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Some Effects of Phonotactic Probabilities on the Processing of Spoken Words and Nonwords by Post-Lingually Deafened Adults with Cochlear Implants[1]

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Some Effects of Phonotactic Probabilities on the Processing of Spoken Words and Nonwords by Post-Lingually Deafened Adults with Cochlear Implants

Abstract. Probabilistic phonotactics refers to the frequency with which segments and sequences of segments occur in syllables and words. Knowledge of phonotactics has been shown to be an important source of information in segmenting and recognizing speech in normal hearing listeners. A post-perceptual task (nonword rating) and two on-line tasks (an auditory same-different and an auditory lexical decision task) were used in the present set of experiments to examine the use of phonotactic information by post-lingually deafened adults who have received a cochlear implant. The results of all three experiments showed that both normal-hearing and hearing-impaired listeners are sensitive to differences in phonotactic information to varying degrees. Furthermore, cochlear implant patients with better word recognition abilities (as measured by the NU-6) tended to be more sensitive to phonotactic information than cochlear implant patients with poorer word recognition abilities. The implications of these results for outcome assessments and clinical interventions are discussed.

Phonotactic information refers to the sequential arrangement of phonetic segments in morphemes, syllables, and words (Crystal, 1980). Sounds and sequences of sound that are found in a given language are said to be *legal* within that language, whereas sounds and sequences of sound that are not found in a given language are said to be *illegal* within that language. Awareness of the sounds that are legal in one’s native language occurs very early in life. For example, Jusczyk, Frederici, Wessels, Svenkerud, and Jusczyk (1993) showed that Dutch and American children as young as nine months of age listen longer to lists of words with patterns of segments and sequences allowed in their native language than to lists of words with patterns from the other language. These results show that listeners are sensitive early in life to the sounds and sequences of sound that are legal in their native language.

Although phonotactic information is often described as a set of rules—or a “phonological syntax” (Malmkaer, 1991)—specifying the sequences of segments that are legal or illegal in a language, recent work has explored the *probabilistic* nature of phonotactic constraints (Kessler & Treiman, 1997; Treiman, Kessler, Knewasser, Tincoff, & Bowman, 1996; Vitevitch & Luce, 1998, 1999; Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997). That is, rather than using stimuli that contained either legal or illegal sequences, these researchers created stimuli that were completely legal in a given language, but that varied in how common the segments and sequences were in that language. Jusczyk, Luce, and Charles-Luce (1994) demonstrated that nine-month old infants are also sensitive to the *probabilities* of sound patterns within their native language. Using the same procedure as Jusczyk et al. (1993), Jusczyk, Luce, and Charles-Luce (1994) found that American infants listened longer to lists of nonwords that contained high probability segments and sequences of segments than to lists of nonwords that contained low probability segments and sequences in English. These results suggest that sensitivity to *probabilistic* phonotactic information may also develop early in life and may be important for the processing of spoken language later in life.

For example, sensitivity to the phonotactic probabilities of the ambient language may assist children in acquiring and building a lexicon. Computational (e.g., Brent & Cartwright, 1996; Cairns, Shillcock, Chater, & Levy, 1997) and experimental investigations (e.g., Mattys, Jusczyk, Luce & Morgan, 1999; Saffran, Newport, & Aslin, 1996) suggest that phonotactic information may play a role in the segmentation of words from continuous speech. Sensitivity to the patterns of segments that occur only within words (such as /tl/), or only at the edges of words (e.g., /ŋ/ does not occur in the initial portion of

English words) may allow a child to identify the beginning and endings of words. With the beginning and ending of a word identified, the child can isolate an individual word from the continuous stream of speech and begin acquiring a lexicon. Other research suggests that older children may also use phonotactic information to add new words to the lexicon (e.g., Gathercole, Willis, Emslie, & Baddeley, 1991; Gupta & MacWhinney, 1997; Storkel & Rogers, 2000). Thus, phonotactic probabilities in language are valuable sources of information early in life for processing spoken language.

Phonotactic information is not only used in the acquisition of language. Adults are also sensitive to phonotactic information and may use it to process spoken language. For example, Vitevitch, Luce, Charles-Luce, and Kemmerer (1997; see also Messer, 1967) created bisyllabic nonword stimuli containing segments and sequences of segments that were completely legal in English, but varied in how common they were in English. Stimuli comprised of segments and sequences of segments that occur frequently in English, such as /kikrig/, are said to have high phonotactic probability. Stimuli comprised of segments and sequences of segments that occur less frequently in English, such as /j^ʃð^tʃ/, are said to have low phonotactic probability. The researchers asked participants to rate how “good” each item would be if it were a real word in English. Their results showed that participants’ subjective ratings of the spoken nonwords followed the objective measure of phonotactic probability: Nonwords with high probability patterns were rated as being more word-like than low probability patterns. These results suggest that adults are sensitive to fine-grained probabilistic phonotactic information within their native language, and can access and use this information in tasks requiring explicit judgment about nonword patterns.

Vitevitch et al. (1997) also asked another group of participants to repeat the same nonwords presented auditorily. An analysis of the response latencies showed that nonwords with high probability patterns were repeated more quickly than nonwords with low probability patterns, suggesting that probabilistic phonotactic information may play a role in spoken word recognition in normal hearing listeners (see also Vitevitch & Luce, 1998, 1999; Vitevitch, Luce, Pisoni, & Auer, 1999). That is, phonotactic information may be one of several sources of information, such as word frequency (e.g., Savin, 1963; Solomon & Postman, 1952) or the stress pattern of a word (e.g., Cutler & Norris, 1988) that normal hearing listeners use to understand spoken language.

In the present study, we were interested in determining whether a group of post-lingually deafened adults who have subsequently received a cochlear implant also make use of phonotactic probabilities to understand spoken words. Doyle et al. (1995), for example, reported that cochlear implant users have difficulty distinguishing among segments varying in manner of articulation, voicing, and place of articulation. Given the difficulty in discriminating fine phonetic details in speech, cochlear implant users may no longer consistently rely on information or representations related to segments or sequences of segments to process spoken words. Post-lingually deafened adults who used a cochlear implant for at least one year participated in the present set of experiments. Our goal was to determine if these patients are able to make use of information about phonotactic probabilities and whether these cognitive processing strategies help cochlear implant users recognize isolated spoken words.

The post-lingually deafened adults who participated in this set of experiments were all patients who had acquired language with normal hearing. Later in life these individuals became profoundly deafened through trauma or disease and had subsequently received and used a cochlear implant for at least a year. A cochlear implant is a sensory aid--a surgically implanted prosthetic device that bypasses the damaged inner hair cells and transduces an auditory signal into an electrical signal that stimulates the auditory nerve (Wilson, 2000). A cochlear implant provides patients who have profound hearing loss with useable forms of auditory stimulation. A typical multi-channel cochlear implant consists of a microphone that receives auditory input, a speech processor that uses one of several possible preset algorithms to process incoming auditory signals, and an array of electrodes that are surgically implanted into the cochlea to electrically stimulate the auditory nerve. Electrical stimulation of the auditory nerve by the implant results in the perception of spectral information via the tonotopic arrangement of the electrodes in the cochlea. The stimulation also provides durational and intensity information about the auditory signal (Wilson, 2000). The outcome measures of the effectiveness of cochlear implants in adults (across the several types of systems and several processing strategies) ranges from being able to follow a conversation on the telephone to being able to merely detect the presence or absence of sound (e.g., Blamey et al., 1987; Cohen, Waltzman, & Shapiro, 1989; Dowell, Mecklenburg, & Clark, 1986; Gantz et al., 1988; Skinner et al., 1991; Geier, Fisher, Barker, & Opie, 1999; Hollow et al., 1995; Holden, Skinner, & Holden, 1997; Staller et al., 1997).

To examine whether cochlear implant users are still able to make use of phonotactic information to recognize spoken words, we used the nonwords of Vitevitch et al. (1997) with a slightly modified methodology. In the present experiment, participants were presented with bisyllabic nonwords varying in phonotactic probabilities and were asked to repeat the nonword as accurately as possible. After the repetition response, they heard the stimulus again but were asked to rate the goodness of each item as if it were a real word in English. Participants used a scale of 1 (“Bad sounding English word”) to 5 (“Good sounding English word”).

If cochlear implant users are able to access phonotactic information, we would expect to find a difference in the ratings of the nonwords that is similar to that observed by Vitevitch et al. (1997). Specifically, nonwords with high-probability phonotactics should be rated as better sounding English words than nonwords with low-probability phonotactics by the cochlear implant users. Moreover, patients with better word recognition skills (as assessed by scores on the NU-6) may be able to more finely discriminate sound patterns and sequences varying in phonotactic probability and therefore would be more likely to use this more detailed information than those with poorer word recognition abilities (i.e., lower NU-6 scores). We further predicted that the ratings would reflect this difference in word recognition ability. Specifically, patients with poorer word recognition abilities should not be able to make fine-grained discriminations among segments and sequences of segments making it difficult to distinguish a real word from a nonword. This pattern would be expected in cochlear implant patients with poorer word recognition abilities. They would rate all of the nonwords as being "better words" than cochlear implant users with better word recognition ability or normal hearing listeners.

For repetition accuracy, we predicted that if cochlear implant users were able to use phonotactic information, the accuracy with which the nonwords were repeated would also vary as a function of phonotactic probabilities. Specifically, nonwords with high phonotactic probability should be repeated more accurately than nonwords with low phonotactic probability, as in Vitevitch et al. (1997). Finally, we predicted that the cochlear implant users with better word recognition ability would repeat the nonwords more accurately than the cochlear implant users with poorer word recognition ability.

Methods

Participants

Eight adult patients with cochlear implants and four normal-hearing adults participated in this experiment. Based on the preliminary analysis of the repetition data from the present experiment and feedback from the cochlear implant patients, no more than eight cochlear implant patients were tested in this difficult task. Four normal-hearing adults were recruited in order to have equal numbers of participants in each group based on perceptual ability. The normal-hearing listeners were recruited from introductory Psychology classes at Indiana University-Bloomington, reported no history of speech or hearing disorders, and received partial credit toward the fulfillment of a course requirement. All participants were native English speakers. The mean age of the normal-hearing participants was 19.75 years old.

