Thermal sensation presentation to the forehead using electrical stimulation: comparison with other tactile modalities*

Taiga Saito, Jianyao Zhang, Takayuki Kameoka, Hiroyuki Kajimoto

Abstract— **Presentation of warm and cold sensations is effective in improving the immersion of virtual reality contents, and there were several proposals to embed temperature presentation device in head mounted displays (HMD). However, many thermal presentation methods with HMD have issues such as heat accumulation and inability to present quick change of temperature. Here we propose to use electrical stimulation to present the temperature sensation on the forehead. We used an electro-tactile display with 192 electrodes to investigate distribution of cold, warm, pressure, vibration and pain sensations elicited by electrical stimulation. We also compared between anodic and cathodic stimuli. As a result, it was confirmed that cold sensation was easier to present by electrical stimulation than warm sensation, but it was not as robust as pressure and vibration sensations.**

I. Introduction

The spread of low-cost head mounted displays (HMDs) has led to an increase in the number of virtual reality (VR) contents that require the user to wear an HMD, and the growing demand for higher-quality VR experiences. In order to achieve a high level of immersion in the VR space, efforts are being made to present other modalities such as the sense of touch in addition to visual and hearing experiences [1]. In addition, a number of proposals have been made to incorporate a haptic presentation device into the HMD itself in order to present a haptic experience easily when using the HMD [2][3]. In particular, there are a number of researches using various temperature sensation presentations.

As a method to physically present temperature sensation, Peiris et al. [4] incorporated five Peltier elements into the cushion of HMD. They reported that the temperature of the VR environment, such as warmth and coldness, was presented by driving the Peltier elements independently, which enhanced the sense of immersion. Furthermore, a combination of thermal stimulation and low frequency vibration presented wetness sensation[5]. Liao et al. [6] designed a device that simultaneously presented temperature and vibration sensations by controlling the liquid through a water pipe with a valve, which made it possible to present quick temperature change. However, the method of physically presenting temperature using Peltier elements or water flow has issues such as heat accumulation inside the HMD, inability to respond to rapid temperature changes, and large size of the presentation device.

One way to tackle this issue is to avoid using physical temperature. Brooks et al. [7] proposed a low-power method of presenting temperature sensation by stimulating the trigeminal nerve of the nose with chemicals such as capsaicin and eucalyptol by using an olfactory display. These chemical substances are used to stimulate the trigeminal nerve every 6 seconds and every 12 seconds, respectively. This method does not generate heat and the device could be miniaturized in the future, but another issue arises; it takes time for the effect to disappear.

Electrical stimulation activates nerve axons under the skin by applying electric current from electrodes placed on the skin surface to provide tactile sensation[8][9]. The mechanism of action potential generation was shown by McNeal[10] to be caused by depolarization of nerve axons using surface electrodes. In addition, it is known that nerve axons with larger diameters are easier to stimulate in electrical stimulation, and this is even more pronounced for myelinated nerves[11][12]. Kaczmarek et al. [13] discovered that it is possible to present spatial patterns at the fingertips using electrotactile stimulation. And Withana et al.[14] developed Tacttoo, a thin electrotactile device that can keep the sensation of bare skin.

We have proposed the use of electrical stimulation on forehead for the presentation of temperature sensation [14]. Electrical stimulation does not produce heat, small in size, and could be driven quickly. Hayashi et al. [16] have confirmed that cold and warm sensations are generated on the dorsal side of the hand by electrical stimulation. On the other hand, while there have already been studies on the presentation of tactile (pressure and vibration) sensation to the forehead using electrical stimulation [17], to the best of our knowledge, no study has focused on temperature sensation on forehead by electrical stimulation. In this paper, we investigate the distribution and intensity of temperature sensation and other tactile modalities produced by anodic and cathodic electrical stimulation of the forehead, to evaluate the robustness of the temperature-related sensations compared to the other tactile modalities.

