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Effect of Temperature on the Absolute and Discrimination Thresholds of Voltage on Electrovibration Tactile Display

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Abstract—Multi-dimensions tactile displays, such as thermal and texture display, are desirable for enhancing perception while users experience virtual shopping such as touching a garment in virtual reality. Understanding the effect of one dimension on the other is fundamental for the design of multi-dimensions tactile display. In this paper, we report the effect of temperature on thresholds of voltage applied on an electrovibration tactile display. Three temperatures of the electrovibration tactile display at 18 °C (cold), 30 °C (neutral) and 38 °C (warm) were considered in two experiments. In Experiment I, we measured the absolute thresholds of square wave voltage with 25 Hz, 140 Hz and 485 Hz. In Experiment II, we measured the amplitude discrimination thresholds of same voltage signals as in Experiment I. The results show that the absolute thresholds differed significantly between 18 °C and 38 °C for all the three frequencies. No significant difference in the absolute threshold was found between 18 ° C and 30° C, except for the 485 Hz voltage. The amplitude discrimination thresholds were essentially constant except for that of the 485 Hz voltage at 18 °C, which were 17.11 Vpp and 16.86 Vpp larger than those at 30 °C and 38 °C respectively.

Index Terms—electrovibration display, temperature, absolute thresholds, discrimination thresholds

1 Introduction

MODULATING friction between fingertips and the tactile interface shows promise of generating surface tactile sensation [1-3]. One of the major approaches is based on electrovibration effect, which changes the friction by generating electrostatic force between the user fingertip and the interface surface.

The surface tactile texture of a real object could be simulated by the changeable tangential force[4]. The electrovibration displays seem to be particularly well suited for generating this tactile sensation [5-7]. While exploring on the surface of real objects, the tactile texture and temperature are always perceived synchronously. This fact suggests that adding temperature feedback to the electrovibration display may enhance the fidelity of simulated texture sensations [8].

To develop the two dimensions tactile display that could simultaneously simulate thermal and electrovibration stimuli, it is fundamental to understand perceptual coupling between the two dimensions. Although facilitation and inhibition of the finger's temperature or the touching object's temperature on the tactile perception was investigated [9-14], little is known whether the temperature affects the perception of the stimuli rendered on the electrovibration display.

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The goal of this research, therefore, is to investigate how the temperature affects the perception of stimulus on the electrovibration tactile display. Specifically, what is the absolute threshold of the applied voltage of electrovibration display at cold, neutral and warm temperature? Also, what is the amplitude discrimination threshold of the applied voltage at cold, neutral and warm temperature?

In order to address these questions, we developed a thermal-electrovibration apparatus that can generate reliable electrovibration stimuli and control the temperature of the apparatus, and performed two psychophysical experiments. The apparatus can generate the electrovibration stimuli in a 4.5 cm × 13 cm touching area by controlling four waveforms voltage (sinusoidal, square, triangular and saw-tooth) with amplitudes ranging from 0 to 350 Vpp. (±2 Vpp.) and frequencies ranging from 11 to 6 kHz (±1 Hz), and can maintain the touch surface at any temperature with a thermal sensitivity of ±0.1 °C in a temperature range of 18 °C to 38 °C. In the two psychophysical experiments, three temperatures of the electrovibration tactile display at 18 °C (cold), 30 °C (neutral) and 38 °C (warm) were considered. In experiment I, we measured absolute thresholds of the square voltage of 25 Hz, 140 Hz and 485 Hz at the cold, neutral and warm temperatures. In experiment II, we measured the amplitude discrimination thresholds of the applied voltage at the same conditions.

The remainder of this paper is organized as follows: in Section 2, we introduce the related work. In Section 3, we describe the design of the thermal-electrovibration apparatus. The psychophysical experiments for the absolute and discrimination thresholds are described in Section 4, and experiment II in Section 5 respectively. In Section 6, we discuss the results. Finally, the conclusion of our work

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is given in Section 7.

2 RELATED WORK

2.1 Electrovibration Perception

The applied voltage plays an important role in the perception of electrovibration stimulus. Bau et al. [1] measured the absolute and discrimination thresholds (JNDs) of the applied voltage. They found that the absolute thresholds for sinusoidal waveform depend on the frequency of the applied voltage and form a U-shaped curve with a minimum value of 12 dB re 1 V peak around 180 Hz. The amplitude JNDs at five frequencies were about 1.16 dB. The similar result was observed on a flexible electrovibration display[15]. Wijekoon et al. [16] studied intensity of the electrovibration in terms of the applied voltage. Their experimental results showed that there are significant correlations between intensity perception and voltage amplitude.

In addition to the thresholds and intensity for the electrovibration, the parameters affecting the tactile perception for the electrovibration also has received attention from haptics researchers. Strong and Troxel [17] showed that the intensity of the electrovibration sensation is more dependent on the peak voltage than current density. Kaczmarek et al. [18] investigated the sensitivity of electrovibration perception to the applied voltage polarity. They found that the electrovibration perception is more sensitive for negative or biphasic pulses than for positive pulses. Electrovibration tactile display usually consists of three layers: substrate layer, conductive layer and insulator layer. Vardar et al. [19, 20] studied the effect of voltage waveform on electrovibration perception. They measured absolute thresholds using square voltage and sinusoidal voltage at 15, 30, 60, 120, 240, 480 and 1920 Hz frequencies on 3M touch screens. Their results showed that the participants are more sensitive to sensation generated by square wave voltage than sinusoidal one for frequencies lower than 60 Hz. Harald et al. [21] investigated the influence of the applied normal force on absolute threshold of the voltage amplitude. Their results showed that the applied normal force has an effect on the absolute threshold of voltage amplitude at 240, 360 and 540 Hz. Our previous study also demonstrated the intensity of electrovibration perception is affected by the applied normal force [22].

