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Effects of Phonotactic Probabilities on the Processing of Spoken Words and Nonwords by Adults with Cochlear Implants Who Were Postlingually Deafened

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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 recognizing spoken words in listeners with normal hearing. Two online tasks (an auditory same-different task and an auditory lexical decision task) were used to examine the use of phonotactic information by adults who were postlingually deafened who have received cochlear implants. The results of the experiments showed that cochlear implant patients with better word recognition abilities (as measured by the Northwestern University Auditory Test No. 6 *(NU-6) produced patterns of results that were similar to the pattern of results obtained from listeners with normal hearing in Vitevitch and Luce (1999). This finding suggests that cochlear implant patients with better word recognition abilities use lexical and sublexical representations to process spoken words, much like listeners with normal hearing. In contrast, cochlear implant patients with poor word recognition abilities could not differentiate between stimuli varying in phonotactic probability and lexicality, suggesting that less distinct representations are used by these*

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patients to process spoken words. The implications of these results for outcome assessments and clinical interventions are discussed.

Introduction

Phonotactic information refers to the sequential arrangement of phonetic segments in morphemes, syllables, and words. 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 (Jusczyk, Frederici, Wessels, Svenkerud, & Jusczyk, 1993). Instead of describing phonotactic information as a set of rules that specifies those sequences of segments that are legal or illegal in a language, recent work has explored the *probabilistic* nature of phonotactic constraints (Jusczyk, Luce, & Charles-Luce, 1994; Kessler & Treiman, 1997; Mattys, Jusczyk, Luce, & Morgan, 1999; Storkel & Rogers, 2000; Treiman, Kessler, Knewasser, Tincoff, & Bowman, 2000; Vitevitch & Luce, 1998, 1999; Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997). In other words, rather than use stimuli that contained either legal or illegal sequences, researchers have created stimuli that were completely legal in a given language, but that varied in how common the segments and sequences were in that language.

In an experiment using phoneme sequences varying in phonotactic probability, Vitevitch and colleagues (1997; see also Messer, 1967) found that adults with normal hearing were sensitive to the probabilities with which segments and sequences of segments occur in the language. When participants heard bisyllabic, nonword stimuli, Vitevitch and colleagues (1997) found that participants rated the word-likeness of stimuli with common segments and sequences of segments (i.e., high phonotactic probability) as being better-sounding possible words than stimuli with rarer segments and sequences of segments (i.e., low phonotactic probability). When another group of participants repeated the same nonwords presented auditorily, Vitevitch and colleagues (1997) found that the participants responded to nonwords with high-probability patterns more quickly than nonwords with low-probability patterns. Taken together, these results suggest that adults with normal hearing are sensitive to the distribution with which segments and sequences of segments occur in the language and may use this knowledge to recognize spoken words (see also Vitevitch & Luce, 1998, 1999; Vitevitch, Luce, Pisoni, & Auer, 1999).

To further investigate the influence of phonotactic information on the processing of spoken words, Vitevitch and Luce (1998, 1999) used a variety of tasks to present adults with normal hearing with monosyllabic words and nonwords that varied in phonotactic probability. In Experiment 1, Vitevitch and Luce (1999) used a same-different (or AX) task that measures the online processing of listeners who hear a pair of stimuli separated by a short interval of time (e.g., 200 ms). Listeners must decide if the pair of stimuli they heard are the same or different. Looking just at the trials in which the same word or the same nonword appeared, Vitevitch and Luce (1998, 1999) found that for nonwords varying in phonotactic probability, stimuli with high-probability patterns were responded to more quickly than stimuli with low-probability patterns. In contrast, for real words, stimuli with low-probability patterns were responded to more quickly than real-word stimuli with high-probability patterns. Based on these results (Pitt & Samuel, 1995), Vitevitch and Luce (1998, 1999) hypothesized that listeners with normal hearing 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.