II. Equipment

Electrical stimulation was performed with the electrical stimulator shown in Figure 1. The stimulation circuit is mostly the same as that used in the previous electro-tactile presentation to the forehead [17], except for the electrodes. There are 64 electrodes in one electrode module, and three of them are serially connected to make 192 electrodes. Each point can be stimulated individually. When one stimulus point is anode, all other points become cathode (ground), and when one stimulus point is cathode (ground), all other points become anode.

The diameter of each circular electrode was 2 mm, the center distance between electrodes was 3 mm. As there are 8

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by 24 electrodes, the whole electrodes cover about 24 mm by 72 mm area. The pulse width of the electrical stimulation was 0.5 ms, and the cycle period was 11.0 ms (90 pulses per second). 1 mm thick conductive gel (G-grade gel, Sekisui Kasei Co., Ltd.) was placed between the electrodes and skin to stabilize contact and avoid pain. An elastic band was used to softly press the entire electrodes onto the skin (Figure 2). These parameters were determined by the author's preliminary tests. The stimulation point and polarity information were transmitted from the PC to the microcontroller (ESP-WROOM-32) by serial communication, and the current was controlled by the controller for electrical stimulation.

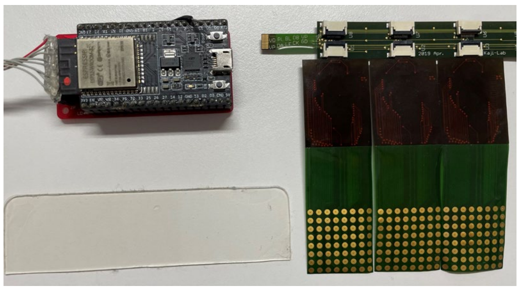


Figure 1 Electrical stimulator (upper left: microcontroller, lower left: 1 mm thick conductive gel , right: switch circuit and stimulating electrodes)

Figure 2 Overview of the electrodes attachment. (left: 1mm thick gel and electrodes, right: elastic band to fix the electrodes)

III. EXPERIMENT

A. Preliminary Experiment

Before starting the main experiment, we measured the current threshold of anodic and cathodic stimulation for each participant to determine the current value used in the main experiment. To ensure that the stimulus was felt at all locations on the forehead, we stimulated seven points at the edge and center of the forehead every second as shown in Figure 3, and measured the minimum current value at which the stimulus was felt. The type of sensation was not limited; it might be vibration, pressure, or temperature sensation. The participants were instructed that no matter the type of the sensation was, the sensation should be elicited every second. We obtained average threshold for each polarity and for each participant.

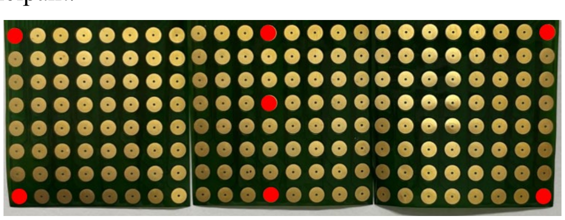


Figure 3 Seven threshold measurement points

B. Main Experiment

In the main experiment, the electrical current 1.5 times of the measured current threshold (for each polarity and each participant) was presented to each stimulus point as a stimulus current for 5 seconds. We chose 1.5 times of the current threshold because our preliminary trials revealed that twice of the current threshold occasionally gave pain and 1.2 times of the current threshold was hard to notice.

The measurements were conducted after the coldness of the gel was no longer felt. Two types of stimuli, anodic and cathodic, were randomly applied to 192 electrodes, giving a total of 384 trials. After each stimulus presentation, the participants were asked to indicate the intensity of cold sensation, warm sensation, pressure sensation, vibration sensation, and pain sensation on a 10-point Likert scale (0 to 9). The cold sensation intensity (0: normal temperature - 9: sensation of contact with ice), the warm sensation intensity (0: normal temperature - sensation of contact with boiling water), the pressure sensation intensity (0: normal pressure - 9: sensation of being strongly pressed by a finger), the vibration sensation intensity (0: none - 9: sensation of vibrating a smartphone), and the pain sensation intensity (0: none - 9: unbearable pain) were evaluated. The temperature sensation for coldness and warmness were evaluated separately, instead of asking physical temperature, because both cold and warm sensations are sometimes generated when a sensation such as “touching a dry ice” occurred. The participants were seven healthy males (22 to 26 years old). The experiment was approved by the Ethics Committee of the University of Electro-Communications (Approved No. 20024).