The eight adult cochlear implant users were outpatients at Riley Hospital, Indianapolis, Indiana who were paid for their participation in the study. All the patients were post-lingually deafened adults. The mean age of the participants who used cochlear implants was 44.8 years old. The mean age of onset of deafness was 29.4 years old. The mean age at which implantation of a cochlear implant device took place was 41.5 years. The 12.1 year difference between the age of onset of deafness and the age at which implantation took place does not mean the participants were without auditory stimulation for an average of 12.1 years; all of the post-lingually deafened participants used hearing aids for some period of time before being implanted with the cochlear implant. Five participants used the Nucleus device, two used the Clarion device, and one used the MedEl device. See Table I for individual participant information.

Table I. Individual Characteristics of Cochlear Implant Users in Experiment 1

	Age	Age at Onset of Deaf	Etiology	Age at Implant-ation	Type of Implant and processing strategy	Years of CI Use	NU-6 Word	NU-6 Phon	NU-6 Cond.
1	50	24	u.k	39	Nucleus-22, SPEAK	11	68	85	HIGH
2	37	35	trauma	37	Nucleus-22, SPEAK	1	34	61	HIGH
3	35	24	u.k	31	Nucleus-22, SPEAK	4	58	77	HIGH
4	52	49	u.k	51	Nucleus-22, SPEAK	1	50	69	HIGH
5	63	39	trauma men.	57	Nucleus-22, SPEAK	6	8	29	LOW
6	42	19	otscl.	41	Combi40, CIS	1	28	53	LOW
7	44	42	ototox	43	Clarion, CIS	2	34	56	LOW
8*	37	3	u.k	33	Clarion, CIS	4	34	59	LOW
	45.0	29.4		41.5		3.75			

Note: Two listeners also participated in Experiments 2 and 3; they are indicated by * next to the participant number. u.k. = unknown

All of the participants were divided into three groups based on word recognition ability: the normal-hearing adults, the cochlear implant patients who had above average speech perception as measured by the NU-6, a standard test of word recognition abilities (High-NU-6 scores), and the cochlear implant patients who had average speech perception (Low-NU-6 scores). A median split on the NU-6 scored by percent words correct and by percent phonemes correct for each patient served as the criterion to divide the cochlear implant patients into the two groups of four participants each. Patients in the High-NU-6 group had a mean NU-6 scored by percent words correct of 52.5%, and a mean NU-6 scored by percent phonemes correct of 73.0%. Patients in the Low-NU-6 group had a mean NU-6 scored by percent words correct of 26.0%, and a mean NU-6 scored by percent phonemes correct of 49.2%. The differences between the NU-6 scored by percent word correct (F (1,6) = 7.84, $p < .05$) and by percent phoneme correct (F (1,6) = 7.65, $p < .05$) between the groups were significantly different.

Although the two groups of cochlear implant patients differed in their word recognition abilities, the two groups did not differ in their hearing thresholds as measured by pure-tone averages (*F* (1,6) < 1). A pure-tone average is the mean sound level for detecting a pure-tone at 500, 1000, and 2000 Hz. Patients in the High-NU-6 group had a pure-tone average of 28.33 dB SPL, and patients in the Low-NU-6 group had a pure-tone average of 29.33 dB SPL suggesting that the two groups had comparable abilities in detecting sound.

Materials

Two-hundred-forty bisyllabic nonwords with the stress on the first syllable were selected from the stimuli constructed by Vitevitch et al. (1997). These nonword stimuli were divided into two lists of 120 stimuli each. One list had nonwords with syllables in the order A-B, whereas the other list had the same syllables forming nonwords, but the order of the syllables in the nonwords was B-A. No syllable was used more than once in a list. Examples of the stimuli are listed in Table II.

Table II. Examples of bisyllabic nonword stimuli varying in phonotactic probability

Condition	List 1	List 2
High-High	`f^ltʃ^n	`tʃ^nf^l
High-Low	`l^nð^z	`ð^zl^n
Low-High	`gaɪbsaɪk	`saɪkgaɪb
Low-Low	`ðaɪbdʒaiz	`dʒaizðaɪb

Phonotactic probability was defined as in Jusczyk et al. (1994) and Vitevitch et al. (1997). The phonotactic probability of a nonword CVC syllable was based on the following statistics: (1) positional segment frequency (i.e., how often a phonetic segment occurs in a particular position in a word), and (2) biphone probability (i.e., the segment-to-segment co-occurrence probability). Log-frequency weighted values were used to compute positional segment frequency and biphone probability from a computer-readable version of Webster's Pocket Dictionary, which contains approximately 20,000 words (see Auer, 1993). Because frequency-weighted values were used in our computations, the segment and biphone statistics can be viewed as being based on word *token* counts, not word *type* counts.

High probability nonword patterns consisted of segments with high segment positional probabilities and frequent biphone probabilities. For example, in the high probability pattern /kik/ ("keek"), the consonant /k/ is relatively frequent in the initial position, the vowel /i/ is relatively frequent in the medial position, and the consonant /k/ is relatively frequent in the final position. The probabilities of the initial consonant-vowel (/ki_/) and the vowel-final consonant (/_ik/) co-occurring were also relatively high.

Conversely, low probability nonword patterns consisted of segments with low segment positional probabilities and less common biphone probabilities. Despite being relatively rare, none of the patterns formed were phonotactically illegal in English. Each of the five vowels used in the CVCs, /^, aɪ, i, e, ɜ/ occurred in equal proportions in each of the syllable types. The same vowel appeared in the first and second syllable of each nonword.

The average segment probability was .1926 for the high-probability pattern list and .0543 for the low probability pattern list. The average biphone probability was .0143 for the high-probability list and .0006 for the low-probability list. The difference in the magnitudes of the segment and biphone probabilities reflects the fact that there are more biphones than segments. This results in biphones having a lower probability of occurrence overall than segments because the same total probability (i.e., 1.00) is divided among many more possible outcomes for the biphones than for the segments.

The same stimulus tokens used in Vitevitch et al. (1997) were also used in this experiment. A trained phonetician originally recorded all the stimuli, which were spoken in isolation. The stimuli were then low-pass filtered at 4.8 kHz and digitized at a sampling rate of 10 kHz using a 12-bit analog-to-digital converter. All nonwords were edited into individual sound files and stored on computer disk using a digital waveform editor. A trained speech scientist measured the amplitude of the vowel of each syllable with a digital waveform editor to confirm correct stress placement by the speaker.

Procedure

Participants were tested individually. Each participant was seated in front of a 200MHz Gateway 2000 Pentium computer that controlled stimulus presentation and response collection. All stimuli were presented in random order one at a time. Cochlear implant users were tested in an IAC sound booth in the DeVault Otologic Laboratory at the IU School of Medicine and heard the stimuli at 70 dB SPL over an Advent AV570 speaker. The normal-hearing participants were tested in a sound attenuated booth using an identical computer system in the Speech Research Laboratory in Bloomington. Normal-hearing participants heard the stimuli over a pair of Beyerdynamic DT-100 headphones. Because of the mechanics of the cochlear implant, headphones could not be used with the eight cochlear implant patients.

Each participant received one of the two lists of 120 randomly ordered stimuli. A scale from 1, labeled "Bad English Word" to 5, labeled "Good English Word" was attached to the first five buttons of a seven-button response box. The sixth button was deactivated for response, and the seventh button was labeled "Play Again."

A trial proceeded as follows: A prompt appeared on the computer screen, and one of the test signals was presented at 70 dB SPL over the headphones or speaker. The participant was asked to repeat the nonword as accurately as possible into a Shure 5755 microphone connected to a Marantz tape recorder. Because of technical considerations, response latencies were not recorded from these patients as they were in Vitevitch et al. (1997). Specifically, cochlear implant users cannot be presented with auditory stimuli over headphones. Rather, the stimuli must be presented free-field. Unfortunately, such presentation would trigger a voice-key interfaced with a microphone normally used to record reaction times in similar experiments. Thus, only the accuracy of the response was examined in the present study. The participant pressed the labeled button on the response box to hear the stimulus again. After the second presentation of the stimulus, the participant rated the item as quickly as possible by pressing one of the five numbered buttons on the response box. After recording the response, the computer began the next trial.

Results

To examine sensitivity to phonotactic information as a function of word recognition ability, a mixed design ANOVA with the Greenhouse-Geisser correction was performed on the mean ratings with phonotactic probability as a within-participants factor and word recognition ability as a between participants factor for each scoring criterion. The mean ratings for the four phonotactic conditions as a function of the three groups of listeners are shown in Figure 1. Ratings on a scale of 1 ("BAD") to 5 ("GOOD") are plotted on the *y* axis. The three groups of listeners are represented on the *x* axis. "High-High" refers to nonwords with high phonotactic probability initial and final syllables and is represented by dotted bars. "High-Low" refers to nonwords with high probability initial and low probability final syllables and is represented by the gray bars. “Low-High” refers to nonwords with low probability initial and high probability final syllables and is represented by the clear bars. Finally, “Low-Low” refers to nonsense words with low probability initial and final syllables and is represented by the striped bars. Figure 1 shows the mean rating for *all* stimuli regardless of whether they were correctly repeated or not.

Ratings to All the Nonwords

Examination of the ratings to all the stimuli revealed a main effect of phonotactic probability (F (3,27) = 7.43, $p < .001$). Stimuli in the High-High condition (mean = 3.02) were rated higher than stimuli in the Low-Low condition (mean = 2.56, F (3,27) = 21.06, $p < .001$). Stimuli in the High-High condition were also rated higher than stimuli in the High-Low condition (mean = 2.76, F (3,27) = 6.57, $p < .05$). Finally, stimuli in the Low-High condition (mean = 2.87) were rated higher than stimuli in the Low-Low condition (F (3,27) = 9.46, $p < .01$). No other comparisons or interactions were significant (all $F < 1$). These results confirm our initial prediction and suggest that cochlear implant patients are able to access phonotactic information. These results also replicate the findings of Vitevitch et al. (1997) who examined sensitivity to phonotactic information in normal-hearing listeners.

