Speech Processors for Auditory Prostheses

NIH Contract NO1-DC-92100

QPR #7: July-Aug-Sept 2000

Noise enhances modulation sensitivity in cochlear implant listeners: stochastic resonance in a prosthetic sensory system

Submitted by

Monita Chatterjee, Mark Robert, Qian-Jie Fu, Deniz Baskent,
Lendra Friesen, Robert V. Shannon, John Wygonski
House Ear Institute
2100 W. Third St.
Los Angeles, CA 90057

And

Fan-Gang Zeng
Department of Otolaryngology
University of California, Irvine

October 31, 2000

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ABSTRACT

In this quarterly progress report, we report on an experiment in cochlear implant listeners that demonstrates enhanced detection of modulation in the presence of added noise. Sensorineural hearing loss results in a loss of spontaneous activity among the remaining auditory neurons and is accompanied by a reduction in the normal stochastic nature of neural firing in response to electric stimulation. It has been hypothesized that the natural stochasticity of the neural response is important for auditory signal processing, and that introducing some optimal amount of noise into the stimulus may improve auditory perception through the implant. Here, we show that, for soft but audible stimuli, an optimal amount of "prosthetic" noise significantly improves sensitivity to envelope modulation in cochlear implant listeners. A nonmonotonic function relates modulation sensitivity and noise level, suggesting the presence of stochastic resonance.

OVERVIEW OF THIS QUARTER'S PROGRESS

Hardware and Software Development - Clarion S-2 Research Interface: John Wygonski continues to define DSP microcode for a research interface for the next generation Clarion cochlear implant (this effort not funded by this contract).

Hardware and Software Development - Nucleus-24 Research Interface: Our DSP interface to the Nucleus-24 implant is fully operational. The software and hardware have been fully developed and debugged. SEMA protocol has been implemented which will allow stimulation rates of up to 8000 Hz and pulse phase durations down to 10 µs/phase for the Nucleus-24 device. Higher stimulation rates (up to 15 kHz) should be possible using the Embedded Protocol, which has yet to be programmed. We anticipate that experiments using this new interface will begin in the next quarter.

Software for Speech and Psychophysical Training: Qian-Jie Fu has developed software to provide focussed training of cochlear implant listeners on selected psychophysical contrasts and speech contrasts. Any set of stimuli can be pre-programmed, consisting of 2 to 20 items. The program will present the stimuli one at a time and the listener is instructed to identify which stimulus was presented. Feedback is then provided. The entire set can also be played repeatedly for familiarization and initial training. We intend to use this software in training experiments to see if people can be trained to distinguish subtle speech distinctions, or to discriminate psychophysical stimuli which differ in temporal properties or spectral properties.

Experiments in Progress:

1. Electrode Interaction in Modiolus-Hugging Electrode Systems.

New modiolus-hugging electrode designs are now available from Nucleus and Advanced Bionics. Initial speech recognition results with these new electrode designs are encouraging. The goal of these new electrode designs was to reduce electrode interaction by placing the stimulating points closer to the residual nerve fibers. We are comparing psychophysical measures of electrode interaction in patients with the older electrode designs and new modiolus hugging designs. In the Clarion system we are measuring thresholds for signals presented in-phase or out-of-phase on electrodes adjacent to a masker stimulus on a standard electrode. Current field interactions are indicated by a large difference in threshold between the in-phase and out-of-phase conditions. We have presented preliminary data at several recent meetings (Stickney et al., 2000a, b) and will present more complete results at the upcoming Acoustical Society of America Meeting in December 2000 in Newport Beach. In short, current field interactions between adjacent electrodes are significantly lower in patients with new electrode designs compared with original electrode designs, suggesting that the new electrodes are achieving their desired result.

2. Frequency-Place Expansion and Compression

In existing cochlear implant systems the electrodes occupy approximately 12-16 mm along the scala tympani of the cochlea. If the electrode arrays are fully inserted the electrode contacts span the normal acoustic range of 500-5000 Hz, according to the frequency-place mapping formula of Greenwood (1990). However, existing cochlear implant systems divide the acoustic spectrum from 200-10k Hz among the electrodes. This expanded frequency range results in a compression of the frequency-place mapping in most cochlear implant patients. We are measuring speech recognition in normal-hearing listeners under conditions that simulate a compression in the frequency-place mapping to evaluate the potential effects of such compression in implants. We will present the preliminary results of these measurements at the Neural Prosthesis Workshop in October 2000 and at the fall meeting of the Acoustical Society of America in Newport Beach in December 2000.

3. Speech Recognition as a function of stimulation rate

In 1999 we published results showing no change in speech recognition for stimulation rates between 150 and 500 pps/channel in 4 channel CIS processors implemented in six Nucleus-22 listeners. Since that time we have collected additional data on speech recognition as a function of stimulation rate in Clarion listeners and in Nucleus-24 listeners – devices in which higher stimulation rates are possible. Preliminary results from 5 Clarion patients and 4 Nucleus-24 patients are consistent with our previously published results, showing no change in speech recognition for stimulation rates between 400 and 2500 pps/electrode. Similar results are observed for 4, 8, 12, and 16 electrode CIS processors. Results from these experiments will be presented at the Neural Prosthesis Workshop in October 2000 and at the fall meeting of the Acoustical Society of America in Newport Beach in December 2000.

4. Modulation Detection and Speech Recognition

Psychophysical capabilities are usually not found to correlate highly with speech recognition. A recent experiment by Qian-Jie Fu has shown a dramatically high correlation between modulation detection and speech recognition in implant listeners. Shannon (1992) measured temporal modulation transfer functions (modulation detection as a function of modulation frequency) in several cochlear implant patients. Although modulation sensitivity varied across the implant listeners tested they did not appear to be correlated with speech recognition performance in those patients. Qian-Jie Fu recently measured modulation detection at 100 Hz in 9 implant listeners with the Nucleus-22 cochlear implant. He measured modulation detection as a function of loudness from just above threshold, to just below the maximum comfortable loudness level. Preliminary results show high correlation between average modulation detection (averaged across the entire dynamic range of each subject) and speech recognition. A correlation of 0.97 was observed with consonant recognition and 0.79 with vowel recognition. Poorer correlations were observed between speech recognition and the best modulation detection or modulation detection at any fixed loudness level. Only when the modulation detection was averaged over the entire dynamic range were high correlations observed. Results from these experiments will be presented at the Neural Prosthesis Workshop in October 2000 and at the fall meeting of the Acoustical Society of America in Newport Beach in December 2000.

EXPERIMENTAL REPORT: ADDED NOISE ENHANCES MODULATION DETECTION (Chatterjee and Robert, submitted to JARO)

INTRODUCTION

The most sensitive auditory neurons in the functioning mammalian cochlea show a considerable amount of spontaneous activity in quiet (Liberman, 1978). Both this spontaneous activity and the stimulus-driven response of the typical auditory neuron in the normal cochlea are stochastic in nature, and have been successfully modeled as a Poisson process with deadtime (Young and Barta, 1986). Much of the "noise" appears to originate in hair cells and at the synapse. Recordings from neurons in mammalian cochleae with damaged hair cells show little to no spontaneous activity (Kiang et al., 1970; Liberman and Dodds, 1984) and much stronger phase-locking in response to periodic electrical stimuli than would be found in the normal stochastic response to periodic acoustic stimuli (Kiang and Moxon, 1972; Hartmann et al., 1984; Parkins, 1989). Recently, evidence in support of such reduced stochasticity has been found in auditory nerve responses of profoundly deaf humans. The sensorineural hearing loss that results from hair cell damage can be partially offset by the surgical insertion of a neural prosthesis known as a cochlear implant. In some cochlear implant users, reverse telemetry makes it possible to record the intra-cochlear neural response to electrical stimuli. When the stimulus is a train of short electrical pulses, the evoked potential response to successive pulses in the train demonstrates an oscillation which rides the decay in response due to adaptation. This oscillation has been found only in recordings from auditory nerves innervating deafened cochleae, and provides evidence for abnormal across-fiber synchrony in both the spike-generation and recovery processes among neurons in the cochlear-damaged sensory periphery (Wilson et al., 1997). It thus appears that along with reduced sensitivity to sound, hair-cell damage results in a loss of the natural stochastic nature of the neural response.

