

Using electrical noise to enhance the ability of humans to detect subthreshold mechanical cutaneous stimuli

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Stochastic resonance (SR) is a phenomenon wherein the response of a nonlinear system to a weak input signal is optimized by the presence of a particular, nonzero level of noise. Our objective was to demonstrate cross-modality SR in human sensory perception. Specifically, we were interested in testing the hypothesis that the ability of an individual to detect a subthreshold mechanical cutaneous stimulus can be significantly enhanced by introducing a particular level of electrical noise. Psychophysical experiments were performed on 11 healthy subjects. The protocol consisted of the presentation of: (a) a subthreshold mechanical stimulus plus electrical noise, or (b) no mechanical stimulus plus electrical noise. The intensity of the electrical noise was varied between trials. Each subject's ability to identify correctly the presence of the mechanical stimulus was determined as a function of the noise intensity. In 9 of the 11 subjects, the introduction of a particular level of electrical noise significantly enhanced the subject's ability to detect the subthreshold mechanical cutaneous stimulus. In 2 of the 11 subjects, the introduction of electrical noise did not significantly change the subject's ability to detect the mechanical stimulus. These findings indicate that input electrical noise can serve as a negative masker for subthreshold mechanical tactile stimuli, i.e., electrical noise can increase the detectability of weak mechanical signals. Thus, for SR-type effects to be observed in human sensory perception, the noise and stimulus need not be of the same modality. From a bioengineering and clinical standpoint, this work suggests that an electrical noise-based technique could be used to improve tactile sensation in humans when the mechanical stimulus is around or below threshold. © 1998 American Institute of Physics.

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Under certain conditions, the presence of noise can increase the detectability of a stimulus via a mechanism known as stochastic resonance (SR). SR-type dynamics have been demonstrated in a wide variety of systems and processes, including human sensory perception. Here we consider cross-modality SR-type effects in human tactile sensation. Specifically, we examine the effects of electrical input noise on the detectability of weak mechanical cutaneous stimuli. We show that the ability of an individual to detect a subthreshold mechanical cutaneous stimulus can be significantly enhanced by introducing a particular level of electrical noise. This effect is likely due to the fact that cutaneous mechanoreceptors can be depolarized with electrical stimuli. This work suggests that an electrical noise-based technique could be used to improve tactile sensation in humans. Such a technique could be utilized to restore sensory function in individuals with

elevated cutaneous sensory thresholds, such as older adults and patients with peripheral neuropathies.

INTRODUCTION

Noise is typically thought to be detrimental to signal detection and information transmission. However, the phenomenon of stochastic resonance (SR) indicates that under certain conditions, noise can enhance the detection and transmission of weak signals in nonlinear systems (Benzi *et al.*, 1981, 1982; Nicolis, 1982; McNamara and Wiesenfeld, 1989; Jung, 1993; Moss *et al.*, 1994; Wiesenfeld and Moss, 1995). 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 has been examined experimentally in a wide range of systems, including biological systems (Douglass *et al.*, 1993; Levin and Miller, 1996; Collins *et al.*, 1996a; Cordo *et al.*, 1996; Morse and Evans,

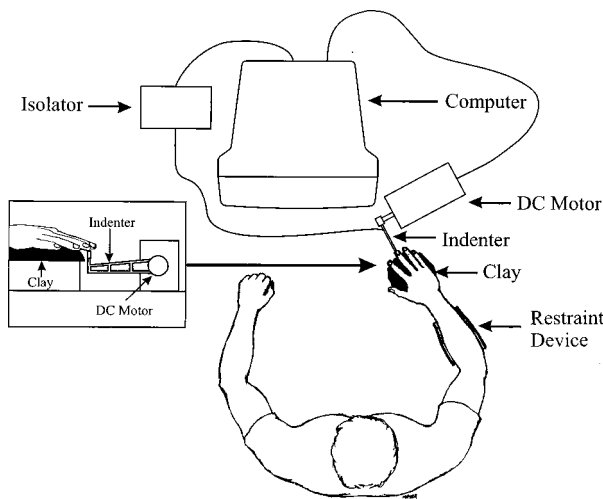


FIG. 1. A schematic representation of the experimental setup. Each subject was seated in front of a computer screen, which provided cues about each presentation period. The subject's forearm and hand were held in a fixed position by a passive restraint device and modeling clay, respectively. Compression stimuli were applied to the glabrous skin of the finger pad of each subject's right middle digit (see inset) using a flat cylindrical probe on an indenter arm that was actuated by a force-controlled dc motor. Actuator forces were controlled using a personal computer. Electrical noise signals were generated on the personal computer, passed through a stimulus isolator, and applied to the subject's right middle digit through the cylindrical probe. [Adapted from Collins *et al.* (1997).]

