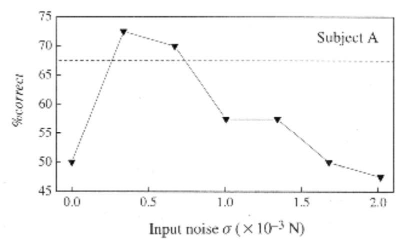

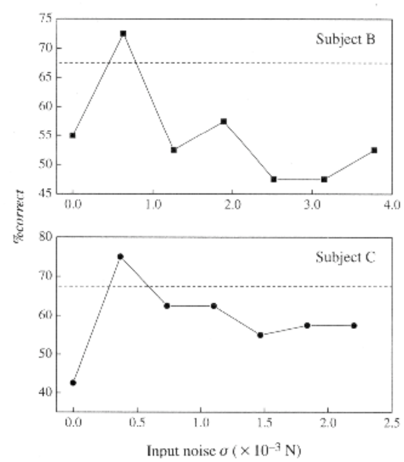

FIG. 2 Values of the *%correct* versus the input noise standard deviation σ for three different subjects. A dashed line is drawn at the level of significance ($P<0.05$), which was determined using the binomial test with the assumption that both events (a correct or an incorrect response for each presentation) were equally likely. Values above the level of significance indicate that the subject's *%correct* was significantly better ($P<0.05$) than that expected by chance.

Noise-enhanced tactile sensation

SIR — Stochastic resonance, a phenomenon in which noise enhances the response of a nonlinear system to a weak signal[1,2], has been demonstrated to be important functionally in various physiological systems[3–6]. Here we demonstrate improvements in human sensory perception mediated by stochastic resonance-type effects. We show that the ability of an individual to detect a subthreshold tactile stimulus can be significantly enhanced by a particular level of noise.

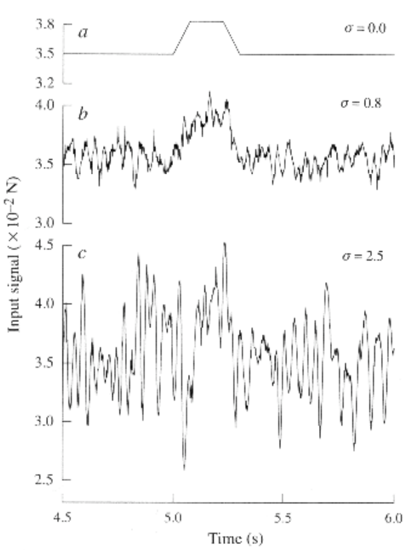

FIG. 1 Representative samples of the input signal for three experimental conditions: *a*, stimulus with no input noise; *b*, stimulus with input noise of moderate intensity; *c*, stimulus with input noise of high intensity. (Respective values for the input noise standard deviation σ are in units of 10^{-3} N.) The amplitude of the stimulus was adjusted so that the stimulus was just subthreshold. The input noise consisted of zero-mean gaussian 'quasi-white' noise. The input signal was convolved with a low-pass filter (cutoff frequency 30 Hz) to limit the excitation of rapidly adapting afferents.

We conducted a series of psychophysical experiments on 10 healthy young subjects. We applied local indentations to the tip of each subject's right middle digit. The protocol consisted of the presentation of either a subthreshold stimulus plus noise (Fig. 1) or no stimulus plus noise, and we instructed the subjects to indicate when they detected a stimulus. Each trial consisted of 20 presentations, equally distributed between 'stimulus' and 'no stimulus', with a randomized presentation sequence and an interpresentation interval of 5 s. We held the intensity of the input noise constant for each trial and varied it between trials (Fig. 1); we included 7–9 different noise intensity levels in the protocol and conducted two trials for each noise level in randomized order.

To characterize stochastic resonance-type behaviour, we used a measure, *%correct*, that quantifies the percentage of trials for which a subject correctly identifies the presentation of 'stimulus' or 'no stimulus'. 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 stochastic resonance-type behaviour: as input noise intensity increases, the *%correct* increases significantly to a peak ($P<0.05$) and then decreases (Fig. 2). We retested several of these subjects on subsequent days and obtained similar results. In one of the ten cases, the introduction of input noise did not significantly affect the subject's ability to detect the subthreshold stimulus.

These findings indicate that input noise can serve as a 'negative masker' for subthreshold tactile stimuli, that is, noise can increase the detectability of weak signals. Negative masking has been observed in vibrotaction for cases where the test stimulus and the masker (or pedestal) are sinusoidal signals of the same frequency and phase[7–9]. This effect has been shown to be robust to small levels of background noise, provided the sinusoidal pedestal is present[9]. We have shown here that, under certain conditions, the noise itself can be used as a suitable pedestal for enhancing the detection of a subthreshold stimulus.

These results suggest that a noise-based technique could be used to improve tactile sensation in humans. Such a technique could be incorporated into the design of haptic interfaces for telerobotics and virtual environments. From a clinical standpoint, a stochastic resonance-based technique could be applied to individuals with elevated cutaneous sensory thresholds, such as older adults[10] and patients with peripheral neuropathies[11] or strokes[12].

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