Vitevitch and Luce (1998, 1999) further hypothesized that the most efficient representation dominates processing of the spoken sound pattern. In other words, when lexical representations are used to process spoken stimuli, competition among similar-sounding word forms activated in memory will be observed. Note that there is a correlation between the frequency of a segment or sequence of segments and the number of words that are activated and compete among each other for recognition (Vitevitch et al., 1999). Common patterns of segments and sequences of segments are found in many words that sound similar. Rare patterns of segments and sequences of segments are found in few similar-sounding words. As demonstrated by Luce and Pisoni (1998), participants generally respond more quickly to words that activate few similar-sounding words in memory (i.e., low phonotactic probability) than words that activate many similar-sounding words in memory (i.e., high phonotactic probability).

In contrast, when sublexical representations are used to process spoken sound patterns, stimuli with common segments and sequences of segments will be processed more quickly than stimuli with less common segments and sequences of segments. Thus, in the AX task of Vitevitch and Luce (1999) participants were using lexical representations to process the spoken words they heard and sublexical representations to process the nonwords, suggesting that listeners with normal hearing may use at least two types of representation to recognize spoken input.

If two types of representation are being used to process spoken language and the most efficient representation dominates processing, Vitevitch and Luce (1999) hypothesized, then real words and nonwords presented in an auditory lexical decision task would both show effects of lexical competition. 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 he or she heard a real word or a nonword. Typically the speed (i.e., reaction time) with which listeners respond to the words is the dependent variable. In this case, however, Vitevitch and Luce (1999) measured the response time for the real words as well as the specially created nonwords varying in phonotactic probability.

Vitevitch and Luce (1999) reasoned that the demands of the task—discriminating a nonword without 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 activated a lexical representation, listeners would respond that it was a real word. If the stimulus item failed to activate a lexical representation, listeners would respond that it was a nonword. Although sublexical representations by themselves may be useful in assessing whether two stimuli are the same or different, 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, forcing listeners to use lexical representations to process all of the spoken stimuli they heard. Thus, when participants use lexical representations to process real words or nonwords that vary in phonotactic probability, they will respond more quickly to stimuli with low phonotactic probability than stimuli with high phonotactic probability. Recall that stimuli with low phonotactic probability activate few similar-sounding words in memory, whereas stimuli with high phonotactic probability activate many similar-sounding words in memory. The results of the lexical decision task used in Experiment 3 of Vitevitch and Luce (1999) supported their hypothesis: Participants responded to both real words and nonwords with low phonotactic probability more quickly than they responded to real words and nonwords with high phonotactic probability. These results support the hypothesis that either lexical or sublexical representations may be used by listeners with normal hearing to process spoken stimuli depending on the demands of the task.

In the present study, we also examined the use of lexical and sublexical representations to process spoken sound patterns. As in Vitevich and Luce (1999), we changed the task for participants, who varied in their word recognition ability. Although there is little variability among listeners with normal hearing in terms of their ability to recognize words spoken in isolation, there is considerable variability among adults who were postlingually deafened who use cochlear implants with regards to word recognition ability. The adults who were postlingually deafened who participated in this set of experiments were all patients who had acquired language with normal hearing. Later in life, these individuals became profoundly deaf through trauma or disease and had subsequently received and used cochlear implants for at least one year.

A cochlear implant (CI), a surgically implanted prosthetic device that bypasses the damaged inner ear hair cells and transduces an auditory signal into an electrical signal that stimulates the auditory nerve (Wilson, 2000), provides patients with profound hearing loss with useable forms of auditory stimulation. A typical multichannel CI 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 effectiveness of CIs in adults (across the several types of systems and processing strategies) ranges from being able to follow a conversation on the telephone to being able merely to detect the presence or absence of sound (e.g., Blamey, Dowell, Brown, Clark, & Seligman, 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).

We hypothesized that those CI users with good word recognition ability (as measured by a monosyllabic word test, the NU-6 [Tillman & Carhart, 1966]) use both types of representations more effectively than CI users with poor word recognition ability. Therefore, CI users with good word recognition ability (high NU-6 scores) should show a pattern of results in an AX task with stimuli varying in phonotactic probability that is similar to the pattern of results observed in Experiment 1 of Vitevitch and Luce (1999). In other words, CI users with good word recognition skills should respond more quickly to real words with low, rather than high, phonotactic probability and more quickly to nonwords with high, rather than low, phonotactic probability.