1996; Chiou-Tan *et al.*, 1996; Gluckman *et al.*, 1996). Such systems include crayfish mechanoreceptors (Douglass *et al.*, 1993), the cricket cercal sensory system (Levin and Miller, 1996), rat cutaneous afferents (Collins *et al.*, 1996a), and human muscle spindles (Cordo *et al.*, 1996). This work has established the functional importance of SR-type effects in neurophysiological systems.

Recently, SR-type dynamics have been demonstrated experimentally in human psychophysical studies involving tactile sensation (Collins *et al.*, 1996b, 1997) and visual perception (Simonotto *et al.*, 1997). In the former set of studies (Collins *et al.*, 1996b, 1997), it was shown that the ability of an individual to detect a subthreshold mechanical cutaneous stimulus can be significantly enhanced by introducing a particular level of mechanical noise (i.e., random vibration). These findings indicated that mechanical noise can serve as a negative masker for the perception of weak mechanical stimuli. These results suggested that a mechanical noise-based technique could be used to improve tactile sensation in humans.

As with most previous SR work in sensory systems, the noise in the psychophysical studies of Collins *et al.* (1996b, 1997) was of the same modality as the stimulus, i.e., the noise and stimulus were each mechanical signals. In this study, our objective was to extend this work by considering cross-modality SR-type effects in human sensory perception. Specifically, we were interested in testing the hypothesis that the ability of an individual to detect a subthreshold mechanical cutaneous stimulus can be significantly enhanced by introducing a particular level of electrical noise.

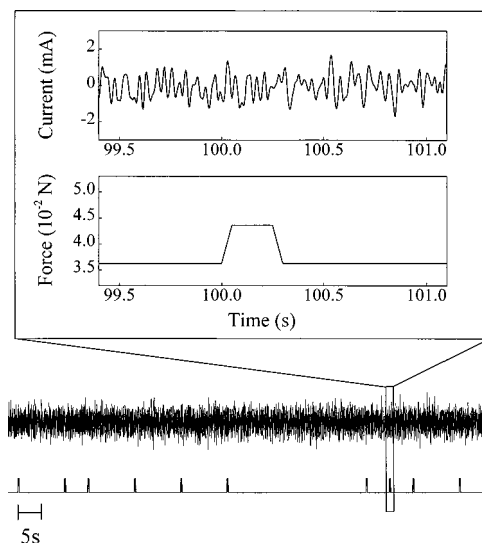


FIG. 2. Trace of a representative full trial. In each trial, electrical noise was presented continuously, and 10 mechanical indentations and 10 control presentations (no mechanical indentation) were presented at 5 s intervals. The indentations were interspersed with control presentations in a random sequence. The inset shows current and force values as a function of time for the electrical and mechanical signals, respectively. The ramp pulse of the mechanical stimulus involved increasing the force of indentation to a level that was just below the subject's detection threshold. The force was ramped up to the target value in 50 ms, held at that value for 200 ms, and then ramped down in 50 ms. Between indentations, the indenter tip was held against the subject's finger with a force of 0.036 N.

METHODS

We conducted psychophysical experiments on 11 healthy young subjects (7 females and 4 males, age 18–27 years, mean 22 years). All subjects were free of any detectable neurological disorder. Local indentations were applied to the glabrous skin of the distal pad of each subject's right middle digit (see Fig. 1 inset) using a 2-mm diameter flat cylindrical probe. Each subject was seated in front of a computer screen, that provided cues signaling an upcoming presentation period and cues indicating the start and end of each presentation period (Fig. 1). The subject's forearm rested on a passive restraint device (a foam cushion) which reduced the subject's arm movement and provided a comfortable resting position for the subject's forearm. The subject's hand was held in a fixed position by a hand-shaped clay molding to ensure that the finger of interest remained over the indenter arm of the mechanical stimulation device. The indenter arm was actuated by a force-controlled dc motor (Cambridge Technology, Watertown, MA; 300B lever system). Stimuli were controlled using a personal computer (PC) and a ComputerBoards (Mansfield, MA) CIO-DAS1600 board. The electrical noise signals (in the form of electrical current) were applied to the subject's finger through the indenter. This served to localize the input electrical noise to the site of the mechanical stimulus.