In recent years, there has been considerable interest in the significance of stochasticity in information processing by biological systems. In particular, a phenomenon termed “stochastic resonance” -- in which an optimum amount of noise results in enhanced transmission of a weakly periodic signal through a nonlinear system -- has stimulated a substantial amount of discussion. The effect of noise in the peripheral auditory system may be two-fold: *within-channel* processing may be improved by small amounts of noise due to stochastic resonance; *across-channel* processing may be improved by forcing greater independence across responding neuronal populations. It is possible that the normal auditory system utilizes both mechanisms. Recent experiments in frog saccular hair cells suggest that stochastic resonance can indeed enhance signal transmission through hair cells (Jaramillo and Wiesenfeld, 1998). In the normal auditory periphery, it has been shown that the spontaneous firings of single neurons constitute mutually independent random processes (Johnson and Kiang, 1976). The notion that noise may play a role in signal-processing suggests that the loss of stochasticity in the auditory periphery may in itself represent a sensory deficit. It seems reasonable to speculate that stimulating the auditory nerves with external noise along with the signal through the cochlear implant may restore the “natural” stochastic response characteristics of the sensory periphery, which may in turn result in improved auditory perception by cochlear implant listeners.

The exact form of noise and how it should be introduced into cochlear implants has been a matter of speculation. Using analog noise and speech signals, noise-induced enhancements have been shown in the vowel formant coding in electrically stimulated frog sciatic nerve responses (Morse and Evans, 1996). It has also been shown (Rubinstein et al., 1999) that stimulating auditory neurons at very high rates may force their responses to enter randomly different states of refractoriness, becoming desynchronized with respect to the stimulus period and pushing them into a state of “pseudospontaneous” activity. More recently, it has been shown that the introduction of a small amount of analog noise may result in small improvements in threshold in cochlear implant listeners (Zeng et al., 2000). To date, there have been no reports of noise-induced improvement in suprathreshold auditory processing tasks (such as those likely to be involved in speech perception) in cochlear implant listeners.

One measure of the temporal resolution of the normal auditory system is its sensitivity to dynamic changes in the signal envelope (Viemeister, 1979). The primary focus of our work is to understand the processing of dynamic stimuli by cochlear implant listeners, and the effects of noise on such processing. Specifically, we are interested in the detection of amplitude- or charge-modulation as a function of modulation frequency and reference carrier amplitude.

A typical cochlear implant system consists of a microphone connected to a speech processor which uses radio frequency (RF) transmission to communicate with an electrode array implanted in the scala tympani of the cochlea. Speech processor output is directed to the RF transmitter positioned opposite the subdermal RF receiver coil. Implanted electronics decode the RF signal and send appropriate current pulses to selected electrode pairs. In these experiments, we bypass the microphone and the speech processor by means of a custom implant research interface (IRI) (Shannon et al., 1990) to deliver stimuli directly to the RF transmitter for transmission to the implant. Stimuli are trains of charge-balanced, biphasic current pulses applied between two electrodes of the implanted array. Using the IRI, we have the capability to stimulate the auditory system with arbitrary combinations of pulses. This, combined with a presumably low-noise auditory periphery, allows us some degree of freedom to define and create “noise”. As a first step, we chose a very simple form - random fluctuations in the carrier amplitude that are uniformly distributed within a specified range. Here, we demonstrate that the introduction of a small, optimal amount of this simple "prosthetic noise" through the cochlear implant results in improved performance in a "within-channel" task that requires the detection of modulations within the speech-music range of envelope frequencies.

METHODS

Subjects. Subjects (N3, N4. N7 and N9) were four postlingually deafened cochlear implant listeners ranging in age from 42 to 59 years. All subjects have participated in our laboratory in various psychophysical experiments and can be considered highly trained. Experiments were conducted with informed consent from the subjects and with prior approval of the procedures from the Institutional Review Board at House Ear Institute.

Materials. All of the subjects use the Nucleus-22 cochlear implant system. The implanted electrode array has 22 electrodes numbered 1-22 from the base of the cochlea (which normally responds to high frequencies) to the apex (low frequencies). The array generally extends two thirds of the cochlear length. The apical-most electrode (22) stimulates the tonotopic region corresponding to 1500-500 Hz, depending on the individual cochlea and details of the surgery. Adjacent electrodes are separated by 0.75 mm along the array.

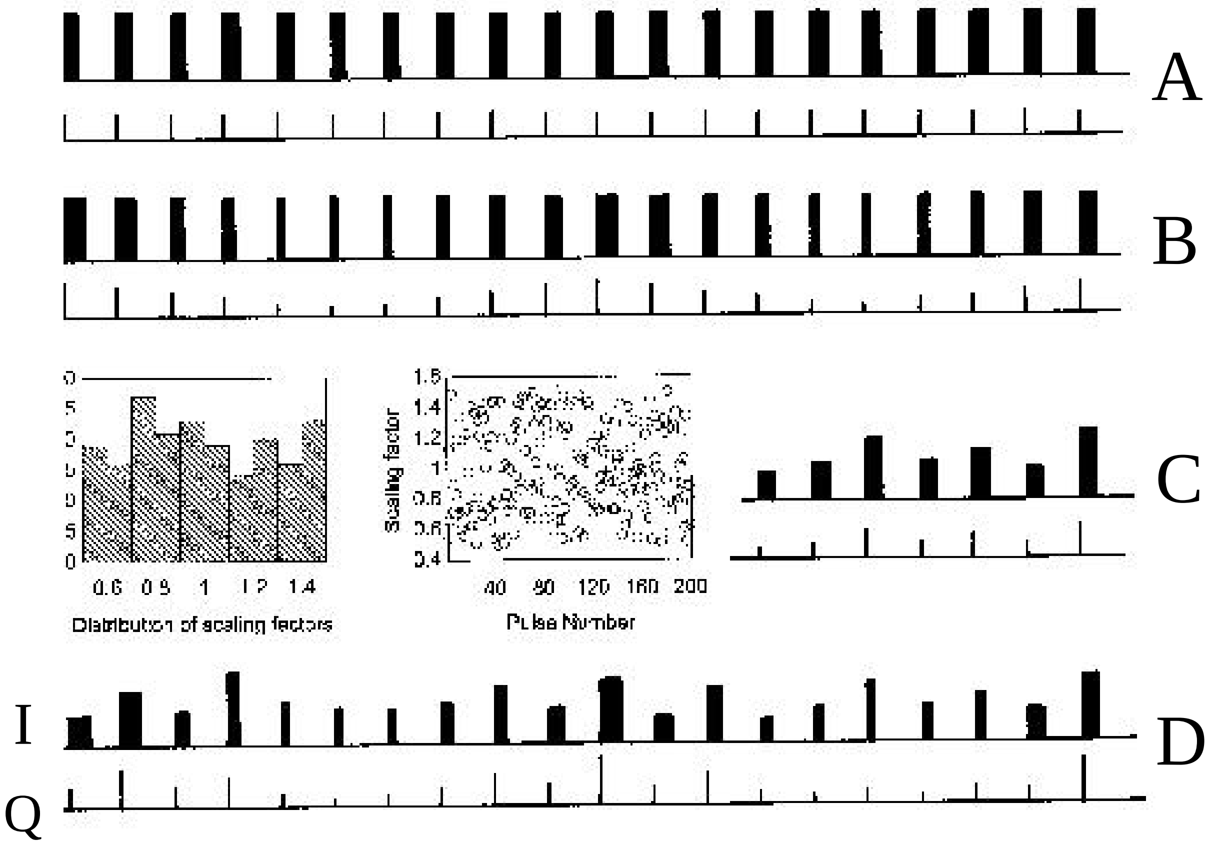
We use a custom implant research interface (IRI) to deliver stimuli to the implanted electrode array throught the RF transmission system. With the IRI current amplitudes are presented in discrete steps according to the listener's device calibration table, which we obtain from the manufacturer.

