Using visual noise to improve tactile two-point threshold

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***Abstract*—Stochastic resonance (SR) refers to the phenomenon in which a specific level of weak noise improves the detection of subthreshold signals. In this study, we hypothesized that the tactile two-point discrimination threshold is improved via SR by the addition of weak visual noise. To test this hypothesis, two-point discrimination thresholds were measured at the index finger using one of five intensities of flickering random visual noise in healthy normal participants. The two-point discrimination threshold was improved by the addition of a near-threshold noise compared with a control with null intensity in most of the individual data (10 of 12). The mean two-point discrimination threshold showed a U-shaped function against the noise intensity with statistically significant improvement at noise intensity near the detection threshold. These findings show that visual noise can enhance tactile sensitivity via cross-modal SR.**

Keywords—tactile-visual interactions, haptic perception, two-point discrimination, cross-modal stochastic resonance, subthreshold signal detection

I. INTRODUCTION

Although noise generally hampers signal detection, it has been shown that signal detection in a nonlinear system may be enhanced by a low level of noise via a mechanism known as stochastic resonance (SR) [1–3]. SR has been thought of as a fundamental mechanism for organisms to adapt to complex and noisy external environments [4, 5].

The detection of a weak signal by the human visual, auditory, and somatosensory systems can be enhanced by the simultaneous presentation of noise, provided that the noise does not mask the signal [6–8]. Collins et al. (1996, 1997) found that subthreshold tactile stimuli may become detectable when presented concurrently with weak vibrotactile noise [9, 10]. Kurita et al. (2011) reported that the two-point discrimination (TPD) threshold at the fingertips decreased upon application of a particular level of vibrotactile noise [11]. Enhanced tactile sensitivity by SR has been detected not only in healthy adults but also in older adults with reduced tactile sensitivity [12, 13], as well as stroke survivors [14]. Also, improved tactile sensitivity via SR can induce enhanced motor function based on tactile inputs [15, 16].

In the preceding studies, vibrotactile noise has been applied to the same site as the area of TPD measurements [9, 10, 12, 13], or the adjacent site [11]. However, attachment of a vibrotactile device near the site of the tactile stimulus has some disadvantages because it may disturb normal motor functions. In such cases, the application of vibrotactile noise from a separated site is required. It has been reported that SR is a ubiquitous phenomenon and can be seen not only at the receptor levels but also in the CNS [17–21]. Based on these studies, it seems probable that SR can be induced if the noise is applied to a separated site from the site of TPD measurement. Indeed, in our previous studies, we showed that a weak vibrotactile noise applied to a relatively remote site from a tactile test signal significantly improved TPD [22, 23]. Also, cross-modal SR has been reported, in which auditory noise improves visual and tactile signal detection [17, 24]. This study aimed to test the hypothesis that visual noise can improve tactile perception via SR. A part of the results has been reported elsewhere in a preliminary form [25].

II. METHODS

A. Participants

Twelve healthy right-handed male undergraduate students participated (mean age ± SD; 20.8 ± 3.7 years) in the experiment. Informed consent was obtained from all participants, and all experimental treatments conformed to the Declaration of Helsinki (1964).

B. Apparatus

Details of the experimental apparatus were described previously [25]. TPD was measured on the third pad of the index finger of the non-dominant hand using an electric digital caliper (CW-80216m, Freedom) attached to two metal shafts (2 mm in diameter). Random dots were generated using a graphic generator (VSG Three, Cambridge Research Systems, Rochester, UK) to provide visual noise. The dot size measured an area of 0.41 mm × 0.41 mm. The dots were presented at the center of a cathoderay tube (CRT) display (Multiscan G42, Sony; at a refresh rate of 100 Hz) with an area measuring 49 mm × 49 mm on an uniform gray background of 70 cd/m^2. The spatial distribution of the dot luminance was pseudo-random. Also, the dots moved from the right to the left at a drift velocity of 45°/s to provide the randomly flickering visual noise. The noise intensity was changed by manipulating the range of luminance for the dots with a mean of 70 cd/m^2. Five noise intensities were used (±5, ±10, ±15, and ±20 cd/m^2) including the null intensity noise as a control (± 0 cd/m^2) (Fig. 1). The graphic generator was controlled by a computer (Power Macintosh 7300, Apple) via a serial-parallel interface (Ichan, data6, Kobe, Japan) using original programs developed in our laboratory with HyperCard (Apple Inc.) [26].

C. *Procedures*

Participants were seated facing the CRT monitor at a distance of 114 cm away in an experimental room under photopic conditions. The head of the participant was loosely restrained using a chin rest. A small white cross (145 cd/m^2) was displayed at the center of the CRT, which served as a fixation point. Participants were instructed to look at the fixation point during experimental sessions. TPD was measured by the method of limit. One session consisted of 10 blocks. Half of the blocks were performed using an ascending sequence and the remainder of the blocks was performed using a descending sequence. Each block was performed with different noise intensity. The sequence order and the noise intensity were pseudo-random. The noise intensity was kept constant, and the noise was presented continuously during each block. In each block, several trials were performed to measure TPD with a tip separation step of 0.5 mm. The tactile stimulus was presented for about 2 s with an inter-trial interval of 3–5 s. For each noise intensity, mean TPDs for the ascending and descending sequences were calculated.

