Speech Processors for Auditory Prostheses

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Effect of Pulse Rate and Pulse Duration on Speech Recognition with Cochlear Implants

Submitted by

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Abstract

There has been considerable controversy regarding the contribution of high stimulation rate processing strategies to speech understanding in cochlear implant patients. Some studies have shown improvement in performance with higher rates and others have not. However, most of the previous studies have utilized the same pulse phase duration for all the rates examined. The present study explores whether there might be an interaction between pulse rate and pulse phase duration in terms of improving speech recognition scores with two cochlear implant devices.

Three Clarion subjects were fit with CIS processors having 4 or 8 electrodes and three Nucleus-24 subjects were fit with CIS processors having 4, 8, or 16 electrodes. For the Clarion device, both 4- and 8-electrode processors were programmed with rates of 200, 400, and 800 pulses per second per electrode (ppse). The 4-electrode device was also programmed with a 1600 ppse rate. The pulse phase duration was 75, 150, 225, or 300 microseconds (μs), depending on the availability for the number of electrodes activated and the stimulation rate. With the Nucleus-24 device, rates of 250, 500, 900, 1200, 1800, and 2400 ppse were utilized. Pulse phase durations of 25, 50, 75, 100, 150, 200, 300, and 400 μs were utilized, with the longest pulse duration determined by the number of electrodes and pulse rate. Speech recognition performance was measured for each stimulation rate and pulse duration on consonant and vowel identification, CNC word recognition, and IEEE sentence recognition. Listeners were also tested with their original clinical processor prior to receiving the experimental processors.

Some listeners scored the highest with their original processor while others scored highest with an experimental processor. Little difference in listener speech understanding was observed as a function of stimulation rate or pulse phase duration. A decrease in speech recognition was only observed at the lowest stimulation rate and with the smallest number of electrodes.

Introduction

Most modern cochlear implant speech processors utilize interleaved pulse stimulation to avoid the deleterious effects of electrical current field summation that can occur when electrodes are stimulated simultaneously. However, when pulses are interleaved in time there is an inherent trade-off between the number of electrodes, the pulse rate and the pulse phase duration. To optimize performance in interleaved pulse processors, it is important to understand how these three parameters interact so we can select the best combination of number of electrodes, pulse rate, and pulse phase duration.

In general, more electrodes should be able to provide more channels of spectral resolution and so more electrodes are desirable. However, several studies have shown that implanted listeners do not appear to be able to utilize the spectral information from more than about 8 electrodes (Fishman *et al*., 1997; Friesen *et al.,* 2001; Dorman and Loizou, 1997; Dorman *et al.,* 1997, 1998). Thus, using more than 8 electrodes may not result in improved speech recognition and may even reduce performance because stimulation of more electrodes requires a lower pulse rate. If additional electrodes do not provide additional information, it is possible that the best speech recognition performance could be achieved by fixing the number of electrodes (at 8 for example) and optimizing pulse rate and pulse phase duration. Adding more electrodes would require reductions in pulse rate per electrode and reductions in pulse phase duration.

The effect of overall pulse rate in an implant speech processor is unclear. Some studies have found significant improvements in speech recognition performance with high pulse rates (Brill *et al.,* 1997), while others have seen no improvements in performance as stimulation rate was increased above 200 pulses/sec/electrode (ppse) (Fu and Shannon, 2000). Still other studies have shown a local maximum in speech recognition performance at intermediate pulse rates (Wilson *et al.,* 1998). Recent physiological and psychophysical studies have shown that there could be beneficial effect of electrical stimulation with very high pulse rates: rates above 4kHz per electrode (Wilson *et al.,* 1998; Rubinstein *et al.,* 1999). These studies reason that such high rates effectively act as an artificial spontaneous rate in the nerve which restores the stochastic response properties of auditory neurons in contrast to the deterministic highly phase-locked response observed with regular electrical stimulation.

Pulse phase duration must covary with the number of electrodes and the stimulation pulse rate in processors that use interleaved pulses. As the number of electrode increases and the stimulation rate increases, the pulse phase duration must decrease. As pulse phase duration decreases the amplitude of each pulse must be increased to maintain the same perceptual loudness level. Studies by Zeng *et al.* (1998) and Chatterjee *et al.* (2001) have demonstrated that pulse amplitude must be raised by a factor of about 1.4 as the pulse duration is halved to maintain constant loudness. As pulse amplitude is increased the current field around that electrode increases in extent. Although the short duration of the pulses may not excite nerves that are distant, the brief current fields may still leave residual effects that could change distant neuron’s response to successive stimulation from other electrodes. In addition, there may be nonlinear integration effects that might require successive pulses to have a period of no current separating them even if they are presented to different electrodes.

Any neuron that “sees” the current fields from two electrodes might be adversely affected if pulses are delivered to the two electrodes with no delay between them. Nonlinear integrative effects at the neural membrane could produce interactions even if the pulses on the two electrodes are sequential in time. Thus, the “optimum” pulse phase duration may not be the one that maximizes pulse rate.

To investigate the potential interaction between the number of electrodes, pulse rate, and pulse phase duration, we measured speech recognition in patients with two commercial cochlear implant devices: the Nucleus-24 and Clarion. Both of these devices allow some control over the combination of these three parameters in the clinical speech processor fitting software.

METHODS

Listeners

Three adults (18 years and older) using the Clarion CIS processor and three adults with the Nucleus-24 Advanced Combination Encoder (ACE) processor, each having at least six months experience, participated in this study. All were postlingually deafened and native speakers of American English. General demographic information for the 6 subjects is presented in Table 1. All Clarion users had eight electrode pairs available for use and all Nucleus-24 listeners had 22 available electrodes.

Table 1. Listeners

Listener	Speech Processing Strategy	# of Electrodes, Rate -ppse)	Age (Years)	M/F	CI Ear	Etiology	Age of HL Onset		Age of Profound HL Onset		Hearing Aid Usage		Duration of CI Use
							L	R	L	R	L	R	(Years)
C1	PPS	8, 800	66	F	L	Otosclerosis	32	32	45	45	Y	N	1
C5	CIS	8, 800	38	M	L	Unknown	3	3	28	22	Y	Y	2.5
C13	CIS	8, 800	68	M	L	Unknown	26	26	55	55	Y	Y	2.5
N24 2	SPEAK	22, 250	55	F	R	Unknown	1	1	28	28	N	N	3
N24 4	SPEAK	22, 250	63	F	L	Unknown	37	37	55	55	Y	Y	1
N24 6	SPEAK	22, 250	60	F	R	Unknown	26	26	55	55	Y	Y	2.5

Speech materials

Speech perception tests used to evaluate the experimental settings were all presented without lip-reading (sound only). The tests consisted of medial vowel and consonant discrimination, monosyllable word recognition and sentence recognition.