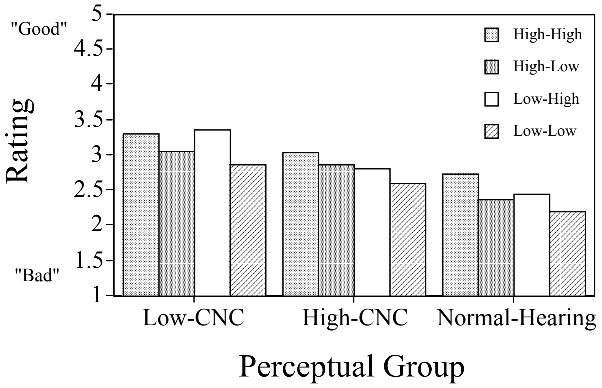

Figure 1. The mean ratings of nonwords on a scale from 1 (BAD English word) to 5 (GOOD English word) as a function of perceptual group for all the stimuli.

A main effect of word recognition ability was also found (F (2,27) = 5.56, $p < .05$). The Low-NU-6 group (mean = 3.15) had higher nonword ratings than the normal-hearing group (mean = 2.43; F (2,27) = 11.07, $p < .01$). The High-NU-6 group (mean = 2.83) also had higher nonword ratings than the normal-hearing group, but this effect was only marginally significant (F (2,27) = 3.41, $p = .09$). The nonword ratings for the Low-NU-6 group were not significantly different from the High-NU-6 group ($F < 1$). Although there was no statistically significant difference in nonword ratings between the two groups of cochlear implant patients, the two groups of cochlear implant patients did have higher nonword ratings than the normal hearing group. That is, normal hearing listeners rated the nonword stimuli as being less like English words than the cochlear implant patients. These results partially support our initial prediction regarding the ability of listeners varying in word recognition skill to make fine-grained discriminations among segments and sequences of segments. Both groups of cochlear implant patients were not as good as the normal hearing listeners at making fine-grained discriminations among segments and sequences of segments. The poorer ability of the cochlear implant patients to make fine-grained discriminations made it difficult for them to distinguish possible real words from nonwords, resulting in the nonwords being rated as "better words" than normal hearing listeners.

Ratings to Nonwords using an Accuracy Criterion

Repetition of the nonwords proved to be a very difficult task for the cochlear implant users. When the repetitions were scored with a strict criterion (all phonemes repeated correctly), a mean value of 6% of the nonwords was correctly repeated across participants and conditions. When a less strict criterion was used, in which a majority of the stimulus (4 out of the 6 phonemes in the stimulus) was repeated correctly, the mean value across participants and conditions of correct repetitions rose to 45%. Figure 2 shows the mean rating from stimuli that were correctly repeated using this criterion. The accuracy rates with which four of the six phonemes in the stimuli were repeated are also shown in Figure 2.

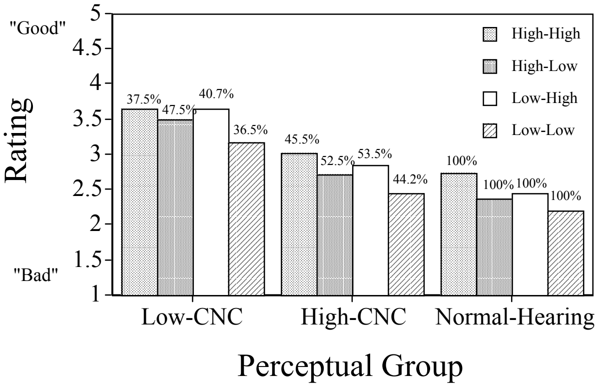

Figure 2. The mean ratings of nonwords on a scale from 1 (BAD English word) to 5 (GOOD English word) as a function of perceptual group for only the stimuli in which four out of the six phonemes were correctly repeated.

Analyses of the ratings for the stimuli in which four of the six phonemes were correctly repeated revealed a similar pattern of results as the analyses of the ratings to all the stimuli. A main effect of phonotactic probability was found for the correctly repeated stimuli (F (3,27) = 6.44, $p < .01$). Stimuli in the High-High condition (mean = 3.13) were rated higher than stimuli in the Low-Low condition (mean = 2.61, F (3,27) = 18.07, $p < .001$). Stimuli in the High-High condition were also rated higher than stimuli in the High-Low condition (mean = 2.86, F (3,27) = 4.88, $p < .05$). Stimuli in the Low-High condition (mean = 2.98) were rated higher than stimuli in the Low-Low condition (F (3,27) = 9.06, $p < .01$). Finally, stimuli in the High-Low condition were rated higher than stimuli in the Low-Low condition (F (3,27) = 4.16, $p < .05$). No other comparisons or interactions were significant in the analysis of correctly repeated nonwords (all $F < 1$). These results further suggest that cochlear implant patients are able to access phonotactic information.

A main effect of word recognition ability was also found (F (2,27) = 5.21, $p < .05$). The Low-NU-6 group (mean = 3.49) had higher ratings than the High-NU-6 group (mean = 2.75) and the normal-hearing group (mean = 2.44). Pairwise comparisons show that the difference between the Low-NU-6 group and the High-NU-6 group was statistically significant (F (2,27) = 4.78, $p < .05$), as was the difference between the Low-NU-6 group and the normal-hearing group (F (2,27) = 9.92, $p < .01$).

However, the difference between the High-NU-6 group and the normal-hearing group was not statistically significant ($F < 1$). These results also provide partial support for our initial prediction regarding the ability of listeners varying in word recognition skill to make fine-grained discriminations among segments and sequences of segments. Normal hearing listeners and cochlear implant patients with High-NU-6 scores were better than cochlear implant patients with Low-NU-6 scores at making fine-grained discriminations among segments and sequences of segments. The poorer ability of the cochlear implant patients with Low-NU-6 scores to make fine-grained discriminations made it difficult for them to distinguish possible real words from nonwords, resulting in the nonwords being rated as "better words" than cochlear implant patients with High-NU-6 scores and normal hearing listeners.

Accuracy Analysis of Repeated Nonwords

Analysis of the accuracy rates for the stimuli in which four of the six phonemes were correctly repeated showed a main effect of word recognition ability (F (2,27) = 16.44, $p < .01$). The normal-hearing group correctly repeated more nonwords (mean = 100%) than the Low-NU-6 group (mean = 40.6%) and the High-NU-6 group (mean = 48.9%). Pairwise comparisons show that the difference between the normal-hearing group and the Low-NU-6 group was statistically significant (F (2,27) = 28.05, $p < .001$), as was the difference between the normal-hearing group and the High-NU-6 group (F (2,27) = 20.70, $p < .01$). The difference in repetition accuracy between the Low-NU-6 group and the High-NU-6 group was not statistically significant ($F < 1$). These results suggest that listeners with a better ability to make fine-grained discriminations among segments and sequences of segments (i.e., normal hearing listeners) are more accurate in their repetition of those segments and sequences of segments.

The main effect of phonotactic probability was not significant, nor was the interaction between perceptual group and phonotactic probability (Fs < 1). The lack of a difference between nonwords varying in phonotactic probability suggests that the four types of nonwords were equally perceptible for each of the three groups of listeners.

The Phonotactic Sensitivity Index

To further assess the relationship between the use of phonotactic information and spoken word recognition performance, we developed a global index of *phonotactic sensitivity* and correlated it with a measure of spoken word recognition ability. Each cochlear implant patient's NU-6 scored by percent words correct was used as the measure of spoken word recognition. Phonotactic sensitivity was calculated by computing a difference score between the nonword ratings each participant gave to stimuli in the High-High condition and to stimuli in the Low-Low condition. We hypothesized that individuals who were more sensitive to phonotactic information in these patterns should display a larger difference between the ratings of High-High stimuli and Low-Low stimuli; the High-High stimuli would be rated much higher (i.e., as better possible words in English) than the Low-Low stimuli. Conversely, we predicted that individuals who were less sensitive to phonotactic information in these patterns would display a smaller difference between the ratings of High-High stimuli and Low-Low stimuli; the High-High and Low-Low stimuli would not be well discriminated and would be rated similarly, thereby producing small differences in the ratings.

The measures of phonotactic sensitivity and word recognition performance were only weakly related ($r = +.32$), and the correlation was not significant. (An analysis using the NU-6 scored by percent phonemes correct showed a similar pattern with a somewhat weaker correlation.) A scatterplot of this relationship is displayed in Figure 3. Examination of these individual data points shows that no participant rated the Low-Low stimuli higher than the High-High stimuli; this would have resulted in a negative difference score. When the data for the two participants who obtained a phonotactic sensitivity measure of zero (one had a difference of .03, the other had a difference of 0.0) were excluded from the analysis, a stronger correlation was observed (*r* = + .66), although this did not reach statistical significance most likely because the sample size was too small. (An analysis using the NU-6 scored by percent phonemes correct shows a similar increase in the correlation coefficient when the difference scores near zero are removed.) Although suggestive, this trend indicates that success in using phonotactic information in this nonword rating task may be related to performance in recognizing isolated spoken words.

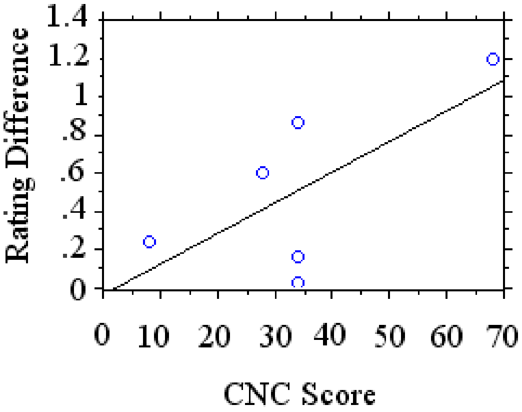

Figure 3. Scatterplot for a measure of phonotactic sensitivity (the difference in ratings to High-High and Low-Low nonword stimuli) and a measure of spoken word recognition ability (NU-6) for 8 cochlear implant users.

