Enhancing fingertip tactile sensitivity by vibrotactile noise and cooling skin temperature effect

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***Abstract*—This paper discusses a method to enhance fingertip tactile sensitivity by applying a vibrotactile noise at the wrist. This is an application of stochastic resonance to the field of haptics. We consider that the tactile sensitivity of the fingertip improves when a sufficiently large noise is propagated to it from the wrist. However, fingertip tactile sensitivity decreases when a large noise that humans can perceive is applied to the wrist. Therefore, in this paper, we cool the wrist skin to reduce the wrist's tactile sensitivity to noise. This allows us to apply noise that is large, but still imperceptible, at the wrist and thus to propagate it to the fingertip. On the basis of these procedures, we propose a method to enhance fingertip tactile sensitivity. Further, we carry out several experiments and confirm that the proposed method improves fingertip tactile sensitivity.**

***Index Terms*—Fingertip tactile sensitivity, Low skin temperature, Stochastic resonance, Vibrotactile noise.**

I. Introduction

ENHANCING tactile sensitivity at the human fingertip improves the efficiency of work using the fingers, such as palpation techniques in the medical field. Stochastic resonance (SR) [1] is one way to improve tactile sensitivity [2]. SR is a nonlinear phenomenon where the addition of a noise can enhance the detection of otherwise undetectable stimuli [3]. SR was initially discussed for a bistable system, i.e., a system with two stable states, and later for an excitable or threshold system. SR for a threshold system is referred to as threshold SR [4], [5]. We focus on threshold SR in this paper.

Threshold SR has three necessary components: a threshold, a subthreshold input, and noise [6]. If the input to the system is below the threshold, the input cannot be detected. Here, when an optimal noise is added to the subthreshold input, the input exceeds the threshold and can be detected, and the period in which the threshold is exceeded is synchronized with the input. On the other hand, if the added noise is too large, the probability of exceeding the threshold increases but the input is buried in the noise. Thus, SR is a phenomenon in which the signal is enhanced at a certain probability by adding a noise of optimal intensity to the subthreshold input. SR is observed in a threshold model such as that using a human tactile receptor. For example, many studies have applied SR to tactile functions of the fingertip [2] and foot [6].

Several studies have shown that the SR effect enhances tactile sensitivity [2], [7]–[12]. For example, Collins et al. first applied SR to human tactile function and found that humans could detect the input after white Gaussian noise was added to a subthreshold input to a finger [2]. Another study [7] enhanced haptic sensitivity at the index finger by applying white Gaussian noise to the side of the finger. However, for precise work using the hands, it is necessary for the hands to move as freely as possible. Thus, it is desirable to apply vibrotactile noise to a remote position, such as the dorsal hand or wrist away from the fingertip, so as not to restrict the user's hand movement, instead of attaching a vibrator directly to the fingertip. Several studies have shown that the SR effect enhances haptic sensation even if the noise is applied at a distance from the fingertip [8], [9]. This is often referred to as remote SR [10]. Enders et al. found that white Gaussian noise applied to the dorsal hand or wrist improved the tactile sensitivity of the fingertip [8]. Another study [9] revealed that remote SR using subthreshold noise enabled participants to detect mechanical vibration on the thumb or on the tip of the index finger. We have also studied a remote SR phenomenon where the fingertip tactile sensitivity is improved by applying two white Gaussian noises at the wrist to boost the SR effect [11]. Although these studies focused on the SR effect on finger tactile sensation, other studies have shown the enhancement of foot skin sensitivity using remote vibrotactile or electrotactile noise [10], [12]. Further, SR is known to enhance the perception of body movements [13]–[16].

In our previous study [11], we showed experimentally that the tactile sensitivity of the fingertip improves when a sufficiently large noise is propagated to it (For more details, see Sections IV and V). Further, the tactile sensitivity of the fingertip decreases when a large noise that humans can perceive is applied to the wrist. This seems to be a matter of human attention; i.e., human attention is directed more to the wrist than to the fingertip. Therefore, if we can reduce the wrist's tactile sensitivity to noise, we can apply a sufficiently large yet still imperceptible noise to the wrist. This allows us to propagate a large noise from the wrist to the fingertip. This, in turn, may allow a great improvement in the tactile sensitivity of the fingertip.

The human tactile sensation of a vibrotactile stimulus depends on temperature; i.e., cooling the skin where the stimulus is applied reduces the tactile sensation. For example, cooling the skin of the finger [17] or the thenar eminence [18], [19] reduces that body part's sensitivity to vibration. Further, cooling the skin surface of the sole of the foot reduces vibration responses [20]. In particular, it is known that low temperature decreases the sensitivity of Pacinian corpuscles [18]. Further, the effects of temperature on the perception of voltage stimuli [21] and the tactile perception of softness [22] have

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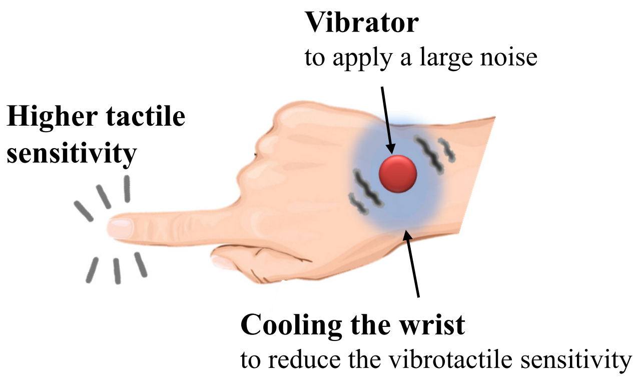

Fig. 1. Proposed method to boost remote SR effects.

been studied. Although the relationship between the skin temperature and tactile sensitivity has long been studied, the relationship between the cooling of the skin at the wrist and vibrotactile perception at the wrist has not yet been clarified.

