Noise Enhances Modulation Sensitivity in Cochlear Implant Listeners: Stochastic Resonance in a Prosthetic Sensory System?

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Received: 20 September 2000; Accepted: 16 January 2001; Online publication: 4 May 2001

ABSTRACT

Cochlear implants restore auditory sensitivity to the profoundly hearing-impaired by means of electrical stimulation of residual auditory nerve fibers. 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. In this article 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.

Keywords: cochlear implants, stochastic resonance, noise, modulation

spontaneous activity in quiet (Kiang et al. 1965). 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. In some cochlear implant users, reverse telemetry makes it possible to record the intracochlear 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). Whether reduced stochasticity in deaf cochleae stems primarily from the loss of hair cells or is a property of electrical stimulation has not been answered definitively as yet. However, recent work that electrically stimulated the auditory nerve in the same animals before and after deafening showed that the presence of hair cells reduces the magnitude of the oscillatory component (Abbas et al. 2000a,b).

INTRODUCTION

The most sensitive auditory neurons in the functioning mammalian cochlea show a considerable amount of

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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 added noise results in enhanced transmission of a signal through a nonlinear system—has stimulated a substantial amount of discussion. The effect of noise in the peripheral auditory system may be twofold: *within-channel* processing may be improved by optimal levels of external noise; *across-channel* processing may be improved by having independent noise sources in each channel at an early stage, forcing greater independence across responding neuronal populations. There is limited evidence that the normal auditory system utilizes both such mechanisms. Recent experiments in single frog saccular hair cells suggest that stochastic resonance may occur in a related sensory system (Jaramillo and Wiesenfeld 1998), suggesting that within-channel processing can be improved by added noise in the periphery. In the mammalian auditory nerve, it has been shown that the spontaneous firings of single neurons constitute mutually independent random processes (Johnson and Kiang 1976), suggesting that the substrate for across-channel independence occurs early in the system.

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 have been matters 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 modulation of 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 various psychophysical experiments in our laboratory 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.

FIG. 1. Schematics of the positive phase of carrier pulse trains that are **1** unmodulated, **2** modulated, **3** noisy, and **4** noisy and modulated. Note that the pulses are biphasic and charge-balanced, but here we show only the positive phase for clarity. The series of lines drawn below each schematic pulse train represents the charge Q per pulse (current amplitude I times pulse phase duration D). Modulation index

m as well as the noise level r is chosen to be 0.50 for clarity. In **3**, the hatched bars on the left show a sample histogram of noisy pulses generated with $r = 0.50$. The scatter plot in the middle shows the actual values of r in a 200 pulse train. While the noise is applied to pulse amplitude, the modulation is applied to the pulse phase duration to achieve the best resolution.

Materials

All of the subjects use the Nucleus-22 cochlear implant system (Manu., City, State). 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 apicalmost 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 through 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. (Figure 2d shows an example of the transformation between current amplitude and step number.) After the desired amplitude of a particular current pulse is calculated, the calibration table for the individual subject is consulted to obtain the step number that will yield the closest value. The discrete step sizes vary from 0 μ A at the lowest current amplitudes (15–24 μ A) to 20 μ A at the highest current amplitudes (1500–1800 μ A).

Stimuli

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

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

Modulated pulse train. 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- μ s steps) than does 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.2). (In either case, charge $q = I * D$ is the modulated quantity.) The equation generating the modulated pulse train is as follows:

$$D(n) = D_{\text{ref}} [1 + m \cos(2 \pi f_m n / f_c)]$$

TABLE 1

Carrier pulse amplitudes used for the modulation sensitivity and pulse phase duration increment detection experiments			
Subject	Soft carrier level	Soft comfortable carrier level	Comfortably loud carrier level
N3	401 μ A (160.9 μ A or 4.45 dB above threshold)	442 μ A (201.9 μ A or 5.3 dB above threshold)	557 μ A (316.9 μ A or 7.3 dB above threshold)
N4	354 μ A (159.5 μ A or 5.2 dB above threshold)		501 μ A (306.5 μ A or 8.2 dB above threshold)
N7	396 μ A (194.9 μ A or 5.88 dB above threshold)	445 μ A (243.9 μ A or 6.89 dB above threshold)	498 μ A (296.9 μ A or 7.87 dB above threshold)
N9	354 μ A (143.3 μ A or 4.5 dB above threshold)	401 μ A (190.3 μ A or 5.59 dB above threshold)	501 μ A (290.3 μ A or 7.52 dB above threshold)

