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Stochastic Resonance Occurring in Tactile Sensation of Human Finger

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Abstract— **In this paper, we review the influence of external noise on human tactile sensation as outlined in prior and current studies. In the last few decades, researchers have found that, although noise is always considered detrimental, it provides the benefit of stochastic resonance (SR) phenomena. Based on previous studies, we investigate the effect of the SR phenomenon on human tactile sensation. In this context, we developed a system consisting of an experimental apparatus and a computer program, and performed a series of psychophysical experiments using different types of stimulus with normal vibration. The experimental results show that tactile sensation precision can be enhanced by an appropriate level of external noise. Furthermore, we introduce a neural network model composed of nonlinear neurons with a bi-stable equilibrium condition to clarify the result. Finally, we perform a sequence of psychophysical experiments with tangential vibration to clarify which conditions of vibration direction and stimulus size cause the strongest SR. The results show that the normal difference limen (DL) is significantly affected by stimulus point size. On the other hand, neither normal nor tangential DL is significantly affected by stimulus point size. Moreover, the characteristics of SR with normal vibration are quite different from those with tangential vibration.**

I. INTRODUCTION

Stochastic Resonance (SR) is of significant concern because of its considerable influence on human tactile sensation and the nervous system through the adding of noise processes. SR is a counterintuitive phenomenon observed in many non-linear and multi-stable systems. SR is caused by the addition of random noise to a weak signal to increase the detectability of the target signal or enhance the precision of the signal information interpretation. The term SR was first introduced in the seminal papers of Benzi, et al. in the 1980s, in which they explained and described SR in the climatic changes of ice ages [1][2]. Since SR in biological systems allows for high adaptability to a wide variety of stimuli, as described in several papers, it has attracted considerable attention from many researchers [3][4]. It was found that SR can enhance the detection and transmission of weak signals in certain nonlinear and multi-stable systems by using noise [5][6]. Deterministic dynamics may be enhanced when fluctuation and random disturbance occur in a nonlinear dissipative system. Due to this SR effect, a signal can be detected by superimposing proper noise on an undetectable weak signal. The SR phenomenon in a single neuron is observed in simulations of a numerical model [7][8], as well as examined in such realms as neuron neurophysics [9][10] and brain science [11].

On the other hand, sensational thresholds presenting vibrotactile stimuli on the skin have been studied [15][16] and it has been determined that there are four kinds of mechanoreceptive units in human skin, such as the fast adaptive type I unit (FA-I), fast adaptive type II unit (FA-II), slowly adaptive type I unit (SA-I), and slowly adaptive type II unit (SA-II). Their ability to detect vibration stimuli depends on stimulus direction and size: FA-I detects normal vibration without dependence on stimulus size; FA-II detects both normal and tangential vibration with dependence on stimulus size; SA-I detects normal low frequency vibrations and static pressure; and SA-II detects tangential vibration without dependence on stimulus size.

The most famous investigation of the effect of SR in tactile sensation is the former work of Collins et al., who found that an individual absolute threshold for tactile stimulus can be significantly enhanced by an appropriate noise level [12]. Although this study is a milestone in tactile psychophysics, SR influence was only obtained on the absolute threshold of tactile sensations and, therefore, further studies are required to elucidate the effect of SR phenomenon on tactile sensation. According to classical psychophysics, one method for measuring tactile sensitivity is to determine the minimum amplitude of vibration of the skin that can be detected by an observer.

The objective of this paper is to show the importance of SR effect on human tactile sensation referring to our previous and present studies. Based on these studies, we have performed several psychophysical experiments to clarify the mechanism of SR on tactile sensation and afterwards introduced a neural network model to demonstrate the model. Although this paper is a review of our prior and present studies, we briefly provide some opinions on SR on human tactile sensation.

II. PSYCHOPHYSICAL EXPERIMENTS

A. *Experimental Apparatus*

The experimental apparatus was composed of a personal computer, a piezoelectric actuator, and a piezoelectric actuator driver to generate step waves. We developed a computer program based on the PEST (Parameter Estimation Sequential Testing) [13] method and used a half-sine pulse signal as a tactile stimulus in our psychophysical experiments. The tactile stimuli and noise were generated by the PEST program and a noise generator program based on the block diagram shown in Fig. 1. The PEST method's algorithm was

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described in a preceding paper [14]. The signal generator program (with noise or without) is included in this system.