Stimuli: Pulse-train stimuli were all presented to electrode pair (10, 12) -- resulting in a relatively focused, centrally located stimulating field -- and had the following characteristics:

1. Unmodulated pulse train: 200 ms long trains of biphasic current pulses (see Fig. 1A). Per-phase duration D of each biphasic pulse was 200 µs. The pulses were presented at a rate of 1000 Hz; thus, there were 200 pulses in the train.

2. Modulation: Cochlear implant listeners are generally very sensitive to modulation. With the Nucleus-22 device, modulating the phase duration D allows for greater resolution (0.4 µs steps) than modulating pulse amplitude I (current is delivered by the device in clinical units, or steps, that increase logarithmically - thus resolution in current amplitude becomes worse at high levels). In these experiments, we modulated the phase duration D of each pulse in the train (See Fig. 1B). (In either case, charge q = I*D is the modulated quantity.) The equation generating the modulated pulse train is as follows: $D(n) = D_{ref}*(1 + m*\cos(2*pi*f_m*n/f_c))$, where D(n) is the phase duration of the nth pulse, D_{ref} is the reference phase duration (200 µs), m is the modulation index ($0<m<1.0$), f_m and f_c are the modulation and carrier frequencies respectively. The increment in energy due to modulation was below detection threshold.

Figure 1



3. Noise: Amplitudes (I) of consecutive pulses were scaled by a sequence of numbers from a uniform pseudorandom distribution (range 1.0 +/- r where $0.00 < r < 1.00$) (see Fig. 1C). The amount of "noise" depends upon r, which we express as a percentage. Thus, 5% noise indicates $r = 0.05$ (the distribution ranges from 0.95 to 1.05). The mean amplitude of the pulse train remains unchanged (=I) as the noise is increased. The variance is given by $(I^2r^2)/3$. Figure 1D illustrates a pulse train that is modulated and noisy.

4. Stimulus levels: The carrier reference levels chosen for the experiments corresponded to subjective loudness judgments of "comfortable", "comfortable but soft", and "soft". Although the level-dependence of modulation sensitivity varied across subjects, modulation detection thresholds at the "soft" levels were similar across subjects at the low modulation frequencies. The "soft" carrier levels were 160.9 µA, 159.5 µA, 194.9 µA, and 143.3 µA above threshold for subjects N3, N4, N7 and N9 (4.45 dB, 5.2 dB, 5.88 dB, and 4.5 dB above threshold respectively). At the "soft" level for each subject, a noise level of 40% yielded fluctuations that did not dip below detection threshold for the 200 ms pulse train. The noise level in these experiments was not increased beyond 40% (r=0.40) for this reason, with the exception of a few additional conditions with subject N3 (Fig. 6). Measurements were made at the "comfortable but soft" level in subjects N3, N7 and N9, at levels corresponding to 201.9 µA, 243.9 µA, and 190.3 µA above threshold (5.3 dB, 6.89 dB, and 5.59 dB above threshold) respectively. The "comfortable" listening level in subjects N3, N4, N7 and N9 corresponded to 316.9 µA, 306.5 µA, 296.9 µA, and 290.3 µA above threshold (7.3 dB, 8.2 dB, 7.87 db and 7.52 dB) respectively.

Procedures: Thresholds were measured using an adaptive, 3-down, 1-up, two-interval, two-alternative, forced choice experimental paradigm. Subjects were given visual feedback. Initial training was provided during pilot runs.

Subjects were presented with two intervals (accompanied by flashing squares on the computer screen), only one of which (randomly) contained the “signal”. They were asked to indicate which of the two contained the signal by clicking on the appropriate square on the screen.

When absolute detection threshold of the unmodulated pulse trains was measured, only one of the two intervals contained the signal. The adaptive procedure changed the reference amplitude of the pulse train until the required number of reversals were completed.

When detection threshold of the noise was measured at a particular carrier amplitude, the “signal” interval contained the noisy pulse train and the other interval contained the same pulse train at the same amplitude but without the noise. The variable being adjusted in this case was the percent noise.

When modulation detection threshold was measured, the “signal” interval contained the modulated pulse train (with the noise) and the other interval contained the identical pulse train with noise only (no modulation). The variable being adapted was the modulation depth m.

When pulse phase duration increment threshold was measured, the two intervals contained identical, unmodulated pulse trains. One of the pulse trains consisted of longer phase duration pulses. The subject indicated which interval sounded louder, and the adapted variable was the pulse phase duration D

A test run consisted of a minimum of 8 and a maximum of 12 reversals or 55 trials. If less than 8 reversals were recorded for the maximum number of trials the test was discarded and the starting level modified until at least 8 reversals were recorded. After the 4th reversal, the step size was reduced to bracket the threshold with finer resolution. The noise series for every case was refreshed for each comparison trial, but was identical in the two intervals within the trial. The mean and standard deviation of the last 8 reversals was calculated at the end of the run. Each threshold value and the accompanying error bars shown represents the mean and standard deviation obtained from a minimum of 4 such test runs (for the absolute threshold measurements, the mean and standard deviation of 2 to 4 runs were calculated).

Loudness estimates were obtained by presenting the stimulus 5 times in succession with an interstimulus interval of 300 ms. The subject was asked to provide a number between 0 ("don't hear it") and 100 ("too loud") that matched the perceived loudness of the stimulus. Stimuli were randomized and the mean and standard deviations of at least 4 repetitions were calculated.

RESULTS

Noise has little effect on absolute detection threshold

The 200 ms, 1,000 Hz, 200 µs/phase biphasic pulse train carriers used in these experiments were made noisy by scaling the amplitudes of successive pulses in the train by random numbers falling within the range (1+/-r), where $0<r<1.0$. Introducing the noise changed the variance of the amplitudes of the pulses in the train but not the mean amplitude. We first measured the effect of the noise on detection thresholds of the unmodulated pulse trains. In the absence of noise, mean detection thresholds for the stimuli were 240.1 µA, 194.5 µA, 201.1 µA, and 210.7 µA for subjects N3, N4, N7 and N9 respectively. The noise did not influence detection threshold in any of the subjects with the exception of subject N7, who showed a statistically significant decrease in detection threshold at $r=0.40$ (a drop of 23.7 µA, $t_{(3)}= 4.412$, $p=0.0216$) but not at lower levels of noise. With increasing amounts of noise, subjects reported little change in loudness at low reference amplitudes; however, loudness estimates given by subjects increased with increasing noise at high reference amplitudes. These observations suggest that at low levels, the system averages the inputs over the stimulus duration. At higher stimulus levels, the increase in loudness with increasing noise is consistent with observations of other investigators (Zhang and Zeng, 1997) showing that envelope fluctuations in the stimulus waveform become more important in loudness perception at suprathreshold levels.

