Thermal Sensation on Forehead Using Electrical Stimulation

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ABSTRACT

Thermal sensation systems are embedded into head-mounted displays using Peltier devices, water, or chemical substances to enhance the sense of presence in virtual reality environments. We propose a new method of presenting thermal sensation to the forehead by using electrical stimulation. This is based on our finding that when electrical stimulation is applied to the forehead, thermal sensation occurs in rare cases. We conducted an evaluation experiment and found that cathodic current pulses frequently provide a cold sensation, and the sensation is highly correlated with pressure sensation.

CCS CONCEPTS

• **Human-centered computing**; • **Human computer interaction (HCI)**; • **Interaction device**; • **Haptic devices**;

KEYWORDS

Electrical stimulation, cold sensation, HMD

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1 INTRODUCTION

The widespread use of inexpensive head-mounted displays (HMDs) has led to an increase in the number of virtual reality (VR) contents that require the wearing of HMDs. To achieve a high level of immersion in a VR space, presenting other modalities, such as the sense of touch in addition to the reproduction of vision and hearing is found to be effective [1], [2].

A haptic presentation device can be added to the HMD to provide a haptic experience in a simple way [3], [4]. In particular, the sense of temperature is important for enhancing the sense of presence; thus, various temperature sense presentation displays have been studied. For example, Peiris et al. [5] integrated a Peltier element into the cushion of an HMD to present temperature of the VR environment and instruct the direction cues. They also found that thermal stimulation only or combination of thermal stimulation and low-frequency vibration enhanced wetness sensation [6], and presented to the face or to the whole body by vibrating collarbone and feet [7]. Liao et al. [8] simultaneously presented temperature and tactile sensations using water flow. Ranasinghe et al. [9] confirmed that a sense of realism was enhanced by presenting heat using Peltier devices on the neck and by presenting the sensation of wind using an air fan attached to the HMD.

However, these previous methods for temperature presentation have issues, such as heat accumulation inside the HMD, which also leads to a slow response. Brooks et al. [10] proposed a chemical presentation method using substances, such as capsaicin and eucalyptol. However, this method also requires a longer time for the thermal effect to disappear.

We propose the use of electrical stimulation of the forehead to present a temperature sensation. An electro-tactile display of the forehead was developed by Kajimoto et al. [11] as a sensory substitution system for blind. We have encountered a phenomenon that electrical stimulation of the forehead occasionally generated a sense of temperature. It was typically a cold sensation, and thus, simple joule heat by electrical current should not be cause of the phenomenon. As the method does not require real heat or chemical substances, its response is fast. In this study, we investigated whether this cold sensation is stably generated by electric forehead stimulation. Electrical stimulation devices can present vibration and pressure sensations. If the cold sensation can be presented stably by electrical stimulation on the forehead, the temperature, vibration, and pressure sensations can be presented by a single device without heat accumulation inside the HMD, thus saving space and power.

2 EXPERIMENTAL DEVICE

Electrical stimulation was realized using an electrical stimulator that consists of 61 circular electrodes arranged at equal distances in a hexagonal close-packed configuration, as shown in Figure 1. The electrical stimulator was based on the device proposed by Kajimoto et al. [12]. The diameter of each electrode was 1.2 mm; the center distance between the electrodes was 2 mm; the pulse width of the electrical stimulation was set to 0.5 ms, and the pulse cycle was set to 11.0 ms.

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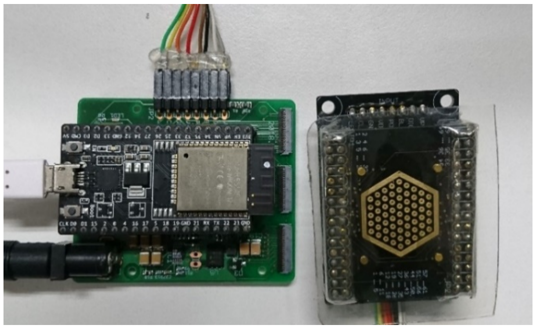

Figure 1: Electro-tactile display (left: microcontroller, high voltage source, and voltage to current converter, right: switching circuit and 61 array electrodes)

