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Human hearing enhanced by noise[☆,1]

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Abstract

Noise was traditionally regarded as a nuisance, which should be minimized if possible. However, recent research has shown that addition of an appropriate amount of noise can actually improve signal detection in a nonlinear system, an effect called stochastic resonance. While stochastic resonance has been described in a variety of physical and biological systems, its functional significance in human sensory systems remains mostly unexplored. Here we report psychophysical data showing that signal detection and discrimination can be enhanced by noise in human subjects whose hearing is evoked by either normal acoustic stimulation or electric stimulation of the auditory nerve or the brainstem. Our results suggest that noise is an integral part of the normal sensory process and should be added to auditory prostheses.

Theme: Sensory systems

Topic: Auditory, vestibular, and lateral line: periphery

Keywords: Auditory; Hearing; Stochastic resonance; Noise; Cochlear implant; Brainstem implant; Threshold; Frequency discrimination

1. Introduction

Stochastic resonance is a nonlinear phenomenon, in which detection of a signal, periodic or aperiodic, can be enhanced by addition of an appropriate amount of noise [5,26]. Initially, stochastic resonance was proposed to explain the periodic oscillation of Earth's ice ages, but has now been found to be a common mechanism in a variety of physical and biological systems including signal transduction in the sensory and neural pathways [1–3,12,21,23]. Here we explore the role of stochastic resonance in human audition, particularly in subjects whose hearing is evoked by electric stimulation of the auditory nerve and the auditory brainstem [29].

A person with normal hearing can detect sound-driven vibrations of about a half nanometer, only the diameter of a hydrogen atom [8]. (S)he can also understand speech under extremely noisy conditions with a signal-to-noise ratio as low as −30 dB [24]. It is not clear how the auditory system accomplishes these extraordinary tasks, but stochastic resonance has been suggested as an underlying mechanism that uses noise to increase the signal-to-noise ratio [7,9]. In fact, research shows that a high level of internal noise exists in normal mammalian auditory nerve fibers, which is evident by spontaneous neural activities in the absence of sound stimulation [14]. This internal noise is reduced as the degree of hearing loss increases [11,15], resulting in behaviorally elevated thresholds, lower frequency selectivity and poor speech recognition [17].

Here we report observations of stochastic resonance in human subjects who performed auditory tasks in noise through normal acoustic hearing, electric stimulation of the auditory nerve (cochlear implants), or electric stimulation of the cochlear nucleus (auditory brainstem implants). We especially focused on the cochlear implant subjects be-

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cause neural spontaneous activities are absent in totally-deafened ears [11] and introduction of an external noise may compensate for their lack of internal noise. We found that detection thresholds of periodic signals were improved by weak noises in all subjects. We interpreted these results as providing evidence for a functional role of stochastic resonance in human audition.

2. Materials and methods

Nine adults, including two male and three female normal-hearing subjects, two male and one female cochlear-implant (Ineraid) subjects, and one male auditory-brainstem-implant subject with a percutaneous plug, were recruited to participate in these experiments. All subjects were informed of the nature and consequences of these experiments according to guidelines of the local Institutional Review Board (House Ear Institute and University of Maryland) and had extensive previous experience in various psychophysical experiments.

Stimuli were generated digitally using Tucker–Davis Technologies System II equipment (Gainesville, Florida). The white noise had a bandwidth from 20 to 14 000 Hz and was presented continuously throughout each run in an experiment. Each subject was presented with a wide range of noise levels from 20 dB below threshold to 10 dB above threshold. Normal-hearing subjects listened to single pure-tones of 1000 Hz and 4000 Hz, and a two-tone complex of 4000 and 4100 Hz under the above noise conditions. The two-tone complex stimulus was used to test whether phase-locking to the 100-Hz envelope could further enhance threshold detection in noise [7]. Cochlear-implant subjects were presented sinusoids with frequencies from 100 to 3000 Hz. To avoid use of potentially unsafe high-amplitude stimuli at low frequencies [22], a biphasic pulse signal (100-μs per phase), in addition to the standard sinusoidal signal, was used for the brainstem-implant subject. All signals had a duration of 400 ms including 10-ms cosine-squared ramps. The signal and the noise were mixed and presented to the normal-hearing subject through an insert earphone, which has less than 5-dB fluctuations in the frequency response for frequencies up to 14 kHz measured in a Zwislocki coupler (Etymotic Research ER-2, Elk Grove Village, Illinois). The signal and the noise were delivered to the most apical electrode (monopolar mode) in the implant subjects through a voltage-to-current source.