where $D(n)$ is the phase duration of the n th pulse, D_{ref} is the reference phase duration (200 μ s), m is the modulation index ($0 < m < 1.0$), and f_m and f_c are the modulation and carrier frequencies, respectively. The increment in energy due to modulation was below detection threshold.

Noisy pulse train. Amplitudes (I) of consecutive pulses were scaled by a sequence of numbers from a uniform pseudorandom distribution (range $1.0 \pm r$, where $0.00 < r < 1.00$) (see Fig. 1b.3). 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). Ideally, over infinite pulses, the mean amplitude of the pulse train would remain unchanged ($= I$) as the noise is increased, and the variance would increase with increasing noise as $(I^2 r^2)/3$. In reality, the resolution of the device constrains the amplitudes of successive pulses to be slightly different from the computed value, so that the mean is only approximately constant.

Stimulus levels. The carrier reference levels chosen for the modulation sensitivity and pulse phase duration increment detection 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 absolute carrier amplitudes and their relative level above threshold are listed in Table 1. 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 only (subject N4 was not able to participate in these measurements because of time constraints). At the “comfortable” loudness level, modulation sensitivity had reached an

asymptote in all subjects and did not increase appreciably with further increases in carrier amplitude.

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 was 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 subject was asked to indicate which interval contained the rougher sound. In this case the variable being adjusted was the percent noise. Subjects reported that the noise sounded like “static on the radio.”

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 adapted variable was the modulation depth m . Subjects were asked to indicate which interval contained the rougher sound or the sound with a fluctuation. The feedback helped subjects learn the appropriate cue to listen for very quickly.

When pulse phase duration increment threshold

was measured, the two intervals contained unmodulated pulse trains, which were identical except that the “signal” pulse train consisted of longer phase duration pulses. The subject indicated which interval sounded louder. 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 fourth reversal, the step size was reduced to bracket the threshold with finer resolution. The noise series for every case was different for each comparison trial but was identical in the two intervals within the trial. The mean and standard deviation of the last 8 reversals were calculated at the end of the run. Each threshold value and the accompanying error bars shown represent 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 2–4 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 magnitude of the perceived loudness of the stimulus. Stimuli were randomized and the mean and standard deviation of at least 4 repetitions were calculated (for details of methods, see Chatterjee 1999 and Chatterjee et al. 2000).

RESULTS

Noise has little effect on absolute detection threshold

The 200-ms, 1000-Hz, 200- μ s/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 of $1 \pm r$, where $0 < r < 1.0$. We first measured the effect of the noise on absolute detection thresholds of the unmodulated pulse trains. In the absence of noise, mean detection thresholds for the stimuli were 240.1, 194.5, 201.1, and 210.7 μ A for subjects N3, N4, N7, and N9, respectively. The noise did not influence detection threshold in any of the subjects except N7, who showed a statistically significant decrease in detection threshold at $r = 0.40$ (a drop of 23.7 μ A, $t_{(3)} = 4.412$, $p = 0.0216$) 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

Sensitivity to noise: unmodulated carrier. 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. This is shown in Figure 2a for the four subjects. Measurements were made at a number of carrier amplitudes, including the carrier amplitudes used for the modulation sensitivity experiments discussed below. For comparison, we have also shown the actual peak change in the pulse amplitudes between the reference and the noisy carriers at detection threshold for the noise (Fig. 2b). 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, as shown in Figure 2c. Note that the current is delivered by the device in steps that increase approximately logarithmically (Fig. 2d).