Apart from the above efforts for understanding of electrovibration perception, little work has been done in studying the effect of the temperature on voltage thresholds for electrovibration perception.

2.2 Effect of Temperature on Haptic Perception

A number of studies reported the effect of temperature on force and vibrotactile stimulation. It is firstly reported in the 1800s that a cool object feels heavier than an identically weighted counterpart at skin temperature. The similar result was observed in [23, 24]. For vibrotactile stimulation, cooling skins of fingertip or thenar eminence could increase absolute thresholds at high frequencies and has little effect on the threshold of lower frequencies vibration[14, 25-27], suggesting that cooling may affect vibrotactile thresholds by decreasing the sensitivity of Pacinian corpuscles [14]. However, Bolanowski and Verrillo found the cooling skins of thenar eminence could increase the absolute thresholds for both high and low frequencies vibrotactile stimuli [28], which also demonstrated in [13] subsequently. Additionally， Bolanowski and Verrillo showed that warming could improve the absolute thresholds for the high frequency vibrotactile stimuli on the thenar eminence and has little effect on the threshold of lower frequencies vibrotactile stimuli [14, 28, 29]. However, observation in [12, 30] showed the absolute thresholds for the low frequency (below 100Hz) vibrotactile stimuli decreased as warming the hand. Additionally, Gescheider et al. found that when the high frequency (250 Hz) vibrotactile stimulus acted on the thenar eminence, the absolute threshold at 40 °C is slightly higher than those at 30 °C [26]. Zhang et al. [12] showed the discrimination thresholds for 25 Hz vibrotactile stimuli does not change with heating the skin. Verrillo and Bolanowski [31] demonstrated the temperature of the skin had an effect upon judgments of the perceived magnitude of vibration at 250 Hz and 400 Hz, but not at 15 Hz. Yang et. al showed a similar result that temperature only affects the perceived magnitude of the high-frequency (over 150 Hz) vibrotactile stimuli [32]. More recently, in context of multisensory cutaneous displays, Jones and Singhal [9] examined effect of temperature on vibrotactile pattern identification. Their results showed that temperature of the skin influenced the ability to identify vibrotactile patterns and warming the skin appeared to impede identification of patterns whose pulse duration varied.

Object's temperature also has an influence on the tactile ability to resolve spatial details presented on skin. It was shown that tactile spatial acuity such as two-point and two-edge thresholds on forearm, forehead and palm depended on the temperature of touching objects [33, 34]. Moreover, effect of skin's temperature on object's roughness was examined [35]. Subjects estimated the roughness of aluminum alloy plates with parallel grooves at different finger skin's temperature. Their results suggested that the perception of the roughness declined as skin temperature falls below normal (32 °C) and enhanced as skin temperature rises above normal (32 °C), although the effect of warming is smaller and less predictable than the effect of cooling.

Above findings clearly indicate that the temperature of skin and objects affects haptic perceptions, such as force perception, vibrotactile stimulation and tactile spatial acuity. However, it is unclear how the perception of the stimuli rendered on the electrovibration display is affected by the surface temperature. In this paper, we address this issue by observing the absolute and discrimination amplitude thresholds of the voltage applied on the electrovibration display at cold, neutral and warm temperature. The present study was motivated by the need for developing the tactile texture display that could simultaneously simulate thermal and friction sensations. Since the absolute and discrimination thresholds determine the baseline of users' sensitivity while interacting with the

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tactile device, it is crucial for the designer to understand the effect of surface temperature on the absolute and discrimination thresholds for the electrovibration stimuli. Therefore, we measured absolute thresholds at three surface temperatures in Experiment I and the amplitude discrimination thresholds at the same temperatures in Experiment II.

3 General Materials and Methods

This section presents the methods that are common to the two experiments in our study. Methods that are specific to each experiment are presented later in the respective sections.

3.1 Participants

Nine right-handed participants (aged between 18 and 31, mean 23) took part in the experiments. They were all graduate students at Beihang University. All of them were interviewed to ensure normal tactile abilities before the experiments. Four participants had previous experience with the electrovibration devices, and none had previous experience with the thermal display described latter. They did not report any history of neurological illness or physical injury that might have affected their hand function. All participants gave written consent to participate in the study, and the experiments were performed in consistent with the human participant testing regulations of the authors' institution.

