Speech Processors for Auditory Prostheses

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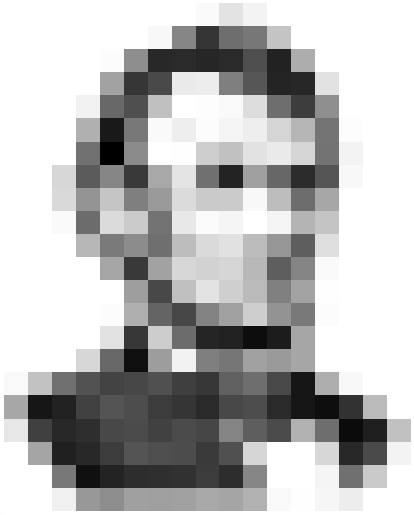

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ABSTRACT

In this quarter we continued hardware and software development on research interfaces for the Clarion and Nucleus-24 cochlear implant systems. The Clarion research interface (CRI) required a bit more time than anticipated to debug the high-speed host port interface between the PC and DSP board. This high-speed port is now fully debugged and the CRI is now being integrated into the general laboratory experiment control software. The software interface for the Nucleus-24 implant system has been tested and is now being integrated into experiment control software. There are several limitations (speed, sample length) of this software that limit its usefulness, particularly for long speech samples. A hardware interface to the Nucleus-24 implant system is under development based on a Motorola 56k family of DSP chips. This interface will allow experimental control over all pulse parameters to both Nucleus-22 and Nucleus-24 implanted devices.

In this report we provide an update on the “holes in hearing” experiment, which assessed the impact of deleting one or more electrodes from a 20-electrode implant system. Complete results are presented from 6 implant listeners. Similar data from acoustic simulations of implant processing in normal-hearing listeners is being collected for comparison.

We also report results from a series of experiments investigating within vs across-channel processing of temporal information. These experiments measured gap detection and forward masking in conditions where the first and second stimulus bursts (masker and signal in forward masking) were on the same or different electrodes. Additional conditions measured gap detection on a single electrode when the two stimuli were qualitatively different (different levels or stimulation rates). We conclude that a “perceptual channel” is defined more in terms of a qualitative distinctiveness rather than strictly in terms of activation of a distinct peripheral neuronal population. In addition, forward masking and gap detection appear to tap into two distinct temporal processing mechanisms – with forward masking indicating a somewhat peripheral recovery from adaptation and gap detection indicating a more central temporal comparison. Across-channel gap detection can provide a method for assessing the interaction between electrodes, or for assessing qualitative similarity of two stimuli.

In the next quarter we anticipate completing a series of experiments on the effect of amplitude manipulations, specifically looking at the use of dynamic wideband stimuli for setting the operating dynamic range of each electrode rather than setting these values using single electrode stimulation. Also, we will report on a series of experiments looking at cross-channel temporal asynchrony.

IMPLANT INTERFACE DEVELOPMENT

Clarion Research Interface

We completed the full command set for the Clarion Research Interface software in the previous quarter. To integrate this hardware with out laboratory software, it was our intention that the DSP portion of the interface software (bootstrap) reside in flash memory of the interface hardware. In this situation the DSP program starts up when the interface is powered up and allows the PC program to immediately begin interacting with the interface through the parallel port**.** Having the program resident on the hardware facilitates use of the interface in at least two practical ways:

1) reduces the number of steps required by the experimenter in beginning a testing session
2) makes it easier to recover from events in which any of the connection are disrupted (e.g., someone unplugs the headset from the processor or the interface is accidentally powered down).

To date, however, we have been unable to start the program when it resides in flash memory and are actively working with the manufacturer (Domain Technologies) of the parallel port interface on a solution. This delay has prompted us to employ a work-around tactic that requires downloading and executing the DSP software via a separate PC program before every testing session or after disruptions in the connections. This slightly more complicated interface is now available and being tested for use in experiments in the next quarter. When we solve the flash memory problem we will incorporate it into the interface.

Nucleus-24 Research Interface

Nucleus-24 Software Interface. Cochlear Corp. has provided us with a software library (DLL) that enables delivery of experimental stimulation sequences to patients with the Nucleus-24 device. We have tested this system on the bench and are integrating it into our laboratory software. The present system has two serious limitations: slow speed and limited duration of stimulation. The software can specify a sequence of approximately 4000 pulses, which is adequate for psychophysical experiments, but is too short for most speech stimuli. For example, this interface would only allow one second of speech to be presented to a 4-channel CIS at a stimulation rate of 1000 pulses/sec/channel. We will shortly receive a newer DLL library from Cochlear Corp. which will have improved properties. We hope to integrate that new DLL into our laboratory software in the next quarter.

Nucleus-24 Hardware Interface. Our original intention was to develop a hardware DSP interface for the Nucleus 24 device that would be code-compatible with our existing laboratory software (for the BTNI-Nucleus-22 interface). However, in the process of software development we discovered that