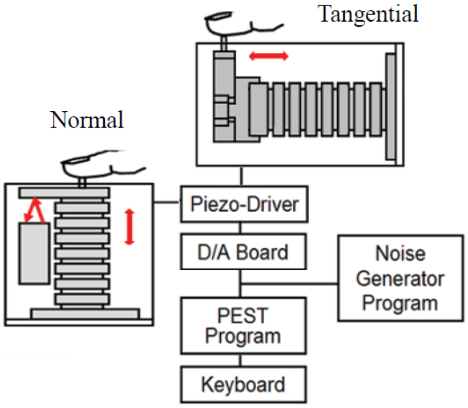

Fig. 1 Schematic block diagram of apparatus

According to the block diagram, a half-sine pulse signal and normally distributed random noise are first calculated by the computer and mixed with an adding operation. Afterwards, the obtained digital signal is sent to the D/A board to transform it from a digital to an analog signal and then sent to the piezo-driver to power the actuator.

In this experiment, we examined the discrimination capability of two stimuli under two conditions: with and without input noise superimposed on the tactile signal. The original half-sine pulse signal was disturbed with an increase of the normal deviation of noise σ . Six noise intensity levels (σ = 0, 0.4, 0.8, 1.2, 1.6, and 2.0 μm) were superimposed on the half-sine pulses of the comparison and standard stimuli in each experiment. If the local minimum point was vague after the experiment, we performed another experiment under larger noise intensity: σ = 4.0 μm .

Fig. 2 Scene of psychophysical experiments

B. *Experimental Procedure*

The psychophysical experiments were conducted on five healthy subjects in their twenties. Each subject sat in front of a computer screen, wore earphones, and placed their left hand on the contactor (Fig. 2). Normal and tangential sinusoidal vibrations were transmitted to the distal pad of their left index fingers. Stimuli were controlled using a personal computer and the amplitudes were changed using the PEST procedure [14]. Each set of stimuli consisted of two tactile stimuli signals: a standard stimulus, which was constant throughout the experiments, and a comparison stimulus, which was varied. The subjects adjusted the comparison stimulus to the standard stimulus. After the PEST procedure was terminated, the difference between the comparison and the standard stimuli was regarded as the difference threshold (DL), which means the human precision of the sensation.

C. *Experiments*

We initially performed three series of psychophysical experiments because vibrotactile sensation depends on frequency and contactor size. Although the result (Fig. 3) is detailed in a previous paper [14], we will discuss it briefly in the next chapter as well.

Experiment A: Wavelength *T* is 150 ms and the contactor diameter *D* is 2.5 mm, normal directional stimulus.

Experiment B: Wavelength *T* is 300 ms and the contactor diameter *D* is 2.5 mm, normal directional stimulus.

Experiment C: Wavelength *T* is 150 ms and the contactor diameter *D* is 8 mm, normal directional stimulus.

Subsequently, we introduced a neural network model composed of nonlinear neurons with the bi-stable equilibrium condition to explain the results [14].

Finally, since the vibrotactile sensation depends on contactor size and the direction of vibration, we performed two series of psychophysical experiments using the tangential stimulus mode to reveal which condition causes the strongest SR.

Experiment D: Wavelength T is 150 ms and the contactor diameter *D* is 2.5mm, tangential directional stimulus.

Experiment E: Wavelength *T* is 150 ms and the contactor diameter *D* is 8 mm, tangential directional stimulus.

III. DISCUSSION

Figures 3 and 4 show the substantial relationship between DL and the applied noise intensity in Experiments A, B, and C with normal vibration and Experiments D and E with tangential vibration, respectively. Vibrations are detected by tactile receptors in the part of the tactile nervous system called the mechanoreceptive unit, which has nonlinear characteristics causing SR [8][9].

Since the experiment's frequency was 6 Hz, the absolute threshold was about 1.8 μm according to Miyaoka [15][16]. As shown in Fig. 3, the DL value at σ = 0 μm (no noise) is around 1.6 μm in Experiment A, and this DL level is rather large. Since a standard stimulus amplitude of 3 μm is near the absolute threshold of 1.8 μm , the subjects had great difficulty judging variations of the small amplitude because the DL value was about half of the standard stimulus.