Vowel stimuli were taken from materials recorded by Hillenbrand et al. (1995) and were presented to the listeners with custom software (Fu, 2000). Fifteen presentations of (5 male, 5 female, and 5 children talkers) each of twelve medial vowels in a h/V/d context (/i ɪ ɛ æ u ʊ ɑ ʌ ɔ ɝ o e) presented in a /h/-vowel-/d/ context (hoed, hayed, heed, hid, head, had, who'd, hood, hod, hud, hawed, heard). Chance level on this test was 8.33% correct and the single-tailed 95% confidence level was 12.4% correct.

Consonant stimuli (5 male, 5 female talkers in a /a/C/a/ context) were taken from materials created by Shannon et al. (1999). Consonant confusion matrices were compiled from 10 presentations of each of 20 medial consonants /b d g p t k m n l r y w f s ʃ v z ð tʃ dʒ /, presented in an /a/-consonant-/a/ context. Tokens were presented in random order by custom software (Fu, 2000) and the confusion matrices were analyzed for information received on the production based categories of voicing, manner, and place of articulation (Miller and Nicely, 1955). Chance performance level for this test was 5% correct, and the 95% confidence level was 8.1% correct.

The CNC Word Test from the Minimum Speech Test Battery for Adult Cochlear Implant Users CD was used to evaluate open-set phoneme and word recognition (House Ear Institute and Cochlear Corporation, 1996). The CD contains 10 lists of 50 monosyllabic words containing 150 phonemes. Listener responses were scored separately for words and phonemes correctly identified.

Recognition of words in sentences was measured using the IEEE sentences (Standards Publication No. 297, 1969) The recordings were made in the Department of Auditory Implants and Perception, House Ear Institute, 2001. For each condition, data was collected for 20 sentences of varying lengths from each listener. The sentences were of moderate-to-difficult complexity and were presented with no context and no feedback. For the Clarion patients no sentences were repeated to an individual listener. Nucleus-24 listeners had more conditions, so that some sets of sentences had to be repeated. Sentence sets were selected for repeat that had received the lowest scores in prior conditions.

Experimental Speech Processor Conditions

Each Clarion listener was tested with seven experimental speech processors while each Nucleus-24 listener was tested with twelve experimental speech processors. Testing was performed immediately after listeners received them (no practice).

Clarion listeners were tested with 4-electrode and 8-electrode processors, each at a variety of stimulation rates. With the Clarion CIS speech processing strategy, 8 frequency bands are normally directed to 8 electrode pairs (Clarion by Advanced Bionics, 1998). With a reduction in the number of electrode pairs to 4, the total frequency range remains the same, but the range for each electrode is broadened. In the 8-electrode processors stimulation rates of 200, 400, and 800 ppse per electrode were utilized. In the 4-electrode [electrodes 1, 3, 5, and 7 were activated] processors stimulation rates of 200, 400, 800, and 1600 ppse per electrode were used. Pulse durations of 75, 150, 225, and 300 µs/phase were used depending on the rate of stimulation and the electrode number.

The Nucleus-24 device with the ACE processing strategy allows for the determination of the sites of stimulation (maximum 22), the number of maxima during each stimulation (maximum 20) frame, and the stimulation rate per channel (maximum 14,400 Hz). During programming, the system automatically assigns frequency information to electrodes based on the processing strategy selected and number of active channels. The default frequency allocation tables were used for all experimental processors (187 - 7937 Hz). Four electrode conditions were selected using 4, 8, or 16 electrode pairs [electrodes used in the 4-electrode processor: 4, 10, 16, 22; 8-electrode processor: 4, 7, 10, 13, 16, 18, 20, 22, and 16-electrode processor: 4, 5, 6, 7, 9, 10, 11, 12, 14, 15, 16, 17, 19, 20, 22]. For one patient with facial stimulation different electrodes were used [electrodes used in the 4-electrode processor: 2, 10, 14, 22; 8-electrode processor: 1, 4, 7, 10, 13, 14, 21, 22, and 16-electrode processor: 1, 2, 3, 4, 5, 6, 7,8, 9, 10, 11,12, 13, 14, 21, 22]. Processors were programmed with the fastest and slowest rates allowable in the clinical system, plus at least one intermediate rate. Stimulation rates ranged from 200 Hz to 2400 ppse, depending on the number of electrodes used. Stimulation rates were 250, 500, 900, 1200, 1800, and 2400 ppse for the 4-electrode condition, 250, 500, 900, 1200, and 1800 ppse for the 8-electrode condition, and 250, 500, and 900 ppse for the16-electrode condition. The pulse durations tested were 25, 50, 75, 100, 150, 200, 300, and 400 µs/phase, depending on the stimulation rate and electrode number.

Procedure

During all testing the listener was seated one meter in front of a loudspeaker (Grason-Stadler audio monitors) in a sound treated room (IAC). The presentation level was 65 dB SPL for all speech perception testing, as measured by a B&K one inch microphone (Model #4144) at the location of the listener's head. All speech materials were prerecorded. A computer with a sound card (Turtle Beach Fiji), CD player, and a GSI audiometer (Model 16) was used to present the test items.

Threshold (T) and most comfortable (M) loudness/maximum comfort (C) levels were measured separately for each rate condition. The experimental processors were presented to each listener in random order. The battery of speech tests was administered to each listener immediately after they were given the experimental processor (no practice).