Sensitivity to noise and sensitivity to modulation are both level-dependent

Cochlear implant listeners are very sensitive to small fluctuations in the envelope of the pulse train, but this sensitivity is strongly level-dependent. *In the absence of modulation*, the subjects in this study were able to detect random fluctuations spanning a range of 1 - 4% of the reference carrier amplitude at comfortable listening levels; however, detection thresholds for the noise increased to a range of 5 - 17% of the carrier amplitude at soft listening levels (Fig. 2). At detection threshold for the noise, the actual detectable range of current (and the number of current steps or clinical units) spanned by the noisy pulses also increased with decreasing carrier amplitude (note that the current is delivered by the device in steps that increase approximately logarithmically: see Fig. 2d).

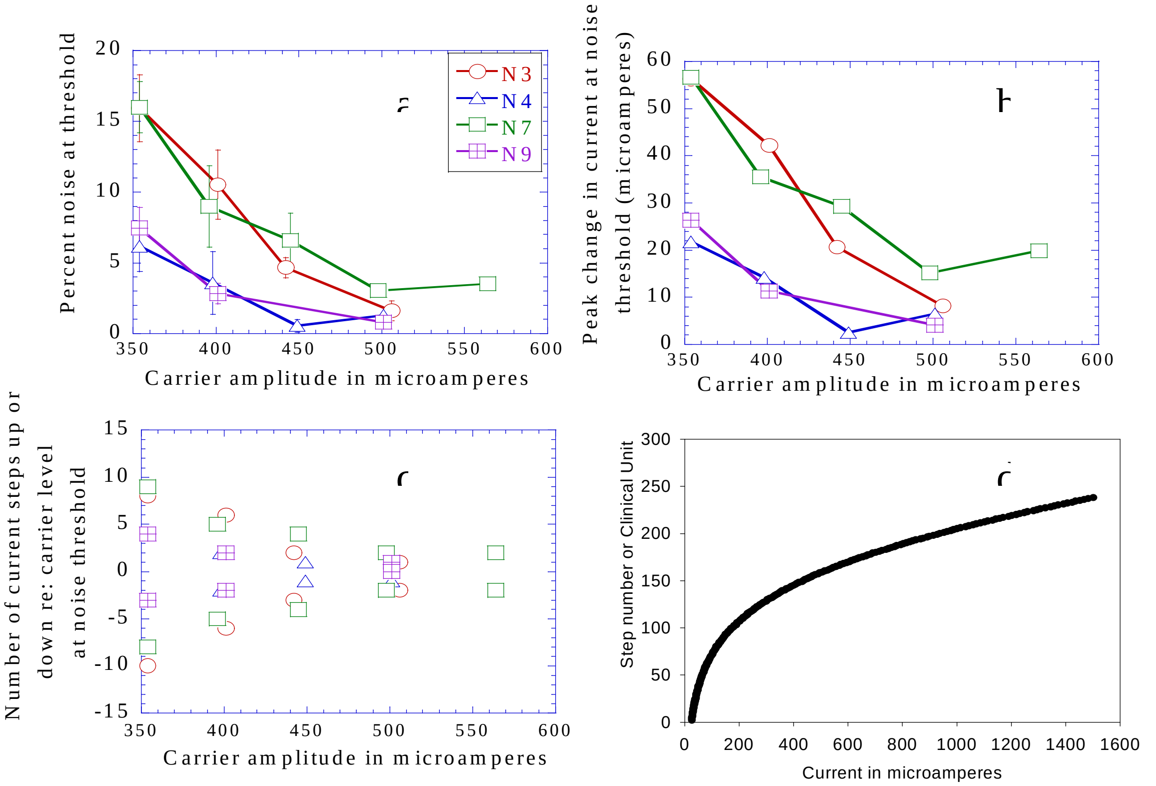


Fig. 2. Detection threshold of the noise as a function of carrier reference amplitude. The carrier pulse train is unmodulated. Each symbol corresponds to a different subject. The threshold is plotted in three ways. 2a shows the noise as percent of the carrier amplitude; 2b shows the noise as the peak change in current in microamperes; 2c shows the noise as the number of current steps (up and down) for this particular device from the reference current step, as a function of reference current amplitude in microamperes. The symbols and error bars in 2a show the mean and standard deviation of at least 4 repetitions of each measurement. Figure 2d shows an example of the relation between the current amplitude in microamperes and the steps (clinical units) used to actually deliver the current (a different calibration function is provided by the manufacturer for each subject's device). In a, b and c, the different symbols show data obtained in a different subject (key in 2a).

In the absence of noise, sensitivity to modulations in the pulse phase duration (i.e., charge per pulse) is also strongly level-dependent in cochlear implant listeners. Modulation thresholds of the subjects increased rapidly with decrease in carrier reference amplitude from comfortable loudness to softer levels (Fig. 3). At comfortable loudness levels, the modulation transfer function assumed a lowpass filter shape, dropping off with increases in modulation frequency beyond approximately 100 Hz. In some subjects, the high frequency cutoff of the modulation transfer function shifted to lower frequencies at lower current levels (Fig. 3). These results are consistent with the findings of other investigators (Shannon, 1992; Busby et al., 1993; Cazals et al., 1994).

