Noise-mediated enhancements and decrements in human tactile sensation

J. J. Collins,[1,2] Thomas T. Imhoff,[2] and Peter Grigg[3]
[1]Department of Biomedical Engineering, Boston University, 44 Cummington Street, Boston, Massachusetts 02215
[2]NeuroMuscular Research Center, Boston University, 44 Cummington Street, Boston, Massachusetts 02215
[3]Department of Physiology, University of Massachusetts Medical Center, Worcester, Massachusetts 01655
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Recently, it has been shown that noise can enhance the detection and transmission of weak signals in certain nonlinear systems. Here we demonstrate noise-mediated improvements in human sensory perception. We show that the ability of an individual to detect a subthreshold tactile stimulus can be significantly enhanced by introducing a particular level of noise. We demonstrate that this effect is robust over time. We also show that the ability of an individual to detect a suprathreshold tactile stimulus can be degraded by the presence of noise. These findings indicate that noise can serve as a ''negative masker'' for the perception of weak stimuli and a ''positive masker'' for the perception of strong stimuli. We discuss the possibility of developing a noise-based technique for improving tactile sensation in humans. [S1063-651X(97)11507-0]

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Noise has traditionally been viewed as a detriment to signal detection and information transmission. Recently, however, it has been shown that noise can enhance the detection and transmission of weak signals in certain nonlinear systems via a mechanism known as stochastic resonance (SR) [1,2]. In general, SR indicates that the flow of information through a system is maximized by the presence of a particular, nonzero level of noise. SR-type dynamics have been examined theoretically and experimentally in a wide variety of systems, including neurophysiological systems [3–8]. On the basis of these studies, it has been speculated that sensory systems and perceptual processes may have evolved the capability to take advantage of noise as a means for improving the detection of weak stimuli [1]. Recently, SR-type dynamics have been examined numerically in a neural-network model for the perceptual interpretation of ambiguous figures (e.g., the Necker cube) [9] and demonstrated experimentally in a human psychophysical study involving visual perception [10]. Here we examine the effects of input noise on tactile sensation in humans. We consider noise-mediated changes in the perception of subthreshold and suprathreshold tactile stimuli. A preliminary account of a portion of this study was reported in Ref. [11].

In this study, we hypothesized that the ability of an individual to detect a subthreshold tactile stimulus can be significantly enhanced by the presence of a particular, nonzero level of noise. To test this hypothesis, we conducted a series of psychophysical experiments on a population of ten healthy young subjects (six males and four females, age 18–31 years, mean 25 years). All subjects were free from any detectable neurological disorder. Each subject was seated in front of a computer screen, which provided cues signaling an upcoming presentation period and cues indicating the start and end of each presentation period (Fig. 1). The subject's forearm and hand were held in a fixed position by a passive restraint device and modeling clay, respectively. Local indentations were applied to the glabrous skin of the finger pad of each subject's right middle digit (see Fig. 1 inset) using a 1-mm flat cylindrical probe on an arm that was actuated by a force-controlled dc motor (Cambridge Technology, Watertown, MA; 300B lever system). Actuator forces were controlled using a personal computer and a ComputerBoards (Mansfield, MA) CIO-DAS1600 board.

The protocol consisted of the presentation of (a) a subthreshold stimulus plus noise or (b) no stimulus plus noise. The test stimulus consisted of a discrete, rectangular ramp pulse (total time duration 300 ms); see Fig. 2. At the outset of each testing session, the subject's detection threshold for the test stimulus was determined using the method of ascending and descending limits. The amplitude of the stimulus was then adjusted so that the stimulus was just subthreshold. The input noise consisted of zero-mean Gaussian ''quasiwhite'' noise. The stimulus and noise were generated digitally on a personal computer. The input signal was convolved with a low-pass filter (with a cutoff frequency of 30 Hz) in order to limit the excitation of rapidly adapting afferents.

Each trial consisted of 20 presentations, which were equally distributed between ''stimulus'' and ''no stimulus.''