Therefore, this paper hypothesizes that cooling the skin at the wrist reduces the wrist's sensitivity to vibrotactile noise, and we verify this hypothesis experimentally. We then adopt this characteristic to reduce the tactile sensitivity of the wrist. This allows us to apply a large but imperceptible noise to the wrist and thus to propagate a large noise to the fingertip. On the basis of these ideas, we propose a method to improve the tactile sensitivity of the fingertip. The novel findings of this paper are as follows: It experimentally shows that cooling the skin at the wrist reduces the wrist's sensitivity to noise; it proposes a method of boosting remote SR effects to enhance fingertip tactile sensitivity compared to the existing remote SR; and it shows the effectiveness of this method through several experiments.

The paper is organized as follows. In the next section, we propose a method to improve the tactile sensitivity of the human fingertip by using both remote SR and the temperature dependence of the skin at the wrist. In Section III, we experimentally investigate why cooling the wrist reduces the wrist's vibrotactile sensitivity and why large noise applied at the wrist can be propagated to the fingertip. In Sections IV and V, we show the experimental results of a texture discrimination task and a monofilament touch task, respectively, to verify the effectiveness of the proposed method. We conclude this paper in Section VI.

II. Proposed Method to Boost Remote SR

A. Concept

As shown in Fig. 1, we propose a method to boost remote SR effects; i.e., to improve the tactile sensitivity of the human fingertip by reducing the vibrotactile sensitivity of the dorsal wrist, which is the part to which noise is added, and by applying a large vibrotactile noise to the wrist.

Our previous study [11] showed that the tactile sensitivity of the fingertip improves when a sufficiently large noise is propagated to it (This is also described in Sections IV and V). On the other hand, the fingertip's tactile sensitivity decreases when a large perceptible noise is applied to the wrist. Thus, our proposed method involves two steps: reducing the vibrotactile sensitivity of the wrist and applying a large but imperceptible noise to the wrist.

For the first step, we consider that cooling the wrist skin reduces the wrist's vibrotactile sensitivity (as described in Section III-A). For the second step, we apply a large but imperceptible noise to the cooling-desensitized wrist (Section III-B). These steps allow us to propagate a large noise to a participant's fingertip without the participant noticing it. Thus, we can emphasize remote SR's effect on improving the tactile sensitivity of the fingertip compared to the normal remote SR. The effectiveness of our proposed method is investigated in Sections IV and V.

B. Experimental environment

For the vibrotactile noise, we used white Gaussian noise, as carried out in many studies. To provide white Gaussian noise at the dorsal wrist on the dominant hand, we used a piezoelectric actuator (APA400M; Cedrat Technology) as the vibrator. The vibrator was placed at the dorsal wrist using a hook-and-loop fastener made from polyvinyl chloride, as shown in Fig. 2. To keep the vibrotactile noise at a consistent level each time the wrist strap was worn, the hook-and-loop fastener was wrapped around the wrist so that the hook-side and loop-side straps connected at the same location. The vibrator was housed in a box made of ABS resin, and the contact area between the vibrator and skin was 5 mm $\times$ 10 mm.

Here, the noise frequency range was selected based on the response properties of the mechanoreceptive afferent units. Pacinian corpuscles, for example, respond to a wide frequency range [23]. Now we consider the effect of skin temperature on the vibrotactile threshold. Cooling and warming the skin of the finger are known to affect vibration perception at the finger in the high frequencies mediated by Pacinian corpuscles [17]. In addition, a previous study [19] investigated the temperature effects on the vibrotactile threshold at the thenar eminence. Those authors found that the lower the skin temperature, the higher the threshold for high-frequency vibrations (the lower the sensitivity of high-frequency vibrations). In particular, the frequency peak at which the vibration threshold is lowest (highest sensitivity) is about 400 Hz when the skin temperature is 40°C, about 250 Hz when 30°C, and about 100 Hz when 25°C. That is, as the skin temperature decreased, the peak value tended to shift toward the lower frequency region. These studies are not wrist vibration thresholds. However, considering that the wrist skin temperature considered in this study is 35°C or less, we believe the noise frequency range up to about 300 Hz would be sufficient to cover the most sensitive frequencies of all tactile receptors. Therefore, white Gaussian noise with a low-pass filter at 300 Hz was selected to cover the most sensitive frequencies of all tactile receptors. Thus, this noise is not strictly white Gaussian noise but quasi-white Gaussian noise. However, we refer to it as white Gaussian noise in this paper.

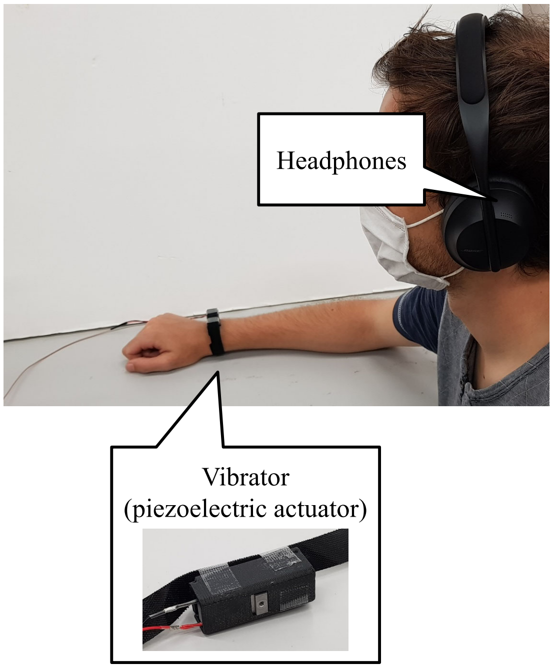

Fig. 2. Experimental setup for measuring the sensory threshold at the wrist.