Sensitivity to modulation in the absence of noise. In the absence of noise, sensitivity to modulation in the pulse phase duration (i.e., charge per pulse) is also strongly level-dependent in cochlear implant listeners. (Figure 3) shows modulation threshold (in dB) plotted as a function of modulation frequency. The parameter is carrier amplitude. Modulation thresholds of the subjects increased rapidly with decrease in carrier reference amplitude from comfortable loudness to softer levels. 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. These results are consistent with the findings of other investigators (Shannon 1992; Busby et al. 1993; Cazals et al. 1994).

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 (see key in **a**). The threshold is plotted in three ways: **a** shows the noise as percent of the carrier amplitude; **b** shows the noise as the peak change in current μA ; **c** 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 μA . The symbols and error bars in **a** show the mean and standard deviation of at least 4 repetitions of each measurement. **d** shows an example of the relationship between the current amplitude μA 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).

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. This is shown in Figures 4–6. Figure 4 shows the level dependence of the effect at three representative modulation frequencies (left to right, 50, 100, and 150 Hz) along the modulation transfer function. The four rows show data obtained in the four subjects. At higher carrier levels, modulation sensitivity dropped sharply with increasing noise. At moderate carrier levels, the drop in sensitivity was slower. At low carrier levels, we observed a nonmonotonic function: an *increase* in sensitivity to modulation with small amounts of noise, followed by a peak at some optimal noise level and a decline in sensitivity with large amounts of noise.

The increase in sensitivity with noise was more significant at higher modulation frequencies (Figs. 5 and 6 and Table 2). Figure 5 shows the frequency dependence of the effect. Here, modulation transfer functions are shown at the comfortable and the soft carrier levels (left- and right-hand columns) for the four subjects (top to bottom rows) as a function of increasing noise level. At comfortably loud carrier amplitudes, even a small amount of noise (5%–10%) resulted in a large drop in sensitivity at all modulation frequencies (left-hand panels). Increasing the noise beyond 15% resulted in smaller further 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. In contrast, at softer carrier amplitudes (right-hand panels), small amounts of noise (5%–15%) resulted in *improved* modulation thresholds, more so at higher

FIG. 3. Modulation transfer functions for the four subjects (N3, N4, N7 and N9) in the absence of noise. Within each panel, the parameter is reference carrier amplitude. In each case, the filled circles, the open triangles, and the open diamonds correspond to subjective loudness levels of “comfortably loud,” “comfortable but soft” and “soft.” Modulation thresholds are plotted in dB or as $2 \log m$, 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.

modulation frequencies than at lower. At softer carrier amplitudes, the larger noise-induced improvement in performance at higher modulation frequencies also resulted in a flatter transfer function than the lowpass-filter shape observed without noise.

It appears that an optimum amount of noise is required to enhance modulation sensitivity at soft carrier levels. The noise-induced enhancement is modulation frequency-dependent, being larger at higher modulation frequencies. The change in the shape of the modulation sensitivity vs. noise level function from monotonically decreasing or flat at 25-Hz modulation to nonmonotonic with a peak at 300-Hz modulation is clearly evident in the right-hand panels of Figure 6. At the higher carrier levels, the net deterioration in modulation sensitivity with noise is somewhat dependent upon modulation frequency, but the shape of the function remains monotonic (left-hand panels in Fig. 6).

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 (Fig. 4). The observed peak in enhancement of modulation sensitivity at an optimal noise level suggests that some form of stochastic resonance occurs at the higher modulation frequencies. Table 2 shows the size and the statistical significance of the enhancement in modulation sensitivity at the lower carrier levels. Note that the size of the enhancement is quite large, ranging from 4.5 to

10.5 dB in magnitude. Note also that the level of significance and the size of the enhancement are greater at higher modulation frequencies.