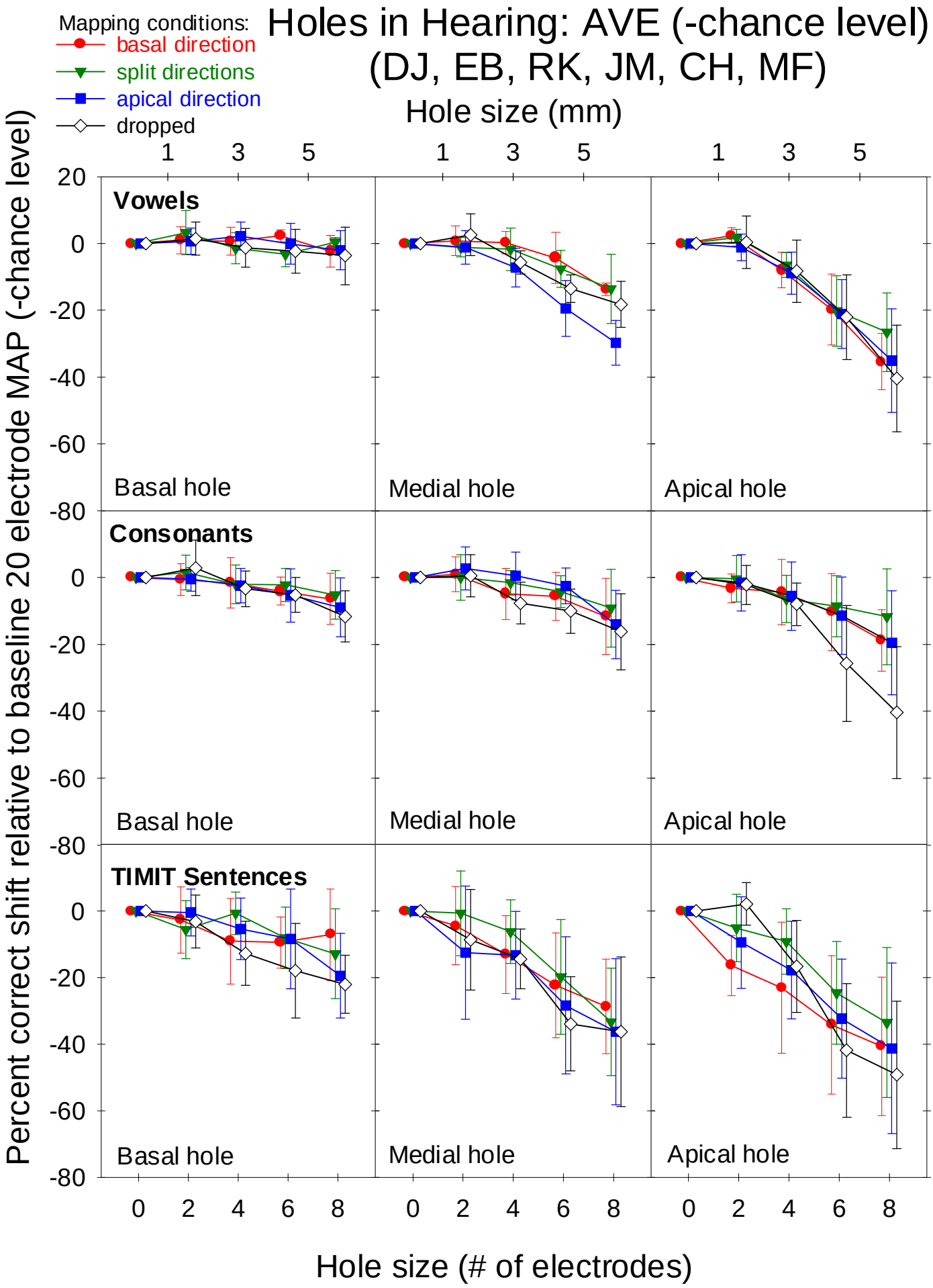
the selected DSP hardware (Domain Technologies) does not support the standard parallel port (SPP) data transfer protocol. According to the manufacturer the circuitry exists but the logic is not implemented. Rather than wait for the manufacturer to recode the logic array we have decided to use the enhanced parallel port (EPP) protocol that we are using successfully with this parallel port interface in the Clarion Research Interface. This means that we will have to rewrite some drivers for existing software that uses the SPP protocols. The upside is that the existing software should be able to take advantage of the faster data transfer capability of the EPP interface.

OVERVIEW OF EXPERIMENTS IN PROGRESS

Holes in Hearing

One of the important issues in electrical stimulation of the cochlea is the uniformity of nerve survival in the deaf cochlea. The density and uniformity of nerve survival may depend on the type of pathology that caused the deafness of the individual patient. If the nerve supply is uneven, then evenly spaced electrodes will not produce the intended pattern of excitation along the auditory nerve population. To assess the importance of the uniformity of nerve survival, we designed an experiment to purposely place “holes” along the tonotopic dimension of the cochlea. We have now collected data from several patients with cochlear implants and will collect similar data in normal-hearing listeners for comparison.

“Holes” were created in Nucleus-22 implant patients by the following method. Two or more sequential electrodes were selected to define the hole. The hole was created in either the apical, middle, or basal region of the electrode array. Holes were created that were 2, 4, 6, or 8 electrodes in width, corresponding to holes 1.5, 3.0, 4.5, and 6.0 mm wide, respectively. The electrodes selected for the hole were turned off. The full 20-band frequency analysis was still used, but the filter bands that would have normally been assigned to the electrodes in the hole were re-routed. Four conditions were assessed: the filter bands normally assigned to the electrodes in the hole were (1) reassigned to the electrode on the apical edge of the hole, (2) reassigned to the electrode at the basal edge of the hole, (3) evenly split between the electrodes at the apical and basal edge of the hole, or (4) dropped. Performance was measured in all conditions on 16 medial consonants, 12 medial vowels, and TIMIT sentences. Figure 1 presents the average results from six Nucleus-22 subject for these conditions. The figure presents the average drop in performance from the full 20-electrode map, corrected for chance, as a function of the size of the hole.


Holes in Hearing: AVE (-chance level)
(DJ, EB, RK, JM, CH, MF)
Mapping conditions:
basal direction
split directions
apical direction
dropped
Hole size (mm)
1
3
5
Vowels
Consonants
TIMIT Sentences
Basal hole
Medial hole
Apical hole
20
0
-20
-40
-60
-80
0
2
4
6
8
Percent correct shift relative to baseline 20 electrode MAP (-chance level)
Hole size (# of electrodes)

These results confirm the preliminary results presented in the last progress report, that:
1. An apical hole is more damaging to intelligibility than a basal hole. A basal hole, even 6 mm wide has very little effect on speech recognition.
2. The disruption of intelligibility increases with the size of the hole.
3. There was no significant difference between the four methods used for distorting or dropping the speech information around a hole. Only for consonant recognition with an apical hole was dropping the information slightly more harmful than reassigning the information to the edges of the hole. This indicates that if a hole exists in the representation of spectral information, the damage to speech recognition is primarily due to the hole itself, rather than to the warping of the spectral information around the hole.