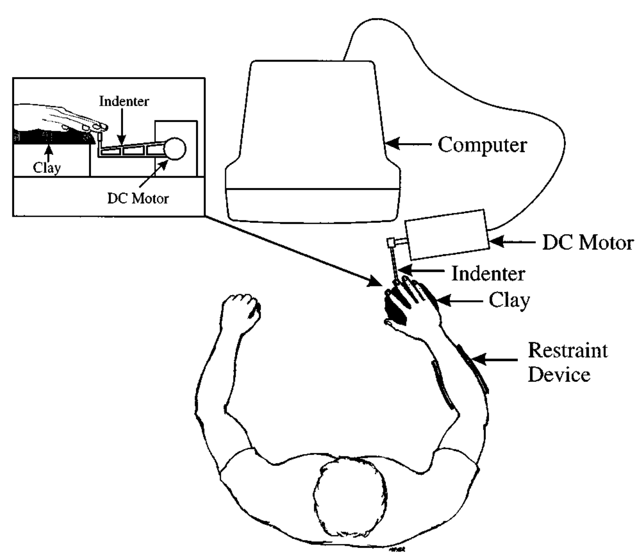

FIG. 1. A schematic representation of the experimental setup for the psychophysical tests.

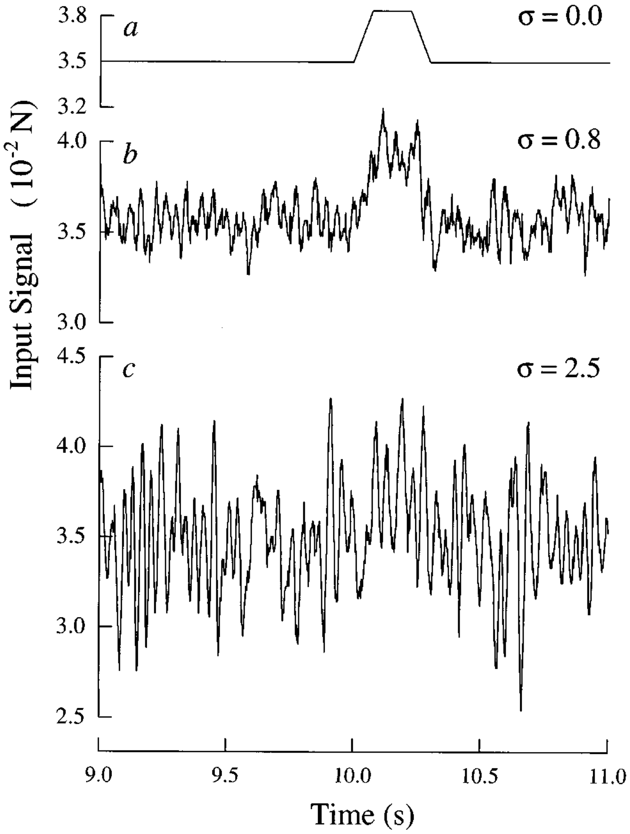

FIG. 2. Representative 2.0 s samples of the input signal for three experimental conditions: (a) stimulus with no input noise, (b) stimulus with input noise of moderate intensity, and (c) stimulus with input noise of high intensity. The respective values for the input noise standard deviation σ are given in units of 10^{-3} N. (Adapted from Ref [11].)

