reliability confirmed that the participants were highly intelligible. If a participant did not respond after approximately 15 s, then a null identification and a confidence rating of 1 were recorded. Participants needed approximately 45 min to an hour to complete the gating task, 10 min to complete the isophonemic word lists, and 1 hour to complete the standardized test battery. All components of the experiment were administered during one testing session, lasting approximately 2 to 2.5 hours.

Results

Standardized Test Scores

Individual standard scores for the three standardized tests are shown in Table 2. Scores are rank ordered from lowest to highest for the EVT, and then kept in the same order for the TONI-3 and the WJ-III VCS standard scores. Each measure resulted in a wide range of scores. The range for the EVT was 77 to 135 ($M = 106.73$, $SD = 18.69$). TONI-3 scores ranged from 83 to 138 ($M = 102.2$, $SD = 15.24$). The range for the WJ-III VCS was 87 to 127 ($M = 107.47$, $SD = 12.51$). The means and standard deviations for these three tests are very similar to the mean ($M = 100$) and standard deviation ($SD = 15$) of the normative sample. Three individual Kolmogorov–Smirnov tests indicated that the distribution of scores on these three tests did not differ significantly from a normal distribution ($z = .56$, $p > .05$ for the EVT; $z = .52$, $p > .05$ for the WJ-III VCS; $z = .73$, $p > .05$ for the TONI-3). The wide ranges of scores on these measures, as well as their normal distributions, suggest that the sample of adults with CIs in this study did not differ significantly from the population of adults with NH who formed the normative sample of the standardized tests.

Table 2. Individual standard scores on the Expressive Vocabulary Test (EVT), Test of Nonverbal Intelligence–3 (TONI-3), and Woodcock-Johnson III Tests of Cognitive Abilities: Verbal Comprehension section (WJ-III VCS) for the participants with cochlear implants.

Participant	EVT	TONI-3	WJ-III VCS
N32	77	90	87
D02	80	83	98
C05	91	85	95
P04	91	88	95
N28	92	89	96
N13	100	107	106
C15	101	102	100
C07	105	90	108
C20	106	113	113
P07	119	112	103
C16	122	106	121
N34	122	138	124
C03	129	110	121
N14	131	120	127
N12	135	100	118

Gating Task

Isolation Points

We measured the isolation points in the gating task as the earliest gate at which a participant correctly identified a stimulus item without changing his or her response at a later gate. When participants failed to correctly identify a word even in the whole-word condition, the isolation point was recorded as one greater than the number of gates for that word. That is, a participant who failed to correctly recognize the word *man*, which has 13 gates, would be scored as having an isolation point of 14 for that word. For each participant, mean isolation points were calculated separately for high- and low-density words. As in previous research using the gating paradigm (e.g., Walley et al., 1995), these mean isolation points served as the dependent measures in a two-factor mixed-model ANOVA, with neighborhood density (low vs. high) as the within-subjects factor and group (CI vs. NH) as the between-subjects factor. Significant main effects were found for neighborhood density, $F(1, 28) = 17.3$, $p < .001$, partial $\eta^2 = .57$; and group, $F(1, 28) = 199$, $p < .001$, partial $\eta^2 = .88$. Listeners required more acoustic information to identify high-density words than low-density words; and listeners with CIs required more acoustic information to identify words than listeners with NH. In addition, there was a Neighborhood Density × Group interaction, $F(1, 28) = 5.2$, $p < .01$, partial $\eta^2 = .28$. This interaction, which is shown in Figure 1, indicates that the effect of neighborhood density was larger for the listeners with NH than for the listeners with CIs. Post hoc tests of significant main effects revealed that the effect of neighborhood density was significant for both groups. No other interactions were significant.

The data for the two groups were completely separated, but individual performance varied. In general, a larger range of performance was noted among the listeners with CIs than among the listeners with NH. Performance on the easy words varied from 5.7 to 10.8 for the listeners with CIs and from 2.5 to 5.3 for the listeners with NH. Performance for the hard words varied from 7.5 to 10.8 for the listeners with CIs and from 4.5 to 6.8 for the listeners with NH.