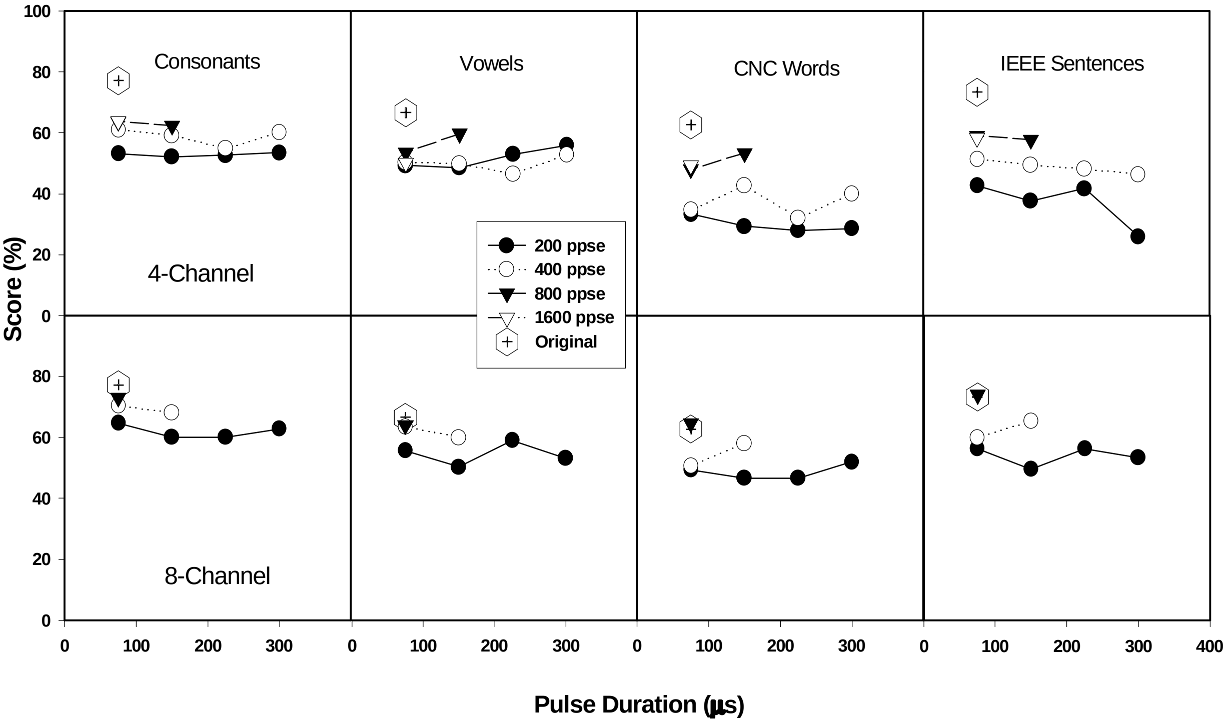
For the Clarion device electrical thresholds (T) and most comfortable loudness (M) levels were obtained using the SCLIN for Windows software, Clinician's Programming Interface (CPI), and power supply with a personal computer. The Input Dynamic Range was set to -60 dB SL for all conditions. All other parameters were set similarly to the listener's original processor. In the CIS processing strategy, threshold levels were estimated by a standard clinical bracketing procedure. Initially, all the electrodes were screened for threshold level and the patient was instructed to identify when they first heard the sound. Then, going back to the first electrode, one to five pulse bursts were presented and the listener was instructed to count the number heard. The T level used in the processor was the level at which the listener counted the number of bursts correctly 50% of the time. To obtain M levels the experimenter increased the electrical level until the listener felt the loudness was at the most comfortable loudness level (the level where they heard the sound at a normal conversational level and could listen to it for a long time without discomfort). Adjacent electrodes were balanced for loudness at M level for each electrode.

With the Nucleus-24 ACE processing strategy, electrical thresholds (T) and maximum comfortable loudness (C) levels were obtained using the WinDPS software, PCI, and computer. A SPRINT processor was used for all the testing. Original processors for all subjects contained the SPEAK strategy. Subjects were switched to ACE for this study. Threshold levels were estimated by a standard clinical bracketing procedure. Initially, all the electrodes were screened for threshold level and the patient was instructed to identify when they first heard the sound. Then, going back to the first electrode, one to five pulse bursts were presented and the listener was instructed to count the number heard. The T level used in the processor was the level at which the listener counted the number of bursts correctly 100% of the time. To obtain C levels the experimenter increased the electrical level until the listener felt the loudness was at the maximum comfortable loudness level (the level where they could listen to it for a long time without discomfort). Adjacent electrodes were balanced for loudness at C level for each electrode. The same number of maxima and electrodes were always selected when programming the processor (CIS-like processing).

Results

Average speech recognition results as a function of the pulse phase duration for the three Clarion listeners are presented in Figure 1, with the individual subject data presented in Figures 2-4. The top row of panels present data from 4-channel processors and the lower row of panels present data from 8-channel processors. From left to right the panels present data from consonant, vowel, word, and sentence recognition, respectively. Within each panel the different symbols present data from different pulse rates, ranging from 200 to 1600 ppse. The hexagonal symbol with a plus-sign in the middle indicates the performance level on each test obtained with the subject’s normal clinical processor. Performance was similar for clinical processors and experimental processors with 8 electrodes and higher stimulation rates. Performance with the clinical processor was significantly higher than all experimental processors with

Figure 1. Averaged Clarion Scores (N=3)



4 electrodes. In general all the curves are flat as a function of pulse phase duration, indicating that speech recognition was not affected by pulse duration. Performance improved for both 4- and 8-channel processors as stimulation pulse rate was increased

Figure 2. Individual Clarion Data (C1)