In some conditions several subjects reported that the sound quality actually improved when several electrodes were dropped. In most cases this quality improvement was accompanied by a slight improvement in recognition as well. While this phenomenon is not represented in the average scores presented in Figure 1, we feel it is a significant observation that we will follow up. More specifically, one listener reported that the sound quality with his clinical MAP had an “echo” and that a hole of 2 or 4 electrodes in the apical location removed the echo, improving quality. We will investigate whether the removed electrodes were causing interference, either in terms of a pitch discontinuity or in terms of undue channel interaction. If this was the case, then identifying and removing a “bad” electrode might provide a path for improving performance.

Within and Across-Channel Temporal Processing

Introduction

The ability to detect silent temporal gaps placed between successive stimuli, has been often considered to be related to the time course of forward masking (Plomp, 1964; Penner, 1977). Both are important indicators of the temporal resolution of the auditory system. It seems reasonable to assume that the faster the auditory system recovers from the first stimulus, the more sensitive it will be to the silent gap preceding the next one. However, the rate or amount of recovery alone may not be sufficient to explain all aspects of gap detection. For example, it is known that increasing the duration of the signal preceding the gap may *improve* gap thresholds, while the amount of forward masking *increases* with increasing masker duration. In addition, it has been recently demonstrated in both normal hearing (Phillips et al, 1997; Formby and Forrest, 1991) and in cochlear implant hearing (Hanekom and Shannon, 1998) that gap detection deteriorates when the stimuli flanking the gap (markers) stimulate spatially distant regions of the cochlea. In this case, forward masking would be unlikely to play an important role.

The finding that gap thresholds increase with increasing spectral (or cochlear) separation between the stimuli flanking the gap, makes gap detection a candidate tool to measure channel-separability in both normal hearing and implant listeners. The ability to detect an across-channel gap may play a role in

certain elements of speech recognition, and is therefore of considerable interest , particularly in studies with hearing impaired or cochlear implant listeners.

In cochlear implant listeners, we (Chatterjee et al, 1998) found a similar deterioration in gap detection thresholds when the markers stimulated the same cochlear region, but at different (loudness balanced) pulse rates. We also found a qualitatively similar effect when the markers stimulated the same electrode pair at the same rate, but at different amplitudes. We suggested that these findings were an extension of the “across-channel” effect found by previous investigators, and proposed that the gap was being detected at a fairly central level in the auditory system, where the perceptual difference between the markers had already been abstracted. Thus, we concluded that gap detection was more a measure of the perceptual discontinuity between the markers and less a measure of temporal resolution.

Although it is unlikely that forward masking plays an important role in gap detection in the across-channel case, the situation may be different in the within-channel case. Forward and/or backward masking may have played a role in the within-channel experiments conducted by Chatterjee et al (1998) when the markers were presented at the same rate, but different amplitudes. Thus, when the first marker was more intense than the second, forward masking could have raised gap thresholds, and when the second marker was more intense, backward masking could have raised gap thresholds. This issue was not explored at that time.

There are other important differences between recovery from forward masking and gap detection in cochlear implant listeners, which may suggest that the connection between the two is not simple. For instance, for a gap inserted into a pulse train, gap threshold is strongly dependent upon the amplitude of the pulse train, whereas the time constant of recovery from forward masking is independent of the amplitude of the masker (Chatterjee, 1999).

In some sense, across-channel gap detection may be considered to be analogous to the “overshoot”- producing experimental paradigm (Zwicker, 1965; Bacon, 1990). Overshoot is the difference in thresholds between a brief increment presented near the onset of an ongoing stimulus and the same increment presented at a later time. In general, it is harder to detect the increment when it is presented near the onset. In addition, it is also harder to detect the increment when it occurs at a distant frequency region (across-channel) than in the same frequency region (within-channel) as the background (see Bacon and Smith, 1991, for review). It has been hypothesized that some sort of “adaptation” plays a role in the overshoot phenomenon. Near onset, both the mean and variance of the response variable (not necessarily at the auditory nerve level) may be high, thus masking the transient easily. However, at steady state, the system may be adapted, and the increment may be easier to detect (Chatterjee and Smith, 1993). The detection of a silent gap, a decrement in the stimulus, may involve like processes.

If similar mechanisms operate in gap detection, we may speculate that as the duration of the leading marker shortens, the gap becomes harder to detect. Indeed, studies of gap detection in both normal hearing and implant listening

generally show decreasing gap thresholds with increasing duration of the leading element (Phillips et al, 1997; Shannon, 1989). Whether the same principle will operate in the “across-channel” condition or not, is not known. In a recent study of recovery from forward masking in cochlear implant listeners (Chatterjee, 1999) we found that shortening the masker duration reduced the slower component of the recovery function, resulting in a more rapid recovery when the masker duration was shortened. If forward masking plays an important role in gap detection, we would expect to find that as the duration of the leading marker shortens, the gap becomes easier to detect. This would be opposite to the “adaptation” effect described above. It is quite possible that, measured across a range of stimulation paradigms, gap detection will display both of these features.

In the across-channel case, forward masking may be expected to play a minimal role; therefore, any “across-channel” effects may be attributed to more central, higher order processes, where information from different “channels” converge and may be compared.

The experiments in this study will elucidate the relations between forward masking, gap-detection, and channel-interaction in cochlear implant listeners in the context of these issues.