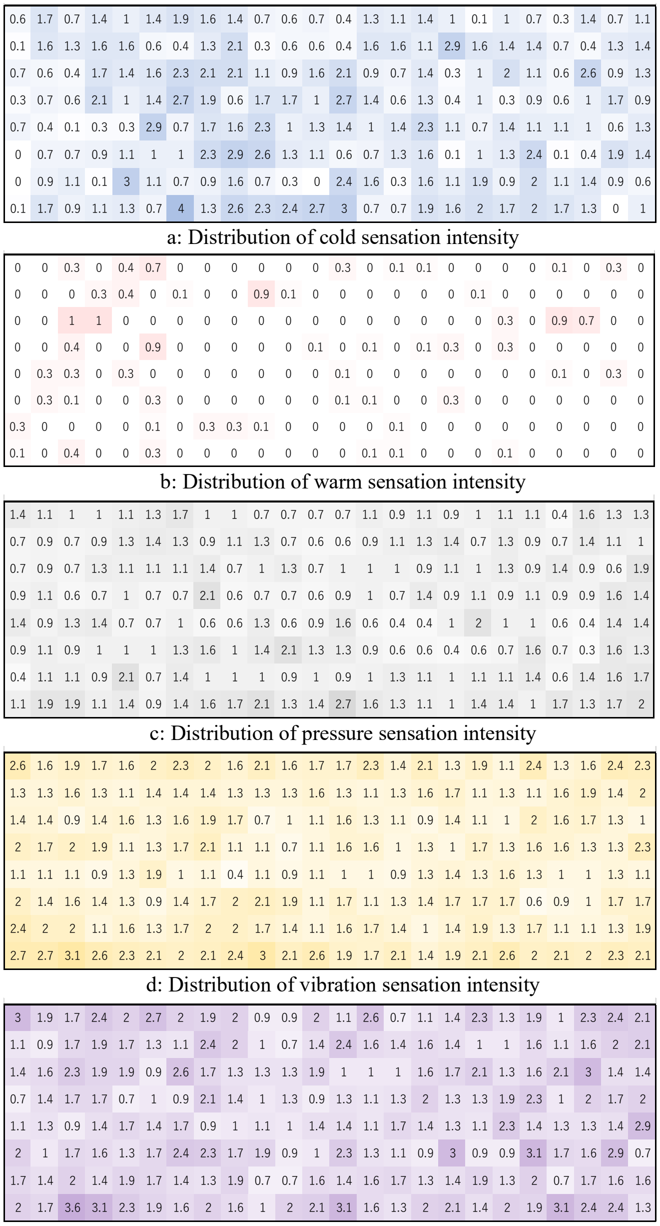
IV. RESULTS

The average current threshold of anodic stimulation for all participants was 1.0 mA, and that of cathodic stimulation was 0.5 mA. The current threshold of cathodic stimulation was lower than that of anodic stimulation in all participants.

The average distributions of cold sensation intensity, warm sensation intensity, pressure sensation intensity, vibration sensation intensity, and pain sensation intensity for all participants are shown in Figure 4 and Figure 5. It was confirmed that temperature sensation was generated without physical temperature presentation by using electrical stimulation. The number of electrodes (hereinafter called the “spots”) that generated cold and warm sensation is shown in Table 1. Table 2 and Table 3 show the mean values of the intensity of each subjective value felt by each participant, for the spots where each sensation was elicited.