Discussion

The results of this experiment confirmed several predictions we made regarding the sensitivity of cochlear implant patients to phonotactic information in isolated nonword patterns. First, all three groups of listeners demonstrated via their "goodness" ratings sensitivity to differences in phonotactic probabilities among the nonword stimuli that corresponded with the objective measures of segment and sequence frequency. That is, nonword patterns comprised of segments and sequences of segments that are common in English (high phonotactic probability) were rated as being more word-like than nonwords comprised of segments and sequences of segments that are less common in English (low phonotactic probability). This result, which was observed for all three groups of listeners, replicates the finding of Vitevitch et al. (1997) in which normal hearing listeners rated the same nonwords in a rating task with a slightly modified methodology. In the present study, differences in ratings among the nonwords varying in phonotactic probability were observed when the ratings to all of the stimuli were analyzed as well as when only those stimuli that had four out of six phonemes correctly repeated were analyzed. These results suggest that cochlear implant users, like normal-hearing listeners (Vitevitch et al., 1997), still have access to and can use phonotactic information to make judgments about the sound patterns of spoken stimuli.

The results of this study also demonstrate that ratings of nonwords varying in phonotactic probabilities differ as a function of word recognition ability. Normal hearing listeners consistently rated the stimuli as being less word-like than the cochlear implant users with low word recognition ability regardless of whether the ratings from all stimuli were included in the analysis or just the ratings from those stimuli that were correctly repeated to an accuracy criterion. Although normal-hearing listeners tended to have lower ratings overall (i.e., less word-like) than the cochlear implant users with high word recognition ability, this difference approached statistical significance only when the ratings from all, rather than just the accurately repeated, nonwords were analyzed. Similarly, the cochlear implant users with high word recognition ability tended to have somewhat lower ratings (i.e., less word-like) than the cochlear implant users with low word recognition ability. However, this difference was significant when only the correctly repeated nonwords were analyzed. These results suggest that access to and optimal use of phonotactic information in nonword pattern may be related to performance in recognizing isolated spoken words.

The sensory information that cochlear implant patients rely on in this rating task may be different from the information that normal-hearing listeners have access to. In the present experiment, cochlear implant users generally rated the nonwords as better “English words” than the normal hearing listeners rated them. This trend in the rating data may reflect the fact that cochlear implant users may have more broadly or coarsely defined representations of acoustic-phonetic input compared to normal-hearing listeners, thus, many more nonword patterns sound like a possible word in English and therefore are rated as more word-like. Normal-hearing listeners, however, are able to make much finer-grained phonetic distinctions in their encoding of the initial acoustic-phonetic input in these nonword patterns. Consequently, normal-hearing listeners may have different equivalence classes than cochlear implant users; these different perceptual categories may contribute to the overall difference in ratings as a function of word recognition ability.

The analysis of the nonword repetitions showed that the cochlear implant users were less accurate than the normal hearing listeners in the repetition of the nonword stimuli, regardless of the word recognition ability of the cochlear implant users. There were no differences in repetition accuracy between the two groups of cochlear implant users based on word recognition ability. We also found no differences in repetition accuracy as a function of phonotactic probability, in contrast to the significant difference observed among normal hearing listeners in Vitevitch et al. (1997). It should be noted, however, that the significant effect of repetition accuracy as a function of phonotactic probability observed in Vitevitch et al. (1997) was due to the extremely poor performance of participants repeating stimuli containing low phonotactic probability segments and sequences in both syllables (LOW-LOW condition). On average, the stimuli in the remaining three conditions (HIGH-HIGH, HIGH-LOW, and LOW-HIGH) were repeated approximately 10% more accurately than stimuli in the LOW-LOW condition in Experiment 2 of Vitevitch et al. (1997). That is, repetition performance was approximately equivalent across conditions, except when attempting to repeat stimuli that contained segments and sequences of segments in both syllables that are not common in English. The poorer performance in the LOW-LOW condition may also have been a function of the speeded nature of the task used by Vitevitch et al. (1997).

Furthermore, a strict accuracy criterion (*all six phonemes* had to be repeated correctly) was used in Vitevitch et al. (1997), further contributing to the difference in the accuracy results between that study and the present experiment. When a less stringent criterion is used to score stimulus repetitions among normal hearing listeners—such as four out of the six phonemes in the stimulus being repeated correctly—the performance of normal hearing listeners (as seen in the present experiment) reaches ceiling across all four of the phonotactic conditions. When the normal hearing listeners were removed from the analysis and the repetition accuracy of the High- and Low-NU-6 groups of patients are compared, the differences as a function of phonotactic probability still fail to reach significance ($F < 1$), although the differences are in the predicted direction. The equivalent repetition performance across the four conditions of phonotactic probability for the normal hearing listeners and for both groups of cochlear implant users suggests that the stimuli in each condition are equally perceptible. That is, LOW-LOW nonword patterns were not more difficult to perceive than HIGH-HIGH nonword patterns. This finding contrasts with our initial prediction, perhaps because the present task was not a speeded task as in Vitevitch et al. (1997). Finally, the significant difference in repetition accuracy between the normal hearing listeners and the cochlear implant users underscores the difficulty that these patients had in performing this task.

In summary, the results of the first experiment suggest that cochlear implant users still have access to and may use phonotactic information--knowledge of the sounds and sequences of sounds in a word or syllable--to process spoken language. Furthermore, the results of Experiment 1 suggest that the extent to which phonotactic information is used by these patients may vary as a function of spoken word recognition ability, as measured by scores on the NU-6. To further investigate how cochlear implant users access and use phonotactic information to process spoken words, we presented stimuli varying in phonotactic probability in two additional tasks that measure on-line processing by using reaction time in addition to accuracy rates as dependent measures. Tasks that measure online processing may be more sensitive to certain aspects of linguistic representations and processes than offline or post-perceptual tasks, such as the rating task used in Experiment 1. Furthermore, these online measures may lead to new methods and assessments that can be used to develop clinical outcome measures or for treatment purposes (Tompkins, 1998).

Experiment 2

An example of a task that can be used to measure on-line processing is the AX or same-different task. In this task, a participant hears two stimuli separated by a short interval (e.g., 200msec). After hearing both signals, the listener must decide as quickly and as accurately as possible if the two stimuli they heard were the same or were different, and indicate their decision by pressing a button on a response box. The time required for the participant to respond (measured from the beginning of the second stimulus to the press of the button) and the accuracy with which the participant responds constitute the dependant measures. In Vitevitch and Luce (1999) and in the present study, the label for the "SAME" response was placed under the dominant hand on the response box. Due to the wider variability of non-dominant hand responses compared to dominant-hand responses, only reaction times from dominant hand responses were analyzed.

Using the same-different task, Vitevitch and Luce (1999) were able to better describe the influence of phonotactic information on the processing of spoken words than by using the rating task--a task that can be influenced by post-perceptual processes. For example, in the post-perceptual rating task used by Vitevitch et al. (1997) and in Experiment 1 of the present study, responses to the nonword patterns could have been based on activation from sublexical representations, lexical representations, or both types of representations. Specifically, high probability segments and sequences might have been activated to a greater degree than low probability segments and sequences. Responses based on the level of activation solely at the sublexical level may have resulted in the significant effects of phonotactic probability on the nonword ratings. Alternatively, the segments and sequences in the nonwords may have partially activated whole words in the mental lexicon (i.e., lexical representations). Nonwords with high probability segments and sequences, which are common to many words (Vitevitch, Luce, Pisoni, & Auer, 1999), would have partially activated more lexical representations than nonwords with low probability segments and sequences. Responses based on the level of activation at the lexical level may also have produced the observed results. Finally, given that there was no time pressure to make a response, listeners may have developed a cognitive strategy that combined the activation among lexical and sublexical representations, also producing the observed results. Thus, it is possible that the pattern of results observed in Experiment 1 may not have been due to the direct access of phonotactic information, but to information about multiple words indirectly activated in the lexicon.

With a task that measured on-line processing activities, Vitevitch and Luce (1999; see also Pitt & Samuel, 1995) found evidence for the hypothesis that two levels of representation are involved in the process of spoken word recognition. In one study, Vitevitch and Luce (1999) presented normal-hearing listeners with monosyllabic words or monosyllabic nonwords varying in phonotactic probability. For *nonwords* varying in phonotactic probability, they found stimuli with high probability patterns were responded to ("SAME") more quickly than stimuli with low probability patterns. In contrast, for *real words,* stimuli with low probability patterns were responded to ("SAME") more quickly than real word stimuli with high probability patterns.

Based on these results, Vitevitch and Luce (1999) concluded that normal hearing listeners use *two* types of representations to process spoken language: lexical and sublexical. Lexical representations consist of phonological word forms, whereas sublexical representations consist of units smaller than a whole word, such as segments or sequences of segments. When lexical representations are used to process spoken stimuli, competition among similar sounding word forms results in stimuli with common sequences to be responded to more slowly than spoken stimuli with less common sequences. Note that there is a correlation between the frequency of a segment or a sequence of segments and the number of words that are activated and compete among each other for recognition. Common patterns of segments and sequences of segments are found in many words, whereas rare patterns of segments and sequences of segments are found in few words (see Luce & Pisoni, 1998; Vitevitch, Luce, Pisoni & Auer, 1999). On the other hand, when sublexical representations are used to process spoken patterns of segments, stimuli with common segments and sequences of segments are processed more quickly than stimuli with less common segments and sequences of segments. In the same-different task, Vitevitch and Luce (1999) found that participants used lexical representations to process the spoken words they heard and sublexical representations to process the nonwords they heard.

Just as Vitevitch and Luce (1999) found that a task that measured on-line processing was more sensitive to certain aspects of linguistic representations and processes in normal hearing listeners than an offline or post-perceptual task (such as the offline rating task used in Vitevitch et al., 1997), we predicted that the use of similar on-line tasks might reveal additional information about the processes and representations that cochlear implant users rely on in processing spoken language. In the present experiment, we used a subset of the monosyllabic words and nonwords varying in phonotactic probability used in Vitevitch and Luce (1999), and presented them to cochlear implant patients who differed in their spoken word recognition abilities (as measured by the NU-6) in a same-different task.

