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Use of Gap Duration Identification in Consonant Perception by Cochlear Implant Users[1]

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Abstract. Cochlear implant (CI) users show substantial individual differences in their ability to understand speech. Even the most successful CI users do not understand speech as well as normal hearing listeners. One explanation for these individual differences and limited speech perception abilities lies in their difficulty in discriminating or identifying spectral cues (e.g., formant frequencies; Tong & Clark, 1985). In contrast to their discrimination of spectral cues, CI users are quite proficient in perceiving temporal cues. It has been demonstrated that postlingual adult CI users can detect the presence or absence of a gap in an acoustic stimulus as well as listeners with normal hearing (Shannon, 1989). Although detecting silent gaps within speech sounds is known to be important in consonant identification, the ability to discriminate between gaps of different duration may also be important. For example, the gap in "acha" is longer than the gap in "aba" and may be a cue for differentiating these phonemes. The present study examined the ability of listeners who use CIs and listeners with normal hearing to identify gaps of varied duration. After a short period of training, nine postlingual adult CI users and five adult listeners with normal hearing were presented with one of seven one-second synthetic vowel-like stimuli generated with Klatt 88 software (Klatt & Klatt, 1990). One stimulus was continuous, while the other six contained an intervening gap ranging in length from 15 to 90 ms. This range was chosen to encompass the range of silent gaps found in English consonants. Each listener was asked to identify the stimulus that was presented. This task was repeated until performance reached plateau. A *d'* was calculated for each pair of adjacent stimuli from the identification scores. All listeners, normal hearing and CI users, were able to perfectly discriminate the continuous stimulus from the stimulus with the 15 ms gap. However, the ability to differentiate among stimuli with gaps ranging from 15 to 90 ms varied between these two groups. The cumulative *d'* for the six gapped stimuli ranged from 6.0 to 6.6 for the normal hearing listeners and from 0.1 to 6.8 for the cochlear implant users. These cumulative *d'* scores were significantly correlated with consonant identification scores on the Iowa Consonant Test for the CI users. In addition, analyses of consonant confusion matrices suggested that CI users do not make optimal use of the temporal information they receive through their implant.

Introduction

Cochlear implants (CIs) are electronic devices that have enabled individuals with severe to profound hearing losses to regain some hearing. Nearly all of those who receive cochlear implants regain the sensation of sound. Some patients receive enough perceptual benefit that they can even communicate using a standard telephone (Dorman et al., 1991). This is a difficult task because there are no visual cues and the signal itself is not optimal. There is, however, substantial variability in speech perception performance among users of cochlear implants (Staller et al., 1997). Unfortunately, there is much we do not know about the exact mechanisms used by listeners with cochlear implants to understand speech. By studying psychophysical mechanisms, researchers have sought to more precisely determine the cues that patients with cochlear implants use for speech perception. A better understanding of these cues may eventually guide the development of better speech processing algorithms, and will also lend insight into the peripheral and central processes involved in speech perception by users of cochlear implants. It is generally accepted that one of the reasons why CI users have more difficulty understanding speech sounds than listeners with normal hearing is that the former are limited in formant perception ability (for a comparison see: McDermott & McKay, 1994; Kewley-Port & Watson, 1994). It is also generally accepted that, in contrast to their discrimination of spectral cues, CI users are quite proficient at perceiving temporal cues. For example, it has been demonstrated that users of cochlear implants can detect the presence or absence of a gap in an acoustic stimulus as well as listeners with normal hearing (Shannon, 1989).

Gap detection, the detection of a silent period within an acoustic or electric stimulus, in contrast to gap identification, has frequently been used to evaluate the temporal ability of users of cochlear implants. Using gap detection, several researchers have studied the ability of postlingualy deafened adults with cochlear implants to detect gaps. They have found that the minimum gap detection threshold for these listeners (Shannon, 1989; Preece & Tyler, 1989; Moore & Glasberg, 1988) is similar to that of normal hearing listeners (Fitzgibbons & Gordon-Salant, 1987; Fitzgibbons 1984, 1983; Fitzgibbons & Wightman, 1982; Florentine and Buus, 1984) , ranging from 2 to 15 ms when sensation level and stimulus characteristics are taken into account. In general, studies of this type have seldom found a strong correlation between gap detection abilities and measures of speech perception. Some have reported a statistically significant correlation between psychophysical and speech perception measures (Hochmair-Desoyer et al., 1985) whereas others have argued against using a gap detection threshold measurement as a predictor of speech recognition (Shannon, 1989). This argument is not surprising because the speech perception measures of subjects with normal hearing and of those with cochlear implants are widely divergent, particularly among users of cochlear implants, yet their gap detection abilities are nearly the same. If gap detection ability is fundamental to speech perception, this would not be expected. It should be noted, however, that the similarity of thresholds for postlingual adult CI users and normal hearing adults may be specific to postlingually deafened CI users: a recent study of prelingually deafened users of cochlear implants has shown substantial variability in gap detection thresholds for congenitally deaf participants but did not find a significant correlation between detection thresholds and their scores on several speech perception measures (Busby & Clark, 1999).