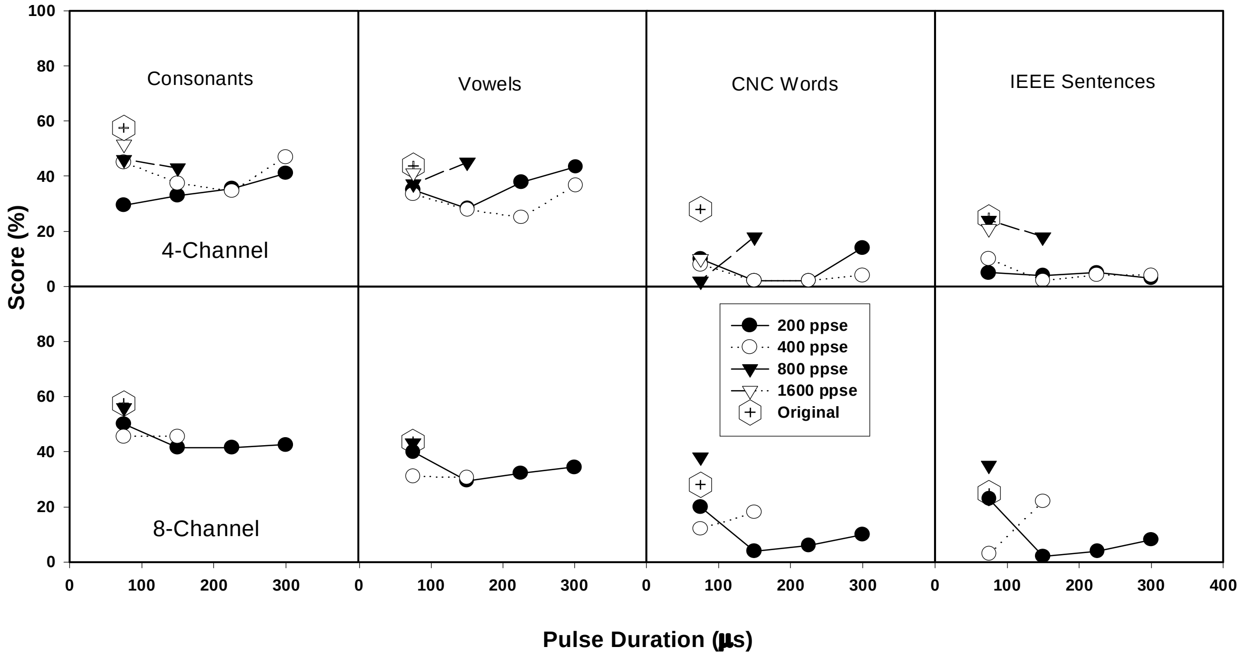


Figure 3. Individual Clarion Data (C5)

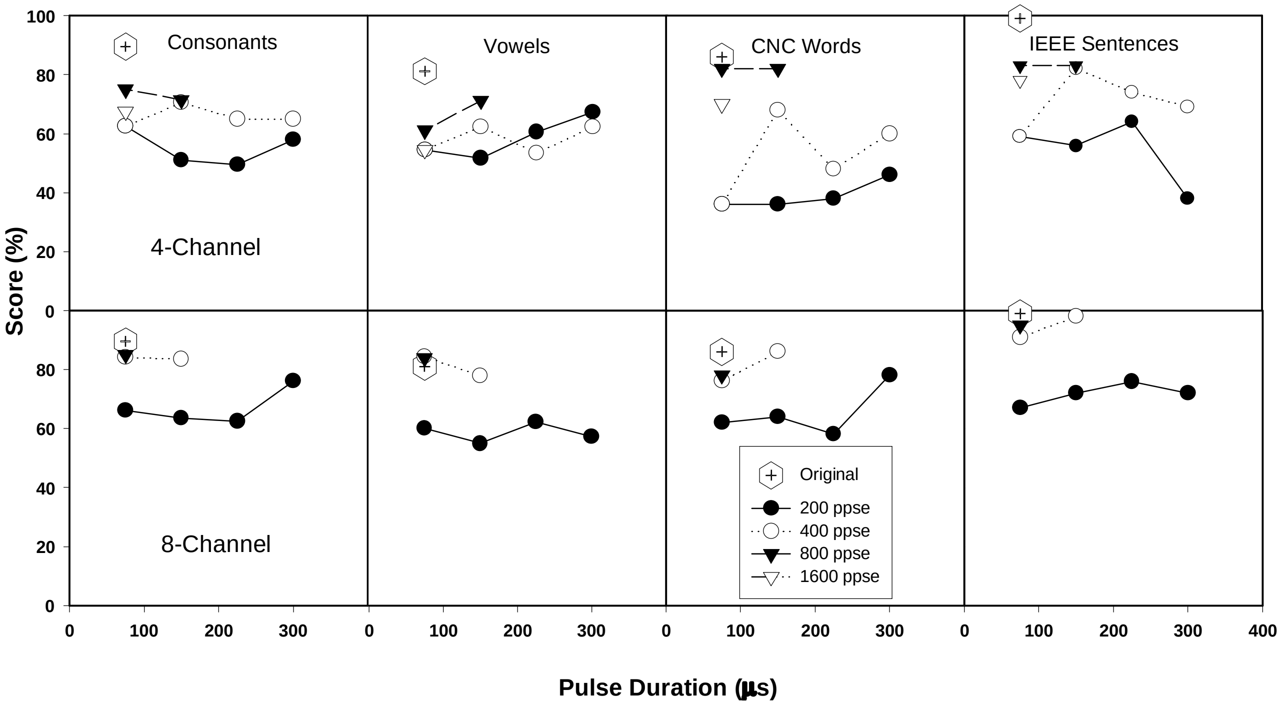


Figure 4. Individual Clarion Data (C13)