If listeners with cochlear implants use representations and processes that are similar to the representations and processes used by normal hearing listeners to process spoken words (Vitevitch & Luce, 1999), we would expect that the pattern of results for the two groups of listeners should be similar. Specifically, if cochlear implant users rely on sublexical representations to process nonwords as normal hearing listeners do in the same-different task (Vitevitch & Luce, 1999), we would expect that patients with a cochlear implant should respond more quickly to nonwords with high phonotactic probability than to nonwords with low phonotactic probability. Similarly, if cochlear implant patients rely on lexical representations to process real words as normal hearing listeners do in the same-different task (Vitevitch & Luce, 1999), then we would expect them to respond more quickly to words with low phonotactic probability than to words with high phonotactic probability.

As in the previous study, we predicted that the representations and processes used by patients with cochlear implants may vary as a function of spoken word recognition ability as measured by scores on the NU-6 test of spoken word recognition. Specifically, patients with cochlear implants who have good word recognition abilities should have more detailed lexical and sublexical representations and may use both types of representation in an optimal way, producing a pattern of results that is fundamentally similar to the normal hearing listeners of Vitevitch and Luce (1999).

In contrast, cochlear implant patients with poor word recognition abilities may not be able to construct detailed lexical and sublexical representations, or may not use both types of representation in an optimal manner. Some listeners may try to process words using sublexical representations. Others may try to process nonwords with lexical representations, or they may switch back and forth on a trial-by-trial basis between lexical and sublexical representations regardless of lexical status. An attenuation of the effect of phonotactic probability on processing for the real words in Experiment 2 of Vitevitch and Luce (1999) demonstrates such non-optimal processing in normal-hearing listeners when words and nonwords are mixed together rather than blocked in the same-different task. In the present experiment, if cochlear implant users with poor word recognition skills are unable to make optimal use of both types of processes and representation we would expect a similar attenuation of the effects of phonotactic probability for listeners in this group.

Methods

Participants

Eighteen adult users of a cochlear implant, all outpatients at Riley Hospital, Indianapolis, Indiana, were paid for their participation this experiment. Two of the participants in the present experiment had also participated in Experiment 1, which was conducted at least six months prior to participation in the present experiment. All participants were right-handed, native English speakers. Data from two other participants were not included in the final analysis because one participant was pre-lingually deafened, and the other participant experienced technical problems during testing because the battery in the processor ran out. The remaining participants were post-lingually deafened adults who had used their cochlear implant for at least a year prior to testing.

The mean age of the participants was 55.9 years old. The mean age of onset of deafness was 34.0 years old. The mean age at which implantation of a cochlear implant device took place was 53.3 years. Nine participants used the Nucleus device, 5 used the Clarion device, and 2 used the MedEl device. See Table III for individual participant information.

The cochlear implant patients were divided into two groups based on word recognition ability. A median split on the NU-6 scored by percent words correct for each user served as the criterion to divide the cochlear implant users into the two groups of eight participants each. Patients who had above average speech perception as measured by the NU-6 were in the High-NU-6 group and had a mean NU-6 scored by percent words correct of 46.75%. Patients who had average speech perception as measured by the NU-6 were in the Low-NU-6 group and had a mean NU-6 scored by percent words correct of 12.50 %. The difference in the NU-6 scores between the groups was significantly different ($F(1,14) = 22.64$, $p < .001$).

As in Experiment 1, the two groups of cochlear implant users did not differ in their hearing thresholds as measured by pure-tone averages, even though their speech perception abilities did differ ($F(1,14) < 1$). Users in the High-NU-6 group had a pure-tone average of 32.15 dB SPL, and users in the Low-NU-6 group had a pure-tone average of 31.05 dB SPL suggesting that the two groups had comparable abilities in detecting sound.

Table III. Individual Characteristics of Cochlear Implant Users in Experiments 2 and 3

	Age	Age at Onset of Deafness	Etiology	Age at Implant	Type of Implant and processing strategy	Years of CI use	NU-6 Word	NU-6 Phon	NU-6 Cond.
1	60	18	unknown	56	Clarion, CIS	4	0	13	LOW
2	44	27	otosclerosis	42	MedEl, SPEAK	2	28	53	HIGH
3*	53	49	unknown	51	Nucleus-24, SPEAK	2	50	69	HIGH
4	69	21	unknown	67	Nucleus-24, SPEAK	2	12	33	LOW
5	71	10	unknown	63	Nucleus-22, SPEAK	8	14	30	LOW
6	37	30	hereditary	34	Clarion, CIS	3	76	90	HIGH
7	68	43	cryoglubli.	62	Clarion, CIS	6	68	83	HIGH
8	69	40	miniere's	68	Clarion, CIS	1	38	61	HIGH
9	48	44	unknown	47	Nucleus-22, SPEAK	1	24	41	LOW
10*	39	3	unknown	33	Clarion, CIS	5	34	59	HIGH
11	71	63	hereditary	68	MedEl, SPEAK	3	2	32	LOW
12	40	38	unknown	39	Nucleus-24, ACE	1	34	57	HIGH
13	77	45	neuroma	75	Nucleus-24, SPEAK	2	46	70	HIGH
14	60	30	unknown	59	Nucleus-24, CIS	1	0	17	LOW
15	49	45	trauma	48	Nucleus-22, SPEAK	1	22	48	LOW
16	40	38	infection	39	Nucleus-24, ACE	1	26	59	LOW
	55.9	34.0		53.3		2.68			

Note: Two listeners also participated in Experiment 1; they are indicated by * next to the participant number. Also note that participant #10 in the present experiment was classified in the "Low-NU-6" group in Experiment 1.

Materials

Fifty of the words and 50 of the nonwords used in Vitevitch and Luce (1999) were used in this experiment. Phonotactic probability was calculated with the same two measures--positional segment frequency and biphone frequency--and with the same computerized dictionary used in Experiment 1. Words and nonwords that were classified as high-probability patterns consisted of segments with high segment positional probabilities. Words and nonwords that were classified as low-probability patterns consisted of segments with low segment positional probabilities and low biphone probabilities. For the words, the average segment and biphone probabilities were .1740 and .0070 for the high probability lists and .0960 and .0030 for the low probability lists in the present experiment. For the nonwords, the average segment and biphone probabilities were .1550 and .0050, respectively, for the high probability lists and .0670 and .0010 for the low probability lists in the present experiment.

Similarity Neighborhoods. Frequency-weighted similarity neighborhoods were computed for each stimulus by comparing a given phonemic transcription (constituting the stimulus pattern) to all other transcriptions in the lexicon (see Luce & Pisoni, 1998). A neighbor was defined as any transcription that could be converted to the transcription of the stimulus word by a one phoneme substitution, deletion, or addition in any position. The log frequencies of the neighbors were then summed for each word and nonword, rendering a frequency-weighted neighborhood density measure. The mean log-frequency-weighted neighborhood density values for the high and low probability nonwords were 41 and 13 respectively. The same values for the high and low probability words were 45 and 30 respectively.

Word Frequency. Frequency of occurrence (Kucera & Francis, 1967) was matched for the two probability conditions for the words. Average log word frequency was 2.004 for the low probability words and 2.005 for the high probability words (*F* < 1).

Durations. The average durations of the stimuli in the two phonotactic conditions were equivalent. For the words, the high probability items had a mean duration of 650 ms and the low probability items had a mean duration of 657 ms (*F* (1,48) <1). For the nonwords, the high probability items had a mean duration of 699 ms and the low probability items had a mean duration of 697 ms (*F* (1,48) < 1).

The words and nonwords were spoken one at a time in a list by the same trained phonetician who made the recordings used in Experiment 1. All the stimuli were treated in the same way as the stimuli in Experiment 1.

Procedure

Participants were tested individually. Each participant was seated in front of a Macintosh Performa 6200CD computer equipped with a PsyScope response box (with three response buttons) and an Advent AV570 speaker. The computer program PsyScope 1.2.2 (see Cohen, MacWhinney, Flatt, & Provost, 1993) controlled stimulus presentation and response collection. The response box had the label "DIFFERENT" on the left button and the label "SAME" on the right button (the middle response button was deactivated).

An experimental trial proceeded as follows: The word "READY" appeared in the center of the computer screen for 500ms to indicate the beginning of a trial. Participants were then presented with two of the spoken stimuli at 70dB SPL. The inter-stimulus interval was 150 ms. Reaction times were measured from the onset of the second stimulus in the pair to the button press response. If the maximum reaction time (3 s) expired, the computer automatically recorded an incorrect response and presented the next trial. Participants were instructed to respond as quickly and as accurately as possible on each trial. SAME responses were made with the dominant hand.

The words and nonwords were presented blocked in separate lists. Order of list presentation was counterbalanced across participants. Half of the trials consisted of two identical stimuli (constituting SAME trials) and half of the trials consisted of different stimuli. Half of the SAME pairs had high phonotactic probabilities and half had low probabilities. Non-matching stimuli were created by pairing stimulus items from the same phonotactic category. For the DIFFERENT stimulus pairs, items with the same initial phoneme and (when possible) the same vowel were paired.

Prior to the experimental trials, each participant received ten practice trials. These trials were used to familiarize the participants with the task and were not included in the final data analysis.

Results

To examine the on-line processing of phonotactic information as a function of word recognition ability, a mixed design ANOVA was performed on the mean reaction times with phonotactic probability and lexicality as within-participant factors and word recognition ability as a between participants factor. The mean reaction times for each phonotactic condition as a function of lexicality and word recognition ability are shown in Figure 4. The top panel shows data plotted from the normal hearing listeners that participated in Experiment 1 in Vitevitch and Luce (1999) for comparison. These data were not included in the statistical analyses below. The middle panel shows the reaction times from the High-NU-6 group. The bottom panel shows the reaction times from the Low-NU-6 group. Lexicality is represented on the *x* axis. Reaction time in milliseconds is represented on the *y* axis. Words and nonwords with high phonotactic probability are represented by the clear bars. Words and nonwords with low phonotactic probability are represented by the stripped bars. Accuracy rates for responding SAME in each condition are also presented in the figure. There were no significant differences in the accuracy rates (all *F*s < 1) indicating that participants did not sacrifice speed for accuracy in making their responses.