III. RESULTS

A. *The detection threshold of the visual noise*

A preliminary experiment was conducted to measure the detection threshold of visual noise using a constant method. One of five noise intensities was presented for 2 s with a pseudo-random order. Participants were required to report whether the noise was present or absent. The test was repeated six times. The detection threshold was defined as the noise intensity with a detection rate of 50%. Figure 2 shows the histogram and the cumulative distribution curve of the detection threshold. The detection threshold of the noise was 70 ± 9.13 cd/m^2, which was between intensities N1 and N2.

B. *Individual data for effects of visual noise on TPD*

Figure 3 shows individual data from the 12 participants of the TPD changes after the addition of different visual noise intensities. A slight decrease in the TPD was observed for N1 intensity compared with the control (N0). The maximum TPD decrement was obtained for N2 intensity in 10 out of 12 participants (Fig. 3a–j). The TPD gradually recovered for N3 and N4, showing a U-shaped curve. The remaining two participants did not show such a curve (Fig. 3k–l).

C. *Mean data for the effect of noise on TPD*

Changes in the mean TPD after exposure to visual noise are shown in Fig. 4. The mean TPD plotted as a function of visual noise intensity showed the U-shaped curve with the maximal sensitivity at N2. A similar result was observed with the individual data.

Statistical analysis using one way repeated measures analysis of variance showed that the main effect was significant ($F_{4, 44} = 24.740$, $p < 0.001$). Multiple comparisons using the Tukey–Kramer method were conducted. Significant differences were found between N0 and N2 ($p < 0.01$); N1 and N2 ($p < 0.01$); N2 and N4 ($p < 0.01$); N0 and N3 ($p < 0.05$); and N3 and N4 ($p < 0.05$) (Fig. 4).

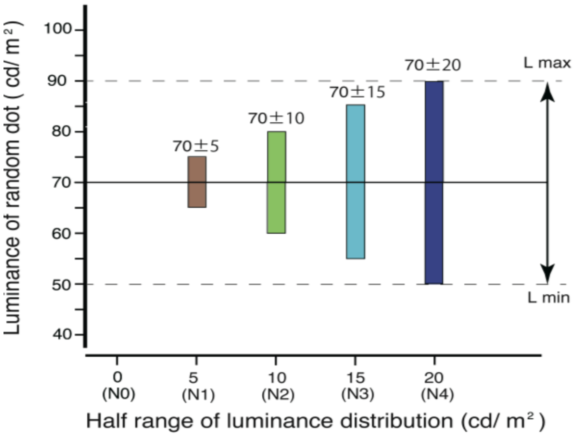

Fig. 1. Visual noise intensities. Five noise intensities (N0, N1, N2, N3, and N4; ±0, ±5, ±10, ±15, and ±20 cd/m^2 with a mean of 70 cd/m^2) were used in this experiment. The intensity of visual noise was defined by a range of luminance contained in a random dots (maximum luminance – minimum luminance; $L_{max} - L_{min}$).

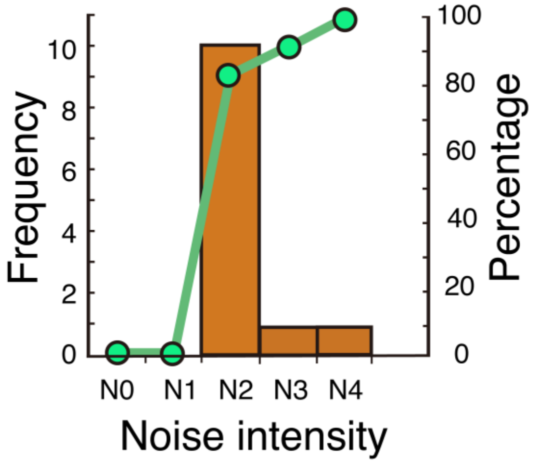

Fig. 2. Histogram (bars) and cumulative curve (lines) of the detection threshold.

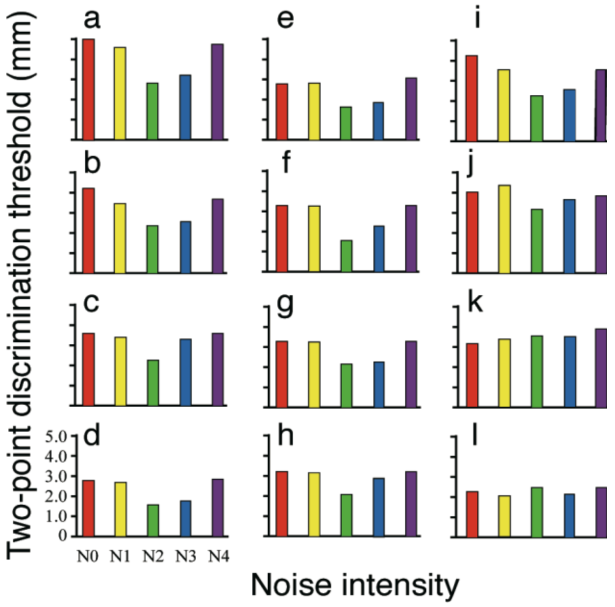

Fig. 3. Effect of visual noise on TPD in individual participants. In 10 of the 12 participants (a–j), the minimum TPD score (maximum sensitivity) was obtained at the noise intensity N2.