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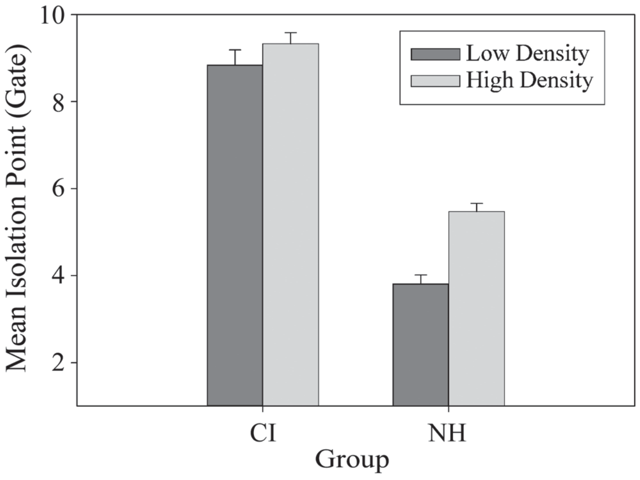
Figure 1. Mean isolation points for low- and high-density words for listeners with cochlear implants (CI) and listeners with normal hearing sensitivity (NH). Error bars represent one *SEM*.



The identification results for both groups are shown in Table 3, in terms of the average gate at which a word was recognized and for the average length of the stimulus at which correct identification occurred. The listeners with NH required considerably less acoustic information to identify both low- and high-density words than did the listeners with CIs (i.e., 240.7 and 323.7 ms versus 541.0 and 562.8 ms, respectively).

Confidence Ratings

Confidence ratings for individual target words were calculated by taking the average confidence ratings across gates. For each participant, mean confidence ratings were calculated separately for high- and low-density words. A significant main effect was found for group, $F(1, 28) = 13.8$, $p = .001$, partial $\eta^2 = .33$. The listeners with CIs were less confident of their responses in the gating task than were the listeners with NH ($M = 3.33$, $SD = 1.04$, for the listeners with CIs; $M = 4.68$, $SD = 0.94$, for the listeners with NH). No significant effect of neighborhood density was found. Again, variability across participants was higher for the listeners with CIs than for the listeners with NH. Confidence ratings for the easy words ranged from 1.6 to 4.9 for the listeners with CIs and from 3.1 to 6.5 for the listeners with NH. Ratings for the hard words ranged from 1.5 to 4.9 for the listeners with CIs and from 3.1 to 6.5 for the listeners with NH.

Table 3. Confidence ratings and mean isolation points for listeners with cochlear implants (CIs) and normal hearing sensitivity (NH). The isolation points are expressed both as gate and as absolute duration in ms.

Measure	Low-density words *M*	Low-density words *SD*	High-density words *M*	High-density words *SD*
CI group				
Isolation point (ms)	541.0	67.0	562.8	48.0
Isolation point (gate)	8.8	1.3	9.3	1.0
Confidence rating	3.4	1.1	3.3	1.0
NH group				
Isolation point (ms)	240.7	39.0	323.7	36.0
Isolation point (gate)	3.8	0.8	5.5	0.7
Confidence rating	4.7	0.9	4.6	1.0

CVC-Word Repetition

Performance on the CVC-word-repetition task was measured in two ways: percentage words correct (PWC) and percentage phonemes correct (PPC). The PWC score equaled the total number of correct whole-word repetitions divided by the total number of words and multiplied by 100; the PPC score equaled the total number of phonemes correctly repeated divided by the total number of phonemes (240) and multiplied by 100. A phoneme was only scored as correct if the participant identified it in the correct position within a word. For example, for the target word *ball*, participants received credit for /b/ if they said *back*, but not if they said *cab*.

The mean PWC score for listeners with CIs was 44% correct ($SD = 15$), and the mean PPC score was 66% correct ($SD = 23$). The mean PWC score for the listeners with NH was 95% ($SD = 3$), and the mean PPC score was 98% ($SD = 1$). These differences were highly significant, $F(1, 28) = 77$, $p < .001$, partial $\eta^2 = .73$ for PWC; $F(1, 28) = 46$, $p < .001$, partial $\eta^2 = .621$ for PPC. A very restricted range of performance was measured for the listeners with NH; their PWC scores ranged from 91% to 99%, and the PPC scores ranged from 96% to 100%. A much larger range of performance was measured for the listeners with CIs; the PWC scores ranged from 5% to 75%, and the PPC scores ranged from 33% to 88%.

Correlations Between Standard Scores and Word Recognition

Raw Scores

To examine the relations among cognitive and linguistic skills and word recognition, Pearson product–moment correlations were calculated for the three standardized tests (EVT, WJ-III VCS, and TONI-3) and four word-recognition measures (PPC and PWC for CVC-word repetition, and mean isolation point in the two conditions of the gating task). A significant positive

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correlation was found between EVT standard score and isolation points for the low-density gated words ($r = .51$, $p = .05$). This positive correlation was contrary to predictions and suggested that participants with higher standard scores had larger isolation points in this condition (i.e., they needed more acoustic–phonetic information to identify the word). Visual inspection of the data revealed that this result was due to the performance of 1 participant, N34. She had high standard language and nonverbal cognition scores but performed poorly on all spoken-word-recognition measures. This participant was not a consistent CI user postimplantation, which may explain her poor speech-perception performance. All of the other users reported using their devices consistently. When participant N34's data were removed from the analysis, no significant correlations among the measures were found. (The analyses of variance on isolation points and confidence intervals were later recalculated with this participant's data removed. Although small changes in the effect sizes were noted, no change in the overall pattern of significant main effects and interactions was noted.)