In contrast, we hypothesized that users with poor word recognition ability (low NU-6 scores) do not receive fine-grained acoustic details from their implants, resulting in broader phonological representations being used less effectively while processing spoken input. We predicted that implant users with poor word recognition ability would show a pattern of results similar to the pattern of results observed in the AX task in Experiment 2 of Vitevitch and Luce (1999).

In Experiment 2 of Vitevitch and Luce (1999), listeners with normal hearing heard real words and nonwords in a single block (rather than in separate blocks, as in their Experiment 1). Vitevitch and Luce found that the listeners with normal hearing did not respond differentially to the real words that varied in phonotactic probability as listeners had when the real words and nonwords were presented separately. They hypothesized that on some trials, listeners were using lexical representations and on others they were using sublexical representations to process the word pairs they were hearing. Persistence in using sublexical representations to process real words—perhaps because the listener had just responded to a nonword pair—would result in participants not making overall efficient use of either type of representation in their responses to real words. In the case of CI users with poor word recognition ability, the broader phonological representations may also result in less efficient use of either type of representation in their responses. That is, CI users with poor word recognition ability may also switch between lexical and sublexical representations from trial to trial, resulting in an overall failure to respond differentially to stimuli that varied in phonotactic probability.

To test these hypotheses, we used a subset of the monosyllabic real words and nonwords varying in phonotactic probability used in Vitevitch and Luce (1999). In the present study, we presented this subset of stimuli to CI users who differed in their spoken word recognition abilities (as measured by the NU-6) in an auditory AX task in Experiment 1 and an auditory lexical decision task in Experiment 2.

Experiment 1

Methods

Participants. Eighteen adult patients with cochlear implants, all outpatients at the Indiana University Medical Center, were paid for their participation in this experiment. Data from 2 participants were not included in the final analysis because 1 participant was prelingually deafened, and the other participant experienced technical problems during testing when the battery in the processor ran out. The remaining participants were all right-handed, native English speakers who were deafened after acquiring knowledge of English phonotactics (Jusczyk et al., 1993; Jusczyk et al., 1994; Mattys et al., 1999) and had used their cochlear implant for at least 1 year prior to testing.

The mean age of the participants was 55.9 years. The mean age at onset of deafness was 34.0 years. The mean age at implantation was 53.3 years. Nine participants used a Nucleus® device, 5 used the Clarion® device, and 2 used the Med-El COMBI device. See Table I for individual participant information.

The CI users were divided into two groups based on word recognition ability. A median split on the NU-6 (Tillman & Carhart, 1966) scored by percent words correct for each user served as the criterion to divide the CI users into the two groups of 8 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 12.5%. The difference in the NU-6 scores between the groups was significantly different, $F(1,14) = 22.64$, $p < .001$.

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

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 (two-segment sequence) frequency—and with the same computerized dictionary used in Vitevitch and Luce (1999). Real words and nonwords

Table I. Individual Characteristics of the Cochlear Implant Users in Our Study

Participant	Age in Years	Age at Onset of Deafness	Etiology	Age at Implantation	Type of Implant and Processing Strategy	Years of Implant Use	NU-6 Word[a]	NU-6 Phone[b]	NU-6 Cond.
1	60	18	unknown	56	Clarion®–CIS	4	0	13	LOW
2	44	27	otosclerosis	42	Med-El–SPEAK	2	28	53	HIGH
3	53	49	unknown	51	Nucleus® 24–SPEAK	2	50	69	HIGH
4	69	21	genetic	67	Nucleus® 24–SPEAK	2	12	33	LOW
5	71	10	unknown	63	Nucleus® 22–SPEAK	8	14	30	LOW
6	37	30	unknown	34	Clarion®–CIS	3	76	90	HIGH
7	68	43	Ménière's	62	Clarion®–CIS	6	68	83	HIGH
8	69	40	Ménière's	68	Clarion®–CIS	1	38	61	HIGH
9	48	44	hereditary	47	Nucleus® 22–SPEAK	1	24	41	LOW
10	39	3	unknown	33	Clarion®–CIS	5	34	59	HIGH
11	71	63	hereditary	68	Med-El–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
M	55.9	34.0		53.3		2.68			

[a]NU-6 percent words correct; [b]NU-6 percent phonemes correct

that were classified as high-probability patterns consisted of segments with high segment positional probabilities. Real words and nonwords that were classified as low-probability patterns consisted of segments with low segment positional probabilities and low biphone probabilities. For the real words, the average segment and biphone probabilities were .1740 and .0070, respectively, for the high-probability lists and .0960 and .0030, respectively, for the low-probability lists. For the nonwords, the average segment and biphone probabilities were .1550 and .0050, respectively, for the high-probability lists and .0670 and .0010, respectively, for the low-probability lists.