The Box–Muller method [24] was used to generate white Gaussian noise $x(t)$ through the vibrator as follows:

$$x(t) = \sigma\sqrt{-2\ln\alpha(t)}\sin\left(2\pi\beta(t)\right), \quad (1)$$

where $x(t)$ is the electric voltage signal used to control the piezoelectric actuator, t is time, σ is the noise intensity (σ^2 is the variance), and α and β are independent random variables in the interval $(0, 1)$.

The wrist skin was cooled by a cold pack; however, some participants reported that the pack caused pain from the sudden temperature change, so for those participants we used the cooling water-circulation apparatus (HC-100ST; Thermictechno) shown in Fig. 3 instead. Here, the participants are described in the following sections. For all participants, we used a noncontact thermometer (DT-8806H; CEM) to confirm that the wrist skin had reached the desired temperature.

III. Sensory Threshold of the Wrist and Noise Propagation under Cooling Skin Temperature

We investigated the vibrotactile threshold of the dorsal wrist and the possibility of a large noise reaching a finger from the wrist under cooled-skin conditions.

A. *Sensory thresholds of the wrist at several skin temperatures*

We investigated the vibrotactile thresholds of the dorsal wrist at several skin temperatures. The novelties of this experiment are that we dealt with a tactile stimulus for white Gaussian noise and examined the relationship between the tactile perception of a noise and the skin temperature of the wrist. We experimentally investigated our hypothesis that cooling the skin at the wrist reduces the wrist's vibrotactile sensitivity, and we determined the most suitable wrist skin temperature for our method.

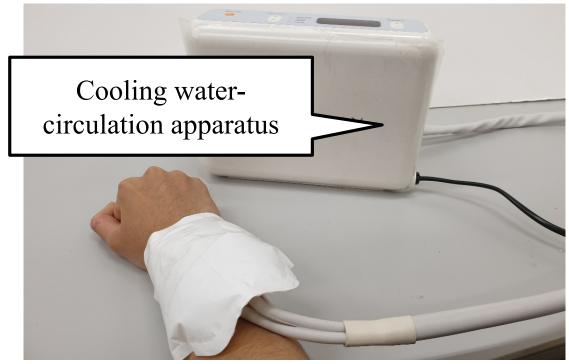

Fig. 3. Experimental setup for cooling the skin temperature at the wrist.

1) Experimental setup: A total of ten healthy individuals (mean age $\pm$ standard deviation (SD): 25.50 $\pm$ 2.87 years; 6 males and 4 females) participated in this experiment. All participants understood and consented to the experimental protocol approved by the Ethics Committee, Graduate School of Engineering, Kyoto University (No. 202012).

The temperature in the experimental room was set to 25°C. In the experiment, we examined five skin temperature conditions: 15, 20, 25, 30, and 35°C. The wrist skin was cooled to each temperature, and the sensory threshold for white Gaussian noise at the dorsal wrist on the dominant hand was measured. The experimental apparatus for applying the noise and for cooling the wrist are described in Section II-B. The order of the experiments was as follows. We divided all participants into two groups. One group participated in experiments in descending order from 35°C to 15°C and then in ascending order from 15°C to 35°C. The reverse order was used for the other group. The sensory threshold for each participant under each temperature condition is the average value under that temperature condition. Participants wore passive noise-canceling headphones to avoid hearing the vibration sound of the piezoelectric actuator. Figure 2 shows the experimental setup.

The sensory threshold was measured using the staircase method [25], which sought to determine the lowest level of noise intensity σ that the participant could detect. To define the threshold, noise stimuli were provided in increasing and decreasing intensity sequences. When the response of the participants changed, the direction of the stimuli sequence was reversed. After that, the average of the last four reversal values was set as the value of the sensory threshold. Thus, to measure the threshold value at each temperature, it was necessary to apply white Gaussian noise with different intensities multiple times. Specifically, we took about 40s to apply one noise intensity level (noise for about 10s and noise intensity change for about 30s). We cooled the participant's wrist skin to the desired temperature before applying a white Gaussian noise. When we cooled the wrist, the vibrator was removed from it. Then, the cooling water-circulation apparatus or cold pack was wrapped around the wrist to cool it, as shown in Fig. 3. After the wrist skin had cooled, the vibrator was reattached,

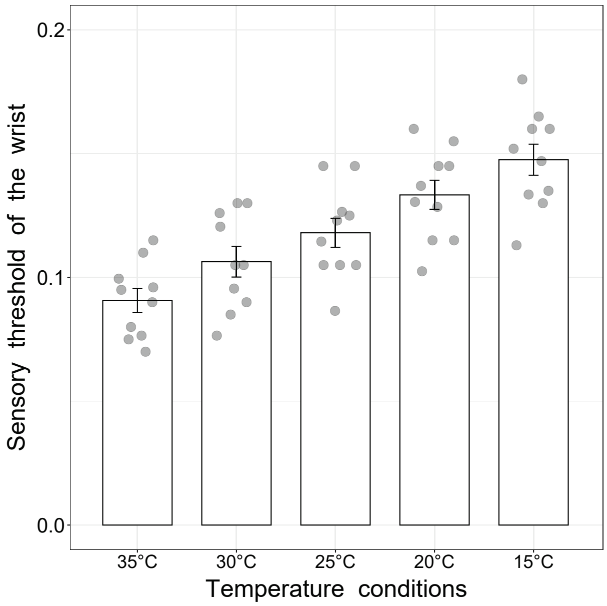

Fig. 4. Sensory thresholds of the wrist for the temperature conditions.

as shown in Fig. 2, in the same manner as before cooling. Therefore, it took about 15 minutes to measure the threshold for one temperature condition.

2) Experimental results: Figure 4 presents the sensory threshold of the dorsal wrist for white Gaussian noise when the wrist skin temperature was changed. In this figure, the horizontal axis indicates the skin temperature conditions at the wrist, and the vertical axis indicates the average value of the sensory threshold of the wrist. The error bars represent the standard error (SE), and the jitter data points are overlaid on the bar. Here, the higher the threshold value, the lower the perception of noise.