3.2 Apparatus

A multi-dimensions tactile display was built to provide electrovibration and thermal stimuli to the fingertip. The schematic illustration of the display was shown in Fig. 1. A 6.5 inches capacitive touch screen panel (SCT3250, 3M Inc.) was used as the electrovibration tactile display as its availability and being used in many tactile displays [1, 20-22, 36-45]. To reduce heat transfer between air and 3M touch screen, we glued some thermal insulation sponge (poly ethylene-vinyl acetate, thermal conductivity < 0.0325 W/m·℃) on the screen to cover the area unused in the experiments (Fig. 1, left). The thermal insulation sponge has an open area (4.5 cm × 13 cm, shown in Figure 1) at the center, where participants touched the 3M touch screen during the experiment. A web camera with a resolution of 1280×720 was mounted over the electrovibration tactile display for finger position tracking.

When exciting the 3M touch screen with a periodic voltage, an electrostatic force exerts on the fingertip. By controlling the voltage parameter (i.e., waveform, amplitude, and frequency), different electrovibration feelings can be perceived while fingertip sliding on the touching surface [46-48]. The voltage generator consists of a microcomputer (C8051F320, Silicon Laboratories, United States) and a custom designed amplification circuit used in our previous studies [15, 22]. The voltage generator can generate four waveforms (sinusoidal, square, triangular and sawtooth) with amplitudes ranging from 0 to 350 Vpp (± 2 Vpp) and frequencies ranging from 11 to 6 kHz (±1 Hz). The frequency error of the voltage is no more than ±0.2% and the amplitude error of the voltage is no more than ±4%. The participants' finger is grounded via a copper foil band. The thermal module in the apparatus consists of three Peltier elements (TEC-12706) of 40 x 40 mm and 3.4 mm thick. A water-cooling heat sink provided forced convection cooling for the Peltier elements. The Peltier elements were attached to the water-cooled heat sink by a piece of thermally conductive silicone, and the water-cooling heat sink was mounted in the fixture. The 3M touch screen was glued on the Peltier elements by high thermal grease (HY410, Halnziye Electronics Co., Ltd., China). Two thermistors (NTC 10K, Dongtai UPS Technology Co., Ltd., China) were attached on the 3M touch screen for feedback control of the surface temperature. To provide good thermal conductivity, the high thermal grease was used to fix the thermistors on the 3M touch screen.

To decrease possible effect of skin moisture on electrovibration, participants were asked to clean their index finger and use talcum powder to dry their fingertip at the beginning of each session. The 3M touch screen was cleaned with isopropyl alcohol before each session. Indoor temperature was kept at around 23 °C.

To evaluate transient time of temperature of the experimental apparatus, we conducted an experiment to record the temperature while applying step signals of temperature. The temperature was measured by the thermal sensors of the apparatus and the step signals of temperature cover all conditions of temperature change in the Experiment I and II. To avoid the influence of temperature error on the experimental results, we began each session when the temperature response was in steady state during which the temperature error was no more than 0.05 °C. The measured transitory response was shown in Fig. 2. The transient time was shown in Table 1 and the maximum value was 4.16 min, occurring when the temperature changes from 38 °C to 18 °C.

4 Experiment I: Effect of Temperature on Absolute thresholds

The aim of Experiment I was to investigate the effect of temperature on the absolute thresholds for the electrovibration stimuli. We measured the magnitudes of applied voltage that participants could barely detect at three surface temperature.

4.1 Stimuli

Vardar et al. showed the participants were more sensitive to stimuli induced by square wave voltage than sinusoidal one [19, 20]. Thus, no bias square wave voltage was used in this study. As knowledge that the effect of temperature on the vibrotactile stimuli depended on the frequency [14, 25-27], in our experiments, we choose three frequencies: 25, 140, 485 Hz. The 140 Hz lies in the range of the most sensitive frequency [1, 15, 19, 20], the other two are outside the range.

The surface of 3M touch screen was set to one of three temperatures: 38 °C (warm), 30 °C (neutral) and 18 °C

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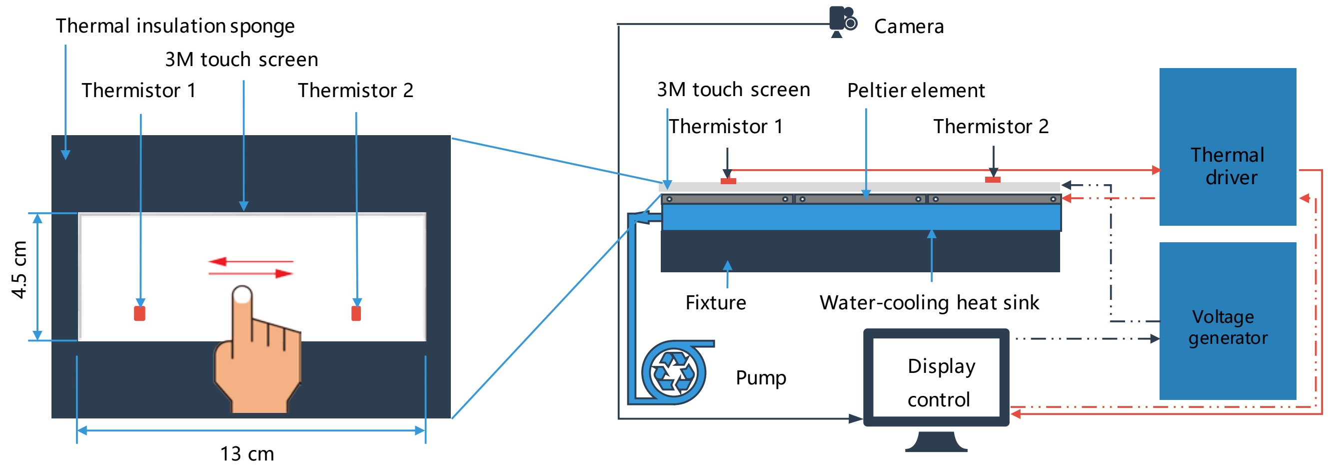