We observe from Table 1 that the number of spots that generated cold sensation differed greatly among participants. For example, the maximum number of cold spots generated by anodic stimulation ranged from 20 to 149, and that of warm spots ranged from 0 to 35. On the other hand, there was a clear trend that the cold sensation was more frequently elicited than warm sensation. We checked the normality of the number of cold and warm points of the anode and cathode stimuli. The results showed that there was no normality in the number of warm points.

We also observed from Table 2 and Table 3 that the intensity of cold sensation was stronger than warm sensation. Wilcoxon's signed rank test showed significant difference between the two sensations (p=0.028 for anodic stimulation, p=0.018 for cathodic stimulation). Therefore, it can be safely concluded that cold sensation is easier to be generated by electrical stimulation than warm sensation.



a: Distribution of cold sensation intensity

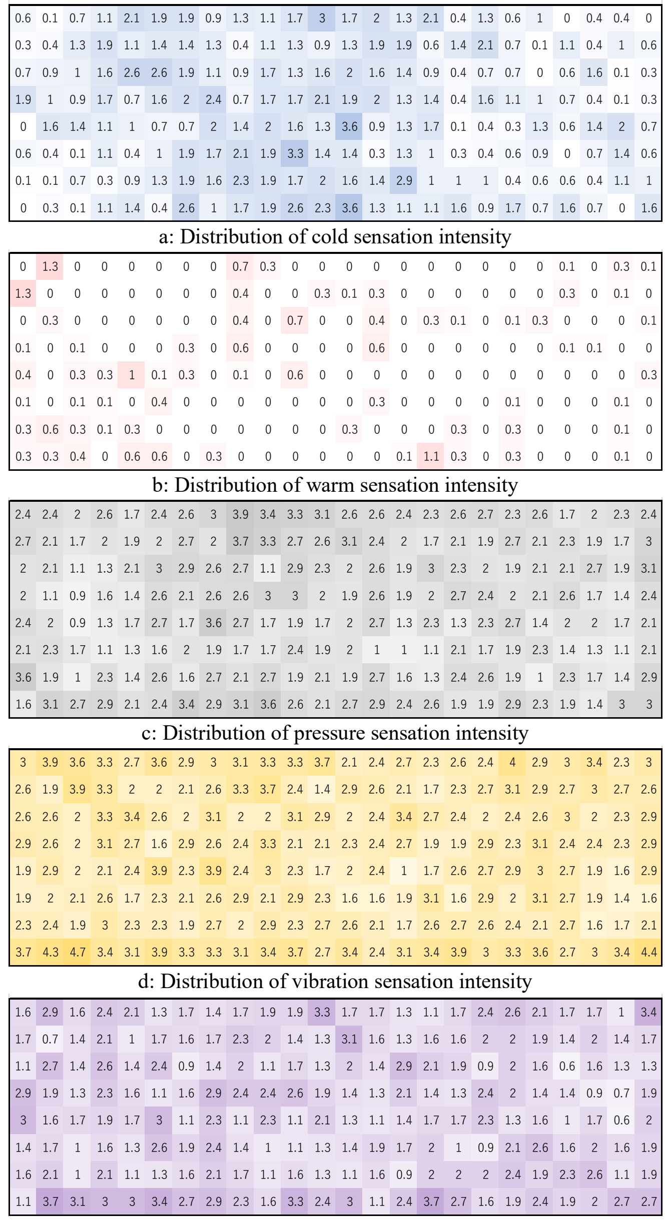
b: Distribution of warm sensation intensity

c: Distribution of pressure sensation intensity

d: Distribution of vibration sensation intensity

e: Distribution of pain sensation intensity

Figure 4 Distribution of the mean of the subjective value intensities of all participants for anodic stimulus



a: Distribution of cold sensation intensity

b: Distribution of warm sensation intensity

c: Distribution of pressure sensation intensity

d: Distribution of vibration sensation intensity

e: Distribution of pain sensation intensity

Figure 5 Distribution of the mean of the subjective value intensities of all participants for cathodic stimulus