All data were considered normally distributed using the Shapiro-Wilk test. Thus, we conducted a one-way analysis of variance (ANOVA) and found a significant difference between the temperature conditions ($F(4, 45) = 14.58$, effect size $\eta^2 = 0.56$, $p = 1.04 \times 10^{-7} < 0.05$). Further, a post-hoc Tukey multiple comparison revealed statistically significant differences ($p < 0.05$) for all combinations of temperature conditions except for the pairs 20 and 15°C ($p = 0.43$), 25 and 20°C ($p = 0.35$), 30 and 25°C ($p = 0.62$), and 35 and 30°C ($p = 0.33$). Further, as shown in Fig. 4, we found that cooling the skin at the wrist reduced its noise sensitivity. Therefore, it was possible to apply a large but imperceptible noise at the wrist under low-temperature conditions.

The lower the wrist temperature, the less the tactile sensitivity. Here, we gave questionnaires to 6 of the 10 participants, and 5 of the 6 commented that a wrist temperature of 15°C was too cold to tolerate for long. On the other hand, 5 participants responded that 20°C was an appropriate low temperature to use in this study. Further, from the multiple comparisons described above, the threshold at 20°C was statistically significantly higher than that at 35°C, which corresponded to the normal temperature. Therefore, we determined 20°C to be the most suitable wrist temperature for our method.

Fig. 5. Experimental setup for measuring noise at a fingertip.

B. Propagated noise under cooled skin conditions

To boost the remote SR effects, our method reduces the vibrotactile sensitivity of the wrist by cooling the skin and then applying a large vibrotactile noise. We next investigated whether applying a large white Gaussian noise at the wrist would allow us to propagate a large noise to the fingertip.

1) Experimental setup: A total of 12 healthy participants (mean age $\pm$ SD: 26.25 $\pm$ 2.80 years, 9 males and 3 females) participated in this experiment. All participants understood and consented to the experimental protocol approved by the Ethics Committee, Graduate School of Engineering, Kyoto University (No. 202012).

The temperature in the experimental room was set to 25°C. This pilot study was conducted at skin temperatures of 20 and 35°C. The skin at the wrist on the dominant hand was cooled by the method described in Section III-A, and the sensory threshold (T) for white Gaussian noise at the wrist was measured under each temperature condition. Here, T at 20°C and 35°C are denoted as $T_{20^\circ\mathrm{C}}$ and $T_{35^\circ\mathrm{C}}$, respectively. After T was measured at each temperature, the participants kept their index fingers under a laser displacement sensor (CL-L015; Keyence), as shown in Fig. 5. The noise was applied by the vibrator described in Section II-B for 30s, where the noise intensity was set as 60% of T, that is, $0.6T_{20^\circ\mathrm{C}}$ and $0.6T_{35^\circ\mathrm{C}}$, at 20 and 35°C, respectively. Here, we set the noise intensity as 60% of T because several studies [8], [9], [11], [15] showed that the noise intensity level at $0.6T$ is optimal for producing the SR effect at the fingertip. In addition, we found that the fingertip tactile sensitivity peaked at 60% of threshold noise (For more details, see Sections IV and V). We then measured the displacement data at the index fingertip using the laser displacement sensor as the intensity of the noise propagated to the fingertip.

2) Experimental results: The experimental results are shown in Fig. 6. The experimental results for 1 of the 12 participants are shown; the other 11 showed similar patterns of results. The horizontal axes represent the frequency, whereas the vertical axes represent the power spectral density (PSD) of the propagated noise calculated using Welch's method, where we used a window of 200ms and an overlap of 50%. In the figure, the black and gray lines show the PSD when the wrist temperature was 20 and 35°C, respectively.

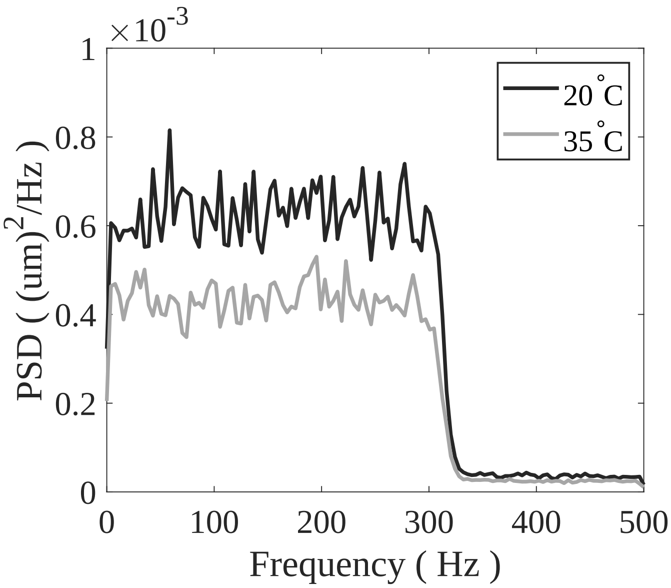

Fig. 6. PSDs of the propagated noise at the index finger for different skin temperatures.

The results indicated that a larger noise was propagated to the fingertip at 20°C than at 35°C. For the participant in Fig. 6, the values of $T_{20^\circ\mathrm{C}}$ and $T_{35^\circ\mathrm{C}}$ were 0.13 and 0.09, respectively. Here, we note that the average values of $T_{20^\circ\mathrm{C}}$ and $T_{35^\circ\mathrm{C}}$ for all participants were 0.14 ± 0.02 and 0.09 ± 0.01, respectively. Thus, the intensity of the noise applied at the wrist was greater when the skin temperature was 20°C than when it was 35°C.