General methods

Stimuli were generated using a custom interface (Shannon et al, 1990) and controlled by custom software. Stimuli were trains of biphasic pulses, 200 microseconds/phase, presented at 1000 pulses/second. Six cochlear implant listeners implanted with the Nucleus-22 device participated in these experiments. For all subjects except one, the pulses were presented in bipolar+1 mode. For the remaining subject, the pulses were presented in bipolar+3 mode. Pulse amplitude was determined from calibration tables obtained for each individual’s device from Cochlear Corporation.

Amplitude detection thresholds (with or without a forward masker) as well as gap detection thresholds were measured using a 3-down, 1-up, 2-interval, forced choice procedure. Visual feedback was provided after each trial. The mean and standard deviation of two to three measurements is used to obtain each data point.

Loudness balancing was done using a two interval forced choice double staircase procedure. Two interleaved tracks, each starting at a higher and lower level, run together. One of the stimuli serves as the standard: the other is adaptively adjusted in each track according to a 3 down, 1 up (for the track starting higher) or a 3 up, 1 down (track starting lower) rule. The mean of the last eight reversals is calculated to arrive at the loudness balanced amplitude for each track. The mean of the amplitudes obtained from each track is calculated and serves as the final balanced amplitude.

Five adult users of the Nucleus-22 cochlear implant system participated in these experiments.

Experiment 1: Effects of duration in the within-channel case

We first measured the dependence of gap threshold on the relative durations D1 and D2 of the two markers M1 and M2 defining the gap. The pattern of results was similar across subjects. Figure 1 shows results obtained with subject N4, for two conditions. In one, D1 = D2, and both are varied together (filled symbols). In the second, D2 is fixed at 100 ms (open symbols). Gap thresholds are plotted as a function of D1. Measurements were made at comfortable (circles) and soft (squares) listening levels. As has been shown before in both normal hearing and cochlear implant listeners, gap thresholds generally decline with increasing duration. The data suggest little dependence upon the duration of the trailing marker

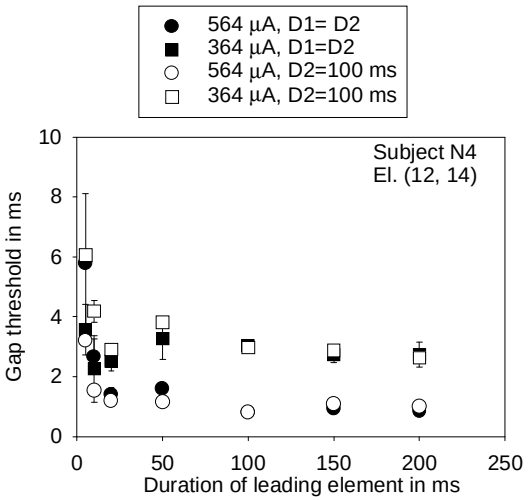


Fig. 1. Gap thresholds as a function of D1. Circles: comfortably loud, squares: soft. Filled symbols: D1=D2. Open symbols: D2 = 100 ms.

Experiment 2: Effects of duration in the across-channel case

Gap detection thresholds were measured as a function of the duration of the leading marker when the trailing marker stimulated a distant cochlear region relative to the first marker. In each case, loudness balancing was performed using the double staircase loudness balancing procedure, for 100 ms duration stimuli presented to the two electrode pairs. The previous experiment indicated that gap detection is relatively independent of the duration of the second marker. In general, we found similar results in the across-electrode case. Results are shown in Figure 2. Each row represents results obtained with a different subject. The left hand column shows measurements made at a soft level, and the right hand panel shows measurements made at a comfortably loud level. The electrode pairs stimulated by the leading and trailing markers are indicated in each panel. The filled symbols show results obtained with the leading and trailing markers equal in duration. The open symbols show results obtained with a fixed

duration (D2) of the trailing marker. In general, consistent with the findings of Hanekom and Shannon (1998), gap detection thresholds are higher in this condition than when the markers are presented to the same electrode pair. Notice that when the markers are presented to different electrode pairs, gap thresholds increase with increasing duration of the first marker. In some cases, at very short durations of the leading element, gap thresholds decrease with increasing duration, reach some minimum between 10 and 50 ms, and then increase with increasing duration of the second marker.

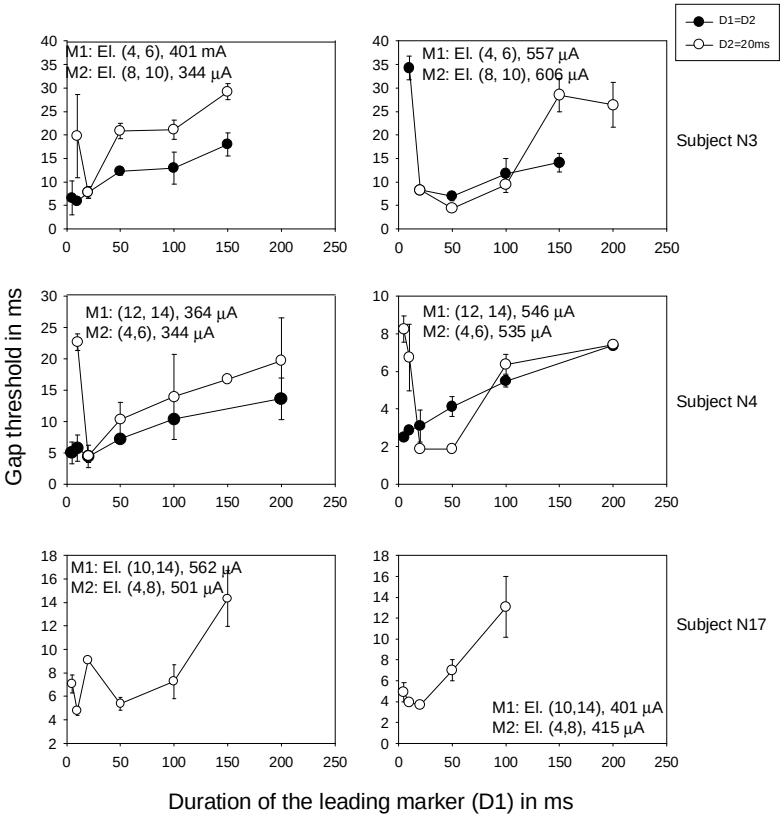


Fig. 2. Gap thresholds as a function of D1, for leading and trailing markers presented to different electrode pairs.