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 in the modulation detection process. 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 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 $r = 0.30$ ($t_{(10)} = 2.359$, $p = 0.0400$). Overall, the pattern of results obtained in

FIG. 4. Modulation threshold as a function of percent noise for three 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.

this experiment is very different compared with the pattern of results obtained with modulation detection, where we observed large enhancements in sensitivity with optimal amounts of noise (Figs. 4 and 6). We infer that mechanisms underlying the influence of noise are inherently different for static vs. dynamic stimuli.

DISCUSSION

Compared with normal-hearing listeners, cochlear implant listeners show considerable individual variabil-

ity 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 presented in this article. 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 with 120 dB in normal hearing). With respect to everyday listening tasks that require fine resolution of within-channel and across-

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 represent the functions obtained without noise.

Increasing noise is represented by the increasing size of the open triangles and the increasing “temperature” of the dotted lines, i.e., from blue to orange (see the legend in the upper-right-hand panel). Symbols show the mean of at least 4 repetitions: error bars are omitted for clarity.

channel timing changes, the “effective” dynamic range of the cochlear implant listener is even more constrained by the strong level-dependence in their per-

formance. At soft stimulus levels, cochlear implant listeners have much higher gap-detection thresholds (Shannon 1989) and modulation detection thresholds

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 extended range of data. Symbols and error bars show the mean and standard deviation of at least 4 repetitions.

than at comfortable listening levels. This dependence on level approximately halves the usable range of amplitudes within the dynamic range.

We have found a twofold effect of noise on sensitivity to temporal fluctuations in cochlear implant listeners. At comfortable loudness levels, when subjects are very

TABLE 2

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 4 subjects and 6 modulation frequencies, for the "soft" carrier level

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 $t_{(7)} = 3.409$ $p = 0.0113$ $r = 0.20$

^aConditions 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.

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 nonmonotonic 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 (5–10 dB) enhancement in modulation sensitivity that we observed 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 supra-threshold listening situations; thus, the addition of optimal noise may improve modulation sensitivity at carrier levels that, though clearly audible, would normally not transmit as much modulation information.

We have observed that the improvement due to the noise begins to occur just below or at the just detectable noise level for a particular low-level carrier (noise thresholds shown in Fig. 2). One interesting point to note is that a noise level of $r = 0.05$ to $r = 0.10$ may be easily detectable at the comfortable loudness level

but just perceptible when the carrier is soft. Would we see the noise-induced enhancement at comfortable loudness if we used just perceptible noise at that carrier level? Preliminary experiments show no improvement in modulation sensitivity with just detectable levels of noise at comfortable loudness levels. At the soft comfortable level, small amounts of noise do yield improvements in modulation sensitivity (Fig. 4). It is possible that a ceiling is reached in performance at the comfortable listening level, beyond which improvements are more difficult to observe. We presently are conducting further experiments to examine both within-channel and across-channel effects of small amounts of noise in greater detail.

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 that occurs at a later (more central) stage than the lowpass filtering of the carrier envelope. 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. With such a model, one can explain the observation that modulation detection falls more rapidly at higher frequencies for softer carriers; the attenuated output of the lowpass filter at high modulation frequencies brings it closer to the internal noise, thus lowering the signal-to-noise ratio. We speculate that at low carrier amplitudes and with optimal added noise levels, stochastic resonance increases signal strength at a relatively early stage of processing, lifting the signal above the internal noise floor.

Whether the natural stochasticity of the normal

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.

auditory periphery has a similar effect is a matter of conjecture. It is important to recognize that the particular kind of noise we have used in our study 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 appear 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.

ACKNOWLEDGMENTS

This research was funded by NIDCD R03DC03519 and NIH N01-DC-92100. We thank Xiaosong Wang for her help with data collection. John J. Galvin III assisted in the experiments and is thanked for his comments on the manuscript. We thank Cochlear Corporation for providing us with the calibration tables for the subjects. We gratefully acknowledge the subjects' continued participation in our research. Two anonymous reviewers are thanked for their constructive comments on the manuscript.

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