Fig. 1 Schematic illustration of the multi-dimensions tactile display

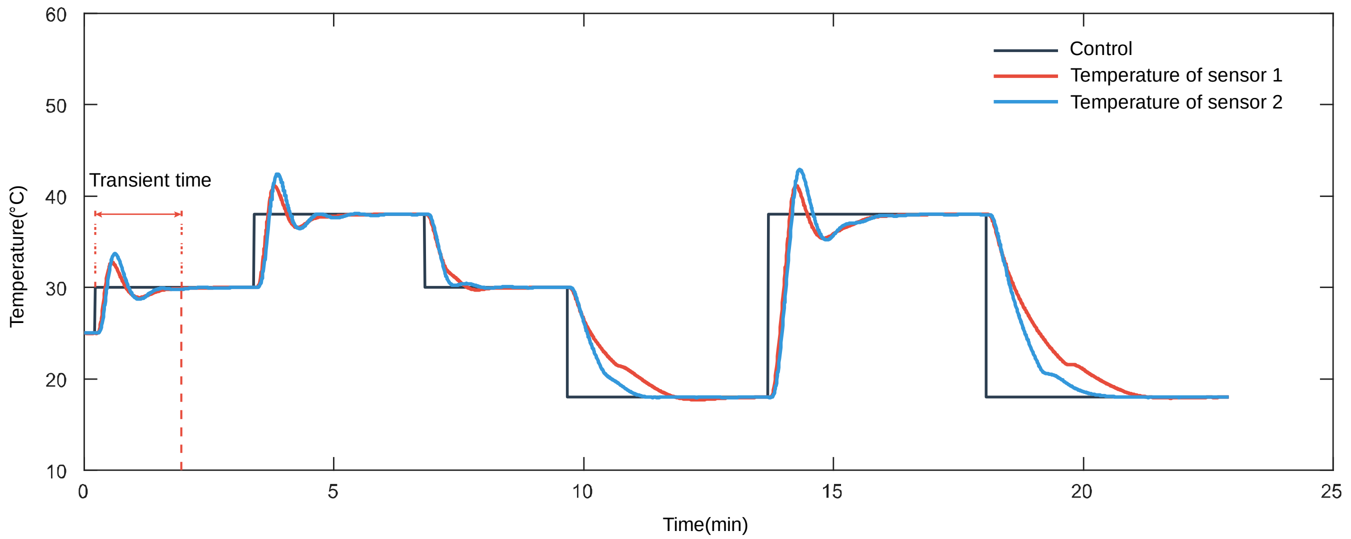

Fig. 2 Temperature response of the experimental apparatus for step signals. The black line denotes the control signal. The red line and blue line denote the data recorded by temperature sensor 1 and 2 respectively

Table 1 Transient time

Step signal	Transient time (min)	
	Sensor 1	Sensor 2
25→30℃	1.96	1.94
30→38℃	2.11	2.55
38→30℃	1.37	1.76
30→18℃	3.37	1.54
18→38℃	2.78	2.86
38→18℃	4.16	2.55

Table 2 Experimental stimuli

Experimental condition	Temperature	Voltage Frequency
1	18 ℃	25 Hz
2	18 ℃	140Hz
3	18 ℃	485Hz
4	30 ℃	25Hz
5	30 ℃	140Hz
6	30 ℃	485Hz
7	38 ℃	25Hz
8	38 ℃	140Hz
9	38 ℃	485Hz

(cold). The three temperatures we selected include the working temperature of the display which is assumed as room temperature (about 25 °C). The lower and upper limits were chosen on the basis of pilot studies, in which participants feel cold at 18 °C and warm at 38 °C while sliding on the 3M touch screen, but did not report any discomfort. As the resting temperature of the hand skin is typically between 28 and 36 °C [49], we set the neutral temperature as 30 °C. All experimental stimuli are tabulated in Table 2.

4.2 Experimental Procedure

Two-alternative forced-choice paradigm [50] was used to estimate the absolute thresholds of the amplitudes of applied voltage. The touching area of the apparatus was divided into two regions marked as right and left by a narrow white paper tape, shown in Fig. 4. One of the two regions was excited by an applied voltage, while the other was not. In each trial, the applied voltage was randomly assigned to one of the two regions. For example, when the applied voltage was assigned to the right region in a trial, the target voltage would be applied if the camera detect-

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ed that the index finger was in the right region, whereas a zero voltage would be applied if the index finger was detected in the other region. To detect the index finger easily, we glued a black marker on the index fingernail.