The result of Experiment A has a local minimum point of 0.93 μm at σ = 0.8 μm (Fig. 3). The minimum DL is around half of the threshold under the no-noise condition. Weber's fraction, which is defined by

$$\text{Weber's fraction} = DL/St, \tag{1}$$

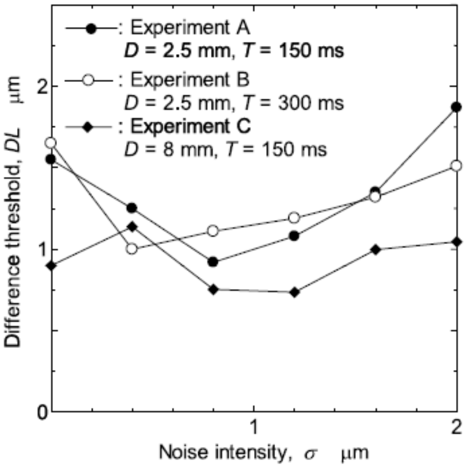

Fig. 3 Experimental results of Experiments A, B, and C

is around 0.53 in the no-noise condition, where DL and St are the difference threshold and standard stimulus values, respectively.

On the other hand, Weber's fraction is reduced by 0.3 at $\sigma = 0.8$ μm, showing that the subjects recognized the amplitude variation under a subtle stimulus of 3 μm. Therefore, the tactile sensation's just noticeable difference (JND) is decreased by the appropriate external noise. If too much noise is applied, the DL value increases again (Fig. 3).

The result of Experiment B is presented as white circles in Fig. 3. The signal frequency (3 Hz) differs from the other experiments. The DL in the no-noise condition is larger than that of Experiment A. This inclination resembles the result of Experiment A. There is a local minimum point of $DL = 1$ μm at $\sigma = 0.4$ μm and the SR effect is exhibited even in a low frequency condition.

The result of Experiment C, performed using the large contactor ($D =$ 0.8 mm), is presented as solid diamonds in Fig. 3. The DL value at the no-noise condition ($\sigma = 0$ μm) is around 0.9 μm, which is almost half of the DL of Experiment A. There is also a local minimum point when the noise intensity is $\sigma = 0.8$ μm and $\sigma = 1.2$ μm. The local minimum value of DL is about 0.74 μm and Weber's ratio is 0.25, which is close to the DL value of the no-noise condition. Variation in DL is not relatively large in Experiment C and the subjects easily recognized the difference even in the no-noise condition. Since they have enough sensitivity to discriminate the signals, the SR is not relatively obvious.

Although there is no considerably large SR effect in Experiment C, DL is decreased by appropriate external noise. This result suggests that external noise enhances tactile sensing precision.

To interpret the result, we introduced a neural network model with a bi-stable equilibrium condition. We assume that one neuron is represented by the single Schmitt Trigger circuit, which emulates the Hodgkin and Huxley model [17]. Since the one-neuron model simulates judgment on one JND level, an aggregate of neuron models having various thresholds simulates how the excitement level increases with the increase of JND levels. On the basis of the above discussion, we introduced the three-layered neural network shown in Fig. 4 [14]. Several neurons possessing different thresholds L_i and U_i (i = 1, 2, 3, . . . , n; n: number of neurons in intermediate layer) are connected to form one layer, as shown in Fig. 4. Each activated neuron outputs 1, otherwise 0: $z_i = 1$, activated; $z_i = 0$, non-activated. Outputs emitted from the neurons are summarized into an output neuron. Since values of thresholds L_i and U_i are graduated, the number of neurons exceeding threshold U_i is increased with increasing magnitude of the input wave amplitude.