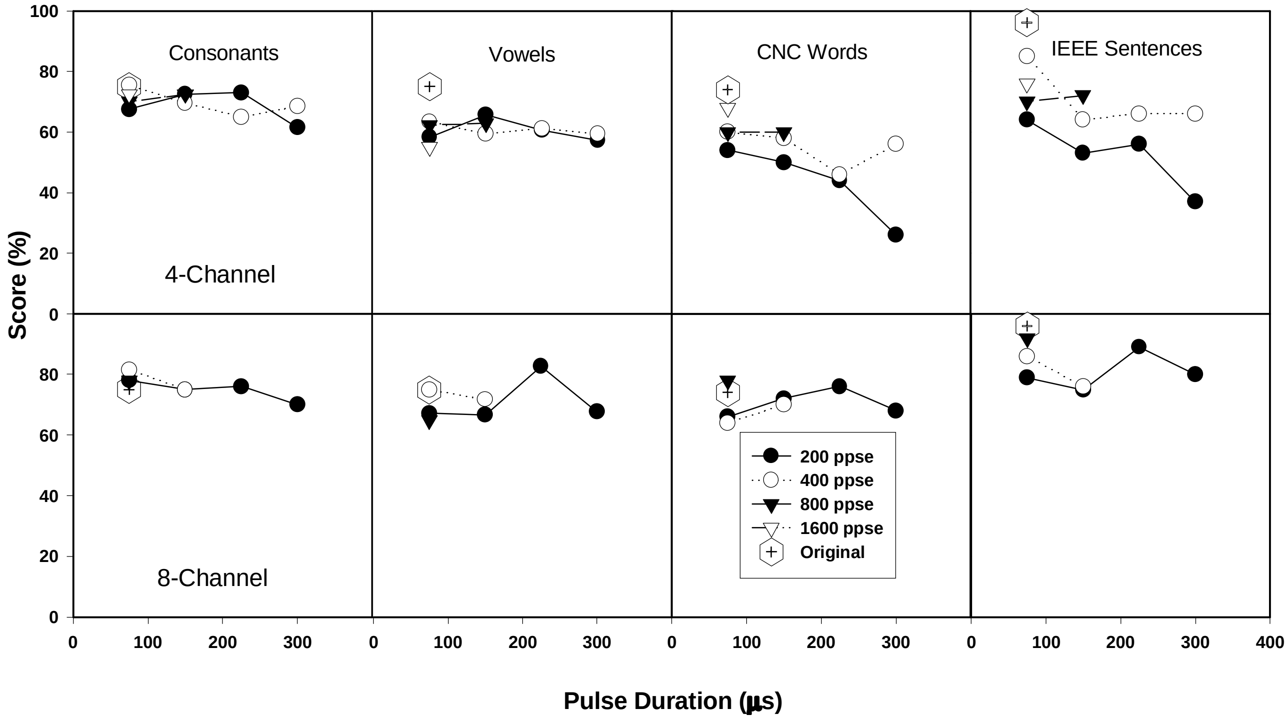
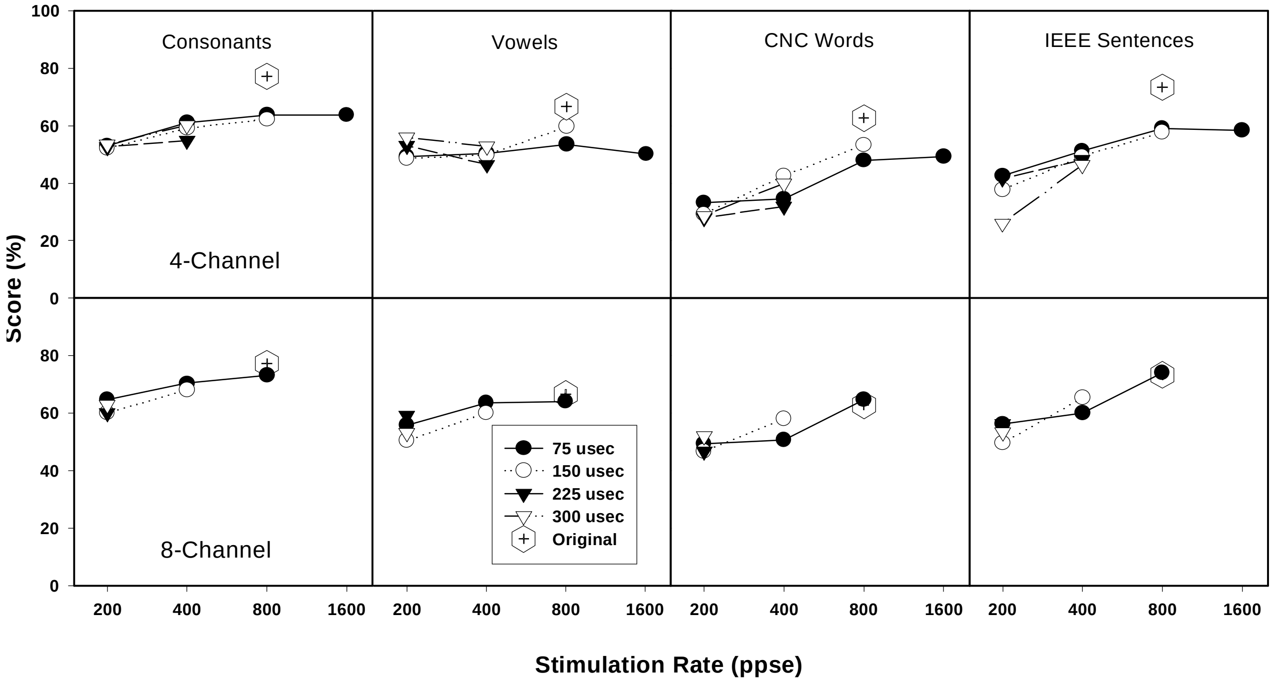


Figure 5. Averaged Clarion Scores (N=3)



from 200 to 800 ppse. However, there was little improvement when the rate was increased from 800 to 1600 ppse. Although the data from individual listeners are a bit more variable than the average data, the basic trends are similar. Subjects C1 and C13 appear to achieve the best performance at the shortest pulse duration for most pulse rates. In contrast, subject C5 achieved highest performance on several tests at the longest pulse duration. It is not clear that any of these individual differences are significant; they may just reflect the test-retest variability in the data from individual listeners.

Figure 5 presents the average Clarion data plotted as a function of pulse rate, with pulse duration as the parameter. The same trends are apparent in this presentation of the results: performance improves with stimulation rate up to 400 ppse, but pulse duration has no effect.

Average speech recognition results as a function of the pulse phase duration for the three Nucleus-24 listeners are presented in Figure 6, with the individual subject data presented in Figures 7-9. The top row of panels present data from 4-channel processors, the middle row presents results from 8-channel processors, and the lower row 16-channel processors. From left to right the panels present data from consonant, vowel, word, and sentence recognition, respectively. Within each panel the different symbols present data from different pulse rates, ranging from 250 to 2400 ppse. As with the results from the Clarion subjects, there was no apparent change in speech recognition as a function of pulse duration. There may be a slight improvement in speech recognition as the pulse rate was increased from 250 to 500 ppse, but no further increase as pulse rate was increased further. There was an increase in speech recognition from 4-channel to 8-channel processors, but no further increase from 8- to 16-channels.

Figure 6. Averaged Nucleus-24 Scores (N=3)