We adopted the one-up/three-down adaptive staircase algorithm [50, 51] that is widely used in psychophysics to estimate the absolute threshold, as shown in Fig. 3. At the beginning of each session, the applied voltage amplitude was set much higher than the anticipated absolute threshold. The amplitude was then reduced by 10 Vpp if the participant had made three consecutively correct answers. If the participants made an incorrect response, the voltage amplitude was increased by 10 Vpp. A reversal is defined as the stimulus amplitude varied from increasing to decreasing, or vice versa. After the first three reversals, the step size of the applied voltage amplitude was set to 2 Vpp. The larger step size (10 Vpp) ensured faster convergence of amplitude towards the threshold level and the smaller 2 Vpp step size aim to acquire fine resolution of the threshold. Each session was ended after 8 reversals at the 2 Vpp step size and the average of the last 8 reversals was considered as the voltage amplitude threshold level.
The absolute thresholds of the voltage were estimated at three frequencies and three temperatures. Thus, there are nine experimental conditions as shown in Table 2. We randomly arranged the order of those experimental conditions to avoid the effects of the temperature's order. To avoid the influence of outdoor temperature, the participants were asked to rest in the room for 20 minutes before the start of the absolute thresholds experiment. To percept the electrovibration stimuli naturally, participants sat comfortably in front of the apparatus. They wore a grounded band on right wrist as shown in Fig. 4 and a head-mounted earmuffs (PELTOR H10A, 3M Inc.) to block auditory cues from the apparatus and ambient noise. The participant's task was to identify which region provided an electrovibration sensation by pressing the "right" or "left" key on the keyboard within 5 seconds. To avoid temperature adaption, participants were asked to take a 5 seconds break between two trials and a 5 minutes break between two sessions. The duration of each session was about 10 minutes and the entire experiment took about 120 minutes. No correct-answer feedback was provided during the experiment.

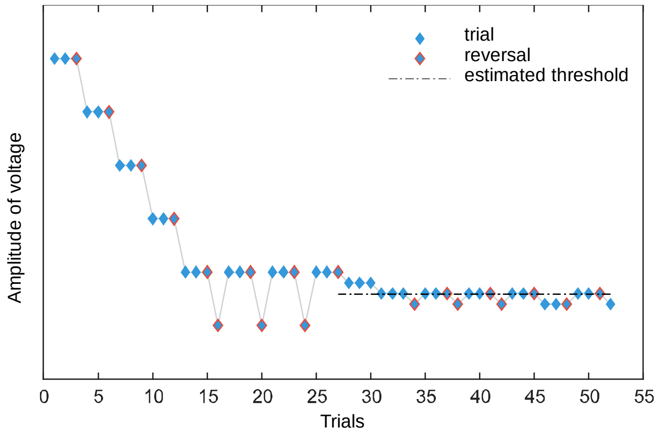

Fig. 3 A sample data of one-up/three-down adaptive staircase algorithm.