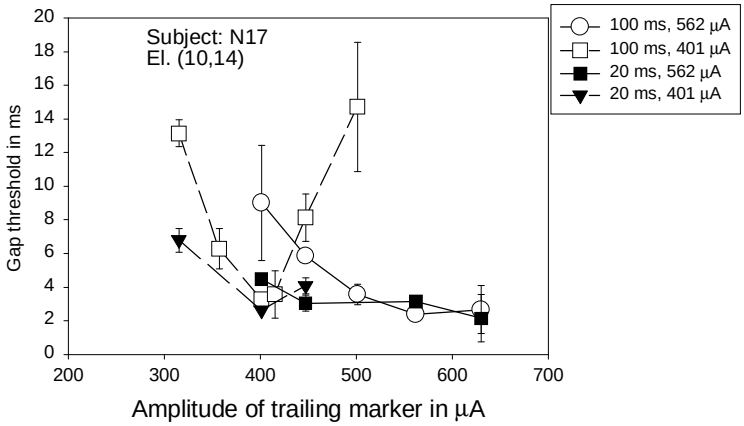


Fig. 3 Gap thresholds as a function of the amplitude of the trailing marker. The amplitude and duration of the leading marker are given in the inset. The duration of the trailing marker was fixed at 20 ms

Experiment 3. The relation between gap detection and forward masking

In these experiments, gap detection was measured for a series of conditions in which the first marker was fixed in amplitude and the amplitude of the second marker was varied from below to above the amplitude of the first. The duration of the first marker was fixed at either 100 or 20 ms, and the duration of the second marker was fixed at 20 ms. In this case, gap detection may be expected to be strongly influenced by forward masking when the level of the second marker is much lower than that of the first, the effect of forward masking decreasing with increasing level of the second marker.

A. Within-channel effects:

Fig. 3 plots gap detection thresholds as a function of the level of the second marker, for subject N17. (Open) symbols represent data obtained with a 100 ms long leading marker, and (closed) symbols show data obtained with a 20 ms long leading marker. Both markers were presented to the same electrode pair. The duration of the second marker was fixed at 20 ms. Solid lines correspond to data obtained with the leading marker at a fixed amplitude of 562 μA, and dotted lines correspond to data obtained with the leading marker at a fixed amplitude of 401 μA. As reported before (Chatterjee et al), when the two markers are at the same amplitude level, gap thresholds are lowest, and rise as the level of the second marker is decreased or increased relative to the first. Notice that with the shorter duration of the first marker (D1), gap thresholds are lower than with the longer D1, and the slope of the function on either side of the minimum is shallower, trends that would be consistent with the influence of forward masking. Further results obtained in the other subjects are shown in Fig. 4. In each case, the amplitude of the leading marker and the electrode pair are indicated in the inset. As in Fig. 3, filled symbols correspond to D1 = 20 ms, and open symbols correspond to D2 = 100 ms.

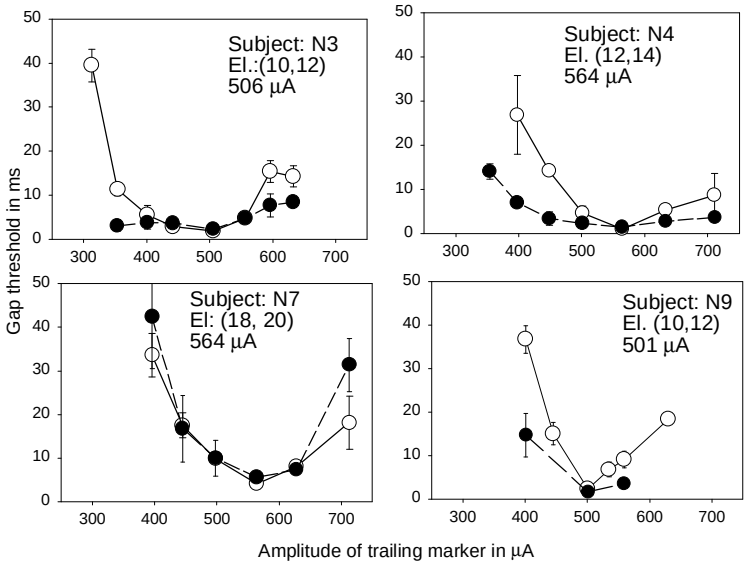


Fig 4. Gap thresholds as in Fig. 3, for the 4 other subjects.