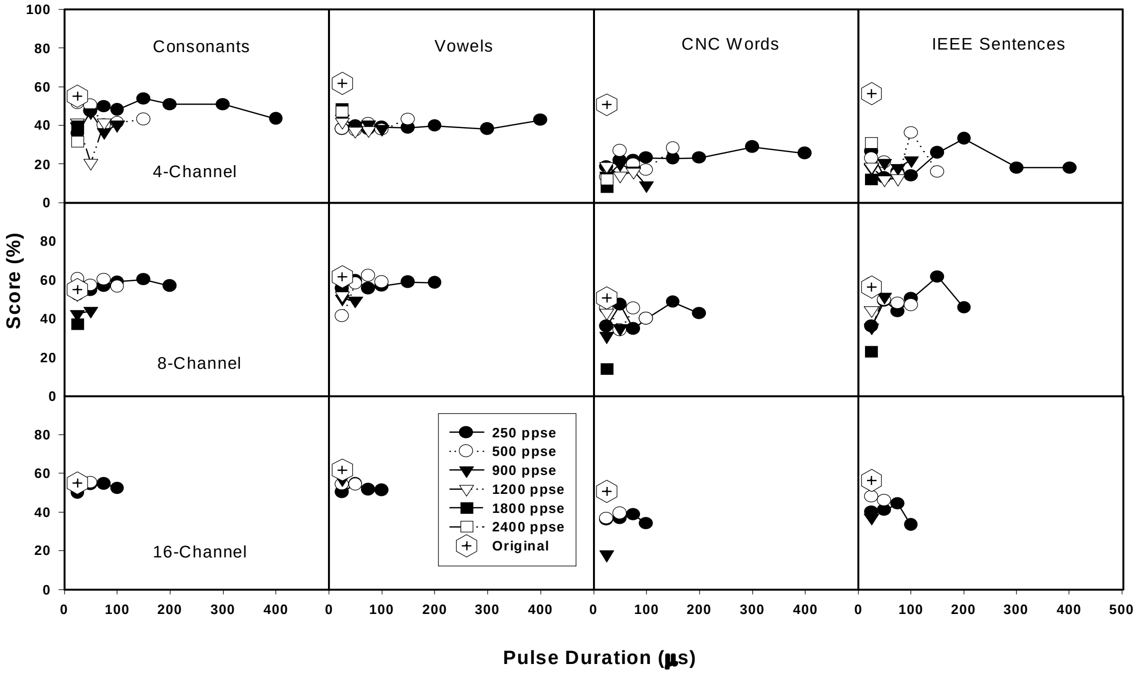


Figure 7. Individual Nucleus-24 Scores (N24-2)

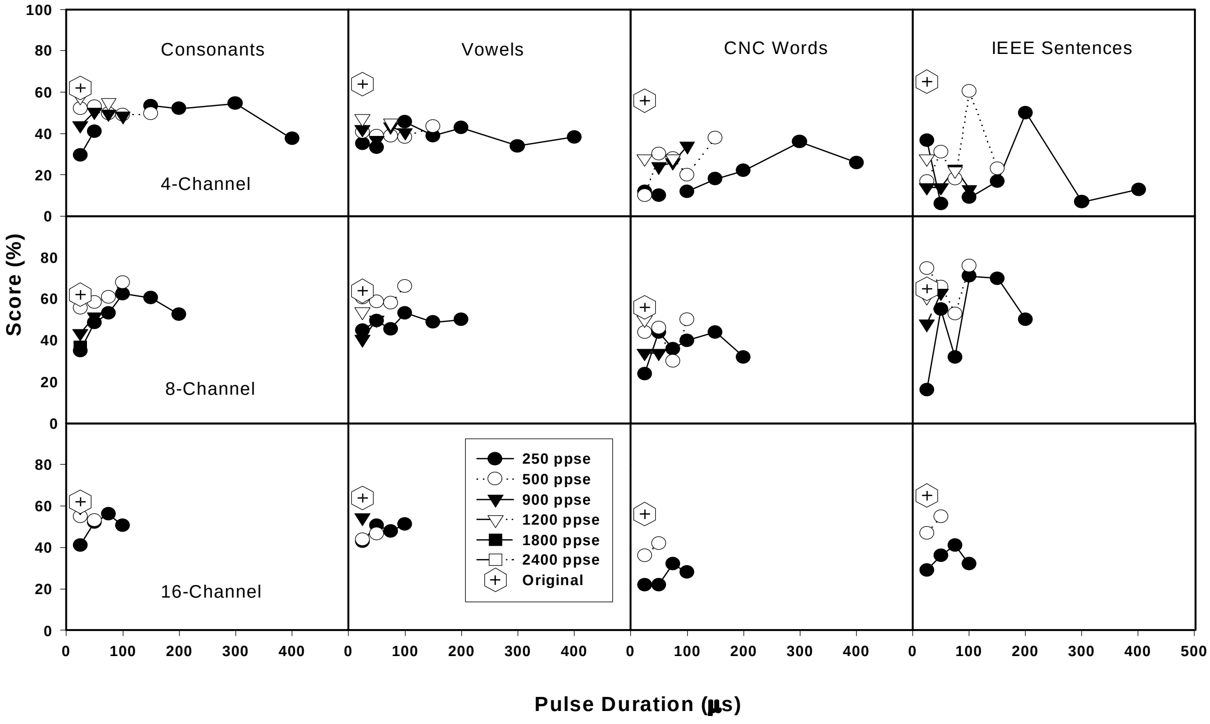


Figure 8. Individual Nucleus-24 Scores (N24-4)