The ability of listeners to detect the presence of acoustic gaps is potentially important in speech perception. For example, some intervocalic consonants, such as in *acha* and *aba*, contain acoustic gaps, while others such as *aza* and *ama* do not. Thus, detection of an acoustic gap may be used to distinguish between sounds. Additionally, the average length of the gap may be a useful cue for phoneme identification. For example, the gap in *acha* is, on average, longer than the gap in *aba* and thus could be a potential cue for identification of these phonemes. Temporal cues such as gap duration may be particularly important for CI users because their perception of spectral cues is significantly worse than that of normal hearing listeners.

In the present study listeners had to identify stimuli containing gaps of lengths ranging from 0 ms (i.e., no gap) to 90 ms. Using this absolute identification task, we evaluated the ability of CI users and normal hearing listeners to identify silent gaps spanning the range of gaps that occur in the English language. One motivation for obtaining these data was to calculate just noticeable differences (JNDs) for gap duration based on *d'*. These measurements are important input to our multidimensional phoneme identification (MPI) model, a quantitative framework that has been proposed to explain the mechanisms employed by CI users to understand speech sounds (Svirsky, 1991; Svirsky & Meyer, 1998; Svirsky, in press). In addition, we aimed to assess the possible relation between performance in this temporal processing task and speech perception by CI users.

Method

Subjects

Fourteen adult listeners were tested in this study. Nine of the listeners were postlingually deafened adult users of cochlear implants who were recruited from the clinical population at Indiana University (Table 1). All of these subjects had profound bilateral sensorineural hearing losses and greater than one year of experience with their device. Each subject was reimbursed for travel to and from testing sessions and for the time of participation. Five of the subjects used the Nucleus 22 device, one used the Nucleus 24 device, and four others used the Clarion device. The comparison group consisted of five adults with normal hearing.

Table 1

Demographics of subjects with cochlear implants (S) and normal hearing (NH)

Subject	Age (Years)	Age at Onset Of Deafness	Age at Implantation	Implant Use (Years)	Implant Type
S1	67	*	65	2	Nucleus 22
S2	41	*	38	2	Clarion 1.0
S3	62	56	57	5	Nucleus 22
S4	69	55	66	2	Nucleus 22
S5	73	27	71	2	Nucleus 22
S6	58	*	52	5	Clarion 1.0
S7	41	32	34	7	Nucleus 22
S8	66	43	61	5	Clarion 1.0
S9	45	42	43	1.7	Clarion S
S10	37	34	36	1.1	Nucleus 24
S11	35	29	31	3	Clarion 1.2
NH1	35	-	-	-	-
NH2	30	-	-	-	-
NH3	25	-	-	-	-
NH4	22	-	-	-	-
NH5	22	-	-	-	-
NH6	32	-	-	-	-

* S1, Progressive; S2, Progressive since childhood; S6, Progressive since childhood

Stimuli and Equipment

Seven stimuli were created using the Klatt 88 speech synthesizer software (Klatt & Klatt, 1990). The first stimulus in the continuum was a synthetic three-formant steady state vowel with a duration of 1 second. Formant frequencies were 500, 1500, and 2500 Hz. Onset and offset of the vowel envelope occurred over a 10 ms period, and this transition was linear (in dB). The other six stimuli were similar to the first one, with the exception that they contained an intervening silent gap of length: 15, 30, 45, 60, 75, or 90 ms. The transitions in volume from full volume to silence (the silent gap) and from silence back up to full volume were made over a period of 10 ms., and they were linear in dB. The gap length was specified as the interval between the midpoint of the upward and downward slopes of the envelope represented in dB. The total amount of energy in each of the seven stimuli was identical, because the stimuli with longer gaps had correspondingly longer duration (see Fig. 1). The stimuli were digitally stored using a sampling rate of 11025 Hz at 16 bits of resolution. They were presented from an Intel® based PC equipped with a SoundBlaster compatible sound card. Stimuli were presented at a level of at least 70 dB C weighted SPL over an Acoustic Research loudspeaker. Custom software was used to present stimuli and record responses.