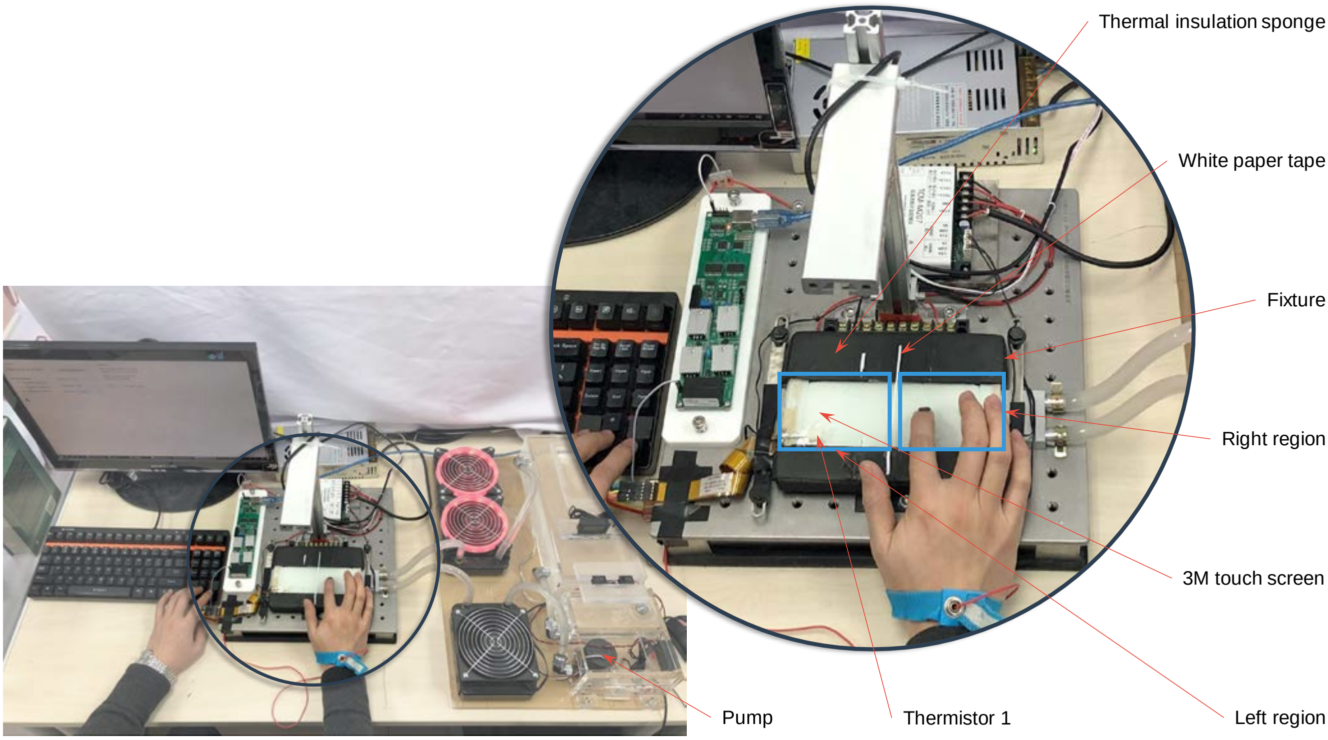

Fig. 4 Illustration of the experiment of absolute threshold measurement

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4.3 Results

Fig. 5 illustrates the mean and standard deviation of the absolute thresholds of the applied voltage at 18 °C, 30 °C and 38 °C. The absolute thresholds at 25 Hz and 140 Hz varied little among three temperatures, and the absolute thresholds at 485 Hz dropped with increasing temperature. Additionally, a visual inspection of the measured data suggested that the mean absolute thresholds at 140 Hz is lower than those at 25 Hz and 485 Hz.

We analyzed the results by two-way RM-ANOVA. Both main effects (frequency and temperature) and an interactive effect of frequency × temperature were statistically significant on the absolute threshold ($F(2,14)=32.65$, $p < 0.05$, $F(2,14)=17.76$, $p < 0.05$, $F(4,28)=10.68$, $p < 0.05$). In addition, simple effect analysis of temperature showed that the absolute thresholds at each frequency differed significantly among the three temperature (25 Hz ($F(2,14) = 6.88$, $p < 0.05$), 140 Hz ($F(2,14) = 5.33$, $p < 0.05$) and 485 Hz ($F(2,14) = 15.58$, $p < 0.05$)). Post hoc tests using the Bonferroni method showed a significant difference between 18 °C and 38 °C for all three frequencies ($p <0.01$). The threshold at 18 °C is 5.87 Vpp, 6.80 Vpp and 31.22 Vpp higher than those at 38 °C for 25, 140 and 485 Hz voltages respectively. Moreover, for the 485 Hz voltage, the threshold at 18 °C is 23.02 Vpp higher than that at 30 °C. And the difference is significant ($p<0.01$).

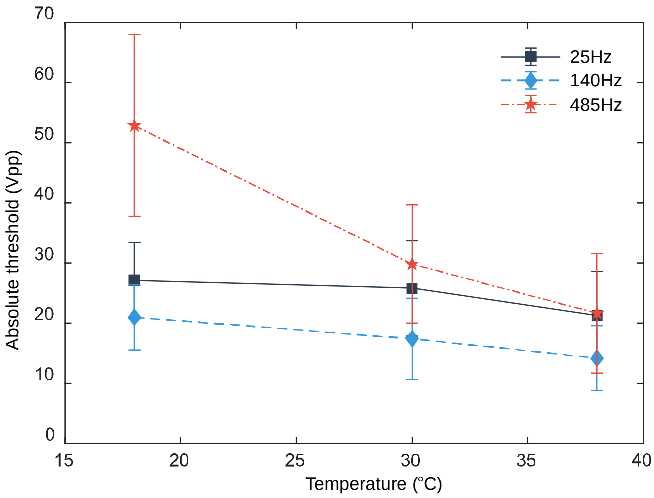

Fig. 5 Mean values and standard deviations of absolute threshold of applied voltage amplitude at three temperature.

5 Experiment II: Effect of Temperature on Amplitude Discrimination Thresholds

Experiment II investigated amplitude discrimination thresholds for applied voltage at the three surface temperatures.

5.1 Stimuli

We measured the amplitude discrimination thresholds at three surface temperature: 18, 30, 38 °C. The reference frequencies of the applied voltage were 25, 140, 485 Hz. The voltage amplitude was fixed to 90 Vpp, which is sufficiently higher than the absolute thresholds shown in Fig. 5

5.2 Experimental Procedure

A three-alternative forced-choice paradigm [50] was adopted to estimate the amplitude discrimination thresholds. The touching area of the apparatus was divided into three regions marked as right, middle and left by the white paper tape. The participant was presented randomly with three stimulus signals in each trial. One was the test signal S_t and others were the reference signals S_{ref}. The correlation between the test signal and the reference signal is defined as

$$S_t = S_{ref} + \Delta S \quad (1)$$

where ΔS is the signal increment. For example, when the test voltage was assigned to the right region in a trial, it would be applied if the index finger was detected in the right region, whereas the reference voltage would be applied if camera detected the index finger in the other region.

The one-up/three-down adaptive staircase was used to estimate the discrimination thresholds. At the start of the experimental session, the signal increment ΔS was well above the anticipated discrimination threshold. Three consecutively correct responses decreased and one incorrect response increased ΔS by 10 Vpp for the first three reversals and by 2 Vpp for the rest of the session. The session was terminated after 8 reversals at the smaller step size. The average of ΔS from the last 8 reversals was then taken as the discrimination threshold.