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 real 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 real words were 45 and 30, respectively.

Word frequency. Frequency of occurrence (Kučera & Francis, 1967) was matched for the two probability conditions for the real 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 real 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 same digital audio files used in Vitevitch and Luce (1999) were used in the present set of experiments. The real words and nonwords were spoken one at a time in a list by a trained phonetician. All stimuli were low-pass filtered at 4.8 kHz and digitized at a sampling rate of 10 kHz using a 12-bit analog-to-digital converter. Stimuli were edited into individual files and stored on computer disk.

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 (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 500 ms to indicate the beginning of a trial. Participants were then presented with two of the spoken stimuli at 70 dB SPL. The interstimulus 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. 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. Because of differences in reaction times between nondominant- and dominant-hand responses (Kauranen & Vanharanta, 1996), only reaction times from dominant-hand responses were analyzed.

The real words and nonwords were 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. Nonmatching 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.

Each participant was allowed 10 practice trials prior to the experimental trials. These trials were used to familiarize the participants with the task and were not included in the final analysis.

Results

To examine the online processing of phonotactic information as a function of word recognition ability, a mixed-design analysis of variance (ANOVA) was performed on the mean reaction times, with phonotactic probability and lexicality as within-participants factors and word recognition ability as a between-participants factor. The mean reaction times and accuracy rates for each phonotactic condition as a function of lexicality and word recognition ability are shown in Table II. The two columns headed "Normal Blocked" and "Normal Mixed" show data from the listeners with normal hearing who participated in Experiment 1 (blocked AX task) and Experiment 2 (mixed AX task) in Vitevitch and Luce (1999). These data are provided for comparison only and were not included in the statistical analyses below. The two right columns show the reaction times and accuracy rates from the High NU-6 and the Low NU-6 group.

For the accuracy rates, the results showed no significant effects for responding *SAME* across all the conditions (all $Fs < 1$). These results suggest that participants did not sacrifice speed for accuracy in making their responses. These results also demonstrate that both groups of patients were accurate in identifying real word and nonword pairs as the *same*. Finally, these results show that the High NU-6 group was as accurate as the Low NU-6 group in responding to the stimuli heard.

Table II. Reaction Times and Accuracy Rates from Experiment 1

			Normal Blocked	*Normal Mixed*	*High NU-6*	*Low NU-6*
Words	High	RT	972 ms	881 ms	999 ms	1020 ms
		% Correct	97.5%	98.6%	89.0%	83.5%
	Low	RT	926 ms	869 ms	955 ms	1039 ms
		% Correct	98.3%	98.1%	91.0%	85.5%
Nonwords	High	RT	1055 ms	916 ms	937 ms	1035 ms
		% Correct	92.5%	96.9%	90.0%	86.5%
	Low	RT	1102 ms	984 ms	1028 ms	1064 ms
		Correct	92.9%	96.8%	90.5%	82.0%

For the reaction times, the results showed no significant main effects (all Fs < 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 nonsignificant 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, $F(1,14) = 6.30$, $p < .05$.

Subsequent analyses of the Lexicality × Phonotactic Probability interaction revealed that for real words participants tended to respond to low-probability stimuli more quickly (997 ms) than high-probability stimuli (1009 ms); however, this difference did not reach statistical significance, $F(1,14) < 1$. For the nonwords, though, the opposite pattern was observed. Participants responded to high-probability nonwords more quickly (987 ms) than low-probability nonwords (1046 ms): $F(1,14) = 11.53$, $p < .01$. Although not statistically significant, this pattern is fundamentally similar to the pattern of data for listeners with normal hearing found in Vitevitch and Luce (1999), which is displayed in the "Normal Blocked" column of Table II.