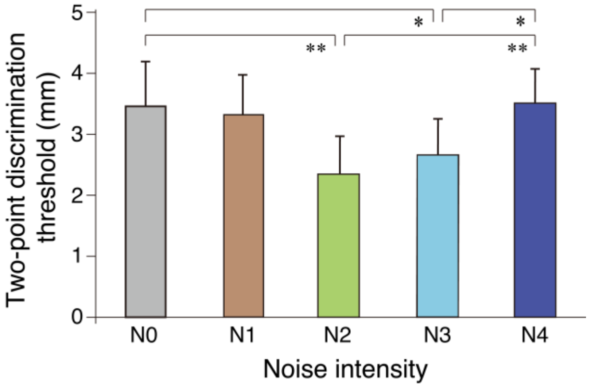

Fig. 4. Changes in the mean TPD by the visual noise intensity (mean ± SD, * $p < 0.05$, ** $p < 0.01$).

IV. DISCUSSION

A. TPD on the third pad of the index finger

The TPD obtained without noise on the third pad of the index finger was 3.5 ± 0.735 mm. This finding is inconsistent with the previous reports [23, 27]. It is also well known that TPD is the lowest at the fingertips. Likewise, the TPD at the tip of the index finger was lower than that on the third pad of the finger [22]. The current study hypothesized that TPD will increase following the addition of weak visual noise. This is the reason why the TPD was measured on the third pad in the present experiment. Because the improvement of the TPD was expected, it is better to study TPD on the third pad compared to the first pad.

B. Cross-modal SR of TPD

In our previous experiment, TPD at the hand showed a U-shaped curve against the intensity of vibrotactile noise [22]. The most effective noise intensity was near the detection threshold of the noise, which is consistent with the results of most studies on the stochastic resonance of TPD [9, 10, 28]. In these studies, both the signal and noise are the same modality and have been presented to the same hand. In the present study, we investigated whether a different modality of noise can improve the detection of subthreshold signals. TPD measured with the addition of visual noise showed the U-shaped curve against the noise intensity, thus showing the SR-like effect. Such behavior of TPD was observed not only in the mean scores but also in the individual data from 10 out of 12 participants. This suggests a high level of reproducibility for the present results.

This finding is also consistent with the results from a previously reported study on cross-modal SR. Auditory noise facilitated tactile perception as well as visual and proprioceptive perception [17, 24]. Furthermore, visual noise facilitated auditory perception [29]. These results suggest that sensory inputs interact with each other to integrate information from different sensory modes. Interactions between haptic and visual signals have been identified in several phenomena, such as the rubber hand illusion [30] and synesthesia [31].

A negative correlation between TPD and balance ability has been reported in normal participants. Improvement of TPD is effective to restore the decrease in balance control due to aging [16]. The present findings might be useful for the clinical application of SR to restore or improve tactile sensitivity.

C. Mechanisms of cross-modal SR

In the present study, signal and noise were presented to different sensory receptors. However, TPD was improved via SR, which is based on the subthreshold summation of signal and noise [7, 13, 32]. Therefore, the summation should occur at a site other than the receptors in the skin. Some studies on cross-modal SR reported that the summation can occur at the synaptic levels in the CNS [21]. Nevertheless, the finding that somatosensory processing can be improved by the visual noise, which was found in the present study, is the first report we have identified.

Although precise neural mechanisms underlying the TPD are not yet well understood, it seems probable that if the two TPD points are well-separated, excitation occurred at the haptic receptors conducts along the somatosensory pathway to reach the somatosensory cortex. The excitation of different neurons in the somatosensory cortex could be a basis for the perception and discrimination of the two-point stimulation.

Recent studies on cross-modal interaction suggest that visual information is transferred to the primary somatosensory cortex as well as the posterior parietal cortex [33–35]. These cortical areas may serve the neural bases for the subliminal summation of visual and tactile inputs, which underlie the mechanisms of SR.

V. CONCLUSION

In the present study, we examined whether TPD is improved by the addition of weak visual noise via SR. The mean TPD showed a U-shaped function against the intensity of visual noise. The most effective noise intensity was near its detection threshold. A more intense or less intense noise had no such effect. These findings demonstrate tactile-visual cross-modal SR, in which a weak visual noise is effective at enhancing the detection of subthreshold tactile signals.

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