The control signal for the mechanical stimulus was generated digitally on a PC and transmitted through an attenuator (10K potentiometer) into the dc motor. The mechanical test stimulus, shown in Fig. 2, consisted of a ramp pulse (total time duration 300 ms). A constant indentation force

offset of 0.036 N was applied to the subject's finger throughout each trial.

The electrical noise signals were formed by lowpass filtering (with a cutoff of 30 Hz) zero-mean Gaussian "quasi-white" noise signals that were generated digitally on a PC (Fig. 2). The filtered noise signals were transmitted through a biphasic stimulus isolator (that was operated in constant-current mode) into the indenter arm of the mechanical stimulation device. The associated electrical current was passed through the tip of the indenter arm into the subject's finger. The indifferent electrode was placed on the back of the subject's finger.

The force offset of the indenter arm ensured constant contact of the subject's finger with the cylindrical probe on the indenter arm. A conductive gel was applied to the subject's finger in order to improve electrical contact between the indenter probe and the subject's finger. The maximum level of electrical noise used in the trials was determined by asking the subject to adjust the level of the noise (by turning an attenuation knob on the isolator) to the highest level that would be comfortable for 120 s, which was the approximate duration of each trial. Separate experiments showed that the temperature and electrical impedance, respectively, of the contact site did not change significantly during the course of a typical experiment.

The protocol consisted of the presentation of: (a) a subthreshold mechanical stimulus plus electrical noise, or (b) no mechanical stimulus plus electrical noise. Each trial consisted of 20 presentations, which were equally distributed between "stimulus" and "no stimulus" (Fig. 2). The presentation sequence of stimulus versus no stimulus for each trial was randomized. The time between presentations was 5 s, resulting in a total trial time of approximately 120 s. The intensity of the input electrical noise was held constant for each trial (Fig. 2) and varied between trials. Five to seven noise intensity levels (ranging from no noise to the maximum level determined for the subject, as described above) 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 s, during which the subject removed his or her finger from the indenter. From pilot experiments, this intertrial interval was found to be sufficient to allow subjects to recover from previous stimuli presentations, both mechanical and electrical.

At the outset of each testing session, the subject's detection threshold for the mechanical stimulus was estimated using a variation on the method of levels (Yarnitsky, 1997). A series of the ramp pulse stimuli (in which the interpresentation interval was 5 s) was introduced to the subject. After each presentation, the subject was asked whether or not they detected the stimulus. If the subject was able to detect the stimulus (indicated by a "yes" response), then the amplitude of the mechanical stimulus was decreased. If the subject could not detect the stimulus (indicated by a "no" response), then the amplitude of the mechanical stimulus was increased. The amplitude at which the subject appeared to be unsure as to the presence of the stimulus was taken as the estimate of the subject's detection threshold. Subsequent pre-testing trials, which consisted of randomized presentations of

stimulus and no stimulus (in the absence of electrical noise), were conducted in order to confirm that this level was at threshold. The amplitude was then adjusted so that the stimulus was just subthreshold. The amplitude of the stimulus was held at this level for all subsequent trials. If, after multiple pre-testing trials, a subject's detection threshold could not be identified, then that subject was not included in the study.

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

To characterize SR-type dynamics, we used a measure, *%correct*, which quantifies the percentage of trials for which a subject correctly identified the presentation of "stimulus" or "no stimulus." [We used the same measure in our earlier psychophysical studies that involved mechanical test stimuli and mechanical noise (Collins *et al.*, 1996b, 1997).] The *%correct* for each intensity level of the input electrical noise was computed using the expression: $\%correct = (N_{correct} / N_{total}) \times 100$, 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, $N_{total} = 40$.) 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.

RESULTS

Eight of the eleven subjects exhibited clear SR-type behavior: as the intensity of the input electrical noise increased, the *%correct* increased significantly ($p < 0.05$) to a peak and then decreased (Fig. 3). In one of the three other subjects, the *%correct* increased to a significant peak ($p < 0.05$) but did not decrease at higher noise levels. In this case, it is possible that the range of noise explored was not large enough to demonstrate SR-type effects, i.e., the explored region may have been limited to the rise portion of the SR curve. Regardless, in 9 of the 11 subjects, the introduction of a particular level of electrical noise significantly enhanced the ability of the subject to detect a subthreshold mechanical cutaneous stimulus. In 2 of the 11 subjects, the introduction of electrical noise did not significantly change the subject's ability to detect the mechanical stimulus.