Consider now the Lexicality × Phonotactic Probability × Word Recognition Ability interaction. For the Low NU-6 group, there were no significant differences in the response times for real words and nonwords, or between high- and low-probability stimuli (all Fs < 1). For the High NU-6 group, however, 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 (955 ms) than to real words with high phonotactic probability (999 ms): $F(1,14) = 4.62$, $p = .07$. For nonwords, on the other hand, listeners in the High NU-6 group responded significantly more quickly to high-probability nonwords (937 ms) than low-probability nonwords (1028 ms): $F(1,14) = 20.06$, $p < .01$.

The pattern of data observed for the High NU-6 group was similar to the pattern of data found in the blocked AX task used in Vitevitch and Luce (1999, Experiment 1). This pattern of data suggests that listeners in the High NU-6 group were using lexical and sublexical representations in an optimal manner, much like the listeners with normal hearing in the blocked AX task used in Vitevitch and Luce (1999, Experiment 1). The pattern of data observed for the Low NU-6 group was similar to the pattern of data found in the mixed AX task used in Vitevitch and Luce (1999, Experiment 2). This pattern of data suggests that listeners in the Low NU-6 group were not using lexical and sublexical representations in an optimal manner (or perhaps even at all), much like the listeners with normal hearing in the mixed AX task used in Experiment 2 of Vitevitch and Luce (1999).

Discussion

The results from the AX task used in the present experiment show that CI users with poor word recognition ability (Low NU-6 group) did not respond differentially to stimuli varying in lexicality (real word or nonword) and phonotactic probability. In contrast, CI users with good 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 CI users with high NU-6 scores replicated the pattern of results obtained by Vitevitch and Luce (1999) with listeners with normal hearing. Vitevitch and Luce (1999) suggested that listeners with normal hearing were making optimal use of two types of information—lexical and sublexical—to process real words and nonwords. CI users with high NU-6 scores also seem to use these two types of representation to process spoken words and nonwords optimally. In contrast, CI users with low NU-6 scores apparently do not use these two types of representation to optimally process the spoken stimuli. 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 as hypothesized in Experiment 2 of Vitevitch and Luce (1999). The CI users with poor word recognition skills in the present study may also have been switching between lexical and sublexical representations in attempting to process the input, resulting in the attenuation of effects observed in the present study for CI users with poor word recognition abilities.

An alternative, but not necessarily independent, account may be that some CI users may construct representations that are more coarsely coded. In other words, 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 /ʌ/, 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 on the sounds contained in the words in the coarsely coded representations, the fine-grained phonetic details that allow one to discriminate between them are 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 CI users to process real words and nonwords, we presented a different set of nonwords that varied in phonotactic probability to the same sample of CI listeners in an auditory lexical decision task in Experiment 2.

Experiment 2

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 he or she had 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. In this case, however, we measured these variables in response to the specially created nonwords varying in phonotactic probability.

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 et al., 1999). In that experiment, Vitevitch and Luce hypothesized that the demands of the task—discriminating a nonword without a lexical representation from a real word with one—would require that only lexical representations be used for processing. The results of that experiment showed that participants responded to nonwords with low phonotactic probability more quickly than nonwords with high phonotactic probability. This pattern was similar to the pattern of results observed for real words in the same task, suggesting that lexical representations were being used to process the spoken input. The reversal in the pattern of the reaction times for the nonwords (compared to the pattern observed in the AX task) suggests that there is some flexibility in the use of lexical and sublexical representations in the processing of spoken stimuli. Specifically, listeners with normal hearing are able to dynamically shift between cognitive processing strategies depending on the demands of the task.

If CI users use lexical and sublexical representations in an optimal and efficient manner like listeners with normal hearing, they should also show a reversal in reaction times to nonwords (relative to the nonwords in the AX task). That is, in a lexical decision task, CI users should dynamically shift to using lexical representations to process all of the spoken input they hear and should respond more quickly to nonwords with low phonotactic probability than to those with high phonotactic probability. To examine how efficiently CI users can use lexical and sublexical representations, we presented a different set of nonwords varying in phonotactic probability to the same sample of CI listeners in an auditory lexical decision task.