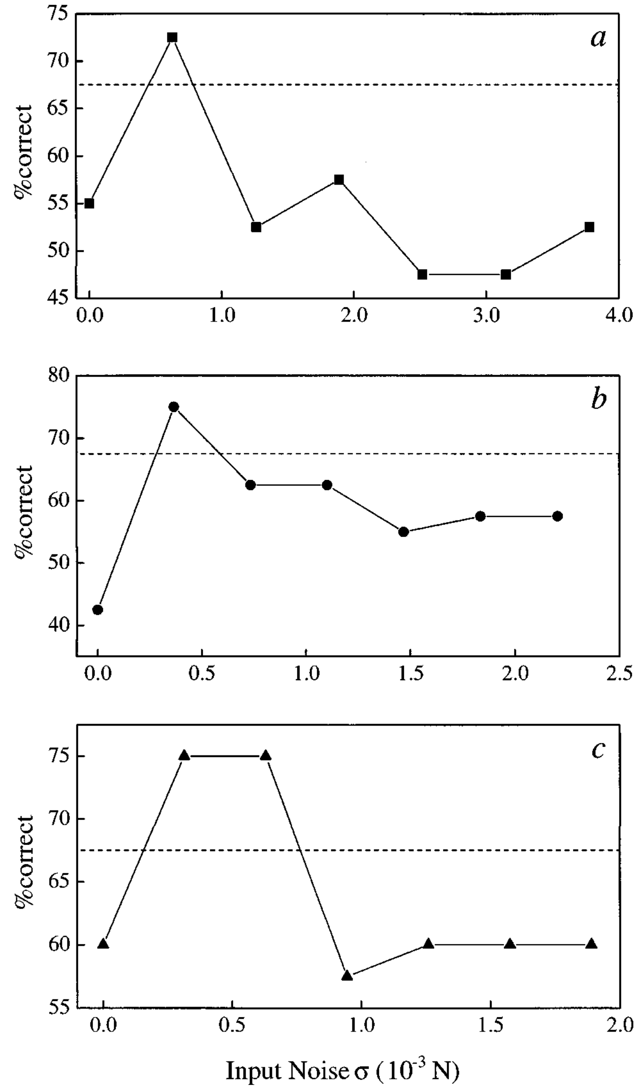

FIG. 3. Values of the % correct versus the input noise standard deviation σ for three different subjects with subthreshold test stimuli. A dashed line is drawn at the level of significance ($p<0.05$), which was determined using the binomial test with the assumption that both events (a correct response or an incorrect response for each presentation) were equally likely. Values at or above the level of significance indicate that the subject's % correct was significantly better ($p<0.05$) than that expected by chance. Each of these subjects exhibited clear SR-type behavior: as input noise intensity increased, the % correct increased to a significant peak and then decreased. (Adapted from Ref. [11].)

The presentation sequence of stimulus versus no stimulus for each trial was randomized. The interpresentation interval was 5 s. The intensity of the input noise was held constant for each trial and varied between trials (Fig. 2). Seven to nine different noise intensity levels were included in the protocol. Two trials were conducted for each noise level. The presentation order of the different noise levels was randomized. The intertrial interval was 120–240 s.

Subjects were instructed to indicate when they detected a stimulus. During the tests, the subjects' responses were recorded on a personal computer by an investigator. Before each trial, the subjects were presented with multiple suprathreshold stimuli to remind them of the general nature of the stimulus. Multiple practice trials were conducted on each subject prior to data acquisition.

The output signal-to-noise ratio has commonly been used to characterize SR-type behavior in systems with periodic input signals [1,2]. Recently, cross-correlation [5,6] and information-theoretic [7] measures have been proposed for systems with aperiodic input signals. In general, to characterize SR-type behavior, one needs a measure which quantifies the coherence between the input stimulus and the system response. In this study, we used a measure, % correct, which quantifies the percentage of trials for which a subject correctly identified the presentation of stimulus or no stimulus. The % correct for each noise intensity level was computed using the expression % correct $=(N_{\mathrm{correct}}/N_{\mathrm{total}})\times 100$, where N_{correct} is the number of correct responses and N_{total} is the number of presentations of stimulus or no stimulus. (In this study, $N_{\mathrm{total}}=40$.) The % correct should, on average, be 50 for a protocol involving a subthreshold stimulus and an equal number of stimulus and no stimulus presentations. On the other hand, this measure should be near 100 for a protocol with test stimuli that are well above the detection threshold.