A two-interval, forced-choice, adaptive procedure was used in the normal-hearing threshold experiment (Fig. 1) and in the frequency discrimination experiment (Fig. 4). The subject sat in a sound-treated booth (IAC, Bronx, New York) and was instructed to identify which of the two listening intervals contained the signal (a tone in the detection experiment or the tone of higher pitch in the frequency discrimination experiment). A light bar on a computer screen in front of the subject defined the timing of the listening intervals. The signal was randomly presented in one of the two intervals. The tone level or the tone frequency was reduced for three consecutive responses of correctly identifying the signal interval, whereas the tone level or the tone frequency was increased for each incorrect response. This ''three-down, one-up'' rule would converge to produce a threshold level corresponding to 79.4% correct responses [13]. Data are reported as the mean of three estimates obtained with this procedure.

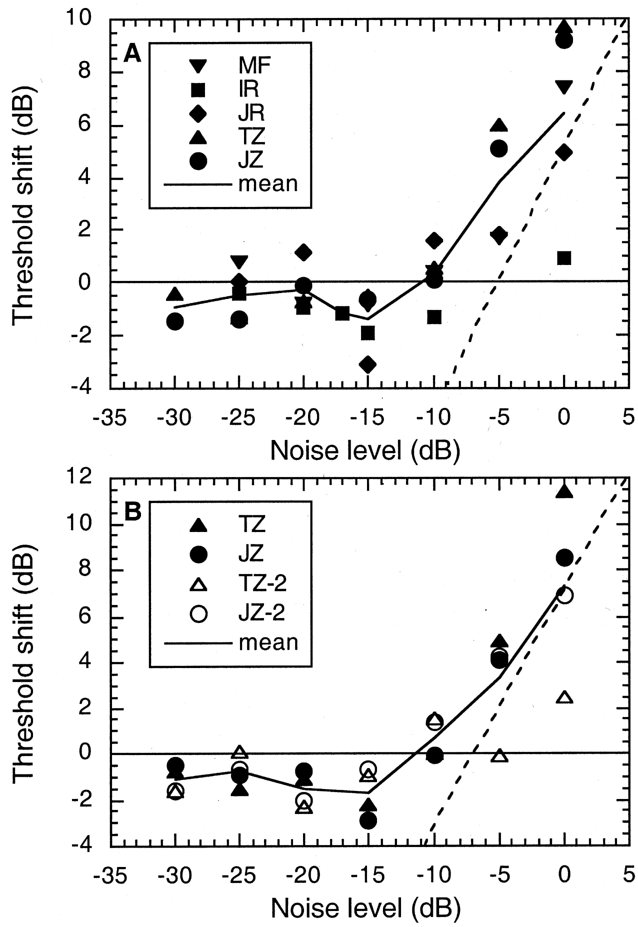

Fig. 1. Threshold shifts for a 1000-Hz sinusoid as a function of noise level in five normal-hearing subjects (top panel) and for a 4000-Hz sinusoid (filled symbols) and for a 4000/4100-Hz two-tone complex (open symbols) in two normal-hearing subjects (bottom panel). The noise level is represented as spectrum level (dB/Hz). The averaged absolute threshold for the noise was estimated to be −10 dB/Hz for the normal subjects. The solid line represents the averaged data across all subjects. The dashed line represents a hypothetical masking growth function. Standard deviations for the three threshold measures ranged from 0.1 to 4 dB with an average of 0.8 dB.