Methods

Participants. The same listeners who took part in Experiment 1 also participated in the present experiment. Data from the 2 listeners who were excluded from Experiment 1 were also not analyzed in the present Experiment 2.

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 1. Real words and nonwords that were classified as low-probability patterns consisted of segments with low segment positional probabilities and low biphone probabilities. For the real words, the average segment and biphone probabilities were .2170 and .0110, respectively, for the high-probability lists and .1440 and .0050, respectively, for the low-probability lists. For the nonwords, the average segment and biphone probabilities were .1730 and .0070, respectively, for the high-probability lists and .0570 and .0010, respectively, for the low-probability lists.

Similarity neighborhoods. Frequency-weighted similarity neighborhoods were computed for each stimulus in the same manner as Experiment 1. 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 (Kučera & 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 real 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, $F(1,48) < 1$.

Procedure. Participants were tested individually with the same equipment used in Experiment 1. 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 real words and nonwords in Experiment 3 of Vitevitch and Luce (1999) were made by different groups of participants. One group of listeners had the *WORD* label under the dominant hand and the other group had the *NONWORD* label under the dominant hand. The same group of CI users made the *WORD* and *NONWORD* responses in the present experiment, with the *WORD* label under the nondominant hand and the

NONWORD label under the dominant hand. Thus, one must interpret the *WORD* responses in the present experiment with caution.

A trial proceeded as follows: The word *READY* appeared in the center of the computer screen for 500 ms to indicate the beginning of a trial. Participants were then presented with one of the randomly selected spoken stimuli at 70 dB 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, and half of the trials consisted of the nonwords. An equal number of real words and nonwords had high and low phonotactic probabilities. Each participant was allowed 10 practice trials prior to the experimental 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 online 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 CI users as in Experiment 1. 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 mean aided pure-tone averages (PTAs).

The mean reaction times for each phonotactic condition as a function of lexicality and word recognition ability are shown in Table III. Data from the listeners with normal hearing who participated in Experiment 3 in Vitevitch and Luce (1999) are presented in the "Normal Blocked" column of Table III. These data are presented for comparison only and were not included in the following analyses. The middle column shows the reaction times and accuracy rates from the High NU-6 group, and the right column shows the reaction times and accuracy rates from the Low NU-6 group.

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

There was a significant main effect of Lexicality, $F(1,14) = 5.80$, $p < .05$, such that CI users responded to real words (1349 ms) more quickly than nonwords (1446 ms), even though *WORD* responses were made with the nondominant hand, which are typically slower than dominant-hand responses. More interestingly, the interaction of lexicality and word recognition ability was significant, $F(1,14) = 5.04$, $p < .05$. Real words were responded to more quickly than nonwords by the High NU-6 group, but not by 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 real words (1251 ms) more quickly than to nonwords (1438 ms), whereas listeners in the Low NU-6 group did not respond differentially to real words (1447 ms) and nonwords (1454 ms), $F(1,7) < 1$. These results suggest that patients in the High NU-6 group were able to discriminate between real words and nonwords to some degree. Listeners in the Low NU-6 group were unable to discriminate any differences between real 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 $p > .10$).

Table III. Reaction Times and Accuracy Rates from Experiment 2

			Normal Blocked	*High NU-6*	*Low NU-6*
Words	High	RT	972 ms	999 ms	1020 ms
		% Correct	97.5%	89.0%	83.5%
	Low	RT	926 ms	955 ms	1039 ms
		% Correct	98.3%	91.0%	85.5%
Nonwords	High	RT	1055 ms	937 ms	1035 ms
		% Correct	92.5%	90.0%	86.5%
	Low	RT	1102 ms	1028 ms	1064 ms
		% Correct	92.9%	90.5%	82.0%