7

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Figure 1: Graphical representation of psychophysical stimulus waveforms arranged by stimulus number.

Procedure

Subjects were tested using a seven-alternative absolute identification task. Each of the seven stimuli was randomly presented ten times during each block of testing (for a total of 70 presentations per block). Prior to each block of testing, the subjects were familiarized with each stimulus and its corresponding number. Subjects were allowed to listen to the stimuli at will prior to running each testing block. During the testing proper, subjects verbally responded with the corresponding stimulus number following stimulus presentation. After each response, feedback was provided on the computer monitor before moving on to the presentation of the next stimulus. Normal hearing subjects were tested until they reached asymptotic performance, determined by failure to improve their scores. The number of testing blocks for these subjects was from 6 to 10. We determined that the average of the best two scores during the first eight blocks was essentially the same as asymptotic performance for all the normal hearing listeners. Therefore, we decided to administer eight testing blocks to the CI users, which can be accomplished in one experimental session lasting three hours. This was done to minimize testing time for CI users, allowing them to participate in several other studies. The results presented below represent the best two of the first eight blocks, both for CI users and normal hearing listeners.

CI users were asked to return at a later date to complete a speech perception battery. Tests in this battery included CNC word lists, a 50 item monosyllabic open-set word identification task (Peterson & Lehiste, 1962), and 16 consonants from the Iowa Consonant Identification Task (female speaker) (Tyler et al., 1987). Both of these tests used natural speech and were presented in an auditory only condition. The consonant identification task is a closed-set 16 alternative task that uses 16 consonants in an /a/consonant/a/ format. For example, the consonant *m* would be presented as *ama*. All subjects performed at least 5 repetitions of the consonant identification task for a total of fifteen presentations of each consonant except for S2 and S7 who performed 4 and 2 repetitions respectively. Most subjects were administered three CNC word lists.

Analysis

A discrimination index or *d'* was calculated for each pair of adjacent stimuli (1 vs. 2, 2 vs. 3, . . .) for each testing block, using equation 1 (Levit, 1972). *d'* is a parameter that indicates the discriminability between two normal distributions (or, equivalently, between two stimuli associated with percepts that follow a normal distribution). For example, a *d'* of 0 indicates total lack of discriminability: an optimal observer trying to identify one of two stimuli that had a *d'* of 0 would give correct responses 50% of the time, i.e., random performance. A *d'* of 1 would result in 69% correct responses in the same two-stimulus task, and a *d'* of 3 would result in 93% correct responses. Given that a *d'* of 3 indicates near perfect discrimination, it is customary to assign a value of 3 to any calculated *d'* that is greater than that.

$$d_n' = \frac{\bar{x}_{n+1} - \bar{x}_n}{\frac{s_{n+1} + s_n}{2}}$$

Equation 1: *d'* Calculation: where *d'* is the discriminability index calculated for the stimulus pair n. $\bar{x}_{n+1}$, s_{n+1}, $\bar{x}_n$, σ_n are the means and standard deviations of the responses to stimulus n and stimulus n+1 respectively.

This index was calculated for each adjacent set of stimuli, 1vs 2, 2 vs. 3, 3 vs. 4 etc. The results from these individual comparisons were then summed to arrive at a cumulative *d'* which is a more global measure of the subjects' discrimination abilities across all of the gap lengths. The best two cumulative *d'* scores were averaged to arrive at the final score for this task.

The performance on the CNC wordlists was calculated as a percent correct. The scores for the Iowa Consonant Identification task, however, underwent a more detailed analysis. First, a percent correct score was calculated. In addition, since the ability of the subjects to perceive acoustic gaps in the speech tokens was of particular interest, the responses to consonants that either contained or did not contain gaps were also examined. Specifically, information transfer analysis as described by Miller and Nicely (1955) was used to calculate the percent information received by the listener in the task of identifying gapped vs. non-gapped stimuli. For example, a listener who never confuses a gapped stimulus with a non-gapped one is said to receive 100% of the "gap" information.