A procedure combining Bekesy's tracking and the method of limits was used in the experiments involving the cochlear-implant (Fig. 2) and brainstem-implant subjects (Fig. 3). The subject was first presented an ascending sequence of signals, in which the signal level was steadily increased from an inaudible level. The subject was in-

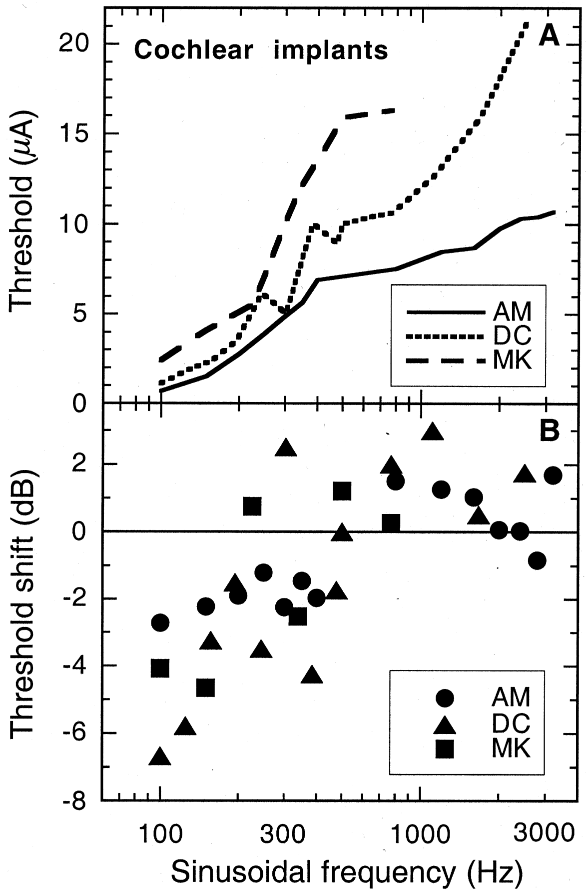

Fig. 2. Detection thresholds of sinusoids without noise in three cochlear-implant subjects (panel A) and their threshold shifts in the presence of noise (panel B). The noise threshold was 14, 31, and 56 microamperes (peak level) for subject AM, DC, and MK, respectively.

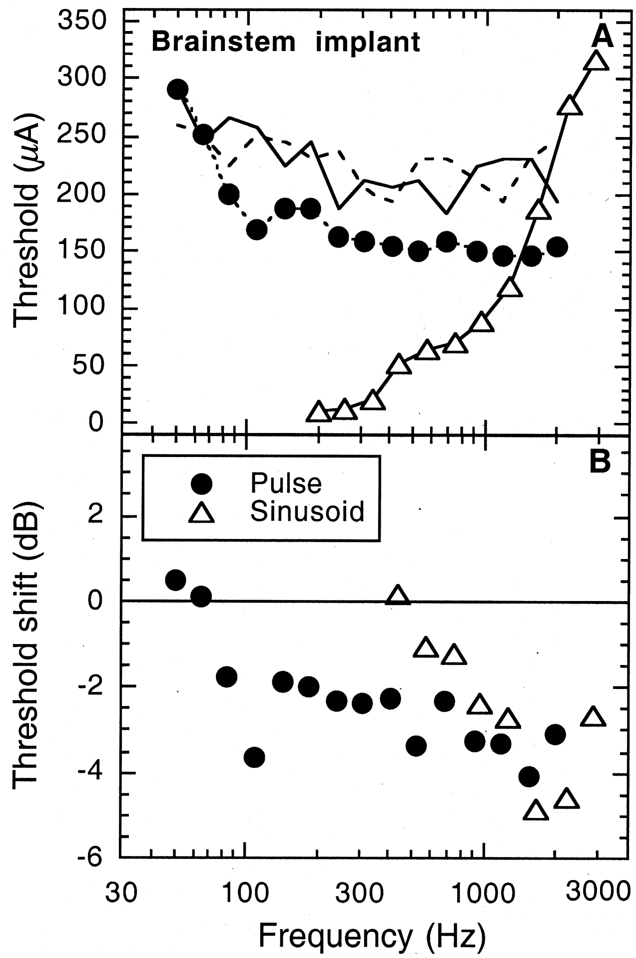

Fig. 3. Detection thresholds for sinusoids and pulses in a brainstem implant subject (panel A). The open triangles represent sinusoidal thresholds without noise. The thick line and the dashed line represent, respectively, the pulsatile thresholds without noise that were measured immediately before and after the noise condition (filled circles). Threshold shifts with noise (panel B) for pulses (circles) and sinusoids (triangles). The noise threshold was 125 microamperes (peak level).