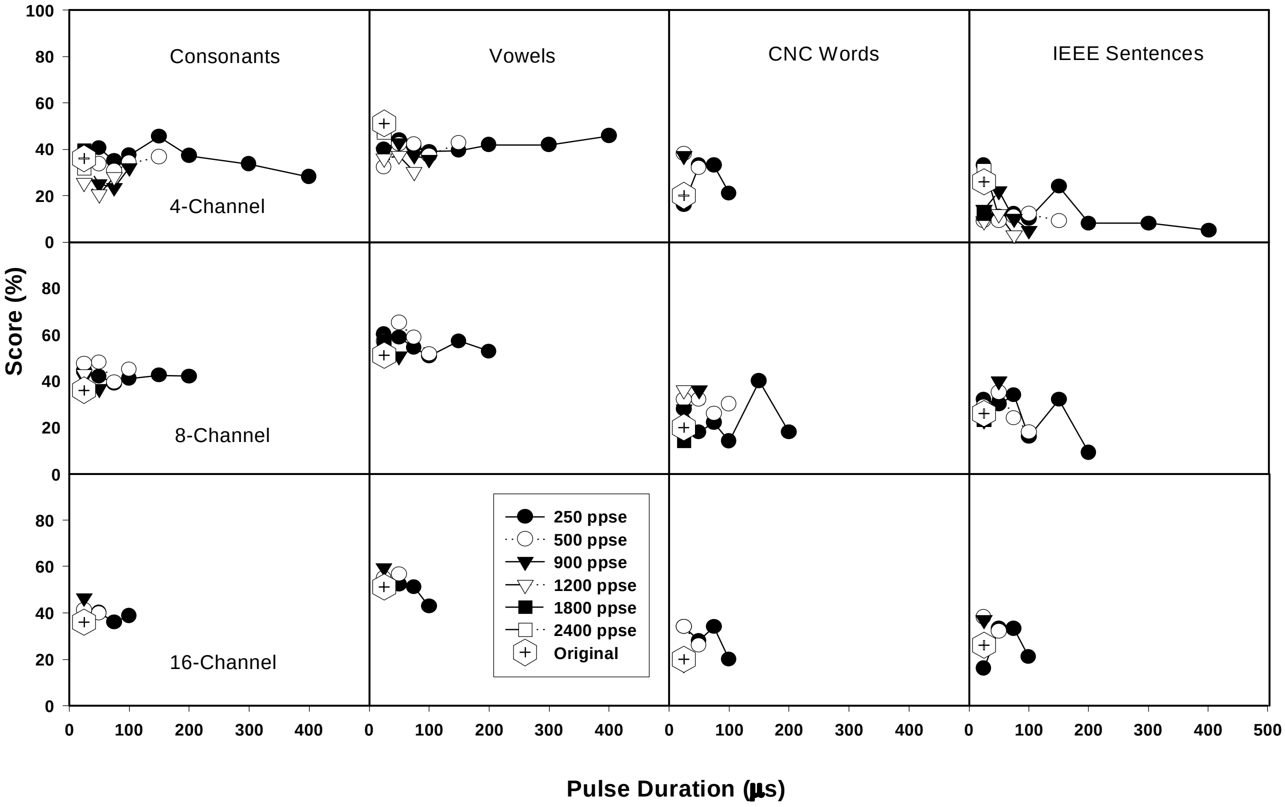


Figure 9. Individual Nucleus-24 Scores (N24-6)

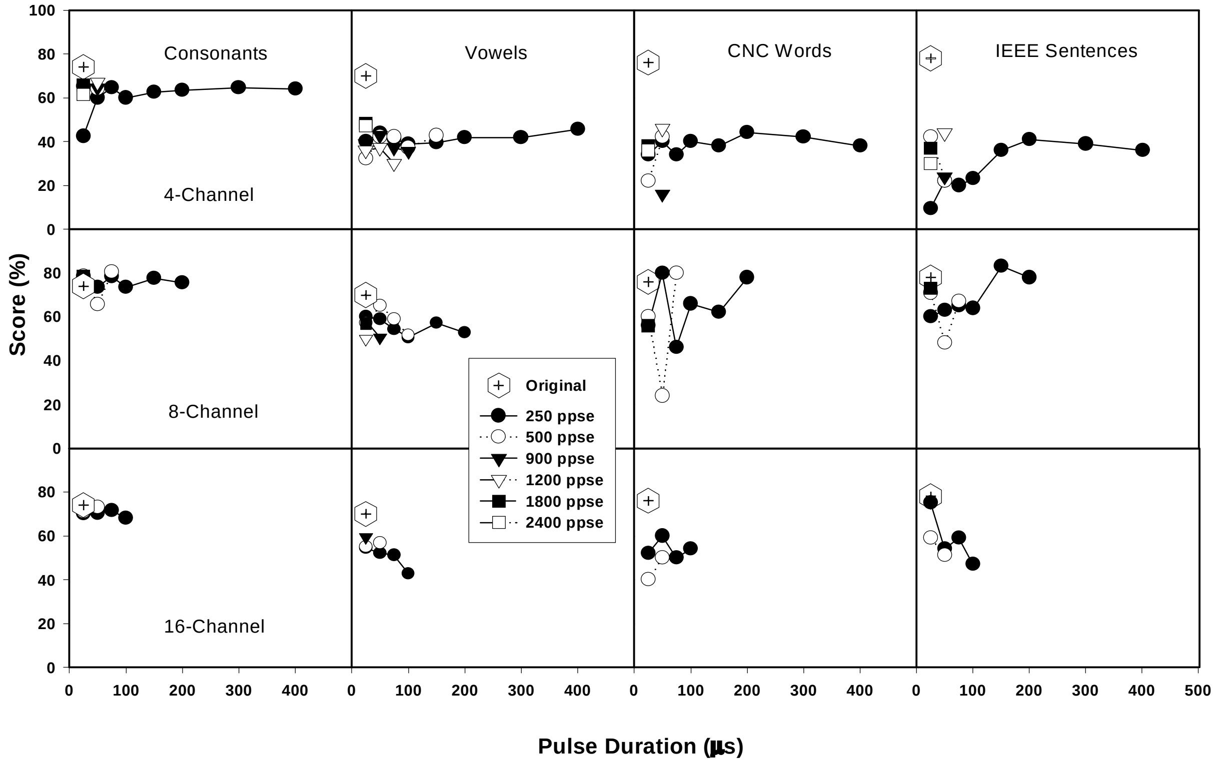


Figure 10. Averaged Nucleus-24 Scores (N=3)