CVC-Normalized Scores

The 15 participants in this experiment varied in their isophonemic (CVC) open-set word-recognition accuracy, with scores ranging from 5% to 75%. The first set of correlation analyses did not control for this variability across individuals in their whole-word repetition accuracy. Some of the variability in the isolation points might have been attributable to overall differences in word-recognition accuracy across listeners. Indeed, Pearson product–moment correlations for the listeners with CIs indicated strong, significant ($p < .05$) negative correlations among a number of the gated-word-recognition scores and the CVC-repetition scores. These negative correlations suggest that participants who had good open-set word-recognition scores required less acoustic information to identify words accurately in the gating task. In the second set of correlation analyses, we controlled for the influence of CVC-word recognition on gated-word recognition by normalizing the isolation point scores relative to the participants' isophonemic word-recognition accuracy. This normalization was achieved by completing a series of regression analyses predicting participants' performance on the gating task from their isophonemic word-recognition accuracy. For those regressions in which a predictive relation was found, we used the standardized residual scores as normalized measures of gated-word recognition. These measures represented the extent to which performance on the gating task was under- or overpredicted by performance on the open-set isophonemic word-recognition task.

Two regression analyses were completed, with the isolation points for the high- and low-density gated words as the dependent variables and the isophonemic word-correct scores as the independent variable. A significant relation was found between the CVC-word-correct scores and the isolation points for the low-density words, but no significant relation was obtained between the high-density isolation points and the isophonemic word-correct scores. A positive standardized residual indicated that a participant had a larger isolation point than what would be expected by their isophonemic score. A negative standardized residual indicated that a participant had a smaller isolation point than what would be expected by their isophonemic score.

Table 4 shows the correlation coefficients for the standardized language and cognitive measures and these standardized residuals. No strong and consistent relations between the cognitive and linguistic measures and the speech-perception measures were found. Although all three correlations were in the predicted direction, none was strong enough to achieve statistical significance. These results do not support the hypothesis that cognitive and linguistic skills are related to speech-perception skills in adults with CIs.

Discussion

This study examined three research questions. The first concerned the range of cognitive and linguistic ability evidenced by adults with CIs. Both qualitative and

Table 4. Correlations between standardized tests and measures of spoken word recognition.

Dependent measure	Stimulus type	EVT standard score	WJ-III VCS standard score	TONI-3 standard score
Raw isolation points	Low-density words	.514*	.383	.476
	High-density words	.108	−.032	.119
CVC-normalized scores	Low-density words	.501	.286	.155
Isophonemic words	Percentage words correct	−.243	−.258	−.498
	Percentage phonemes correct	−.208	−.227	−.474

*Significant at $p < .01$.

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statistical analyses of standard scores on three measures—the EVT, the WJ-III VCS, and the TONI-3—suggested that the listeners with CIs in this study demonstrate a range of abilities similar to that in the adult population with NH. It should be emphasized that the listeners for this study were not chosen because of their cognitive or linguistic skills; the only criterion used to select them was that their speech be sufficiently intelligible for the examiner to score their open-set speech-perception responses. The fact that these listeners demonstrated a wide range of linguistic and cognitive abilities suggests that the lack of strong, consistent relations among the cognitive and linguistic measures and the speech-perception measures was not because of a restricted range of behaviors in this population.

The second objective of this study was to examine the influence of neighborhood density on performance for the gating task. All listeners required more acoustic information to identify words with higher neighborhood densities accurately. However, a Difficulty × Group interaction was found. Namely, neighborhood density influenced performance for listeners with CIs less than performance for listeners with NH. Vitevitch and Luce (1999) argued that the finding that neighborhood density affects word-recognition accuracy supports a relation between linguistic processing and speech perception because it shows that listeners perceive stimuli in relation to other words in their lexicons. The fact that the influence of neighborhood density on perception is smaller for adults with CIs than for adults with NH suggests that perception of speech among persons using CIs is less related to linguistic processing than it is in the NH population.

The final objective of this study was to examine relations among the cognitive and linguistic skills and speech-perception measures. Strong, consistent relations between those two sets of measures were not found in the two correlation analyses—those using raw isolation-point measures and those using CVC-normalized isolation-point measures. Moreover, the listeners with CIs in this study exhibited a smaller influence of neighborhood density on performance than did the listeners with NH. Together, these results do not provide support for the hypothesis that linguistic and cognitive skills predict speech-perception performance in adults with CIs.