structed to push and hold a computer button when (s)he first heard the signal. As soon as the subject pushed the button, the signal level was increased by 5 or 10 dB depending on the subject's dynamic range. Then a descending sequence of signals was presented to the subject, in which the signal level was steadily decreased and the subject was instructed to let go of the button when (s)he no longer heard the tone. The threshold was estimated as the average of the ascending level and the descending level. The procedure measured the threshold as a function of frequency, which was increased in one run and decreased in the other run. Data reported were the average of the two runs.

3. Results

3.1. Improved thresholds in acoustic hearing

Fig. 1 shows pure-tone detection threshold shifts (re: threshold obtained without noise) as a function of noise level (*x*-axis) in normal-hearing subjects. The averaged detection threshold for the noise was at a spectrum level of −10 dB/Hz. Panel A shows threshold shifts for the 1000-Hz sinusoid in five normal-hearing subjects, while panel B shows threshold shifts for the 4000-Hz sinusoid (filled symbols) and that for the two-tone-complex (open symbols) in two normal-hearing subjects. Because the 1-tone and 2-tone complex produced essentially the same results, their thresholds were averaged in panel B (solid line). Negative threshold shifts indicate that the presence of the noise actually produced lower detection thresholds than the absence of noise. Although the magnitude of the noise effect was small, the results showed a typical pattern of stochastic resonance. Only at optimal noise levels were the signal detection thresholds significantly improved (1.4 dB at the −15-dB noise level for the 1000-Hz tone, 1.7 and 1.6 dB at the −15- and −20-dB noise levels, respectively, for the 4000-Hz tones, 2-tailed paired *t*-test, $P<0.05$). At lower noise levels (less than −15 dB for the 1000-Hz tone and −20 dB for the 4000-Hz tones), there was no significant difference in thresholds between the noise and no-noise conditions. At higher noise levels (greater than −10 dB), the noise elevated the tone detection thresholds and eventually produced a masking effect, in which a 1-dB increase in the noise level would result in a 1-dB increase in the threshold (dashed line).

3.2. Improved thresholds in electric stimulation of the auditory nerve

Fig. 2 shows three cochlear implant subjects' detection thresholds as a function of sinusoidal frequency in the absence of noise (panel A) and the threshold shifts in the presence of noise (panel B). In the absence of noise, detection thresholds for sinusoids increased monotonically as a function of the sinusoidal frequency. In the presence of a threshold-level noise, the detection thresholds improved only at low frequencies (<300 Hz). The noise slightly elevated the thresholds (0–3 dB) at high frequencies (300–3000 Hz). Because there appeared to be no theoretical basis for expecting stochastic resonance to be dependent on signal frequency, we hypothesized that the observed frequency-dependent effect is due to a low-pass filtering process in the auditory brainstem [4,10,25].

3.3. Improved thresholds in electric stimulation of the auditory brainstem

We tested this hypothesis in an auditory brainstem subject who was implanted with an electrode attached to the surface of his cochlear nucleus while undergoing a bilateral acoustic tumor removal surgery. Because the surface electrode most likely stimulated undiscriminatingly any intrinsic processing circuits in the cochlear nucleus, we would expect a more uniformly enhanced performance at all frequencies in the brainstem implant subject. Fig. 3 shows both sinusoidal and pulsatile signal detection thresholds (panel A) and their changes due to noise (panel B) in such a subject. The sinusoidal thresholds (triangles) increased monotonically as a function of frequency. The pulsatile thresholds, on the other hand, decreased gradually as a function of frequency, with the thick line and the dashed line representing an initial and a repeated measure of the noise-absent thresholds, respectively. These data were collected immediately before and after the noise condition (circles). In contrast with the data obtained in cochlear-implant subjects, the threshold-level noise improved detection thresholds at high frequencies (>60 Hz for pulses and >400 Hz for sinusoids), but not at low frequencies in the auditory-brainstem subject. While the presence of a noise effect at high frequencies in the auditory-brainstem subject is consistent with the low-pass filtering hypothesis in the cochlear nucleus, the reason for the absence of the noise effect at low frequencies is not clear.