TABLE 1 NUMBER OF COLD AND WARM SPOTS GENERATED BY ANODIC AND CATHODIC STIMULATION FOR EACH PARTICIPANT

participants	anodic stimulus		cathodic stimulus	
	cold spots	warm spots	cold spots	warm spots
A	56	2	20	2
B	85	5	116	9
C	20	0	112	0
D	149	35	141	50
E	114	6	94	4
F	98	1	75	5
G	41	4	13	0
mean	80.4	7.6	68.3	10
standard deviation	41.3	11.4	48.1	16.6

TABLE 2 INTENSITY OF EACH SUBJECTIVE VALUE AT ANODIC STIMULUS FOR EACH PARTICIPANT

participants	mean cold sensation intensity	mean warm sensation intensity	mean pressure sensation intensity	mean vibration sensation intensity	mean pain sensation intensity
A	2.8	1.5	2.0	2.2	2.8
B	2.7	1.2	1.4	1.5	2.1
C	3.6	0	2.3	3.5	3.4
D	3.2	2.3	1.5	1.4	1.7
E	2.6	2	1	1.6	2.1
F	3.5	1	2.4	1.8	1.9
G	1.4	1.8	1.4	1.5	2.3
mean	2.8	1.4	1.7	1.9	2.3
standard deviation	0.67	0.71	0.49	0.67	0.55

TABLE 3 INTENSITY OF EACH SUBJECTIVE VALUE IN CATHODIC STIMULUS FOR EACH PARTICIPANT

participants	mean cold sensation intensity	mean warm sensation intensity	mean pressure sensation intensity	mean vibration sensation intensity	mean pain sensation intensity
A	2.1	1.5	2.6	1.9	2.1
B	3.1	1.1	1.9	2.3	2.2
C	3.8	0	3.2	3.5	3.7
D	4.5	2.6	3	2.7	3.3
E	2.4	1.3	1.4	3.7	1.8
F	3.1	1.4	3.5	3.3	1.6
G	1.4	0	3.1	3.1	3.1
mean	2.9	1.1	2.7	2.9	2.5
standard deviation	0.98	0.85	0.69	0.59	0.75

Looking at individual distribution of cold sensation distribution, we found that the cold sensation spot was "clustered" along certain lines such as rows and columns. A typical example is shown in Figure 6. In addition, we found that warm sensation was generated in the area where pain sensation intensity was high. A typical example is shown in Figure 7. The correlation coefficients between warm sensation and pain sensation were 0.499 for the anode and 0.432 for the cathode in the subject who generated the strongest warmth, confirming the correlation for both anode and cathode. However, the correlation coefficients between warm sensations and pain in the average among subjects were 0.116 for the anode and 0.223 for cathode, indicating a weak correlation in cathodic stimulation, but no correlation in anodic stimulation.

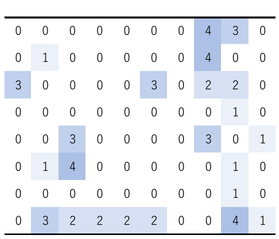


Figure 6 Typical example of cold sensation distribution. The sensed points aligned rows or columns

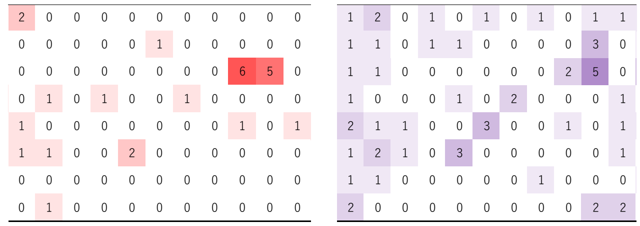


Figure 7 A typical example of distribution showing correlation between warm and pain sensation (left: warm sensation, right: pain sensation)

Contrary to temperature sensations, the mean distributions of the pressure and vibration sensation intensities showed that they were flatter and more frequent than the temperature sensations (Figure 4 and Figure 5). Table 2 and Table 3 showed that there was a difference in the intensity of pressure and vibration sensations between anodic and cathodic stimuli, with cathodic stimuli tending to generate stronger sensations. Wilcoxon's signed rank test showed a significant difference (p=0.018) between the mean pressure sensation intensity generated by the anode and cathode stimuli. The same test was conducted for vibration sensation, and a significant difference was also shown for vibration sensation (p=0.046).