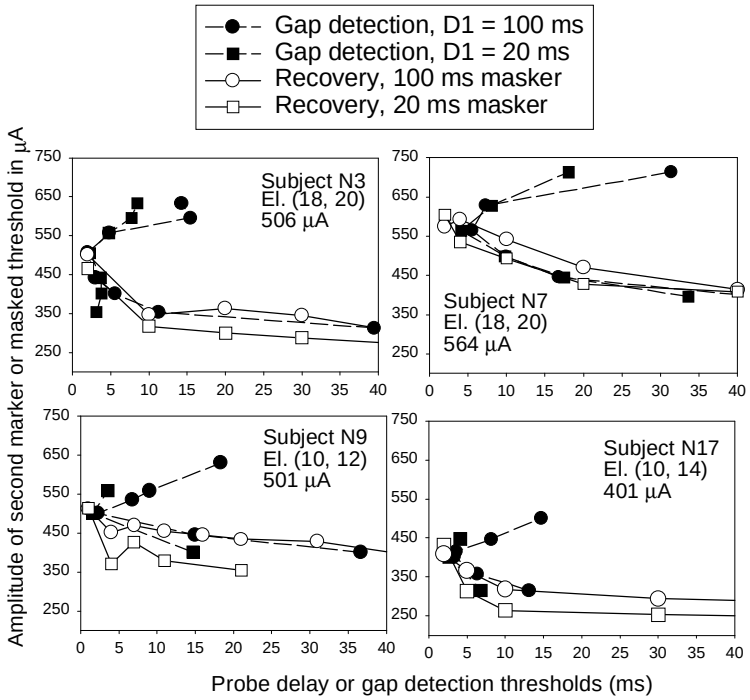


Fig. 5. Filled symbols show gap thresholds (horizontal axis) plotted against the amplitude of the trailing marker (vertical axis). Open symbols show forward masked thresholds (vertical axis) plotted against masker –probe

To test for the role of forward masking directly, we measured forward masked detection thresholds at various probe delays, keeping the masker stimulus identical to the first marker in the gap detection experiment. The probe stimulus was 20 ms long, and identical to the second marker in all respects except for its amplitude, which was varied adaptively to obtain detection threshold. Fig. 5 shows the recovery function plotted together with the gap detection thresholds in the five subjects. It is apparent that below some critical amplitude of the second marker, the gap detection threshold under these conditions is well accounted for by the recovery from forward masking function. Above that amplitude, other factors may determine gap detection threshold. It is possible that backward masking accounts for some of the elevation in gap detection thresholds when the amplitude of the second marker exceeds that of the first.

An inspection of these data reveals that when the amplitude of the second marker is low enough for forward masking to occur, increasing the duration of the first marker increases gap detection thresholds. In the equal-loudness region, increasing the duration of the first marker improves gap detection (lowers gap detection thresholds). Above the loudness-balanced amplitude, perhaps with backward masking occurring, increasing the duration of the first marker again increases gap detection thresholds.

B. Across-channel effects

It is reasonable to expect that as the electrode separation between the two markers increases, the effect of forward masking decreases. In this case,

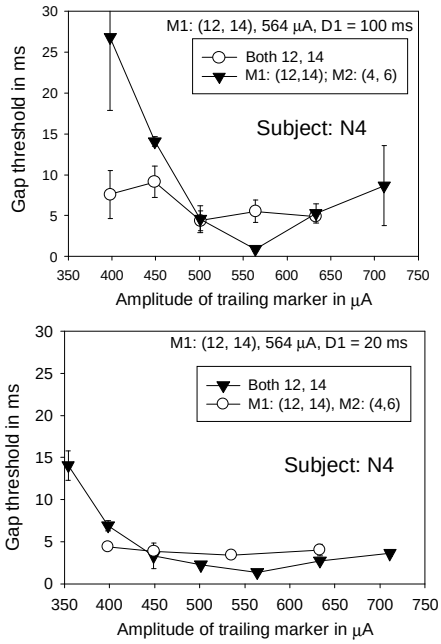


Fig 6. Gap thresholds plotted against the amplitude of the trailing marker. Results are compared for within-channel (open symbols) and across-channel gap detection, with D1 = 100 ms (top panel) and D1 = 20 ms (lower panel). D2 is always 20 ms long.

however, the across-channel effect found by Hanekom and Shannon (1996) may be expected to pull in the opposite direction – thus, gap detection would become harder as electrode separation increased. The observed gap threshold would then be the result of some trade-off between the two phenomena. Recall that in the previous experiment, we found that, for loudness balanced markers, increasing the duration of the leading marker generally increased gap thresholds for large electrode separations, suggesting that recovery from forward masking does not play an important role in these tasks.

In this experiment, we explored this issue in detail with one subject (N4) only. First, the subject loudness balanced 100 ms stimuli presented to two different electrode pairs. The leading marker (el. (12, 14)) was presented at this (reference) amplitude. The trailing marker (el. (4, 6)) was presented at different amplitudes, varying from below to above the loudness-balanced level. The duration D2 of the trailing marker was fixed at 20 ms.

Results (Fig 6) show a much smaller effect of changing the relative amplitudes of the trailing and leading markers when the two are presented to sufficiently distant electrode pairs. Gap threshold appears to be almost independent of the amplitude of the second marker relative to the first. At loudness-balanced amplitudes of M1 and M2, gap threshold is generally higher than in the within-channel case. However, as the amplitude of M2 increases or decreases from the loudness-balanced level, gap thresholds do not increase as much as in the within channel case. Thus, when the relative amplitudes of the first and second markers are different, gap thresholds in the across-channel case may be actually lower than gap thresholds in the within-channel case. The difference is due to within-channel masking.

Forward masked thresholds were also measured as in the previous section. The results showed that forward masking does not account for higher gap detection thresholds as it does in the within-channel case. Thus, even

though both markers are highly detectable in the across-channel case, the gap is difficult to detect.

Experiment 4: Same-electrode gap detection with different-rate markers

The "across-channel" effects discussed previously occurred when the two markers were presented to spatially distant electrode pairs, which are known to evoke different tonal percepts. It is of interest to know whether a similar effect would be observed using two markers that stimulate the same electrode pair, but have different stimulation rates, thus presumably evoking different percepts also, although perhaps not along the same perceptual dimension as stimuli activating distant electrode pairs.

In a few subjects, we measured gap thresholds as a function of the duration D1 of the leading marker, in a condition where both markers were presented to the same electrode pair, but the leading and trailing markers had different pulse rates. The duration D2 of the trailing marker was fixed at 50 ms. In all cases, the pulse rate of the leading marker was fixed at 1000 pulses/sec (pps), while the pulse rate of the trailing marker was varied. The amplitudes of the two markers were fixed at loudness balanced levels obtained when both were 100 ms in duration. Figure 7 shows results obtained with subjects N4 and N7, for the condition where the trailing marker's pulse rate was 100 pulses/second.