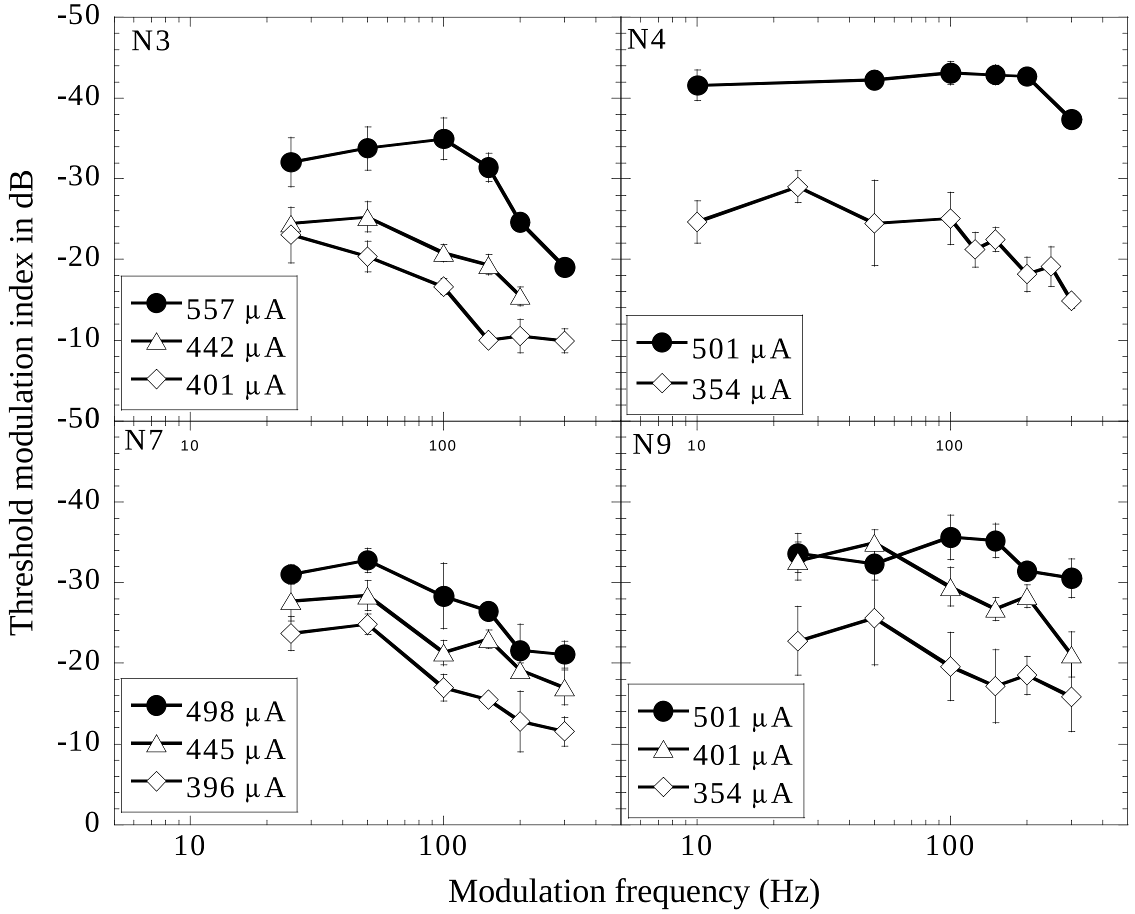


Fig. 3. Modulation transfer functions for the four subjects in the absence of noise. The four panels show data from the four subjects (N3, N4, N7 and N9). Within each panel, the parameter is reference carrier amplitude in microamperes. In each case, the filled circles, the open triangles and the open diamonds correspond to subjective loudness levels of "comfortably loud", "soft-comfortable" and "soft". Modulation thresholds are plotted in dB, or as 20log(m), where m is the modulation index at threshold. Modulation was applied to the pulse phase duration. Note that the vertical scale is reversed, so that change in the upward direction indicates increasing sensitivity and decreasing thresholds. Symbols and error bars show the mean and standard deviation of at least 4 repetitions.

Noise improves modulation detection at soft carrier amplitudes and high modulation frequencies

We measured sensitivity to sinusoidal modulation of the pulse phase duration of successive carrier pulses in the presence of different levels of noise in the carrier pulse amplitude. We found that noise has a level- and frequency-dependent effect on modulation sensitivity (Figs. 4-6). At higher carrier levels, modulation sensitivity dropped sharply with increasing noise (Fig. 4). At moderate carrier levels, the drop in sensitivity was slower. At low carrier levels, we observed a non-monotonic function: an *increase* in sensitivity to modulation with small amounts of noise, followed by a peak at some optimal noise level, and

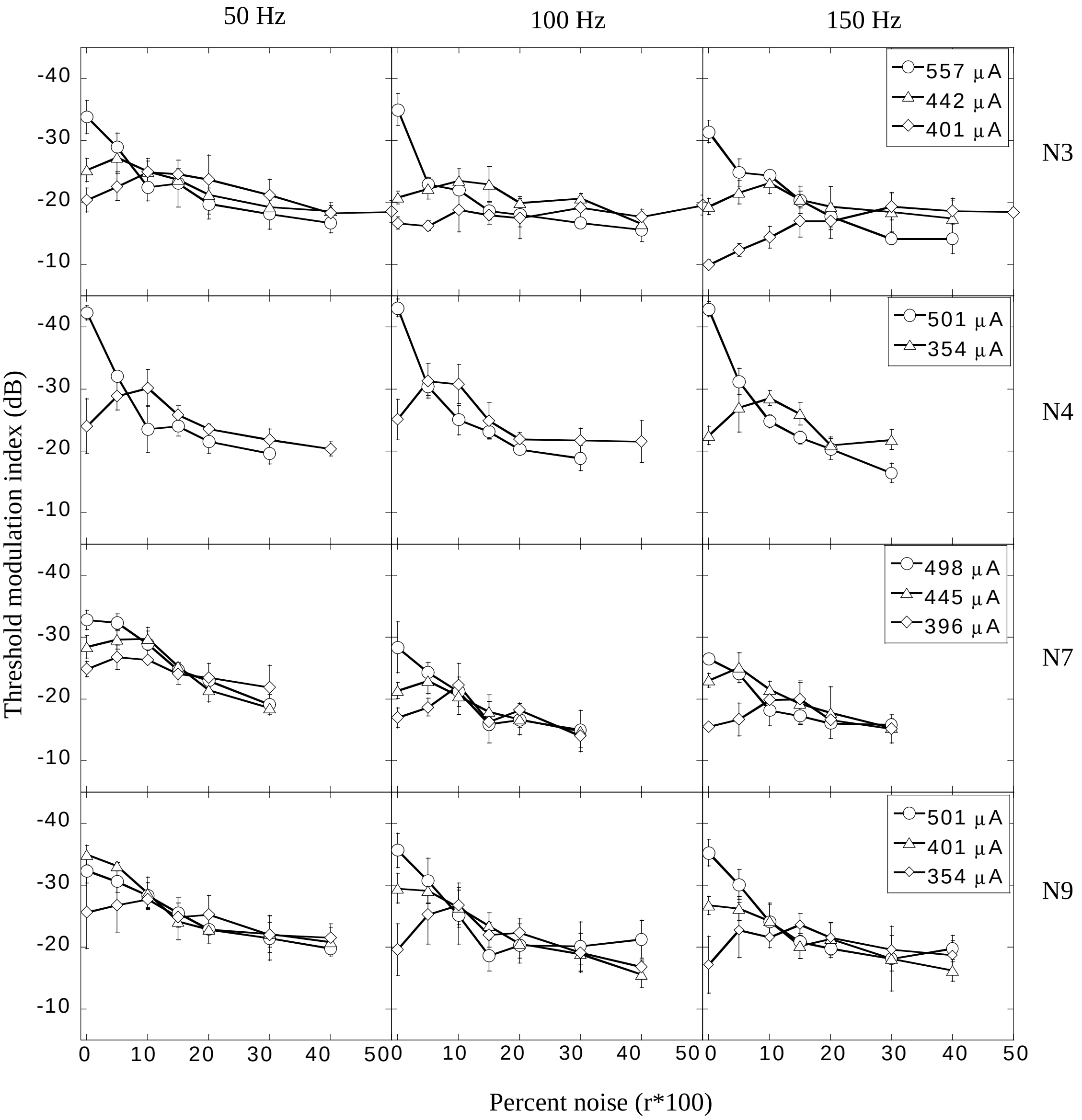


Fig. 4. Modulation threshold as a function of percent noise, for three particular modulation frequencies (50, 100 and 150 Hz). Each column shows a different modulation frequency, and each row shows data from a different subject. Within each panel, the parameter is the carrier reference amplitude. Symbols and error bars show the mean and standard deviation of at least 4 repetitions.

a decline in sensitivity with large amounts of noise. The increase in sensitivity with noise was more significant at higher modulation frequencies (Figs. 5-6 and Table I). As a result of these level-dependent changes, sensitivity to modulation with noise at a lower carrier amplitude sometimes exceeded that with the same percent noise at a higher carrier amplitude (Figs. 4-5). The observed peak in sensitivity at an optimal noise level suggests some form of stochastic resonance. Note that the size of the enhancement is quite large, ranging from 4.5 to 10.5 dB in magnitude (Table I).

Table I. The peak enhancement in modulation sensitivity shown as the absolute decrease in modulation threshold (dB) and its statistical significance (results of Student's t-test) for the four subjects and the 6 modulation frequencies, for the "soft" carrier level. Conditions in which p values were greater than 0.05 are listed as "Not significant". Statistically significant increases in sensitivity are indicated in bold. The noise level (r value) at which the peak occurred is also listed.