On the other hand, we refer to the average value of the PSD in the interval from 0 to 300 Hz as the average PSD. For the participant in Fig. 6, the average PSDs when the wrist temperature was 20 and 35°C were calculated as 6.25×10^{-4} and 4.30×10^{-4}, respectively. Further, the average values of the average PSD for all participants at 20 and 35°C were $(6.39 \pm 0.36) \times 10^{-4}$ and $(4.42 \pm 0.19) \times 10^{-4}$, respectively. That is, the average PSD at 20°C was 1.45 times that at 35°C. This scale factor corresponds to the scale factor of the noise intensities applied to the wrist. Therefore, we can reduce the vibrotactile sensitivity of the wrist by cooling its skin and can apply a higher-amplitude yet still imperceptible noise to the wrist, allowing us to propagate a large noise to the fingertip. The mechanism by which noise reaches the fingertips and whether the noise propagates through bones, flesh, or skin remain unknown. We will investigate the propagation mechanisms in future work.

The mechanism by which remote SR enhances tactile sensitivity has not been clarified. For example, one study [8] claimed that remote SR's effect is mediated by the central nervous system, because the imperceptibly small noise applied to the wrist is unlikely to reach the fingertips. However, another study [11] and the present section showed that imperceptible noise applied to the wrist propagates to the fingertips, and the inferred mechanism described above does not seem to be correct. In other words, the following is also quite possible as a mechanism for enhancing fingertip tactile sensitivity by remote SR: Vibrotactile noise given to the wrist propagates to the fingertips through bones and flesh. Then, similar to the mechanism underlying SR (that is, normal rather than remote SR) [26], the propagated noise is superimposed on the finger's external mechanical stimulus to enhance the fingertip's haptic sensation. In any case, the principle of remote SR is still unclear.

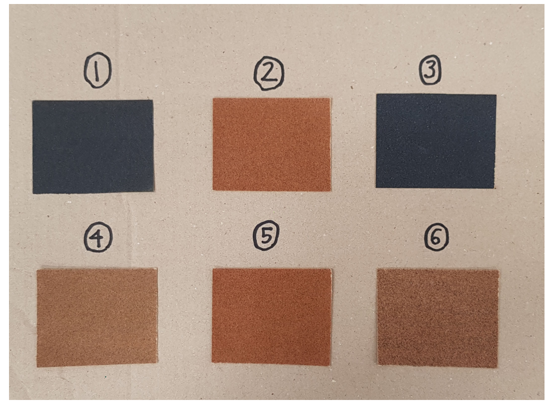

Fig. 7. Sandpapers used in the texture discrimination task. The numbers correspond to sandpaper grades as follows: 1 is #280, 2 is #240, 3 is #220, 4 is #180, 5 is #150, and 6 is #120.

IV. Texture Discrimination Task

In the previous section, we found that larger but imperceptible noise could be applied by raising the wrist threshold, allowing us to propagate a large noise to the finger. Here, we show that our proposed method improves the fingertip's tactile sensitivity. That is, we examined the effectiveness of our method experimentally in a texture discrimination task.

A. Experimental setup

The experimental environment (including the method for presenting white Gaussian noise and the cooling method) was the same as in Section III-A. We used six grades of sandpaper (#120, #150, #180, #220, #240, and #280, where the numbers indicate the U.S. CAMI grit size) as shown in Fig. 7. 14 healthy participants (mean age ± SD: 24.21 ± 2.65 years, 10 males and 4 females) took part in this experiment. All participants understood and consented to the experimental protocol approved by the Ethics Committee of the Graduate School of Engineering, Kyoto University (No. 202012). The temperature in the experimental room was set to 25°C.

In this experiment, two conditions of wrist skin temperature (normal temperature and 20°C) were used. For reference, the average normal temperature of 10 of the participants' wrists was 34.27 ± 0.75°C. For the 20°C condition, the wrist was cooled using the method described in Section III-A; for the normal condition, the wrist was not cooled. For each temperature condition, we first measured the participant's sensory threshold at the dorsal wrist on the dominant hand for 0-300Hz white Gaussian noise. The sensory threshold T was measured using the method described in the previous section. Then, five intensities of white Gaussian noise were applied to the wrist under each temperature condition: $0T$, $0.4T$, $0.6T$, $0.8T$, and

$1.0T$, and the participants completed the experiment. Here, T values when the skin temperatures were 20°C and the normal temperature are $T_{20^\circ\mathrm{C}}$ and T_{normal}, respectively, and $0.xT$ means that white Gaussian noise with an intensity of $0.xT$ was applied to the wrist (for example, $0.4T$ means 40% of T), and $0T$ means the noise was not applied.

In the experimental procedure, the participant's wrist was first cooled to the desired temperature by the method described in Section III-A. Then, the experimenter first randomly presented one of the six sandpaper grades to the participant as a test sandpaper. For this, the participant wore an eye mask and used the index finger of their dominant hand. After touching the test sandpaper for about 3s, the participant removed the eye mask and touched the six sandpapers as shown in Fig. 7 for about 30s in total. Some participants touched all of the sandpapers in less than 30 seconds. The participant was then asked to select the test sandpaper from among the six sandpapers, and the ratio of correct identifications was recorded. This experimental trial was performed four times for each sandpaper grade under the two temperature conditions and five noise-intensity conditions. The order of the test sandpaper presentation and that of the noise-intensity conditions were randomized. On the other hand, we divided all participants into two groups. One group performed the experiment with the 20°C wrist temperature first and then carried it out with the normal temperature. The other group conducted the experiments in the reverse order.

One experiment was completed within 30s in most cases and in no more than 40s. The skin temperature increased as time passed. At 40s after the wrists of all participants were cooled to 20°C, the wrist temperatures of 10 of the participants were measured, and the average value was 24.76 ± 0.89°C. Thus, skin temperature did not return to normal during the experiment. Improving the environment in which the wrist skin temperature increases after the wrist is cooled is a critical issue and will be addressed in future research.