DISCUSSION

In this study, we demonstrated cross-modality SR-type effects in human sensory perception. Specifically, we showed that the ability of an individual to detect a subthreshold mechanical cutaneous stimulus can be significantly enhanced by introducing a particular level of electrical noise. This effect is likely due to the fact that cutaneous mechanoreceptors can be depolarized with electrical stimuli. In most previous SR work in sensory systems, including our earlier psychophysical studies (Collins *et al.*, 1996b, 1997), the

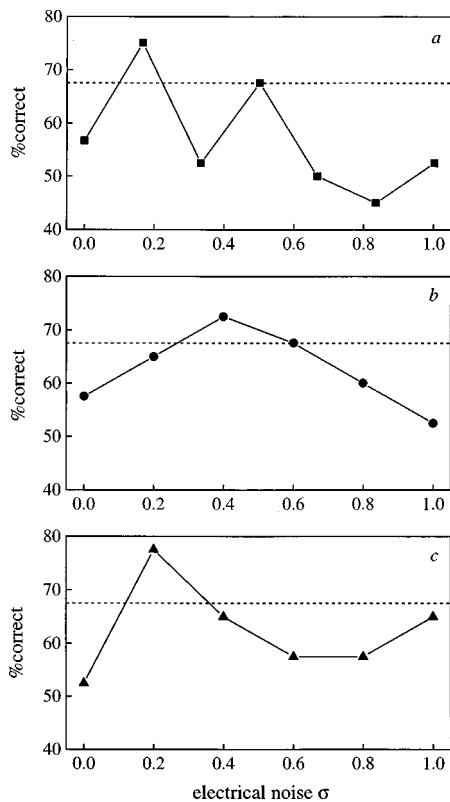


FIG. 3. Values of the %correct versus the normalized standard deviation σ of the input electrical noise (where $\sigma=0.0$ corresponds to the no-noise condition and $\sigma=1.0$ corresponds to the maximum noise level determined for the subject—see Methods) for three different subjects. A dashed line 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 the intensity of the input electrical noise increased, the %correct increased to a significant peak ($p<0.05$) and then decreased.

noise and stimulus were of the same modality. The only exception to this is the work of Pei *et al.* (1996) who showed that light-mediated (internal neural) noise on a crayfish photoreceptor cell can enhance the cell's sensitivity to a hydrodynamic signal via the SR mechanism. The present study and that of Pei *et al.* (1996) show that the noise and stimulus need not be of the same modality for the demonstration of SR-type effects.

These findings indicate that input electrical noise can serve as a negative masker for subthreshold mechanical tactile stimuli, i.e., electrical noise can increase the detectability of weak mechanical signals. Negative masking (i.e., enhancing the detectability of a weak stimulus) has been observed in vibrotactation for cases wherein the test stimulus and the masker (or pedestal) are sinusoidal signals of the same frequency, phase and modality (Hamer *et al.*, 1983; Verrillo *et al.*, 1983; Gescheider *et al.*, 1992). This effect has been shown to be robust to small levels of background noise, provided the sinusoidal pedestal is present (Gescheider *et al.*, 1992). 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, and it

need not be of the same modality as the stimulus.

The present work suggests that an electrical noise-based technique could be used to improve tactile sensation in humans when the mechanical stimulus is around or below threshold. Such a technique could be incorporated into the design of haptic interfaces for telerobotics and virtual environments. In general, a technique of this sort could be used in situations which require heightened tactile sensation. Such situations could involve the use of micro-devices, such as micro-controllers and micro-surgical instruments. From a clinical standpoint, a noise-based technique of this sort could be applied to individuals with elevated cutaneous sensory thresholds, such as older adults (Verrillo, 1979) and patients with peripheral neuropathies (Gelber *et al.*, 1995) or cerebrovascular accidents (i.e., strokes) (Robertson and Jones, 1994). Such a technique could be incorporated into glove electrodes and sock electrodes. In each of these cases, it may be possible to maximize the functional-enhancement effect for the detection of subthreshold mechanical stimuli and eliminate the need for noise tuning by utilizing arrays of electrodes with distributed, independent noise sources (Collins *et al.*, 1995).

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