Subject	25 Hz	50 Hz	100 Hz	150 Hz	200 Hz	300 Hz
N3	0.428 dB Not significant r=0.05	**4.512 dB** $t_{(6)}$=3.050 p=0.0225 r=0.10	**2.475 dB** Not significant r=0.30	**9.332 dB** $t_{(6)}$=8.160 p=0.0002 r=0.30	**7.575 dB** $t_{(6)}$=5.990 p=0.0010 r=0.30	**10.52 dB** $t_{(6)}$=7.400 p=0.0003 r=0.20
N4	2.864 dB Not significant r = 0.05	6.157 dB Not significant r=0.10	**6.178 dB** $t_{(9)}$=3.376 p=0.0082 r=0.05	**6.034 dB** $t_{(6)}$=6.347 p=0.0007 r=0.10	**7.833 dB** $t_{(6)}$=6.243 p=0.0008 r=0.10	**8.956 dB** $t_{(6)}$=6.862 p=0.0005 r=0.10
N7	2.502 dB Not significant r=0.20	1.905 dB Not significant r=0.05	**5.292 dB** $t_{(8)}$=3.109 p=0.0145 r=0.10	**4.443 dB** $t_{(8)}$=2.832 p=0.0221 r=0.15	**6.061 dB** $t_{(10)}$=2.228 p=0.0136 r=0.15	**6.05 dB** $t_{(7)}$=4.879 p=0.0018 r=0.10
N9	4.829 dB Not significant r=0.05	2.08 dB Not significant r=0.10	**7.195 dB** $t_{(15)}$=3.717 p=0.0021 r=0.10	**6.529 dB** $t_{(12)}$=3.318 p=0.0061 r=0.15	**4.749 dB** $t_{(8)}$=2.965 p=0.0180 r=0.05	**7.443 dB** $t_{(7)}$=3.409 p=0.0113 r=0.20

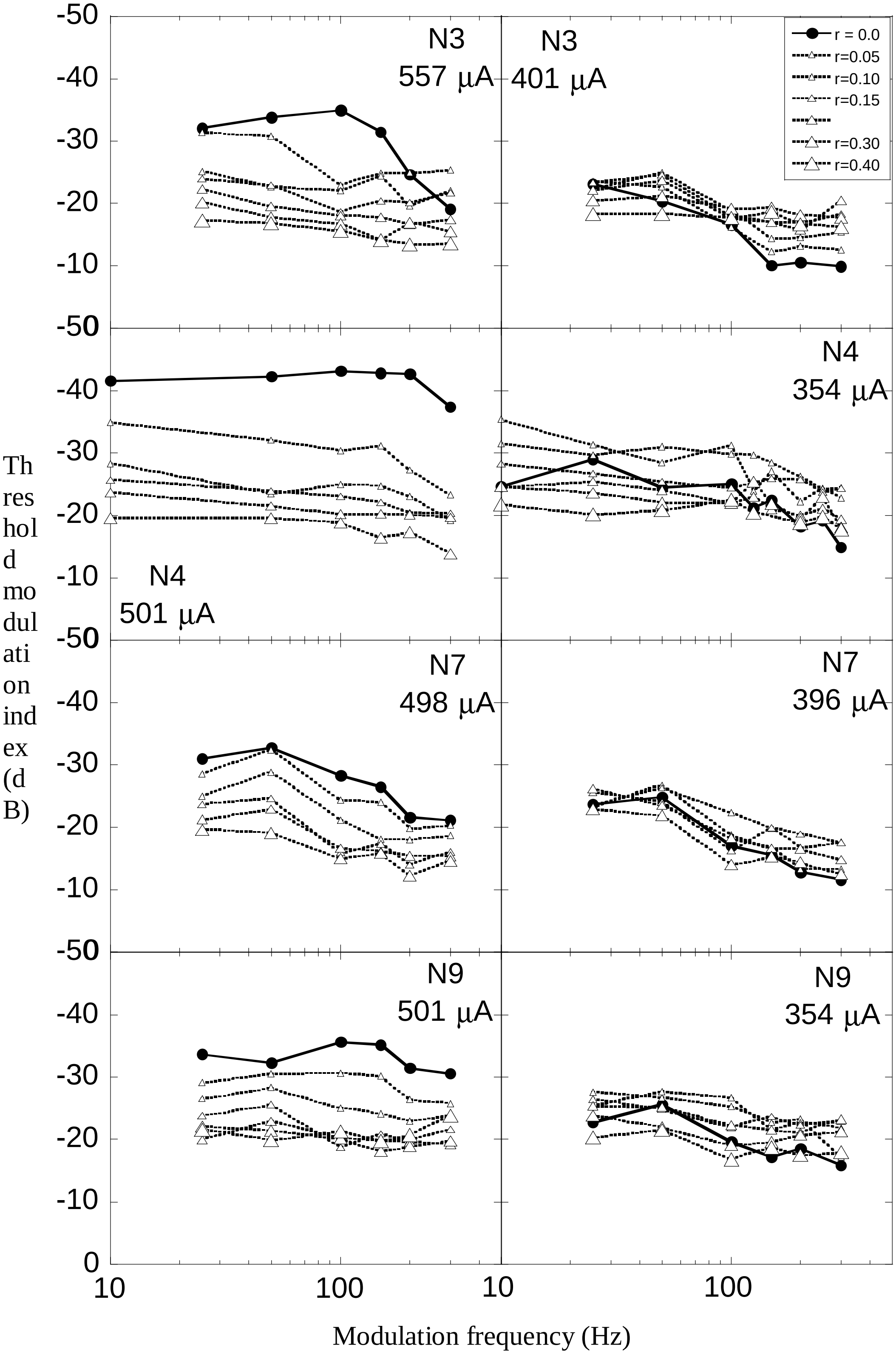


Fig. 5. Changes in the modulation transfer function with noise. Each row shows data from a different subject. The left and right hand panels show modulation transfer functions obtained at the comfortably loud and the soft carrier amplitudes respectively. The filled circles and solid lines show the functions obtained without noise. The dark blue to orange dotted lines and small to large open triangles show modulation thresholds obtained with increasing noise (key in upper right hand panel). Symbols show the mean of at least 4 repetitions: error bars are omitted for clarity.

At comfortably loud carrier amplitudes, even a small amount of noise (5 - 10%) resulted in a large drop in sensitivity at all modulation frequencies (Fig. 6, left hand panels). Increasing the noise beyond 15% resulted in smaller drops in sensitivity. Beyond the 30% noise level, a performance floor was reached. In general, the net drop in sensitivity was greater at lower modulation frequencies than at higher ones, so that with large amounts of noise, the modulation transfer function became flatter than without noise. At softer carrier amplitudes, the larger noise-induced improvement in performance at higher modulation frequencies (Figs. 6-7) also resulted in a flatter transfer function than the low-pass filter shape observed without noise (Fig. 6).