The gaps in all the consonant tokens in the Iowa 16-consonant tests were measured using a special purpose program called Scilab (Bögli et al., 1995). This program captures the stimulation parameters delivered by the cochlear implant speech processor in response to a given incoming sound. All three repetitions of the 16 consonants in the test were played at 70 dB SPL (measured at the level of the speech processor's microphone) and the corresponding stimulation patters coming out of the speech processor were recorded to disk. Silent gaps during the consonants were measured using the display capabilities of the Scilab software. For the purpose of calculating gap length we disregarded stimulation due to voicing during vocal tract closure, which showed up as stimulation pulses delivered to the lowest frequency channel.

Results

Table 2 shows cumulative *d'* scores for all listeners as well as speech perception scores for the CI users. Results in the speech perception tests showed the typically wide performance range found in CI users. In contrast, virtually all normal hearing listeners would be expected to score close to 100% in all these speech perception tests under the same conditions. Cumulative *d'* scores for normal hearing listeners fell within a relatively small range (7.9 to 11.6). However, scores for CI users again fell in a very wide range, 3.1 to 9.8. In general, subjects with normal hearing had better cumulative *d'* scores. However, this was not always the case. S9, S10 and S11 all performed within the range of the group with normal hearing.

Table 2

Performance in the gap duration identification task (all subjects) and in the speech perception tasks (CI users).

Subject Number	Cumulative *d'*	Information Transfer For Gap (%)	Iowa Consonants (% Correct)	CNC Wordlists (% Correct)
S1	3.1	0	6	1
S2	3.3	7	28	18
S3	3.4	6	20	11
S4	3.8	49	63	32
S5	4.0	16	32	25
S6	4.9	4	15	0
S7	5.4	65	54	30
S8	6.3	59	68	52
S9	8.0	35	56	58
S10	8.7	53	50	46
S11	9.8	70	57	68
NH1	7.9	-	-	-
NH2	8.7	-	-	-
NH3	9.7	-	-	-
NH4	10.0	-	-	-
NH5	10.3	-	-	-
NH6	11.9	-	-	-

Note: CI users are listed first (S), and normal hearing listeners follow (NH). Within each group, subjects are listed in order of increasing ability to identify silent gap duration.

Figure 2 graphically illustrates the both the cumulative *d'* scores (i.e., the first column of numbers in Table 2) as the total bar height as well as the fraction due to the comparison between the first two stimuli (in black). The total cumulative *d'* is broken down into two parts: black bars represent a *d'* comparing responses to stimuli 1 and 2 (i.e., the non-gapped stimulus and the stimulus with a 15 ms gap), and white bars represent cumulative *d'* for stimuli 2-7 (i.e., stimuli with gaps ranging from 15 ms to 90 ms). It is very clear from the figure that all listeners, CI users and normal listeners alike, had perfect or near perfect ability to discriminate the non-gapped stimulus from the stimulus with a 15 ms gap, because the corresponding *d'* values are all equal to 3. In contrast, the ability to identify gaps of different lengths (cumulative *d'* for stimuli 2-7) from near zero for S1 to a substantial 6.8 for S11.

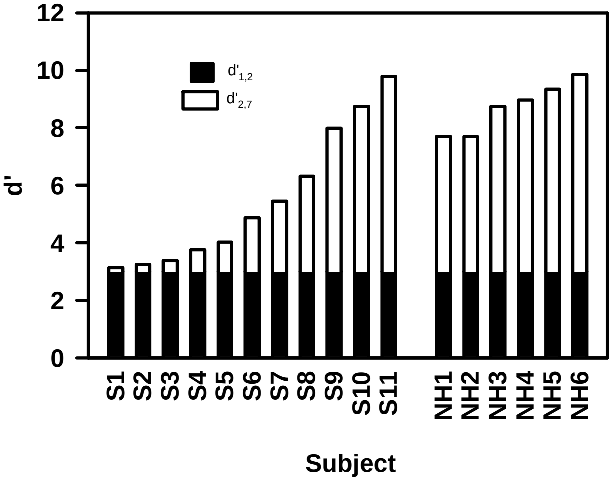

Figure 2: *d'* by subject. The black part of the bar represents the portion of the cumulative *d'* that is due to the subject's ability to discriminate between stimulus 1 and stimulus 2. S=subjects with cochlear implants, NH=subjects with normal hearing