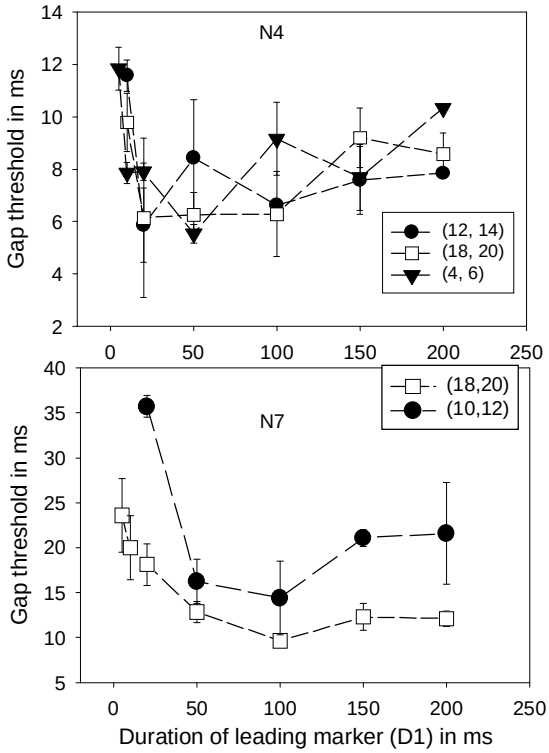


Fig 7 Leading marker: 1000 pps, trailing marker: 100 pps. D2 = 50 ms

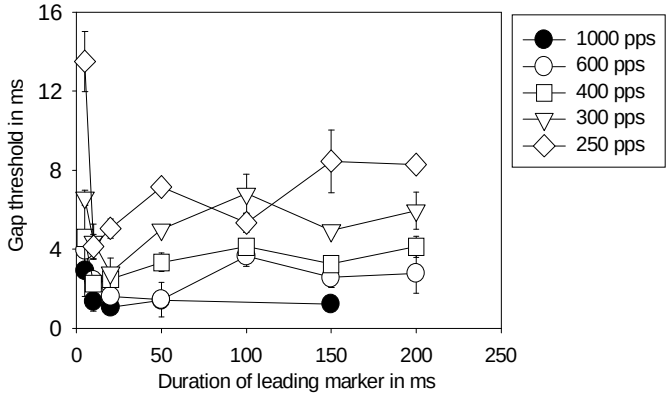


Fig 8 Leading marker: 1000 pps. The parameter (shown in legend) is the pulse rate of the trailing marker. D2 = 50 ms. Results obtained with subject N4.

Within each panel, the different symbols show results obtained with a different electrode pair. Subject N7, who had difficulty with the across-electrode gap detection task, also has high gap detection thresholds in the within-electrode, different pulse rate gap detection task. In the case of subject N4, gap thresholds decrease with increasing D1, reaching a minimum at about 20-50 ms. At higher durations of the leading marker, gap thresholds increase. This pattern is similar to that observed with across-electrode gap detection. In the case of subject N7, the effect is much smaller, similar to the results for this subject in across-electrode gap detection. To examine the transition from the within-electrode, same-pulse rate to the within-electrode, different pulse rate results in some detail, we measured in subject N4 the same function for a few pulse rates of the trailing marker in between 100 pps and 1000 pps. Results, shown in Fig. 8, suggest a gradual progression from the monotonically decaying pattern when both markers are at the same pulse rate, to the nonmonotonic pattern when they are at rather different pulse rates. Overall, the pattern of results are more similar to the results obtained in the across-electrode condition than to the results obtained in the within-electrode, same pulse rate condition. These results would suggest that similar mechanisms underlie the two kinds of gap detection. It seems reasonable to infer, then, that the common denominator across the two tasks, the perceptual difference between the two markers, plays an important role in the processing or detection of the gap.

SUMMARY OF RESULTS

1. When the amplitude of the markers flanking the gaps is equal and they both stimulate the same electrode pair, gap thresholds decline rapidly with increases in duration (D1) of the first marker, reaching an asymptote at D1=50 ms. The rate of decline is relatively independent of the duration of the second marker. The asymptote is dependent upon the level of the markers.

2. When the markers stimulate different electrode pairs, but the amplitudes are loudness balanced, increasing the duration of the first marker results in decreasing or constant gap thresholds for D1 < 20 ms; for D1>20 ms, increasing the duration increases gap thresholds. This rules out a role for adaptation in gap detection in this case.
3. When the amplitude of M1> the amplitude of M2, forward masking accounts for increased gap thresholds reasonably well in the within-channel condition. However, in the across-channel condition, forward masking is too minimal to account for increased gap thresholds. Thus, both markers are quite audible in this case, but it is difficult to detect the gap.
4. When the two markers stimulate the same electrode pair, but have different pulse rates, gap thresholds behave in a manner that appears similar to the behavior when the two markers have the same pulse rate but stimulate different electrode pairs. This suggests that the perceptual difference between the two stimuli dominates the detection of the gap.

DISCUSSION

The experiments described above have partially answered the questions asked in the Introduction about the relation between forward masking and gap detection, and the mechanisms involved in across-channel gap detection. These results also indicate that gap detection in cochlear implant listening shares some features with gap detection in normal hearing. In particular, the results of Experiment 1 show that the duration of the leading marker plays an important role in gap detection, and that the duration of the trailing marker does not influence gap thresholds. As the duration of the leading marker increases, gap thresholds decline rapidly to an asymtote. This behavior may be attributed to some sort of adaptation effect. As discussed in the Introduction, when an increment or decrement in the stimulus occurs near its onset where the variance of the response can be expected to be high, it is harder to detect than at steady state, where the response is adapted and has lower variance.