Nine of the ten subjects we examined exhibited clear SR-type behavior: as input noise intensity increased, the % correct increased significantly to a peak ($p<0.05$) and then decreased (Fig. 3). Thus, in each of these cases, the presence of

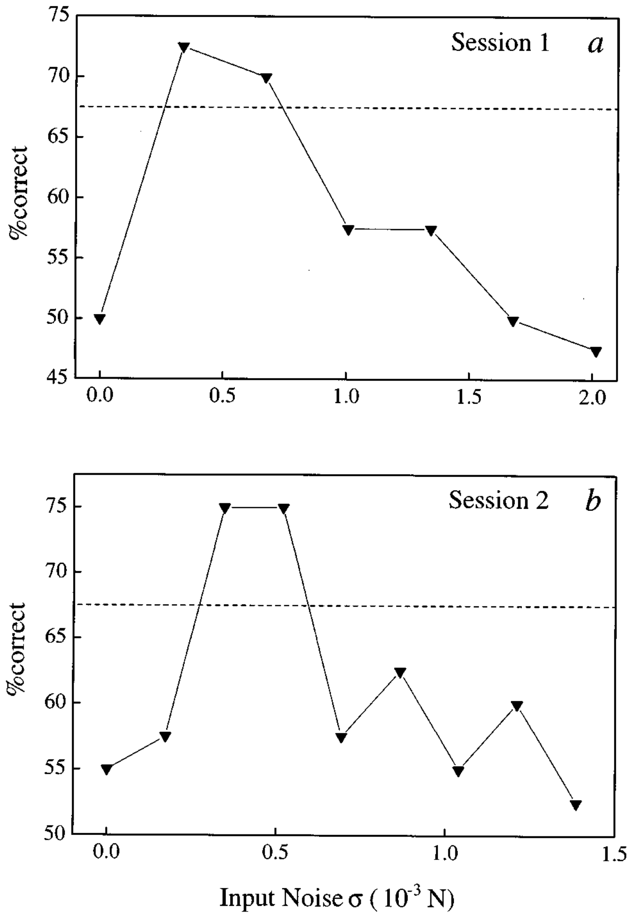

FIG. 4. Values of the % correct versus the input noise standard deviation σ for a fourth subject on two consecutive testing sessions with subthreshold test stimuli. These sessions were separated by 15 days. The stimulus amplitude for the two sessions differed slightly because the subject's detection threshold changed slightly. The % correct was computed as in Fig. 3. A dashed line is drawn at the level of significance ($p<0.05$), as in Fig. 3. This subject exhibited clear SR-type behavior on both days: the % correct increased significantly and then decreased with increasing input noise intensity.