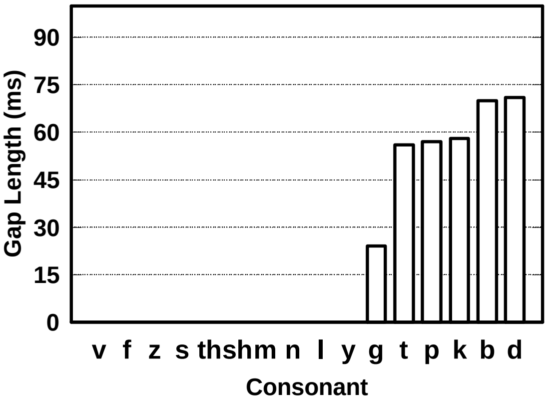

Figure 3: Consonant gap length as measured from the stimulus generated by a Spectra 22 cochlear implant speech processor and visually analyzed using Scilab software.

Figure 3 shows the measured silent gaps for each one of the 16 consonants used in this test. Each bar represents the average of three tokens. Based on these measurements, one would expect that all of the CI subjects would be able to perceive the difference between a consonant with a gap and a consonant without a gap. This is because all of the gapped consonants contain gaps that are at least 15ms in length, and all of the subjects showed that they were able to perfectly distinguish continuous sounds from those containing a 15 ms gap. However, information transmission scores for the gap-no gap feature (shown in the y-axis if the left panel in Fig. 4) were less than 100% for all CI users.