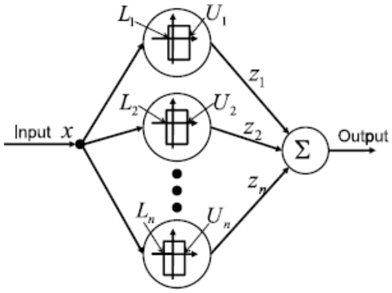

Fig. 4 Three-layered nonlinear neuron model

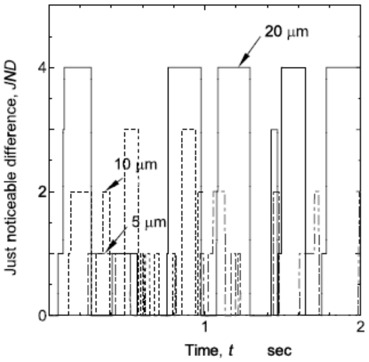

Fig. 5 Simulated result

The simulation result is shown in Fig. 5. This simulation is performed on machine tactile sensing data [17] in which a machine equipped with a tactile sensor scans specimens of three amplitudes of fine ridge strips. The simulated results emit outputs corresponding to the fine ridge amplitude. According to a numerical simulation, our new model output suitable amplitude that was proportional to the amplitude of the texture wave. Although the original sensor data did not represent the morphology of the fine texture, the present model extracted the morphology and distinguished the wave amplitude of the fine texture.

The vibrotactile sensation depends on the direction of vibration. In this context, we finally performed two series of psychophysical experiments using the tangential stimulus mode applying the same experimental methodology to determine the condition that causes the strongest SR in this study. The results are depicted in Fig. 6.

Figure 6 shows the relationship between the DL and the applied noise intensity in Experiments D and E with tangential vibration. The diameter of the contactor is different for each of the two experiments and the results show the average value obtained from the DL of five subjects. According to Fig. 6, the DL value at no-noise intensity ($\sigma = 0\,\mu m$) is around 0.66 μm in Experiment D. When the noise intensity is at $\sigma = 0.8\ \mu m$ and $\sigma = 1.6\ \mu m$, Experiment D has a local minimum DL value of about 0.57 μm, which is close to the DL value of no-noise conditions. When the noise intensity is increased to $\sigma = 4\,\mu m$, the DL value increases again.

According to Fig. 6, the DL of Experiment E is 0.76 mm in the no-noise condition ($\sigma = 0\,\mu m$), which is close to that of Experiment D. When the noise intensity is $\sigma = 0.8\ \mu m$, Experiment E has a local minimum point of $DL = 0.4\,\mu m$. If we increase the noise intensity to $\sigma = 4\,\mu m$, the DL value increases again, as in Experiment D.

Considering the results of Experiments D and E, the two curves in Fig. 6 tend to resemble each other. Consequently, we can say that tactile sensing precision is enhanced by SR, although the effect of SR is not so obvious in this experiment. Since Experiments D and E have been performed with tangential directional vibration, the results show that tangential DL does not depend on stimulus point size.

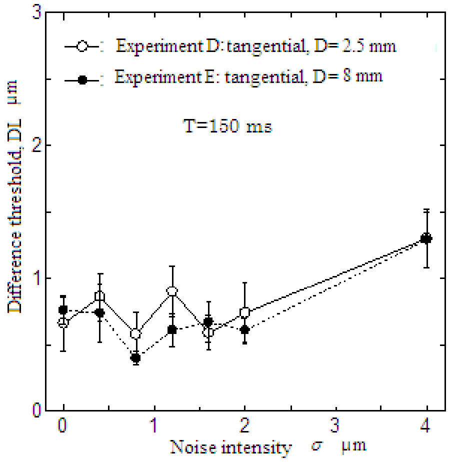

Fig. 6 Results of Experiments D and E

IV. CONCLUSION

In tactile sensing, since noise inevitably occurs through contact with an object and a sensor's movement upon it, sensing accuracy can be increased by SR. In prior and present studies, we performed psychophysical experiments to accumulate basic data on the SR of human tactile sensations. We investigated DL variation under external noise to elucidate the SR mechanism in tactile sensation.

The experimental result had a local minimum point. The minimum DL was around half of the threshold under a no-noise condition for normal stimulation as well. Therefore, the tactile sensation's JND was decreased by appropriate external noise. Since JND denotes the scale divisions of sensation in the human mind, the present result demonstrates that tactile sensing precision is enhanced by appropriate noise.

Furthermore, from the normal stimulus test, the FA-I unit seems to be mainly concerned with the normal SR. Meanwhile, from the tangential stimulus test, the SA-II unit seems to be independently concerned, or the FA-I and SA-II units seem to be cooperatively concerned, with the tangential SR.

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