Our interpretation of the lack of a relation between cognitive and linguistic processing and speech perception among the listeners in this study is limited by the great variability of our participant population. Previous research has argued persuasively that relations exist among cognitive skill, linguistic skill, and many speech and language skills (e.g., sentence comprehension, spoken word recognition, nonword repetition), both in adults and in children. It seems unlikely that adults with CIs would not demonstrate the same relations simply by virtue of having an auditory prosthesis. Rather, we hypothesize that the lack of a relation in this study is because of the potential role of signal perception in mediating the relations among linguistic and cognitive skill and spoken word recognition. The 15 listeners with CIs in this study were heterogeneous with respect to age, etiology, duration of deafness, and implant type. Many of these factors have been documented to have an influence on success of implant use. Indeed, correlation analyses of the data collected in this experiment showed age and duration of implant use to be correlated with isolation points in the gating experiment.

One potential reason why the heterogeneity of the CI population confounded the results in this experiment relates to the robustness with which the acoustic speech signal is encoded electronically. That is, people with CIs differ in the level of acoustic detail that they apprehend through their device. As a consequence, the task of matching an electronic signal to a representation varied considerably in the 15 listeners with CIs as a function of the robustness of the signal. Put differently, each of the 15 listeners faced a unique problem in mapping the electronic signal to a representation in long-term memory.

Thus, it may be the case that subtle predictive relations do exist among cognitive and linguistic skills and spoken word recognition, but only for a group of listeners that is homogeneous with respect to the many other factors that affect implant use. For example, above-average cognitive and linguistic skills may aid speech perception only among the listeners with a short duration of deafness and very poor psychophysical skills. That is, these skills may only be useful for the listeners with the poorest representation of the speech signal and the most recent experience using oral language. These people would presumably require the most contextual information to recognize words accurately (given their poor signal representation) and the most robust knowledge base to exploit in contextual utilization. Future research on this problem should examine these relations in a larger cohort of listeners stratified for other variables known to predict success of implant use. Alternatively, future research might examine a much larger heterogeneous group of listeners with CIs and use multiple regression to assess the relative power of cognitive skill, linguistic skill, and demographic variables in predicting spoken word recognition. Such analyses could not be completed in the current experiment because of the small number of participants.

Despite the limitations in the interpretation of these findings, they have more straightforward clinical implications. Namely, measures of cognitive and linguistic skill do not predict spoken word recognition in a heterogeneous population of adults with CIs similar to those

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in this study (i.e., adults with intelligible speech). These negative findings can be cast in a positive light, inasmuch as the data suggest that adults with below-average cognitive and linguistic abilities may still perform well with their implants. Thus, below-average cognitive and language skills should not be viewed as limiting factors for success with a cochlear implant in the adult population. Conversely, adults with cognitive and linguistic abilities that are considerably better than those in the general population cannot be assured of success in implant use.

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Contact author: Benjamin Munson, PhD, Department of Communication Disorders, University of Minnesota, 115 Shevlin Hall, 164 Pillsbury Drive, SE, Minneapolis, MN 55455. E-mail: munso005@umn.edu

Appendix A. Isophonemic word lists.

Number	A	B	C	D	E	F	G	H	Practice	Practice
1	cheek	cheese	beach	wreath	leaf	deep	sheep	keys	reap	weave
2	ship	wish	thin	live	rib	cheer	him	miss	win	thick
3	daze	rail	page	shape	gave	ways	faith	gain	cave	fade
4	well	hedge	wreck	guess	head	shell	web	chair	shed	jet
5	jug	bug	tug	fun	thumb	numb	rug	shove	hatch	pass
6	rice	dive	vice	wide	wise	five	size	wife	thighs	chime
7	half	sack	dash	hat	cash	bath	catch	path	budge	hug
8	not	mop	was	job	chop	hot	doll	dodge	got	rob
9	both	phone	home	comb	note	joke	vote	hole	foam	shown
10	move	tooth	fool	choose	juice	goose	June	boot	loose	lose

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Appendix B. Monosyllabic words used in the gating experiment.

Gated word	Neighborhood density	Duration (ms)	Number of gates
ball	Low	591	10
dish	Low	471	7
fight	Low	539	9
house	Low	541	9
long	Low	653	11
pull	Low	593	10
road	Low	697	12
tail	Low	696	12
tug	Low	529	9
wood	Low	619	10
boat	High	594	10
dead	High	537	9
fair	High	693	12
hill	High	543	9
line	High	676	12
man	High	756	13
piece	High	590	10
rock	High	494	8
suit	High	522	8
well	High	599	10

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