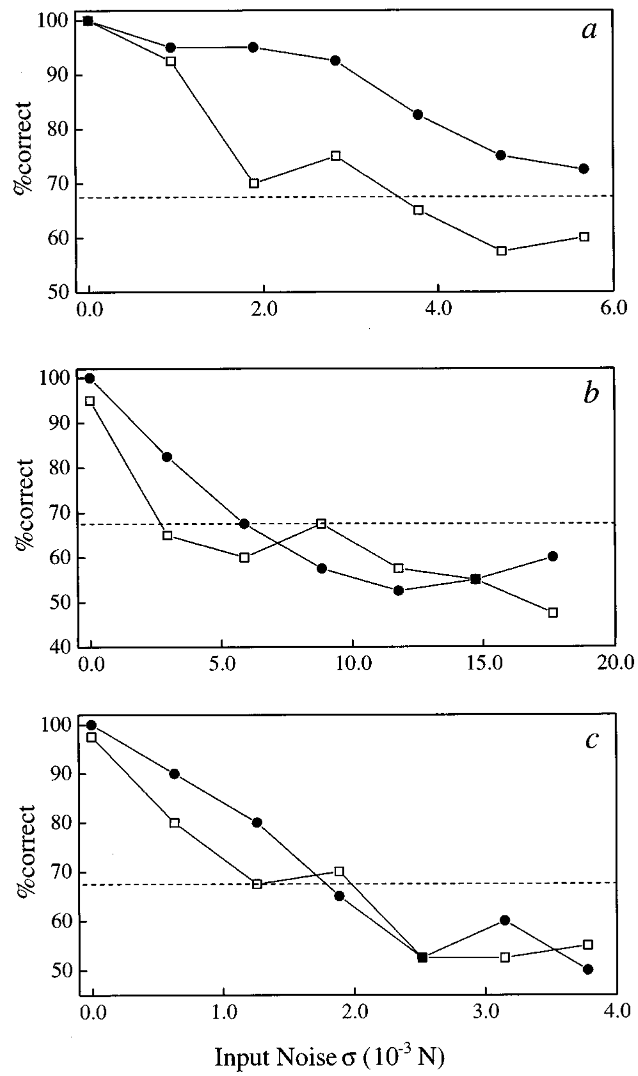

FIG. 5. Values of the % correct versus the input noise standard deviation σ for three different subjects with suprathreshold test stimuli. The solid circles and open squares, respectively, represent trials where the stimulus amplitude was 4 times and 2 times that of the determined threshold value. The % correct was computed as in Fig. 3. A dashed line is drawn at the level of significance ($p<0.05$), as in Fig. 3. Each of these subjects exhibited similar behavior: the % correct decreased with increasing input noise intensity.

a particular level of noise significantly enhanced the subject's ability to detect a subthreshold tactile stimulus. In one case (out of ten), the introduction of input noise did not significantly affect the subject's ability to detect the subthreshold stimulus.

To examine the robustness of these results, we retested four of the subjects on subsequent days. Two of these subjects had initially exhibited SR-type behavior with highly significant peaks ($p<0.01$). Upon retesting, both of these subjects exhibited similar behavior (e.g., see Fig. 4). (One of these subjects also exhibited similar behavior during a third testing session.) The third subject had initially exhibited SR-type behavior with a significant peak ($p<0.05$). During the subsequent testing session, this subject's ability to detect a subthreshold stimulus was enhanced by the introduction of input noise, but not in a significant way ($p<0.20$). The fourth subject did not exhibit SR-type behavior during the initial or subsequent testing session.

To explore this phenomenon more fully, we also examined the effects of input noise on the perception of suprathreshold tactile stimuli. We hypothesized that the ability of an individual to detect a suprathreshold tactile stimulus can be degraded by the presence of noise. To test this hypothesis, we conducted a series of psychophysical experiments on five of the subjects. We used the above protocol, replacing subthreshold test stimuli with suprathreshold stimuli. Each of the subjects exhibited similar behavior: the % correct decreased with increasing input noise intensity (e.g., see Fig. 5). At high noise intensities, most subjects did not perform significantly better than that expected by chance (Fig. 5). In addition, the deleterious effect of the noise was generally smaller for stronger stimuli (Fig. 5).

These findings indicate that input noise can serve as a "negative masker" for subthreshold tactile stimuli and a "positive masker" for suprathreshold tactile stimuli; i.e., noise can increase the detectability of weak signals and decrease the detectability of strong signals. Thus, the role of noise in tactile sensation is ambiguous and dependent upon the size of the stimulus. These psychophysical findings are consistent with the theoretical results of Jung [8] who examined the effects of noise on the performance of a threshold device.

Negative masking (i.e., enhancing the detectability of a weak stimulus) has been observed in vibrotaction for cases wherein the test stimulus and the masker (or pedestal) are sinusoidal signals of the same frequency and phase [12,13]. This effect has been shown to be robust to small levels of background noise, provided the sinusoidal pedestal is present [13]. In this study, we showed that under certain conditions, the noise itself can be used as a suitable pedestal for enhancing the detection of a subthreshold stimulus. Clearly, as shown by Figs. 3 and 4, the negative-masking effect of the noise disappears for sufficiently high intensity levels, as the suprathreshold sensations caused by the noise dominate over the signal.

Our results concerning the noise-enhanced detection of weak stimuli suggest that a noise-based technique could be used to improve tactile sensation in humans when the stimulus is around or below threshold. Such a technique could be incorporated into the design of haptic interfaces for telerobotics and virtual environments. From a clinical standpoint, a noise-based technique could be applied to individuals with elevated cutaneous sensory thresholds, such as older adults [14] and patients with peripheral neuropathies [15] or cerebrovascular accidents (i.e., strokes) [16]. In each of these cases, it may be possible to minimize the deleterious effects of input noise on the detection of suprathreshold stimuli by utilizing arrays of transducers with distributed, independent noise sources [6]. With such arrays, it may also be possible to maximize the functional-enhancement effect for the detection of subthreshold stimuli and eliminate the need for noise tuning [6].

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