For the reaction times, the results showed no significant main effects (all *F*s < 1) for Lexicality, Word Recognition Ability (comparing only the High- and Low-NU-6 groups), or Phonotactic Probability (*F* (1,14) = 3.08, *p* = .10). However, the non-significant main effects should be considered in the context of significant interactions between Lexicality and Phonotactic Probability (*F* (1,14) = 8.34, *p* < .05) and between Lexicality, Phonotactic Probability, and Word Recognition Ability (*F* (1,14) = 6.30, *p* < .05).

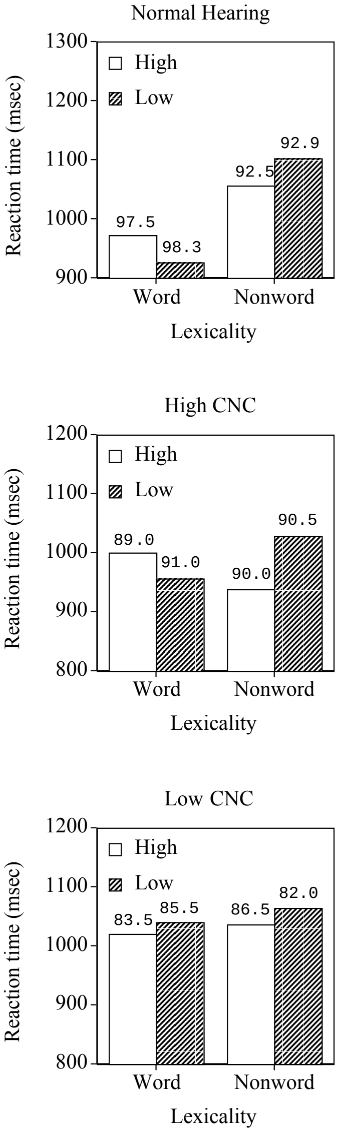

Figure 4. Mean reaction times and accuracy rates to "same" responses for normal-hearing listeners from Vitevitch and Luce (1999; top panel), better than average cochlear implant users (High-NU-6; middle panel) and average cochlear implant users (Low-NU-6; bottom panel) in the SAME-DIFFERENT task.

Subsequent analyses of the Lexicality X Phonotactic Probability interaction revealed that for real words, low probability stimuli tended to be responded to more quickly (997ms) than high probability stimuli (1009ms); however, this difference did not reach statistical significance (F (1,14) < 1). However, for the nonwords the opposite pattern was observed. High probability nonwords were responded to significantly more quickly (987ms) than low probability nonwords (1046ms; F (1,14) = 11.53, $p < .01$). Although not statistically significant, this pattern is fundamentally similar to the pattern of data for normal hearing listeners found in Vitevitch and Luce (1999), which is displayed in the top panel of Figure 4.

Consider now the Lexicality X Phonotactic Probability X Word Recognition Ability interaction. For the Low-NU-6 group, there were no significant differences in the response times for words and nonwords, or between high and low probability stimuli (all *F*s < 1). However, for the High-NU-6 group, a different pattern of results was observed. Listeners in the High-NU-6 group tended to respond more quickly to real words with low phonotactic probability (955ms) than to real words with high phonotactic probability (999ms; F (1,14) = 4.62, $p = .07$). On the other hand, for nonwords, listeners in the High-NU-6 group responded significantly more quickly to high probability nonwords (937ms) than low probability nonwords (1028ms; F (1,14) = 20.06, $p < .01$). The pattern of data observed for the High-NU-6 group, but not the Low-NU-6 group, was similar to the pattern of data found in Vitevitch and Luce (1999) and displayed in the top panel of Figure 4.

We also computed an index of *phonotactic sensitivity* that was similar to the measure of phonotactic sensitivity developed in Experiment 1. We subtracted the mean reaction time to low phonotactic stimuli from the mean reaction time to high phonotactic stimuli for each listener for words and nonwords separately. We predicted that listeners who are more sensitive to phonotactic information would show a larger difference between the means, whereas listeners who are less sensitive to phonotactic information during on-line processing would show a smaller difference between the means. For words, this difference should be negative: listeners should respond more quickly to low probability real words than high probability real words because of competition among lexical representations. In contrast, for nonwords, this difference should be positive: listeners should respond to high probability nonwords more quickly than low probability nonwords because of facilitation among sublexical representations. Furthermore, measures of spoken word recognition ability, such as the NU-6, should be related to this index of phonotactic sensitivity for real-words if phonotactic information in the lexicon is used in the processing of spoken words. The NU-6 should not be correlated with this index of phonotactic sensitivity for nonwords if different representations are used to process nonwords, as predicted based on earlier research (Vitevitch & Luce, 1999).

A correlational analysis of phonotactic sensitivity (i.e., the difference in reaction time to stimuli with high and low phonotactic probability) and NU-6 scores (a measure of spoken word recognition) was performed to examine these predictions for the sixteen participants. For the nonwords, the index of phonotactic sensitivity and NU-6 scores were not significantly correlated ($r = -.10$, $Z < -1$, $p = .69$). However, for real words, the index of phonotactic sensitivity and NU-6 scores were significantly correlated ($r = +.55$, $Z = 2.20$, $p < .05$). Patients with higher scores on the NU-6 were better able to take advantage of the differences in phonotactic probability among the words, and therefore, had a greater difference in reaction time between the words with high and low phonotactic probability. Patients with lower scores on the NU-6 were not able to take full advantage of the differences in phonotactic probability among the words, and therefore, had a smaller difference in reaction time between the words with high and low phonotactic probability. This relationship is displayed in Figure 5.

It should be noted that the measure of on-line sensitivity to phonotactic information is not equivalent to the measure of phonotactic sensitivity developed in Experiment 1. In Experiment 1, the correlation between phonotactic sensitivity for *nonword* stimuli and word recognition performance as scored by the NU-6 approached significance, suggesting that spoken word recognition ability might be related to sensitivity to the sequences of sound patterns found in *nonwords*. Recall, however, that the task in Experiment 1 was a word-likeness rating task. The word-likeness rating task did not have time demands (i.e., it was a post-perceptual task) and listeners were required to rate nonwords in relation to real words. Thus, participants may have had time for lexical representations to become partially activated and may have relied on the activation of those partially activated lexical representations to perform the task, even though the sound patterns they were presented with were nonwords (see also Vitevitch et al., 1997). For example, nonwords that had common segments and sequences of segments may have activated more lexical representations than nonwords that had less common segments and sequences of segments, resulting in the difference in ratings as a function of phonotactic probability observed in Experiment 1.

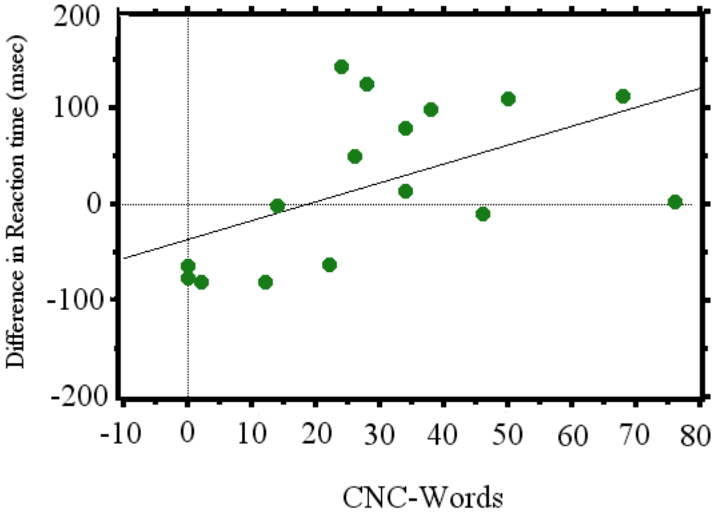

Figure 5. Scatterplot for a measure of on-line phonotactic sensitivity (the difference in reaction times to high and low probability nonword stimuli in the AX task) and a measure of spoken word recognition ability (NU-6) for the cochlear implant users in Experiment 2.

In contrast, the listeners in the present experiment were under time-pressure to respond to the nonwords quickly. This time pressure made decisions to nonwords based on partial activation of lexical representations more difficult. Thus, responses to nonwords in the present experiment were based on more completely activated sublexical representations. Real words, however, activate lexical representations more completely, allowing for decisions regarding real-words to be based on activation among lexical representations. The activation among lexical representations for real-words, and the absence of this activation for the nonwords in the present same-different task accounts for the relationship between the measure of on-line sensitivity to phonotactic information for words and the NU-6 scores, and for the lack of a relationship between the measure of on-line sensitivity to phonotactic information for nonwords and the NU-6 scores.

Discussion

The results from the same-different task used in Experiment 2 show that cochlear implant listeners with average word recognition ability (Low-NU-6 group) did not differentially respond to stimuli varying in lexicality (word or nonword) and phonotactic probability. In contrast, cochlear implant listeners with better than average word recognition ability (High-NU-6 group) tended to respond more quickly to words with low rather than high phonotactic probability. In the case of nonwords, the group of listeners with High-NU-6 scores responded more quickly to nonwords with high rather than low phonotactic probability.

The pattern of results for the cochlear implant users with High-NU-6 scores replicates the pattern of results obtained by Vitevitch and Luce (1998) with normal-hearing listeners. Vitevitch and Luce (1998) suggested that normal-hearing listeners were making optimal use of two types of information--lexical and sublexical--to process words and nonwords. Cochlear implant patients with better than average word recognition ability (High-NU-6 scores) are also able to make optimal use of detailed lexical and sublexical representations to process spoken words and nonwords. In contrast, cochlear implant patients with average word recognition ability (Low-NU-6 scores) may not be able to construct such detailed representations to optimally process the spoken stimuli. The significant correlation between word recognition score (NU-6) and the measure of on-line sensitivity to phonotactic information for words further suggests that optimal use of detailed lexical and sublexical representations in the processing of spoken words may also be required for the accurate recognition of isolated words, especially under speeded conditions.