The results of Experiment 2 show an interesting and different behavior when a gap must be detected across electrodes. The gap becomes *harder* to detect as the duration of the leading marker increases. In some cases, gap thresholds decrease up to some duration, beyond which they increase with D1. We have no explanation for this behavior at present. It is possible that the perceptual salience of the leading marker increases with its increasing duration, resulting in a greater perceptual difference between the markers. If the perceptual difference is important in gap detection, the increasing difference would increase gap thresholds. However, this is merely speculation at this point.

Experiment 3 demonstrates that forward masking plays an important role in gap detection when both markers stimulate the same electrode pair, and the amplitude of the second marker is below the amplitude of the first. Under these conditions, recovery from forward masking accounts for the gap threshold almost completely. Beyond the masked region, however, other factors come into play.

Thus, when the second marker stimulates a different electrode pair, forward masking plays little or no role at all. Both markers are quite audible and distinct. In this case, gap thresholds are generally higher than in the within-channel case. While gap thresholds in this case show little dependence upon the amplitude of the second marker, they do display a small minimum at an amplitude of the second marker that corresponds to the amplitude at which it is loudness balanced with the first marker. This suggests that the loudness difference between the "channels" may play a small role in gap detection. In addition, in the across-channel gap detection task, it is easier to detect the gap when the second marker is much softer than the first than in the within-channel task, where forward masking increases gap thresholds.

The results of Experiment 4 may be interpreted as lending support to the suggestion made by Chatterjee et al (1998) that perceptually different stimuli presented to the same electrode pair are processed in a manner similar to stimuli presented to different electrode pairs. We conclude that, at least in cochlear implant listeners, a "channel" is not necessarily defined by the peripheral extent of stimulation, but may rather be considered to be a region in some as yet undescribed perceptual space, in which pulse rate and electrode separation are two of possibly many dimensions.

Publications and Presentations in this Quarter

This was a busy quarter for publications and presentations, primarily because of the biannual Conference on Implantable Auditory Prostheses in Asilomar on August 29 to September 2. We presented four invited talks at this meeting and four poster presentations. In addition, Bob Shannon was the invited Keynote speaker at the annual convention of the Cochlear Implant Club International, held in Manhattan Beach, CA on July 24-25. We also gave several presentations at University seminars and published two papers in Ear & Hearing related to the work scope of this contract.

Chatterjee, M. (1999). Within- and across-channel processing in multielectrode cochlear implants, 1999 Conference on Implantable Auditory Prostheses, Asilomar, CA, Aug 29-Sept 2. (invited oral presentation)

Friesen, L. (1999). The effect of speech processor manipulations on speech recognition, Cochlear Implant Club International Convention, Manhattan Beach, July 24. (Invited)

Friesen, L., Shannon, R.V., and Slattery, W.H. III (1999). Speech recognition in noise as a function of the number of electrodes used in the SPEAK, SAS and CIS speech processors, 1999 Conference on Implantable Auditory Prostheses, Asilomar, CA, Aug 29-Sept 2. (poster)

Fu, Q-J. and Galvin, J. (1999). Effects of spectral asynchrony on speech perception in normal-hearing and cochlear implant listeners, 1999

Conference on Implantable Auditory Prostheses, Asilomar, CA, Aug 29-Sept 2. (poster)

Fu, Q.-J. and Shannon, R.V. (1999). Effects of electrode location and spacing on speech recognition with the Nucleus-22 cochlear implant, Ear & Hearing, 20(4), 321-331.

Fu, Q.-J. and Shannon, R.V. (1999). Effects of electrode configuration and frequency allocation on vowel recognition with the Nucleus-22 cochlear implant, Ear & Hearing, 20(4), 332-344.

Fu, Q-J. and Shannon, R.V. (1999). Factors affecting speech performance in cochlear implant users, 1999 Conference on Implantable Auditory Prostheses, Asilomar, CA, Aug 29-Sept 2. (invited oral presentation)

Shannon, R.V. (1999). Short-term and long-term implications of alterations in the frequency-to-place mapping in hearing, Departments of Speech and Hearing Sciences and Otolaryngology, University of Iowa, Iowa City, 15 July.

Shannon, R.V. (1999). Pattern recognition in speech: Implications for the design and fitting of cochlear implant speech processors, Cochlear Implant Club International Convention, Manhattan Beach, July 24. (Invited Keynote Speaker)

Shannon, R.V. (1999). Amplitude, temporal, and spectral cues in speech: Implications for cochlear implant speech processor design, Advanced Bionics Corp., August 10.

Shannon, R.V. (1999). Future directions in cochlear implant research, 1999 Conference on Implantable Auditory Prostheses, Asilomar, CA, Aug 29-Sept 2. (invited oral presentation)

Stickney, G., Shannon, R.V., and Opie, J.M. (1999). psychophysical electrode interaction and speech perception in adult cochlear implant listeners with and without the electrode positioning system, 1999 Conference on Implantable Auditory Prostheses, Asilomar, CA, Aug 29-Sept 2. (poster)

Wygonski, J.J., Lee, J., Faltys, M., Shannon, R.V., and Robert, M.E. (1999). Configurable speech strategy implementation using the clarion research interface, 1999 Conference on Implantable Auditory Prostheses, Asilomar, CA, Aug 29-Sept 2. (poster)

Zeng, F.-G., Galvin, J., Shannon, R.V., Opie, J., and Segel, P. (1999). Amplitude mapping and speech recognition in cochlear implant listeners, 1999 Conference on Implantable Auditory Prostheses, Asilomar, CA, Aug 29-Sept 2. (invited oral presentation)

Plans for the Next Quarter

In the next quarter we will continue hardware and software development on the interface for the Nucleus-24 device. The Clarion research interface will be integrated into laboratory experimental software and experiments will be initiated.

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