B. Experimental results

Figure 8 shows the rates of correct sandpaper identification. The horizontal axis indicates the noise-intensity condition, and the vertical axis the correct answer rate. The error bars represent the SE. The white and gray bars show the correct answer rates when the wrist temperature was normal and 20°C, respectively. The rate of correct answers in each bar is the average value of correct rates for all participants. In addition, the jitter data points are overlaid on the bars. A high correct rate indicates high tactile sensitivity of the index finger.

All data were considered normally distributed using the Shapiro-Wilk test. Thus, we conducted a two-way repeated measures ANOVA on the conditions and found a significant difference for the temperature condition ($F(1, 130) = 19.89$, effect size $\eta^2 = 0.05$, $p = 1.75 \times 10^{-5} < 0.05$) and for the noise-intensity condition ($F(4, 130) = 55.16$, $\eta^2 = 0.58$, $p = 4.09 \times 10^{-27} < 0.05$). We did not find any significant differences for the interaction effects ($F(4, 130) = 1.70$, $\eta^2 = 0.02$, $p = 0.15 > 0.05$).

Further, we carried out a post-hoc Tukey multiple comparison. For the correct answer rate at 20°C, we found statistically

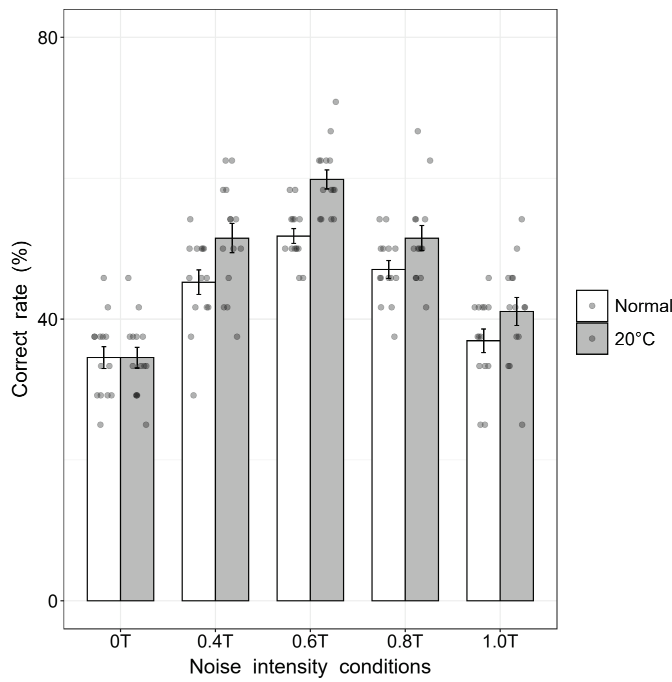

Fig. 8. Rates of correct sandpaper identification.

significant differences ($p < 0.01$) for all combinations of any two of the five noise intensities; the exceptions were for the pairs $0.4T_{20^\circ\mathrm{C}}$ and $0.6T_{20^\circ\mathrm{C}}$ ($p = 0.011$), $0.4T_{20^\circ\mathrm{C}}$ and $0.8T_{20^\circ\mathrm{C}}$ ($p = 1.00$), $0.6T_{20^\circ\mathrm{C}}$ and $0.8T_{20^\circ\mathrm{C}}$ ($p = 0.011$), and $0T_{20^\circ\mathrm{C}}$ and $1.0T_{20^\circ\mathrm{C}}$ ($p = 0.08$). Similarly, for the correct answer rate when the skin temperature was normal, statistically significant differences ($p < 0.01$) existed for all combinations of any two of the five noise intensities, the exceptions being for the pairs $0.4T_{\mathrm{normal}}$ and $0.6T_{\mathrm{normal}}$ ($p = 0.02$), $0.4T_{\mathrm{normal}}$ and $0.8T_{\mathrm{normal}}$ ($p = 0.91$), $0.6T_{\mathrm{normal}}$ and $0.8T_{\mathrm{normal}}$ ($p = 0.17$), and $0T_{\mathrm{normal}}$ and $1.0T_{\mathrm{normal}}$ ($p = 0.79$). Here, we did not find significant differences between $0.4T$ and $0.6T$ or between $0.6T$ and $0.8T$ under either temperature condition. We think this is because the variances of $0.4T$ and $0.8T$ were large and the number of participants was insufficient. However, Fig. 8 shows that the correct answer rate for both temperatures was highest when a noise of $0.6T$ was applied. In addition, the correct rate was low both above and below $0.6T$. Thus, we can consider that the tactile sensitivity of the fingertip was improved by applying a sufficiently large noise, i.e., up to $0.6T$. On the other hand, when too much noise was applied, such as over $0.6T$, the sensitivity of the fingertip was reduced.

However, when the noise intensity was $0T$ (no noise was applied), the correct answer rates at normal temperature and at 20°C were almost the same. Thus, we believe that a decrease in wrist temperature does not affect the tactile sensitivity of the fingertip. In addition, there was a statistically significant difference between the temperature conditions, and the correct answer rates were high when the wrist temperature was 20°C. We can thus infer that applying a higher-amplitude yet still imperceptible noise with a temperature decrease was effective. In particular, a two-tailed paired t-test was carried out for the correct answer rates when a noise with an intensity of $0.6T_{\mathrm{normal}}$ was applied to the wrist and when a noise with an intensity of $0.6T_{20^\circ\mathrm{C}}$ was applied. The t-test showed a significant difference between them ($t = 6.73$, $DOF = 13$, $p = 1.40 \times 10^{-5} < 0.01$). Thus, our proposed method can boost the effects of remote SR. That is, it can improve the tactile sensitivity of the human fingertip by comparing the normal remote SR, which is remote SR using noise with an intensity of $0.6T_{\mathrm{normal}}$. Thus, the results of the texture discrimination task verified the effectiveness of the proposed method.