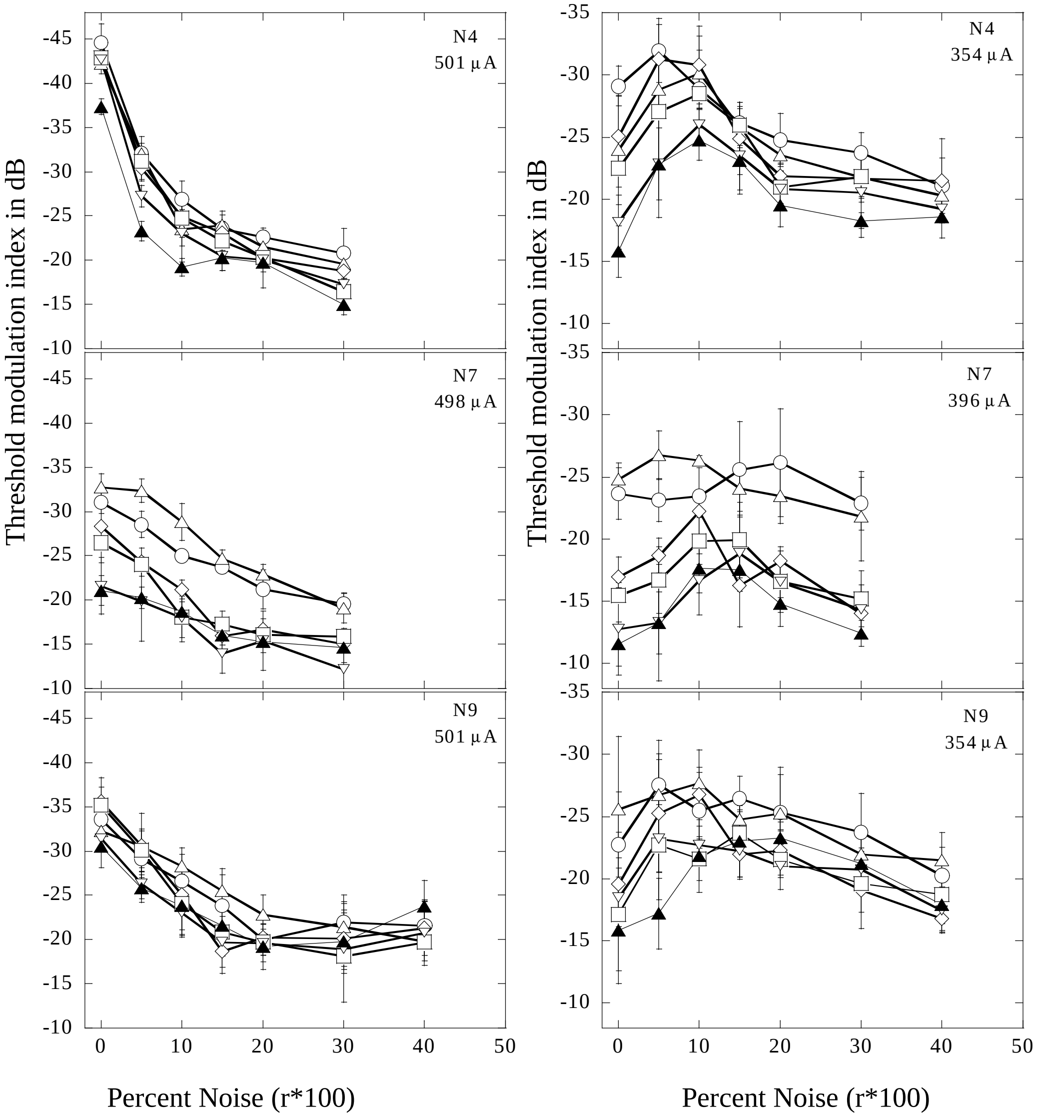


Fig. 6. Modulation threshold as a function of percent noise, for the comfortably loud (left hand panels) and soft (right hand panels) levels. Within each panel, the parameter is modulation frequency (key in upper left hand panel). In the case of subject N3, a set of modulation thresholds was obtained at the 70% noise level, at the soft carrier level. The inset in the top right hand panel shows the full range of data. Symbols and error bars show the mean and standard deviation of at least 4 repetitions.

Noise has little effect on static increment detection

It is possible that the improved modulation sensitivity observed at the low carrier amplitudes was due to something other than stochastic resonance. If so, similar improvements should be observed in a task that does not involve periodicity detection. To test for this possibility, we measured just noticeable differences in pulse phase duration with identical, unmodulated stimuli in the same group of subjects, at the same carrier amplitudes used in the previous experiment. Thresholds for detecting an increment in pulse phase duration were much less influenced by level and also much less influenced by noise (Fig. 7). In general, somewhat poorer performance was obtained at lower carrier levels than at higher carrier levels. At higher levels, increasing the amount of noise resulted in no significant change in the just noticeable increment in pulse duration or even slightly poorer performance. None of the subjects showed significant noise-induced enhancement in performance at the lowest ("soft") carrier level, with one exception: subject N3 showed a statistically significant improvement of 4.7 dB for r=0.30 ($t_{(10)}$=2.359, p=0.0400). The pattern of results obtained in this experiment is very different compared to the pattern of results obtained with modulation detection, where we observed large enhancements in sensitivity with optimal amounts of noise (Figs. 4, 6). We infer that mechanisms underlying the influence of noise are inherently different for static vs. dynamic stimuli.

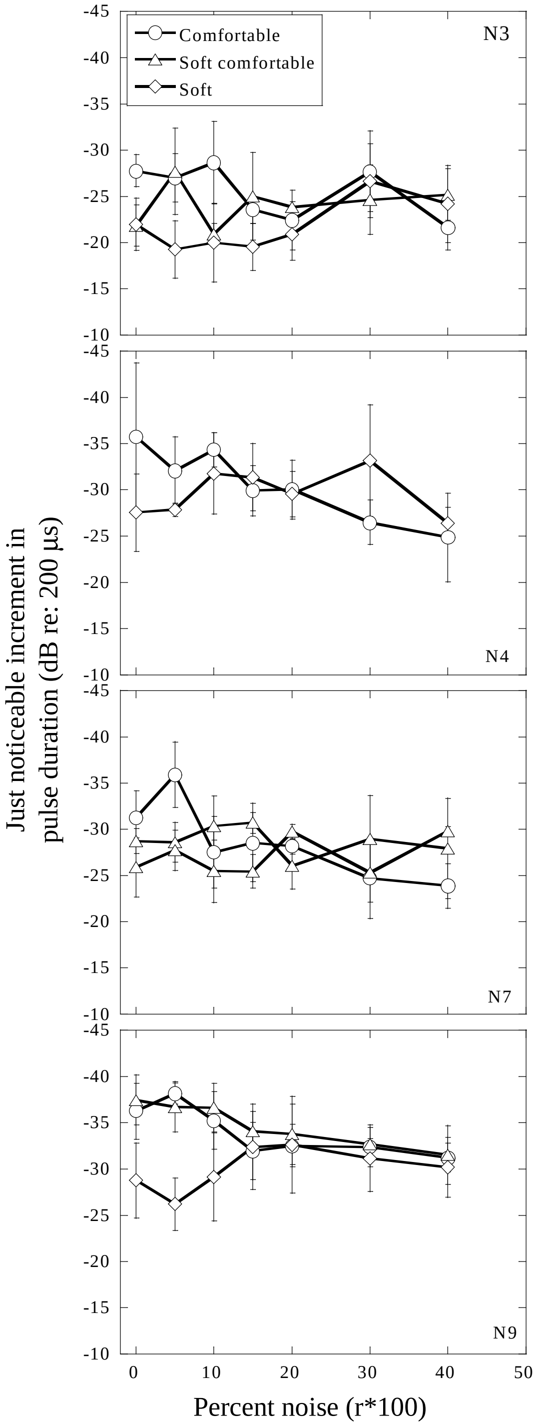


Fig. 7. Just noticeable increments in pulse phase durations for the four subjects plotted as a function of percent noise. Each panel shows data from a different subject. Within each panel, the parameter is carrier reference amplitude. Note that the carrier reference amplitudes are identical to those used in the modulation threshold measurements. Symbols and error bars show the mean and standard deviation of at least 4 repetitions.

DISCUSSION

Compared to normal hearing, acoustically stimulated listeners, cochlear implant listeners show considerable individual variability in psychophysical and speech recognition performance, and these two kinds of measures are not always strongly correlated. Some of this variability can be observed in the results shown here. Perception of sounds by the electrically stimulated auditory system also differs substantially from the normal acoustic case in other ways. Loudness grows as an expansive function of current amplitude, which gives the cochlear implant listener a very narrow dynamic range (6-20 dB compared to 120 dB in normal hearing). With respect to everyday listening tasks that require fine resolution of within- and across-channel timing changes, the "effective" dynamic range of the cochlear implant listener is even more constrained by the strong level-dependence in their performance: at soft stimulus levels, cochlear implant listeners have much higher gap-detection thresholds (Shannon, 1989) and modulation detection thresholds than at comfortable listening levels. This dependence on level approximately halves the usable range of amplitudes within the dynamic range.