To further assess the use of sublexical and lexical representations among CI users, we analyzed the results of Experiment 1 and Experiment 2 in a mixed ANOVA, as in Vitevitch and Luce (1999). Phonotactic probability was a within-participants factor, and experimental task was a between-participants factor. If CI users used sublexical representations to process nonwords in the AX task (Experiment 1) and lexical representations to process nonwords in the lexical decision task (Experiment 2), then a significant interaction between phonotactic probability for the nonwords and experimental task should be found for CI users with high NU-6 scores. Our analysis confirmed this prediction, $F(1,14) = 9.93$, $p < .01$. That is, the pattern of results for the nonwords varying in phonotactic probability in Experiment 1 were significantly different from (indeed, the opposite of) the pattern of results for the nonwords varying in phonotactic probability in Experiment 2 for CI users with good word recognition ability. This result also replicates the findings of Vitevitch and Luce (1999) using listeners with normal hearing and further suggests that CI users with good word recognition ability are using lexical and sublexical representations to process spoken words.

Discussion

The reaction time results from the lexical decision task used in Experiment 2 show that CI users with low NU-6 scores were unable to respond differentially to stimuli varying in lexicality (real word or nonword) and phonotactic probability. The accuracy with which CI users with low NU-6 scores indicated whether they heard a real word or a nonword also did not differ as a function of lexicality and phonotactic probability. These results suggest that CI users with low NU-6 scores do not use lexical and sublexical representations in an optimal manner, as do listeners with normal hearing, to process spoken input. This is not to say that such patients do not use lexical and sublexical representations at all. Rather, CI users with low NU-6 scores might not use this information in an online manner to process spoken input. They may instead use this information to constrain other strategies used primarily to process spoken input. Note that CI users with low NU-6 scores were approximately as accurate in the lexical decision task as CI users with high NU-6 scores, suggesting that they were somewhat able to discriminate real words from nonwords. This result suggests that lexical and sublexical representations may have been used, just not very efficiently, by CI users with low NU-6 scores.

General Discussion

At present, the exact nature of the processes and representations used by CI listeners with poor word recognition ability is unclear. Such listeners may be relying on either lexical or sublexical representations that are more coarsely coded than analogous representations in listeners with normal hearing or CI users with good word recognition ability. Alternatively, such listeners may switch back and forth between lexical and sublexical representations to process the input, or may rely on representations other than lexical and sublexical to process spoken input. Both accounts may ultimately prove to be correct.

In contrast, CI users with good word recognition ability responded more quickly to real words than to nonwords, replicating a pattern commonly found in listeners with normal hearing (e.g., Chambers & Forster, 1975; Forster & Chambers, 1973), despite making the response to real words with their nondominant hand. More important, listeners in the High NU-6 group responded to nonwords with low probability more quickly than to nonwords with high probability in the lexical decision task, but responded to nonwords with high probability more quickly than to nonwords with low probability in the AX task. The statistically significant interaction of response times to nonwords in the lexical decision task relative to the AX task replicates the findings of Vitevitch and Luce (1999), suggesting that CI users with good word recognition ability, like listeners with normal hearing, use lexical and sublexical representations to process spoken words.

The results of the present set of experiments extend the work of Kirk, Pisoni, and Miyamoto (1997) and Vitevitch and Luce (1999). Kirk and colleagues (1997) found that CI users responded differently to *lexically easy* and *lexically hard* words, suggesting that spoken word recognition in CI users occurs within the context of activation among multiple lexical representations. Vitevitch and Luce (1999) found that, among listeners with normal hearing, sublexical as well as lexical representations were used to process spoken words. The results of the present experiments show that CI users not only use lexical representations, as suggested by Kirk and colleagues (1997), but also use sublexical representations to process spoken words (see Vitevitch and Luce, 1999, with listeners with normal hearing).

Finally, the results of the present set of experiments suggest that the use of tasks that measure online rather than offline processing may lead to a better understanding of the processes and representations used by various clinical populations to perform cognitive and perceptual tasks (Tompkins, 1998). Improved understanding of the cognitive processes and linguistic representations used by CI users may promote the development of new methods for measuring and assessing outcome of word recognition and comprehension skills for CI users. Furthermore, interventions that explicitly focus attention on phonotactic relationships among sound patterns in real words and nonwords may help less successful users develop improved spoken word recognition abilities and, therefore, receive greater benefit from their 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 CI users.

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