Less than optimal use of lexical and sublexical representations may be due to one of several factors. One possibility is that some listeners may switch back and forth between lexical and sublexical representations to process the input. In Experiment 2 of Vitevitch and Luce (1999), the researchers again used a same-different task, but mixed word pairs and nonword pairs together instead of separating them into distinct blocks as they did in Experiment 1. They found that the difference in reaction time to real words as a function of phonotactic probability was greatly attenuated. They hypothesized that the normal-hearing participants might have been switching back and forth between lexical and sublexical representations either on a trial-by-trial basis or at some unspecified point in the experiment, resulting in the observed attenuation of effects. The cochlear implant patients with poor word recognition skills in the present experiment may also have been switching between lexical and sublexical representations attempting to process the input, resulting in the attenuation of effects observed in the present study for cochlear implant users with poor word recognition abilities.

An alternative, but not necessarily independent, account may be that some cochlear implant patients may construct representations that are more coarsely coded. That is, some patients may not be able to distinguish between phonological segments that differ in voicing or place of articulation (e.g., Doyle et al., 1995). The inability to discriminate among speech sounds varying on a particular dimension may decrease the utility of phonotactic information in processing. For example, a sequence containing an initial stop, the vowel /^/, and a final stop may represent a word with high or low phonotactic probability, such as the word *cup* and the word *tug* respectively. Although there is still sequential information about the sounds contained in the words in the coarsely coded representations, the fine-grained phonetic details that allows one to discriminate between them is absent. Given the coarse coding of segmental information, listeners may be forced to rely on other types of representations, perhaps using only *lexical* information, to process spoken input. To further examine the efficiency with which lexical representations are used by patients with cochlear implant to process words and nonwords, we presented a different set of nonwords varying in phonotactic probability to the same sample of cochlear implant listeners in an auditory lexical decision task in Experiment 3.

Experiment 3

In an auditory lexical decision task, a listener hears a stimulus--either a real word in English or a nonword pattern--and must press an appropriately labeled button on a response box as quickly and as accurately as possible to indicate whether they heard a real word or a nonword. Typically the speed (i.e., reaction time) and accuracy with which listeners respond to the words are the dependent variables. However, in this case, we measured these variables in response to the specially created *nonwords* varying in phonotactic probability. Note that reaction times from only the dominant-hand are typically used in lexical decision experiments. Reaction times from the non-dominant hand are often slower and have much greater variability than responses made by the dominant hand. Thus, the label for nonwords was under the dominant hand in this task.

Our reason for focusing on the processing of nonwords in a lexical decision task comes from Experiment 3 of Vitevitch and Luce (1999; see also Vitevitch, Luce, Pisoni & Auer, 1999). In that experiment, Vitevitch and Luce hypothesized that the demands of the task--discriminating a nonword that does not have a lexical representation from a real word that does have a lexical representation--would require that only lexical representations be used for processing. If the stimulus item activates a lexical representation, listeners will respond that it was a real word. If the stimulus item fails to activate a lexical representation, listeners will respond that it was a nonword. Although sublexical representations by themselves may be useful in assessing whether two stimuli are the same or different as in Experiment 2, sublexical representations alone cannot be used to assess whether a string of phonemes is a real word or a nonword. Rather, a representation in lexical memory must be activated above some threshold for a sequence to be recognized as a real word.

If lexical representations are used to assess the specially constructed set of nonwords varying in phonotactic probability in the lexical decision task, then we might expect to see a reversal in the pattern of reaction times for the nonwords observed in the same-different task. Recall that in the same-different task, sublexical representations were used to process nonwords. In that task, listeners responded to high probability nonwords more quickly than low probability nonwords. In the present experiment, we predict that the nonwords should now be responded to as if they were real words. That is, listeners should now respond to low probability nonwords more quickly than high probability nonwords due to differences in lexical competition.

Furthermore, we predicted that listeners with above average word recognition skills should demonstrate a greater difference in reaction time between the nonwords varying in phonotactic probability than listeners with average word recognition ability. Recall that listeners with above average word recognition ability (the High-NU-6 group) are hypothesized to have more robust and detailed lexical and sublexical representations. It is further hypothesized that listeners with average word recognition skills (the Low-NU-6 group) have lexical and sublexical representations that are not as fine-grained or detailed as the representations of listeners with above average word recognition ability. Listeners who rely on only one type of representation, or on less robust, or more incomplete and underspecified representations may not be able to determine whether a sequence of sounds is a real word in English or a nonsense word to the same extent as listeners with more distinct lexical and sublexical representations. Listeners with more robust, well-specified representations may be more efficient at identifying and recognizing spoken words because these two types of representation interact during processing to further discriminate among possible candidates activated in memory. To further investigate the on-line use of phonotactic information by patients with cochlear implants, listeners were asked to listen to sound patterns and determine as quickly and as accurately as possible whether the sequence was a real word in English or a nonsense word.

Method

Participants

The same listeners who took part in Experiment 2 also participated in the present experiment. Data from the two listeners that were excluded from Experiment 2 were also not analyzed in the present experiment.

Materials

A different set of 50 real words and 50 nonwords used in Vitevitch and Luce (1999) were used in this experiment. The stimuli used in the present experiment were not presented in Experiment 2. Words and nonwords that were classified as low-probability patterns consisted of segments with low segment positional probabilities and low biphone probabilities. For the words, the average segment and biphone probabilities were .2170 and .0110 for the high probability lists and .1440 and .0050 for the low probability lists in the present experiment. For the nonwords, the average segment and biphone probabilities were .1730 and .0070, respectively, for the high probability lists and .0570 and .0010 for the low probability lists in the present experiment.

Similarity Neighborhoods. Frequency-weighted similarity neighborhoods were computed for each stimulus in the same manner as in Experiment 2. The mean log-frequency-weighted neighborhood density values for the high and low probability words were 52 and 39 respectively. The same values for the high and low probability nonwords were 44 and 12 respectively.

Word Frequency. Frequency of occurrence (Kucera & Francis, 1967) was matched for the two probability conditions for the words. Average log word frequency was 2.33 for the low probability words and 2.30 for the high probability words ($F < 1$).

Durations. The durations of the stimuli in the two phonotactic conditions were equivalent. For the words, the high probability items had a mean duration of 665 ms and the low probability items had a mean duration of 671 ms ($F(1,48) < 1$). For the nonwords, the high probability items had a mean duration of 691 ms and the low probability items had a mean duration of 689 ms ($F(1,48) < 1$).

The words and nonwords were spoken one at a time in a list by the same trained phonetician who made the recordings in Experiment 1. All the stimuli were treated in the same way as the stimuli in Experiment 1.

Procedure

Participants were tested individually with the same equipment used in Experiment 2. In the present experiment, the response box had the label "WORD" on the left button and the label "NONWORD" on the right button. Note that the responses to words and nonwords in Vitevitch and Luce (1999) were made by different groups of participants. One group of participants had the WORD label under the dominant hand and the other group had the NONWORD label under the dominant hand. The WORD and NONWORD responses in the present investigation were made by the same group of cochlear implant users with the WORD label under the non-dominant hand and the NONWORD label under the dominant hand. Thus, one must exercise caution in interpreting the WORD responses in the present experiment.

A trial proceeded as follows: The word "READY" appeared in the center of the computer screen for 500ms to indicate the beginning of a trial. Participants were then presented with one of the randomly selected spoken stimuli at 70dB SPL. Reaction times were measured from the onset of the stimulus to the button press response. If the maximum reaction time (3 s) expired, the computer automatically recorded an incorrect response and presented the next trial. Participants were instructed to respond as quickly and as accurately as possible. NONWORD responses were made with the dominant hand.

Half of the trials consisted of real words in English, half of the trials consisted of the nonwords. Also, an equal number of words and nonwords had high and low phonotactic probabilities. Prior to the experimental trials, each participant received ten practice trials. These trials were used to familiarize the participants with the task and were not included in the final data analysis.

Results

To examine the on-line processing of phonotactic information as a function of word recognition ability, a mixed design ANOVA was performed on the mean reaction times with phonotactic probability as a within-participants factor and word recognition skill as a between participants factor. The word recognition skill condition consisted of the same two groups of cochlear implant users as in Experiment 2. Recall that listeners in the High-NU-6 group had significantly higher scores on the NU-6 than listeners in the Low-NU-6 group as determined by a median split of the NU-6 scores. Also recall that the two groups of listeners did not differ in their hearing thresholds as measured by pure-tone averages.

The mean reaction times for each phonotactic condition as a function of lexicality and word recognition ability are shown in Figure 6. The top panel shows data plotted from the normal hearing listeners that participated in Experiment 3 in Vitevitch and Luce (1999). These data are presented for comparison only and were not included in the following analyses. The middle panel shows the reaction times from the High-NU-6 group. The bottom panel shows the reaction times from the Low-NU-6 group. Lexicality is represented on the *x* axis. "High" refers to words and nonsense words with high phonotactic probability. "Low" refers to words and nonsense words with low phonotactic probability. Accuracy rates for responding NONWORD to the nonwords and WORD to the words in each condition are also presented in the figure.

For the reaction times among the patients with cochlear implants, the main effect of word recognition skill was not significant. That is, there was no significant difference in overall reaction time (F (1,14) = 1.11, $p > .30$) between the two groups of patients (High- and Low-NU-6).