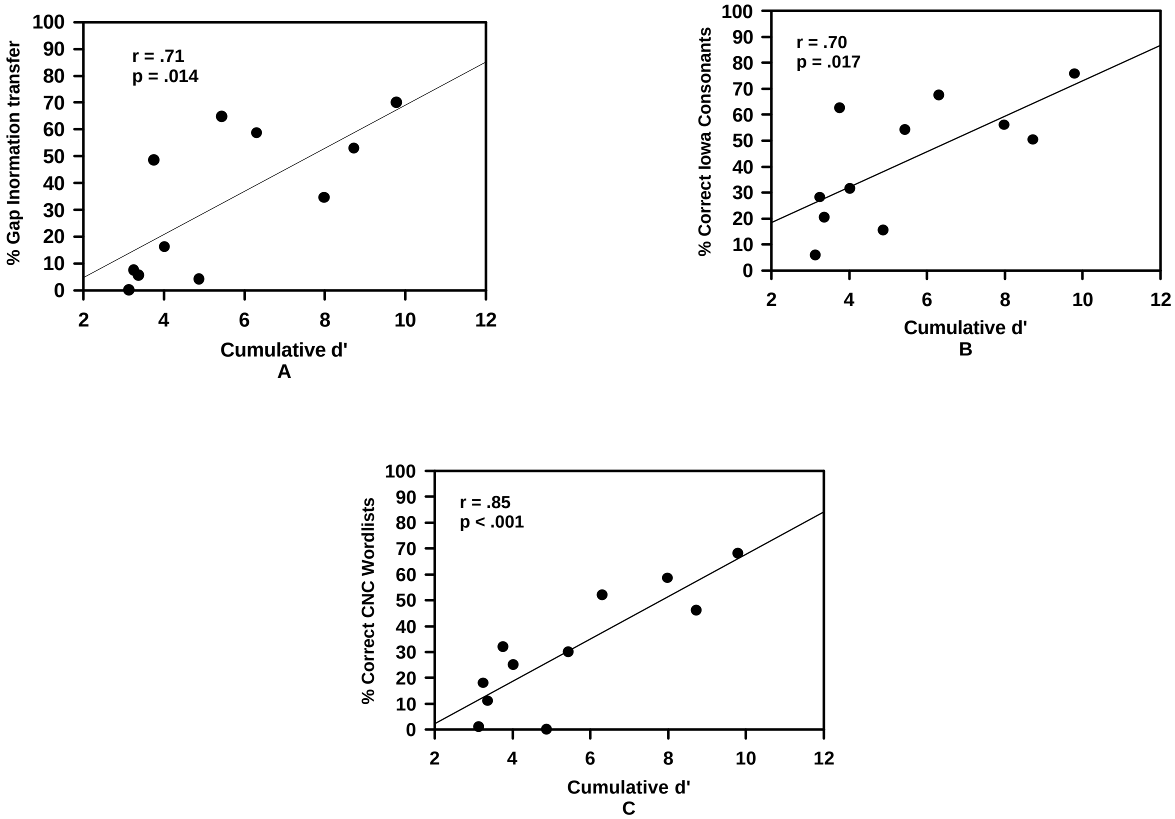

Figure 4: Correlation between cumulative *d'* and (A) gap information transfer, (B) performance on the Iowa Consonant Identification (female) task, (C) and CNC wordlist scores. Information transfer analysis was performed using gapped and gapless consonants as informational categories.

Finally, figures 4A and 4B show scatter-plots of cumulative *d'* scores against percent information transmitted for the gap-no gap contrast, and against the percentage of correctly identified consonants respectively. Figure 4C is a scatter-plot of cumulative *d'* against CNC wordlist percent correct. All speech perception scores were significantly correlated with cumulative *d'*.

Discussion

Speech perception performance by CI users is highly variable from one patient to the next and is also, on average, lower than that of normal hearing listeners. The question remains whether there any psychophysical capabilities that might explain these two facts. The consensus in the cochlear implant field is that CI users suffer from poor frequency discrimination, although their temporal processing skills are comparable to those of normal hearing listeners (Shannon, 1989). The latter conclusion is supported by results from gap detection threshold experiments, and is consistent with our finding that all of our subjects (normal hearing and CI users) were clearly able to label and differentiate a continuous stimulus from one with a 15 ms gap. However, the ability of CI users to identify silent gaps of different lengths was extremely variable, ranging from almost nil to normal. In addition, this ability (as measured by cumulative *d'* scores for stimuli 2-7) was strongly correlated with speech perception scores as shown in 4B and 4C. These results suggest that CI users may use silent gap duration as a cue to consonant identity, and that their differing abilities to identify such gaps may help explain their individual differences in speech perception. This hypothesis receives additional, indirect support from the modeling studies of Svirsky et al. (1999). The MPI model developed by Svirsky et al. can fit consonant confusion data much better when they include a temporal dimension in the model. The temporal dimension used by Svirsky et al. in the MPI model is the duration of a silent gap. In any case, it seems clear that the temporal processing abilities of poorer CI users lag substantially behind those of normal hearing listeners or those of more successful CI users. What is the physiological reason behind this variability in gap duration identification? In our view, the auditory periphery is an unlikely locus for individual differences in temporal processing, because the electrically stimulated auditory nerve is quite capable of encoding the gross temporal differences that were present in our stimuli. Instead, it may be that the differences in cumulative d' that we observed have their origin in more central differences in auditory processing and categorization of sensory input into stable perceptual units.

Another observation is that the CI users' identification of gapped and non-gapped consonants was much lower than would be expected based on their psychophysical performance. We say this because their discrimination of continuous sounds from sounds with a 15 ms gap was virtually perfect in the psychophysical task (where they had to perform absolute identification of synthetic stimuli), but their ability to identify consonants with and without gaps was far from perfect (as evidenced by their information transfer scores for the gap-no gap feature). One possible account for this result is that listeners may have been paying more attention to acoustic cues other than gap duration, or at least weighting those other cues more heavily. In other words, they may have known that a given stimulus contained a silent gap, but other acoustic cues led them to identify the stimulus as a non-gapped consonant. Alternatively, it may be that the cumulative d' estimates obtained in this study can only be achieved by most subjects under relatively ideal conditions, that is, with carefully synthesized acoustic stimuli that are identical to each other except for the silent gap. When subjects have to process gap information in conjunction with other acoustic cues (spectral and amplitude cues, for example) their processing of temporal cues may suffer to some extent.

Perception of speech sounds by human listeners in general and by CI users in particular is a very complex phenomenon. In the case of CI users, we hope to develop a comprehensive quantitative model of speech perception that is based, in part, on the individual listener's discrimination abilities (Svirsky & Meyer, 1998). The present study is a first step in that direction. It is our hope that the existence of a theoretical framework for speech perception by CI users will help guide the search for improved signal processing and aural rehabilitation strategies for this population.

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