We have found a two-fold effect of noise on sensitivity to temporal fluctuations in cochlear implant listeners. At comfortable loudness levels, when subjects are very sensitive to the modulation, noise impedes modulation sensitivity. At soft levels, when subjects are less sensitive to modulation, an optimal amount of noise *improves* modulation sensitivity. The non-monotonic effect of the noise at low carrier levels has the "signature" of stochastic resonance. We note that, at low modulation frequencies and with an unmodulated carrier, the noise is least effective, indicating that its influence is largely in the time-pattern processing (periodicity detection) domain. Further, our results show a similarly strong level-dependence in both sensitivity to noise (with no modulation) and sensitivity to modulation (with no noise); however, the thresholds for increment detection showed much weaker dependence on stimulus level. Taken together, these results suggest that both the periodic and aperiodic fluctuations are processed similarly by the auditory system; however, slow periodic fluctuations and more static changes are processed differently. The large (5 to 10 dB) enhancement in modulation sensitivity observed here with the addition of noise at low levels may be considered as one way to increase the "effective" dynamic range of cochlear implant listeners in their everyday suprathreshold listening situations.

It is apparent that the system behaves like a lowpass filter in the absence of noise. We speculate that the level-dependence of the modulation transfer functions reflects the presence of an internal noise source: it is likely that modulation detection falls more rapidly at higher frequencies for softer carriers because the high frequency roll-off of the filter brings the signal down into the region of the internal noise floor. As the periphery appears to contribute little to the level of internal noise in deafened cochleae, the internal noise is likely to be largely central in origin. We speculate that at low carrier amplitudes, the optimal external noise increases signal strength through stochastic resonance at a relatively early stage of processing, lifting the signal above the internal noise floor. For a given carrier level and at higher modulation frequencies, the smaller signal-to-internal-noise ratio due to the lowpass filter results in a more observable improvement in sensitivity with external noise.

It is important to recognize that the particular kind of noise we have used here is very different from the noise normally present in a healthy cochlea, which probably arises from a number of sources such as the Brownian motion in individual hair cell stereociliary bundles, noise in the transmitter release process, membrane noise, etc. Ultimately, the statistics of neural discharge appears to correspond to a renewal process. In contrast, the noise we have introduced is a simple random variation in the amplitude of successive pulses in a periodic pulse train. Because both the noise and the signal modulate the same carrier (i.e., the same carrier pulse train and the same electrode pair), the effects we describe here are likely to be entirely “within-channel” (i.e., due to activity being modulated in the same group of peripheral neurons). The present experiments indicate that external, "prosthetic" noise can indeed be beneficial to the deafened auditory system: however, a great deal of further work is necessary for such benefit to find its way into an improved speech processor design.

PLANS FOR THE NEXT QUARTER:

Hardware – Nucleus Interface. We will integrate the new Nucleus-24 Research Interface to our existing experimental control software programs in the next quarter. The calling sequence for the new interface is similar to that of the previous BTNI-Nucleus-22 Research Interface, so the modifications are modest. These programs will then allow delivery of any psychophysical or processed speech stimuli to patients with the Nucleus-22 and –24 implant devices at aggregate pulse rates up to 8000 pps.

Experiments – Psychophysics. We will finish data collection on electrode interaction with different electrode designs with the Clarion cochlear implant. With the new research interface we will begin data collection on electrode interaction measures in the Nucleus-24 patients with the original banded electrode design and with the new Contour^{TM} modiolus-hugging electrode design.

Experiments – Speech Processor Design. (1) Continue data collection on the stimulation rate study. At the present time we have complete speech recognition data as a function of stimulation rate for 5 Clarion implant users and partial data from 5 Nucleus-24 implant users. Stimulation rates ranging from 200 to 2500 pps/electrode are being tested in 4, 8, 12, and 16-electrode processors. (2) We will complete data collection in experiments to quantify the effect of frequency compression and expansion on speech recognition. (3) We will collect more data on the relation between temporal resolution and spectral resolution on speech recognition in individual patients.

Publications and Presentations

In the next quarter we will present our results at the NIH Neural Prosthesis Workshop in Bethesda, MD on October 22-24 and we will present four posters at the Acoustical Society of America Meeting in Newport Beach, CA on December 2-6. We will prepare manuscripts for publication based on our studies of “Holes in Hearing” and on the effect of stimulation rate on speech recognition. We plan to submit these manuscripts to the Journal of the Association for Research in Otolaryngology and to Audiology and Neuro-Otology, respectively.

PUBLICATIONS AND PRESENTATIONS IN THIS QUARTER:

Peer-Reviewed Publications:

Friesen, L.M., Shannon, R.V., and Slattery, W.H. (2000). Effects of electrode location on speech recognition in Nucleus-22 cochlear implant listeners, J. Amer. Acad. Audiol., 11(8), 418-428.

Non-peer-reviewed Publications:

Shannon, R.V. (2000). Auditory Pattern recognition: Implications for hearing aids and cochlear implants, Proceedings of AG Bell Association Research Symposium on Biotechnology and the Cochlea, Philadelphia, July 9, 2000.

Shannon, R.V. (2000). New modiolus-hugging electrode designs in cochlear implants, CIAI LA Funshine Chapter Newsletter, 2(4), 5-11.

Manuscripts Submitted this Quarter:

Chatterjee, M. and Robert, M. Noise enhances modulation sensitivity in cochlear implant listeners: Stochastic resonance in a prosthetic sensory system, Journal of the Association for Research in Otolaryngology, Submitted 15 Sept. 00.

Friesen, L., Shannon, R.V., Baskent, D., and Wang, X. Speech recognition in noise as a function of the number of spectral channels: comparison of acoustic hearing and cochlear implants, Journal of the Acoustical Society of America, Submitted 28 Aug 00.

Invited Presentations:

Chatterjee, M. (2000). "Auditory Perception in Normal and Prosthetic (Cochlear-Implant) Hearing", National Centre for Biological Sciences, Bangalore, India, Sept 26. (invited oral presentation)

Shannon, R.V. (2000). New modiolus-hugging electrode designs in cochlear implants, Cochlear Implant Association Inc., LA Chapter, May 13. (invited oral presentation - occurred in previous quarter)

Shannon, R.V. (2000). “Auditory pattern recognition: Implications for hearing aids and cochlear implants”, Symposium on Biotechnology and the Cochlea, A.G. Bell Association for the Deaf and Hard of Hearing International Convention, Philadelphia, July 9. (invited symposium speaker)

Shannon, R.V., Brackmann. D.E., Hitselberger, W.E., Otto, S.R., Moore, J. and McCreery, D. (2000). "Auditory Brainstem Implant: Prosthetic Microstimulation of the Human Brainstem", World Congress on Medicine and Health "Medicine meets Millenium", Hannover, Germany, 22 July. (invited oral presentation)

Shannon, R.V., Galvin, J., and Baskent, D. (2000). Holes in hearing: Implications for cochlear implants and hearing aids, International Hearing Aid Research Conference, Lake Tahoe, August 23-27. (invited oral presentation)

Shannon, R.V. (2000). Implications of hearing loss for speech and music, Audio Engineering Society, Los Angeles, Sept 22. (invited oral presentation)

Presentations:

Chatterjee, M., Shannon, R.V., Galvin, J.J., and Fu, Q.-J. (2000). Spread of excitation and its influence on auditory perception with cochlear implants. International Symposium on Hearing, Aug 4-9, 2000 Mierlo, Netherlands

Shannon, R.V., Fu, Q.-J., and Galvin, J. (2000). Critical cues for auditory pattern recognition of speech: Implications for cochlear implant speech processor design, International Symposium on Hearing, Aug 4-9, 2000, Mierlo, The Netherlands.

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Stickney, G., Shannon, R.V., Opie, J., and Assman, P. (2000b). Electrode interaction in multichannel cochlear implants with different electrode designs and positions, ARO Midwinter Research Meeting, St. Petersberg, FL, Feb 20-24. (poster)

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