There was a significant main effect of lexicality (F (1,14) = 5.80, $p < .05$), such that words (1349 msec) were responded to more quickly than nonwords (1446 msec) by the cochlear implant patients, even though WORD responses were made with the non-dominant hand that are typically slower than dominant hand responses. More interestingly, the interaction of lexicality and word recognition ability was significant (F (1,14) = 5.04, $p < .05$). Words were responded to more quickly than nonwords for the High-NU-6 group, but not for the Low-NU-6 group. Additional analyses (F (1,7) = 6.47, $p < .05$) confirmed that listeners in the High-NU-6 group responded to words (1251 msec) more quickly than to nonwords (1438 msec), whereas listeners in the Low-NU-6 group did not differentially respond (F (1,7) < 1) to words (1447 msec) and nonwords (1454 msec). These results suggest that patients in the High-NU-6 group were able to discriminate between words and nonwords at some level of processing. Listeners in the Low-NU-6 group were unable to discriminate any differences between words and nonwords. None of the other main effects or interactions were significant for the reaction times (all $p > .10$). Finally, there were no significant differences among the accuracy rates (all $p > .10$).

As in Experiment 2, we calculated a measure of *on-line phonotactic sensitivity* by subtracting the mean reaction time to low phonotactic stimuli from the mean reaction time to high phonotactic stimuli for each listener for the nonwords separately. Because only the High-NU-6 group responded differentially to real words and nonwords in terms of reaction time, measures of on-line phonotactic sensitivity to the nonword stimuli in the lexical decision task were calculated only for the High-NU-6 group. Also, a measure of on-line sensitivity to the real words was not calculated because real word responses were made with the non-dominant hand.

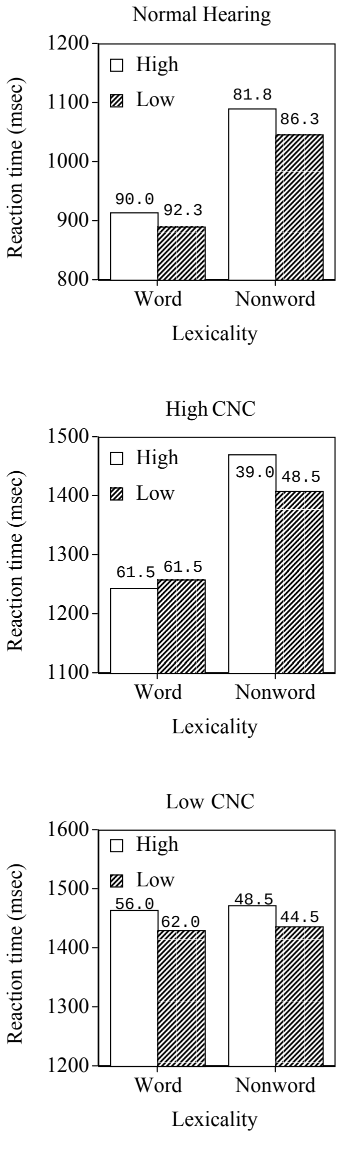

Figure 6. Mean reaction times and accuracy rates to "nonword" responses for normal-hearing listeners from Vitevitch and Luce (1999; top panel), better than average cochlear implant users (High-NU-6; middle panel) and average cochlear implant users (Low-NU-6; bottom panel) in the lexical decision task. "Word" responses for the cochlear implant users were made with the non-dominant hand.

We predicted that the patients in the High-NU-6 group who were more sensitive to the phonotactic information in the nonwords would show a greater difference between the reaction time means. In contrast, the patients who were less sensitive to the phonotactic information in the nonwords during on-line processing would show a smaller difference between the means. If these patients rely primarily on lexical representations rather than sublexical representations to process the nonword stimuli, the difference in the response times between high and low probability nonwords should be negative. That is, listeners should respond more quickly to low probability nonwords than to high probability nonwords because of competition among lexical representations that have been activated by the nonwords. Measures of spoken word recognition skill, such as the score on the NU-6, should be related to the on-line measure of phonotactic sensitivity for the nonwords in the lexical decision task if phonotactic information among lexical representations is used in the processing of spoken words. Listeners with better word recognition ability, even within the High-NU-6 group, should then show greater sensitivity to phonotactic information, whereas listeners with poorer word recognition ability should show less sensitivity to phonotactic information.

An examination of the on-line phonotactic sensitivity for the nonwords in the lexical decision task and the NU-6 scores for the High-NU-6 group revealed that the correlation between these two measures for the nonwords approached significance ($r = -.67$, $Z = -1.84$, $p = .06$). This relationship is displayed in Figure 7. Although the correlation was not statistically significant at the traditional *p*-value of .05, the consistency of this result with the pattern of results obtained across the other experiments suggests that this marginal effect is more than just Type-I error. Overall, the results suggest that the sensitivity to phonotactic information in nonwords and the skills used to recognize isolated words are closely related and draw on the same types of information.

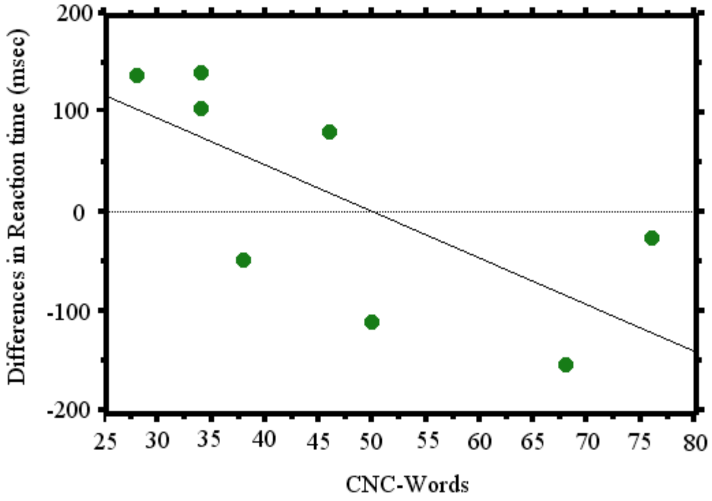

Figure 7. Scatterplot for a measure of on-line phonotactic sensitivity (the difference in reaction times to high and low probability nonword stimuli in the lexical decision task) and a measure of spoken word recognition ability (NU-6) for above average cochlear implant users in Experiment 3.

Discussion

The results from the lexical decision task used in Experiment 3 show that patients with cochlear implants who have average word recognition skills (Low-NU-6 group) were unable to respond differentially to stimuli varying in lexicality (word or nonword) or phonotactic probability. In contrast, cochlear implant patients with better than average word recognition skill (High-NU-6 group) responded more quickly to words than to nonwords, replicating a pattern commonly found in normal-hearing listeners (e.g., Chambers & Forster, 1975; Forster & Chambers, 1973), despite making the response to words with their non-dominant hand. Although listeners in the High-NU-6 group tended to respond to low probability nonwords more quickly (1408 msec.) than high probability nonwords (1469 msec.), this difference was not statistically significant at the $p < .05$ level. When an on-line measure of phonotactic sensitivity was calculated for the nonword responses from the High-NU-6 listeners, a negative correlation ($r = -.67$) that approached significance ($p = .06$) was found between this measure and listeners' scores on the NU-6. This pattern of results suggest that patients with cochlear implants who have better than average word recognition skills are able to make optimal use of detailed lexical and sublexical representations to process the spoken stimuli. That is, information about the sounds and sequences of sounds in a word (i.e., phonotactic information) may still be included in the cognitive repertoire of some cochlear implant users.

In contrast, cochlear implant patients with average word recognition skill may not have such detailed representations to optimally process spoken input and may rely on alternative cognitive strategies. The inability of average users of a cochlear implant (the Low-NU-6 group) to even differentially respond to words and nonwords further suggests that these listeners are not relying on optimal processes and representations of sound-based information. At present, the exact nature of the processes and representations used by average cochlear implant listeners is unclear. Such listeners may be relying on either lexical or sub-lexical representations that are more coarsely coded than analogous representations in normal-hearing listeners or better than average cochlear implant users. Alternatively, listeners may switch back and forth between lexical and sublexical representations to process the input, or may rely solely on alternative representations to process spoken input. As stated earlier, both accounts may ultimately interact and influence each other.

General Discussion

The results of Experiments 1-3 demonstrate the importance of using behavioral tasks that measure on-line processing along with tasks that measure post-perceptual processing. The results of Experiment 1 suggested that patients with cochlear implants who have average and above average word recognition skills were able to access information related to the sequences of sounds (i.e., phonotactic information) to make judgments of spoken nonwords. In contrast, the results of Experiments 2 and 3 indicate that only those cochlear implant patients with above average word recognition skill use this information for the on-line processing of spoken input. Although cochlear implant patients with only average word recognition skills can access phonotactic information to make explicit judgments of spoken nonwords, they may not rely on this information consistently or optimally, and they may not use this information to process spoken input in real time under speeded conditions. We hypothesized that one possible reason cochlear implant users with average word recognition ability may not rely on phonotactic information may be related to the ability to discriminate among the finer details of lexical or sublexical representations. The ability to discriminate among the finer details of lexical or sublexical representations should not be confused with the ability of the patients to detect sounds. Recall that in all three experiments, patients in the High- and Low-NU-6 groups had equivalent hearing thresholds as measured by pure-tone averages, suggesting that the locus of these effects are not in peripheral or sensory systems.

Rather, this research examined the ability of cochlear implant patients to encode and represent the fine phonetic details of speech.

Further experimentation examining the time course of processing phonotactic information is required. The present experiments, however, are important in demonstrating that some patients with cochlear implants can access and process information about the probability of segments and sequences of segments in words and nonwords (i.e., phonotactic information), much like normal-hearing listeners. Furthermore, this source of information is correlated with performance in recognizing isolated spoken words. The relationship observed here between phonotactic sensitivity and spoken word recognition suggests that interventions that explicitly focus attention on phonotactic relationships among sound patterns in words and nonwords may help less successful users develop improved spoken word recognition abilities, and therefore receive greater benefit from their cochlear implant. Additional work will be required to examine the efficacy of such interventions and identify the locus of any effects of these methods in changing the word recognition and comprehension skills of patients with cochlear implants. The three tasks that were used and the index of phonotactic sensitivity developed in the experiments reported could also offer a new method for measuring and assessing outcome of word recognition and comprehension skills for patients who receive cochlear implants.

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