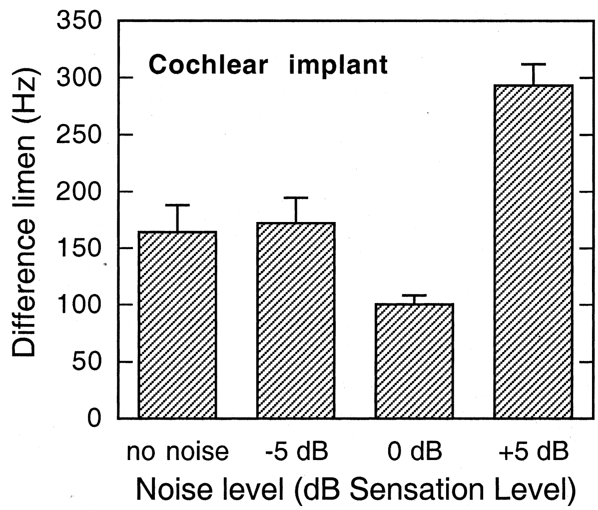

Fig. 4. Frequency discrimination in the absence and presence of noise in a cochlear implant subject, AM. The standard stimulus was a 300-Hz biphasic pulse train (100-μs per phase) and was presented at the most comfortable loudness level (100 microamperes). Frequency difference limen was plotted as the *y*-axis. Noise was presented at 5 dB below threshold (−5 dB SL), at threshold (0 dB SL), and 5 dB above threshold (5 dB SL). Standard deviations across three runs were presented as error bars.

3.4. Improved frequency discrimination in a cochlear-implant subject

We also show that a noise can enhance suprathreshold performance in frequency discrimination. Morse and Evans [18] found that noise could enhance speech formant information in a sciatic-nerve preparation simulating the electrode-nerve interface in cochlear implants. We adopted a simplified paradigm and measured directly frequency discrimination at 300 Hz. Fig. 4 shows the just-noticeable-difference or the difference limen in frequency (*y*-axis) as a function of noise level in the cochlear-implant subject, AM. When the noise level was low (5 dB lower than its threshold, i.e., the −5 dB Sensation Level, or SL condition), the difference limen was 172 Hz, which was not significantly different from the 164-Hz control (*t*-test, $P>0.05$). On the other hand, the 0-dB SL noise produced a significantly lower difference limen (100 vs. 164 Hz; *t*-test, $P<0.05$) and the 5-dB SL noise produced a significantly higher difference limen (293 vs. 164 Hz; *t*-test, $P<0.05$).

4. Discussion

Our results show that human hearing can be enhanced by noise. The enhanced hearing can be either detecting lower amplitude signals at the threshold level (Figs. 1–3) or discriminating smaller frequency differences at the suprathreshold level (Fig. 4). We interpret these results as a demonstration of stochastic resonance in the human auditory system. Although the improvement in thresholds by noise is relatively small (1.4–1.7 dB) in normal-hearing subjects, it suggests that the normal auditory system, while possibly already using the stochastic resonance in hearing, is not optimal. This small noise effect in normal-hearing subjects is also consistent with the known psychophysical data [6] and physiological data [7].

While a 2-dB enhancement by noise is trivial in normal-hearing listeners who typically have a dynamic range of over 100 dB, a 2–6 dB improvement in threshold is significant in cochlear- and brainstem-implant subjects whose typical dynamic range is only 6–20 dB [28,29]. Recent results from other laboratories also showed that noise could increase cochlear-implant subjects' dynamic range and their ability to encode temporal information [16,19,20,27]. Together, these results suggest that an external noise should be introduced in cochlear implants to produce auditory perceptions superior to that produced by the present devices. Further studies are needed to explore fully the role of stochastic resonance in human sensory function and its applications to neural prostheses.

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