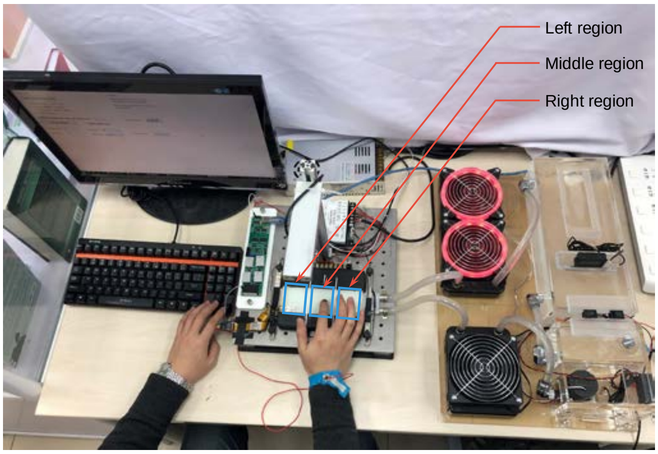

Fig. 6 Illustration of the experiment of discrimination threshold estimation

The experimental configuration is shown in Fig. 6. The participants were asked to rest in the room for 20 minutes before the start of the discrimination threshold experiment. At the beginning of each session, the apparatus maintained at the target temperature about 1 minutes. Participants sat comfortably in front of the apparatus and wore a grounded band on right wrist and head-mounted earmuffs (PELTOR H10A, 3M Inc.). Participants' task was to indicate which one of the three regions contained the electrovibration stimulus that was different from the other two by pressing a corresponding key ("Right", "Down" or "Left") on the keyboard within 6 seconds. To avoid temperature adaption, participants took a 5 seconds break between two trials and a 5 minutes break between two sessions. The duration of each session was about 10

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minutes and the entire experiment took about 120 minutes. No correct-answer feedback was provided during the experiment.

5.3 Results

Fig. 7 showed the means and standard deviations of the amplitude discrimination thresholds of three frequencies for the stimulus at three temperatures. The amplitude discrimination thresholds at 25 Hz and 140 Hz are essentially constant among three temperatures. While the amplitude discrimination thresholds at 485 Hz dropped from 18 °C to 38 °C.

We analyzed the results by two-way RM-ANOVA. The result showed Both main effects (frequency and temperature) and an interactive effect of frequency × temperature were statistically significant on the absolute threshold ($F(2,14)=6.54$, $p < 0.05$, $F(2,14)=4.52$, $p < 0.05$, $F(4,28)=10.48$, $p < 0.05$). In addition, simple effect analysis of temperature showed that there was statistically significant effect of the temperature on the discrimination thresholds at 485 Hz ($F(2,14) = 12.20$, $p < 0.05$), but there was no statistically significant effect of the temperature on the discrimination thresholds at 25 Hz ($F(2,14) = 2.89$, $p > 0.05$) and 140 Hz ($F(2,14) = 0.25$, $p > 0.05$). Post hoc tests using Bonferroni method showed that there were significant differences in the amplitude discrimination thresholds of 485 Hz between 18 °C and 30 °C, 38 °C. The amplitude discrimination threshold is 17.11 and 16.86 Vpp higher at 18 °C than at 30 °C and 38 °C ($p<0.01$) respectively.

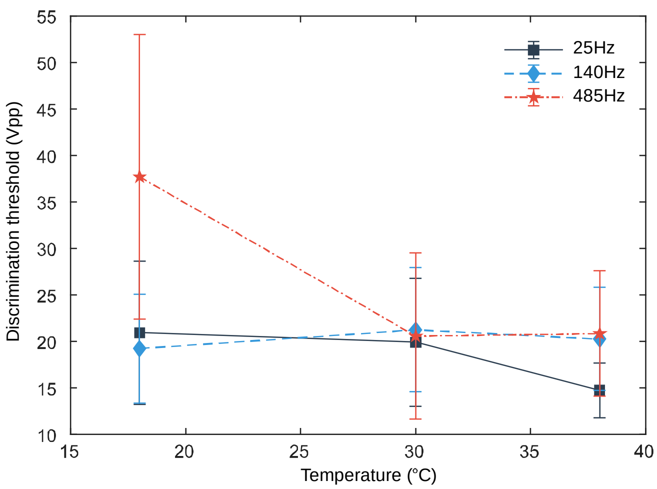

Fig. 7 Mean and standard deviation of discrimination thresholds at three temperature.

6 Discussion

The results of Experiment I showed, for the 485Hz voltage, the absolute threshold at 18 °C (cold) is significantly higher than those at 30 °C (neutral) and 38 °C (warm), and the increases are 23.02Vpp and 31.22Vpp respectively. This result indicated that the cold temperature increases the absolute thresholds at high frequency voltage, which is similar with the prior observation [13]. In [13], the absolute thresholds on the thenar eminence for the vibrotactile stimuli ranging from 0.4-500Hz were measured at skin temperature of 15 °C, 30 °C and 40 °C. The low temperature could induce the high absolute thresholds at high frequency. Additionally, our result is consistent with those studies [14, 25, 27, 32], which indicated the low temperature of the skin degraded the sensitivity for high frequency vibrating stimulus. The reason could be that the high frequency electrovibration stimuli excite Pacinian corpuscles [52] and the low temperature can decrease the sensitivity of Pacinian corpuscles [14].