V. Monofilament Touch Task

In another task to verify the effectiveness of the proposed method, we consider a touch test with monofilaments [27]. In this task, a monofilament stimulates the fingertip while we measure its sensitivity. In the previous texture discrimination task, we showed that the proposed method improves tactile sensitivity in active touch. On the other hand, in the monofilament task, we examine the proposed method's ability to improve tactile sensitivity in passive touch. Here, fingertip sensitivity measurement using a monofilament can assess the fingertip sensitivity of touch pressure. It is said that Merkel cells and Ruffini endings in the fingertips contribute to the perception of touch pressure. However, we note that Meissner and Pacinian corpuscles are known to contribute to the perception when the stimulus force by the monofilament is sufficiently small (less than 0.6 mN) [28]. In this task, we focus on such a small force and show that our proposed method improves the fingertip's tactile sensitivity in passive touch.

A. Experimental setup

The experimental environment (including the method for presenting the white Gaussian noise and the cooling method) was the same as in Section III-A. We used Semmes-Weinstein Monofilaments (Aesthesio®, Precise Tactile Sensory Evaluator 20-piece kit; Danmic Global). In particular, we used four monofilaments (target forces: 0.008, 0.02, 0.04, and 0.07gf). Because the length and diameter of the monofilament are adjusted, the monofilament applies a target force corresponding to the monofilament used. Twelve healthy participants (mean age $\pm$ SD: 26.33 $\pm$ 2.95 years, 10 males and 2 females) participated in this experiment. All participants understood and consented to the experimental protocol approved by the Ethics Committee of the Graduate School of Engineering, Kyoto University (No. 202012). The temperature in the experimental room was set to 25°C. To eliminate visual and auditory information, the participants wore an eye mask and headphones.

In this experiment, two wrist skin temperatures (normal temperature and 20°C) were used. To achieve the 20°C wrist skin temperature, the wrist was cooled using the method described in Section III-A. No cooling was used to obtain the normal temperature condition. Here, we divided all participants into two groups. One group carried out the experiment at 20°C first and then at the normal temperature, while the other group used the reverse order. For each temperature condition, we first measured the participant's sensory thresholds T_{normal} and

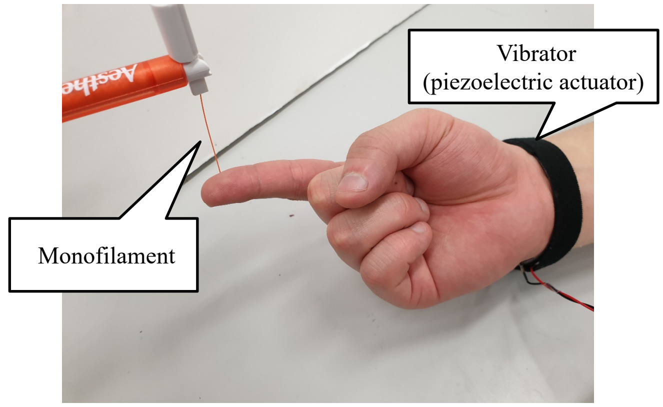

Fig. 9. Example of monofilament touch task for index finger.

$T_{20^\circ\mathrm{C}}$ at the dorsal wrist on the dominant hand for 0-300 Hz white Gaussian noise by using the method described in the previous section. Then, five intensities of white Gaussian noise ($0T$, $0.4T$, $0.6T$, $0.8T$, and $1.0T$) were applied to the wrist at each wrist temperature condition while the participants completed the monofilament test.

The monofilament touch test was performed as follows. First, we used a thin monofilament with a small target force. Then, from a position 2.5 cm above the tip of the participant's index finger, the monofilament was lowered vertically for 1.5 seconds. The monofilament was lowered further until it bent in 1.5 seconds and was then returned to its initial position in the next 1.5 seconds. Then, as shown in Fig. 9, the monofilament was used to stimulate the participant three times. If the participant felt the stimulus even once, we concluded that the participant had felt the target force of the monofilament and terminated the test. If the participant did not feel the stimulus after three attempts, the test was performed using the monofilament with the next largest target force. A test with one monofilament was considered one trial. The test measured the lowest target force, and we call that value the monofilament threshold. One trial took about 15 s at maximum. Therefore, for the 20°C condition, the wrist temperature was cooled by the method described in the previous section after the completion of one trial. The order of the noise-intensity conditions was randomized. Because the levels of forces provided in the monofilament touch task are limited to the four filaments (0.008, 0.02, 0.04, 0.07gf), it should be noted that the monofilament threshold does not represent the real force threshold.

In the monofilament touch test, we adopted the widely used Bell-Krotoski method [27] as the measurement method. In particular, light filaments sometimes do not reach the desired (intended) force, and a series of at least three applications ensures that one of the three is the desired force. Thus, to improve the reliability of the tests, the monofilament was used to stimulate the participant three times in one trial [27]. On the other hand, many similar threshold measurement tasks utilize 3AFC (Three Alternatives Force Choice) for this procedure, and the use of 3AFC to measure tactile sensation with greater