V. DISCUSSION

We found that the warm sensation was rarely generated compared to the cold sensation, and the warm sensation was often generated at the same time as the pain sensation. One of the causes of the pain sensation during electrical stimulation is Joule heat [18], and it is possible that the temperature increase caused by electrical stimulation generated both the temperature sensation and the pain sensation simultaneously.

The nerve fibers related to warm sensation is mainly C fiber, and the nerve fibers related to cold sensation is Aδ fiber [19]. It is known that electrical stimulation tends to stimulate thicker or myelinated nerve fibers more than thin or unmyelinated nerve fibers [11][12], so the tendency for cold sensation to occur more easily than warm sensation is understandable as a property of electrical nerve stimulation.

The number and location of the cold sensation differed greatly among individuals and regions. In addition, while the pressure and vibration sensations were generated almost evenly at all the electrodes, the cold sensation was sometimes felt in clusters along line. There was also a comment after the experiment that the cold sensation was felt as a straight line vertically from the stimulation point to the hairline in some cases. On the contrary, there was no comment that the cold sensation was perceived as a straight line in the horizontal direction. It is conceivable that the nerve travel and branching pathways caused these clustering phenomena, which should be examined in the future research.

The pressure and vibration sensations were more strongly generated by cathodic stimulation than anodic stimulation. In this experiment, the threshold current of cathodic stimulation was about half of the threshold current of anodic stimulation, which means that the cathodic current during the main experiment was less than that of anodic current because the experiment was conducted at 1.5 times of each threshold value. In spite of this, cathodic stimulation generated stronger sensation than anodic stimulation, indicating strong superiority of cathodic stimulation. It is known that cathodic stimulation is generally more superior to anodic stimulation [20], so this result is reasonable. On the other hand, it is also known that anodic stimulation is more stable than cathodic stimulation in electro-tactile stimulation to fingertips [21], and pressure sensation is known to be more strongly generated by cathodic stimulation and vibration sensation is more strongly generated by anodic stimulation in fingertips [22][23]. No such tendency was observed in electrical stimulation on the forehead this time.

While the cathodic stimulation generated stronger pressure and vibration sensations than the anodic stimulation, temperature and pain sensations did not show such trends. On the other hand, we have previously observed that there is a positive correlation between the intensity of cold sensation and pressure sensation when cathodic stimulation was used [15]. The latter implies that there is a common mechanism between cold and pressure sensation in electrical stimulation, while the former implies there is a difference in stimulation mechanism. We need to obtain electrical stimulation model to explain these observations in our future work.

VI. CONCLUSION

In this paper, envisioning the use of electro-tactile display for temperature presentation for HMD, we investigated robustness of several tactile senses elicited by forehead electro-tactile stimulation, which were cold, warm, pressure, vibration, and pain sensations.

As a result, it was confirmed that cold sensation was easier to present by electrical stimulation than warm sensation, but its robustness was not comparable to pressure and vibration sensations. Furthermore, individual distribution data showed nerve pathways might have large influence on the cold sensation, and warm sensation might be coactivated with pain, possibly due to Joule heat. There was also a general trend that cathodic current gave stronger sensation than anodic current.

In our next step, we will investigate in detail whether there are any common distribution patterns among participants or ways of finding good spots for efficient temperature presentation, or ways to generate thermal sensation in each participant robustly, taking into account the neural pathways and the mechanism of thermal sensation generation. In addition, we would like to investigate how to separately generate temperature sensation, vibration sensation, and pressure sensation. Furthermore, we would like to apply the device to VR contents, by presenting several tactile modalities using electrical stimulation.

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