In our experiment, no significant difference in absolute thresholds between 30 °C and 38 °C was found, while the absolute threshold of 25 Hz and 140 Hz showed a significant decrease when the temperature increased from 18 °C to 38 °C. This result seem to be consistent with the result in [12]. In [12], the absolute thresholds about the vibrotactile stimuli of 25 Hz were measured at 25 °C, 40.5 °C, and 43 °C. Their result showed the average of the absolute thresholds decreased with the increasing temperature from 25 ℃ to 43 °C. Statistical analysis showed that the absolute threshold difference between 25 ° C and 40.5 ° C was not statistically significant ($p = 0.18$). However, the absolute threshold at 43 °C is significantly lower than the absolute threshold at 25 °C ($p = 0.047$). We speculate that the small increase in temperature is not enough to induce the change in the threshold of low frequency stimuli.

The results of Experiment II shows there is no significant difference in the discrimination thresholds among three frequencies between 30 °C and 38 °C. Similar result was found in [12], which showed the discrimination thresholds for 25 Hz vibrotactile stimuli changed little between 25 °C and 43 ℃. The reason could be that the warming has little effect on the tactile receptor.

The results of Experiment II also show that, for high frequency (485 Hz) voltage, the discrimination thresholds for 90Vpp reference voltage amplitude at the low temperature (18 °C) is significantly higher than those at neutral (30 °C) and warm (38 °C) temperature, which seem to indicate that the low temperature has an effect on the discrimination threshold for high frequency voltage. This result is similar with the prior observation in [26]. In [26] the discrimination thresholds of the 250 Hz vibrotactile stimuli at 10 reference stimulus were measured at 20, 30 and 40 °C. The value of discrimination thresholds is elevated when the skin was cooled.

For the present work, we determined the effect of the touching surface temperature on the perception of stimulus delivered by electrovibration display. However, this study still has some limitations. One limitation was that the friction induced by the normal force actively applied by the participant's finger could be different at cold, neutral and warm temperature, which may influence the perception with respect to the stimuli delivering via the electrovibration display. Eventually it would be desirable to know how the change in the friction might influence perception of the electrovibration stimuli. Additionally, in our experiment, we asked the participants slide their finger on the apparatus surface in their natural and comfortable way, which means that the sliding velocity and applied normal force were not controlled. Previous study has shown that the electrovibration stimuli only occurred during full slip but not before slip [36]. However, how the sliding velocity in the full sliding state affects the perception of electrovibration is an open problem yet. Thus, the effect of velocity on our results need to be explored further. For the applied normal force, our previous study showed that the perception of electrovibration could increase with the increasing applied normal force ranging from 0.5 N to 4.5 N [22, 37]. For the participants with a high applied normal force, the low thresholds could be obtained. Thus, due to the variability of the applied normal force, the standard deviation of the absolute threshold and the discriminant threshold in a natural and comfortable way may be greater than that in the case of a particular normal force. Furthermore, previous studies [19, 45] indicated the influence of skin moisture on the electrovibration stimuli [19, 45]. In our experiment, to decrease possible effect of the moisture on electrovibration, participants were asked to clean their index finger and use talcum powder to dry their fingertip at the beginning of each session. Due to the above treatment, the finger humidity is lower than the normal finger humidity, which may result in easier perception of electrovibration and a lower threshold. The effect of interaction between moisture and temperature on the electrovibration perception need be explored in the future.

7 Conclusions

In this study, we examined whether the surface temperature of electrovibration display affects the perception of the voltage stimuli. Our finding is that the temperature effect depends on the voltage frequency. In high frequency voltage (485 Hz), the absolute threshold at cold temperature (18 °C) is significantly higher than those at neutral (30 °C) and warm (38 °C) temperatures, and the discrimination thresholds for 90 Vpp reference voltage is significantly higher than those at neutral (30 °C) and warm (38 °C) temperatures. In lower frequencies (25 Hz, 140 Hz), the absolute threshold at warm temperature is different from the absolute threshold at cold temperature but is no significant difference compared to the absolute threshold at neutral temperature and the discrimination threshold for 90 Vpp reference voltage changed little among cold, neutral and warm temperature.

These findings suggest that the perception for electrovibration stimulus with the high frequency voltage is more sensitive to the temperature than the perception for electrovibration stimulus with low frequencies. Furthermore, in the low frequency range, a small decrease in temperature such as from warm to neutral has no effect on the thresholds. However, a large decrease in temperature such as from warm to cold may lead to an increase in the thresholds. It is noted that the above results were obtained while cleaning participants' finger and drying their fingertip by the talcum powder.

One implication of our findings is that when rendering electrovibration stimuli with high frequency, temperature effect on voltage thresholds needs to be carefully considered. For example, at low temperatures, the applied voltage needs to be higher than that at normal temperature. Furthermore, in the case that the temperature change is significantly large, the temperature effect on the thresholds cannot not be neglected. However, the temperature issue is less important for an electrovibration device designed for using in a neutral or warm environment.

Acknowledgment

This work is supported by the National Key R&D Program of China (No. 2017YFB1002803), and the National Natural Science Foundation of China under the grant No. 61532003.

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