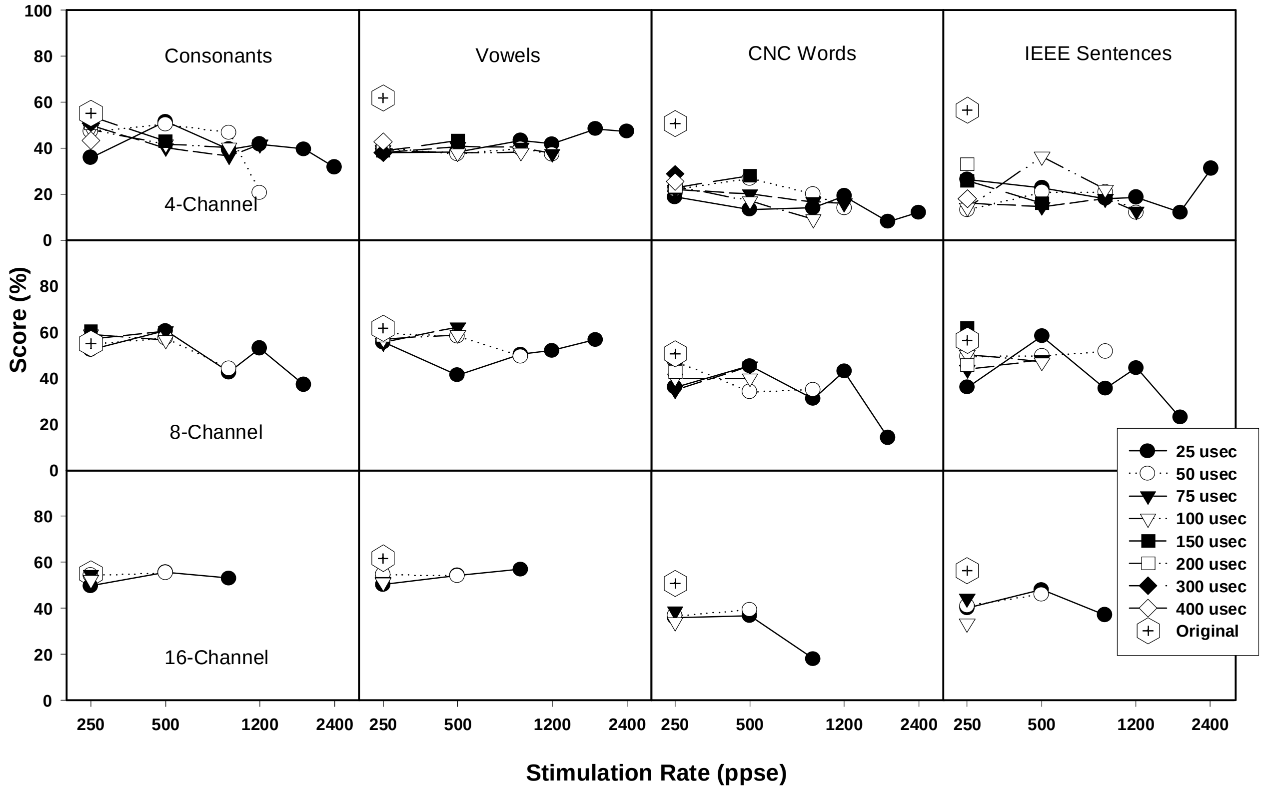


Figure 10 presents the average Nucleus-24 data plotted as a function of pulse rate, with pulse duration as the parameter. The same trends are apparent in this presentation of the results: neither pulse phase duration nor pulse rate had a significant effect on speech recognition.

Discussion

Pulse stimulation rate and pulse phase duration are two main parameters in nonsimultaneous electrical stimulation through a cochlear implant. When biphasic pulses are interleaved in time there is an inherent trade-off between pulse rate, pulse phase duration, and the number of electrodes. The results of the present study appear to indicate that pulse rate and pulse phase duration are not critical parameters for cochlear implant speech processors. Except for stimulation rates lower than 400 ppse, pulse rate and pulse phase duration had no effect on speech recognition for this sample of six subjects with two different implant devices. The present results are also consistent with previous studies (Fishman et al., 1997; Friesen et al., 2001) showing no improvement in performance when more than 8 electrodes are used in the signal processor. The present results showed considerable test-retest variability for an individual listener. Some listeners appear to show a slight improvement in speech recognition for certain combinations of pulse phase duration and pulse rate. However, this pattern was not consistent across tasks, suggesting that these apparent "local" peaks in the parameter space were simply reflections of the variability inherent in the test. It is possible that we would have observed less variability if we had allowed the listeners some time to practice or accommodate to each processor. However, the listeners were quite familiar with the general quality of the processors since there was no clear difference across parameters. In addition, they were all highly familiar with the listening conditions and the stimulus sets. Thus, additional experience with each processor may not have allowed more consistent performance across conditions. In any case, there does not appear to be any difference in performance as a function of pulse rate or pulse phase duration.

This pattern of results suggests that there are no detrimental effects for speech recognition of any nonlinear charge integration at the nerve or broader current fields created by high amplitude short pulses.

Peer-Reviewed Publications in This Quarter:

Chatterjee, M. and Robert, M.E. (2001). Noise enhances modulation sensitivity in cochlear implant listeners: Stochastic resonance in a prosthetic sensory system?, Journal of the Association for Research in Otolaryngology, 2(2), 159-171.

Hsu, C.-J., Horng, M.-J., and Fu, Q.-J. (2000). Effects of the number of active electrodes on tone and speech perception by Nucleus-22 cochlear implant users with the SPEAK strategy, Advances in Oto-Rhino-Laryngology, 57, 257-259.

Manuscript Submitted this Quarter:

Zeng, F.G., Grant, G., Niparko, J., Galvin, J., Shannon, R.V., Opie, J., and Segel, P. Speech dynamic range and its effect on cochlear implant performance, J. Acoust. Soc. Amer., (submitted June 2001).

Presentations this quarter:

Invited Presentations:

Shannon, R.V. (2001). The relative importance of temporal and spectral cues for recognition of speech and music, Processing the Auditory Environment: From Synaptic Mechanisms to Population Codes, 6th Biennial Symposium, Center for Neural Science, New York University, 10-11 June 2001. (Invited symposium speaker)

Presentations:

Baskent, D. and Shannon, R.V. (2001). Speech recognition under conditions of frequency-place compression and expansion, Grodins Research Symposium, USC Dept. of Biomedical Engineering, April 30. (oral presentation)

Padilla, M. and Shannon, R.V. (2001), Effects of English experience and spectral resolution on English phoneme and word recognition by non-native English speakers, Grodins Research Symposium, USC Dept. of Biomedical Engineering, April 30. (oral presentation)

Plans for the next Quarter:

In the next quarter we will present the results of our research on cochlear implants in several forums. Shannon will deliver the Keynote Address at the Cochlear Implant Association International (CIAI) annual convention in Minneapolis in July. This is a cochlear implant patient organization and is an important source of information for people with cochlear implants, for parents of children with cochlear implants, and for people considering implantation. While in Minneapolis, Shannon will also present talks at Starkey Hearing Aid Research Laboratories on common signal processing issues in implants and hearing aids. Shannon will also present a talk sponsored jointly by the Departments of Otolaryngology, Psychology, and Speech and Hearing Sciences, University of Minnesota.

We will also prepare for the Conference on Implantable Auditory Prostheses at Asilomar Conference Center, Pacific Grove, California August 19-24. Our group will present two Invited oral presentations (Shannon and Fu) and 13 poster presentations. Also at that meeting John Wygonski will assist in the presentation of the latest hardware and software developments on the Clarion Research Interface for the Clarion2 implant device. We will also participate in a workshop from Cochlear Corp. presenting a new version of a software interface for the Nucleus-24 implant system (NIC2). We will start software development to integrate the CRI-2 and NIC2 interfaces into our research programs.

In the next quarter we will complete data acquisition and data analysis for the study presented in this report and write it up for submission to a peer-reviewed Journal. We will also complete data collection on a study of the effects of frequency-place compression and expansion in quiet and in noise.

We are particularly interested in the effect of frequency-place mapping on new implant patients, before they have extensive experience with a clinical speech processor. Once interface software is ready, we will recruit newly implanted cochlear implant listeners with the Nucleus-24 and Clarion-II systems for research. We will look for patients who are willing to spend several days testing in the lab within their first few weeks following implant hookup. We will measure consonant and vowel recognition for processors that vary the frequency-to-place assignments in a parametric way, both shortly after initial clinical hookup and at several time points in the first few months

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