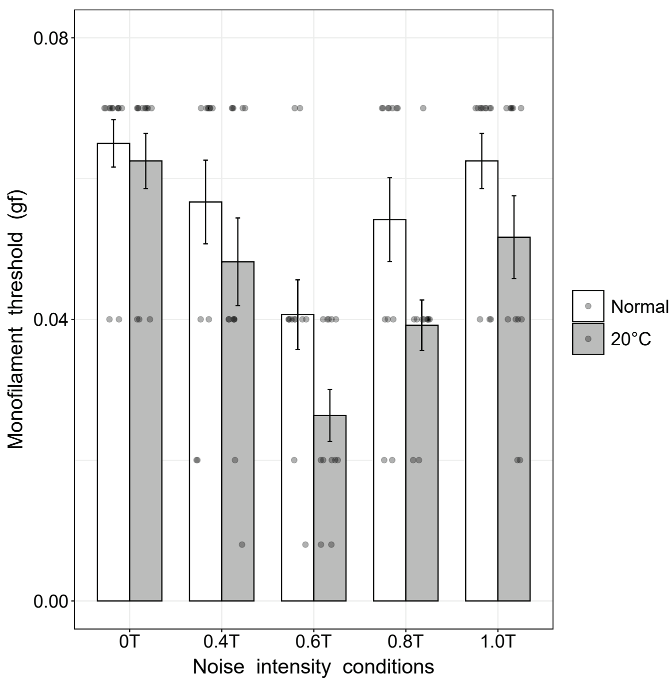

Fig. 10. Monofilament thresholds.

accuracy will be a subject of future work.

B. Experimental results

Figure 10 shows the experimental results of the monofilament touch task. The horizontal axis indicates the noise-intensity condition and the vertical axis the monofilament threshold. The thresholds in the figure are the averages of all participants' threshold values, and the error bars represent the SE. The white bars show the threshold for the normal condition, and the gray bars show it when the skin temperature was 20°C. In particular, the jitter data points are overlaid on the bar. A low threshold indicates the high tactile sensitivity of the index finger.

All data were not normally distributed, and thus we conducted a two-way repeated measures ANOVA after applying Aligned Rank Transfer [29], and found a significant difference for the temperature condition ($F(1,110) = 13.04$, $\eta^2 = 0.07$, $p = 0.46 \times 10^{-3} < 0.05$) and for the noise-intensity condition ($F(4,110) = 12.39$, $\eta^2 = 0.26$, $p = 0.24 \times 10^{-7} < 0.05$). We found no significant differences for the interaction effects ($F(4,110) = 1.30$, $\eta^2 = 0.01$, $p = 0.28 > 0.05$).

Further, we carried out a Steel-Dwass test. For the threshold at 20°C, we found statistically significant differences ($p < 0.05$) existed for the pairs $0.6T_{20^\circ\mathrm{C}}$ and $1.0T_{20^\circ\mathrm{C}}$ ($p = 0.04$), $0.6T_{20^\circ\mathrm{C}}$ and $0T_{20^\circ\mathrm{C}}$ ($p = 0.08 \times 10^{-2}$), and $0.8T_{20^\circ\mathrm{C}}$ and $0T_{20^\circ\mathrm{C}}$ ($p = 0.09 \times 10^{-1}$). We found no significant differences for the other combinations. On the other hand, for the threshold at normal temperature, we found statistically significant differences ($p < 0.05$) for the pair $0.6T_{\mathrm{normal}}$ and $1.0T_{\mathrm{normal}}$ ($p = 0.03$) and for the pair $0.6T_{\mathrm{normal}}$ and $0T_{\mathrm{normal}}$ ($p = 0.01$), and no significant differences for the other pairs. From the Steel-Dwass test, it was difficult for us to describe a clear conclusion, probably due to the small number of data. However, similar to the sandpaper identification results, there was a statistically significant difference between the temperature conditions, and the thresholds were low when the wrist temperature was 20°C. Thus, we can judge that application of a higher-amplitude yet still imperceptible noise along with a temperature decrease is effective for improving monofilament touch sensitivity.

In addition, Fig. 10 shows that the threshold for both wrist temperatures was lowest when a noise of $0.6T$ was applied. A Wilcoxon signed rank test was carried out for the thresholds when noise with an intensity of $0.6T_{\mathrm{normal}}$ was applied to the wrist and for the thresholds when noise with an intensity of $0.6T_{20^\circ\mathrm{C}}$ was applied. The test showed a significant difference between them ($p = 0.08 \times 10^{-1} < 0.05$). Thus, our proposed method can boost the remote SR effects in comparison with the normal SR method. Thus, through the monofilament touch task, we verified the effectiveness of the proposed method for tactile sensitivity in passive touch.

Finally, Sections IV and V showed that our method could enhance fingertip tactile sensitivity in active and passive touches compared to the normal remote SR. Here, our finding that the fingertip sensitivity peaks at a noise intensity of $0.6T$ in our method is similar to that found in earlier normal remote SR [8], [9], [11], [15]. While we do not know why sensitivity peaks at this sub-threshold ratio, we consider one possible reason is a matter of human attention, as described in Section I. That is, human attention is directed more to the wrist than to the fingertip when the noise intensity applied to the wrist exceeds $0.6T$, and the tactile sensitivity of the fingertip is reduced. A clear reason for this point has not been obtained, and elucidation is considered a future task.

VI. Conclusion

This paper proposed a method to improve the tactile sensitivity of the human fingertip by applying a vibrotactile noise to a wrist whose skin had been cooled. In particular, we confirmed that cooling the wrist skin reduced the wrist's vibrotactile sensitivity. Using this temperature dependence effect, we could apply a large but imperceptible noise to the wrist. This allowed us to propagate a large noise to the fingertip, leading to the improvement of the tactile sensation of the fingertip via the SR phenomenon. We also carried out a texture discrimination task and a monofilament touch task. The results showed the effectiveness of the proposed method; that is, our method enhances fingertip tactile sensitivity in both active and passive touches compared to the normal remote SR.

In future work, we plan to investigate the effectiveness of the proposed method in other experimental tasks. A limitation of the present paper is that the sample demographics (young males and females) were limited. Therefore, it will be interesting to extend the use of the proposed method to other groups, such as the elderly, in the future. In addition, we believe that the proposed method should be utilizable for the following wide range of applications that the normal remote SR could not approach: Acquisition of perceptual ability equivalent to skilled workers at manufacturing sites and traditional handicrafts, and restoration of tactile sensation that has deteriorated due to aging.

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