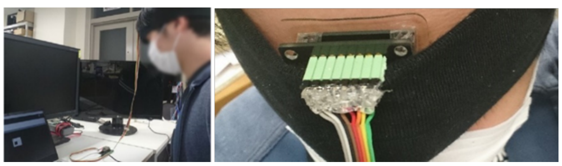

Figure 2: Experiment environment (left: external appearance, right: applied part)

3 EXPERIMENT

3.1 Preliminary Experiment

Before starting the main experiment, we investigated the point where electric stimulus generated maximum temperature sensation. As shown in Figure 2, a 1-mm-thick gel (Sekisui Kasei G grade gel) was applied at the center of the participant's forehead, and the electrode was attached using an elastic band. To decrease the effect of the gel on cold sensation, the experiment was conducted after the coldness of the gel was no longer felt.

Cathodic stimulation of 1 mA was applied to each electrode, and the participants reported whether the cold sensation was generated (Figure 3). The points that generated cold sensation was stimulated again, and participants reported the intensity of coldness on a 10-point scale from 0 (room temperature) to 9 (sensation of touching ice). The point that generated the coldest sensation was thus determined. If there were multiple points with a similar intensity of cold sensation, the points were stimulated sequentially for comparison, and the point that generated the coldest sensation was determined.

3.2 Main Experiment

In this experiment, the point determined in the preliminary experiment was used as the stimulus point. Five different current values (1, 1.5, 2, 2.5, and 3 mA) were presented to the stimulus point, five trials for each; thus, 25 trials were performed in a random order. In each trial, the electric stimulus was presented for 5 s, and then the stimulus was stopped to measure the temperature intensity (0: room temperature to 9: sensation of touching ice), vibration intensity (0: none to 9: sensation of touching a vibrating mobile phone), and pressure intensity (0: none to 9: sensation of pressing a hard surface with a finger). The experiment was approved by the

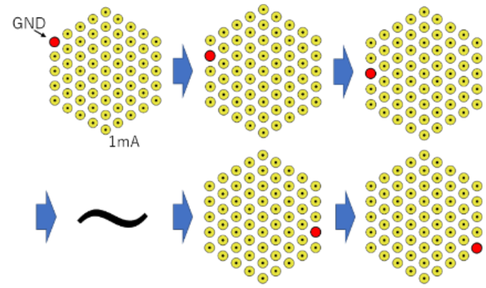

Figure 3: Scanning of stimulus points

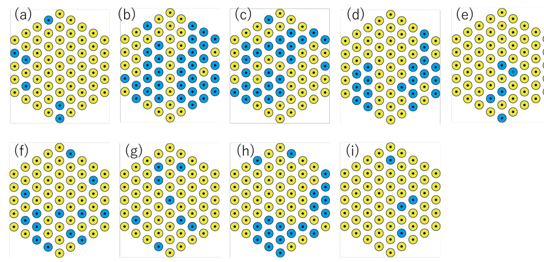

Figure 4: Distribution of the points where cold sensation generated in each participant (blue: points where cold sensation was generated)

Ethics Committee of the University of Electro-Communications (No. 20024).

4 RESULT

We recruited ten participants (nine males and one female, age: 22–43 years). One male participant was treated as an exception, because he felt temperature sensation in the preliminary experiment but almost no temperature sensation in the main experiment.

The average number of cold points (electrodes that elicited cold sensation) was 15.2, and the number had large deviations among participants. Among the 61 electrodes, the minimum number of cold points was 4, and the maximum number of cold points was 34 (Figure 4).

Figure 5 shows the results of the main experiment, comparing two groups: one with greater number of cold points than the average (five participants) and the other with a smaller number of points than the average (four participants). The temperature sensation seemed to increase monotonically along the current value when the number of cold points was greater than the average, although statistical tests were not conducted due to the small number of participants.

The overall average results are shown in Figure 6. Overall, the temperature, vibration, and pressure sensations increased slowly monotonically with an increase in current. We found that there were five people whose temperature sensation tended to increase as the current increased, two people whose sensation tended to decrease continuously, and two people whose sensation tended to first increase and then decrease. For those who felt an increase and then a decrease, the intensity of vibration and pressure sensations

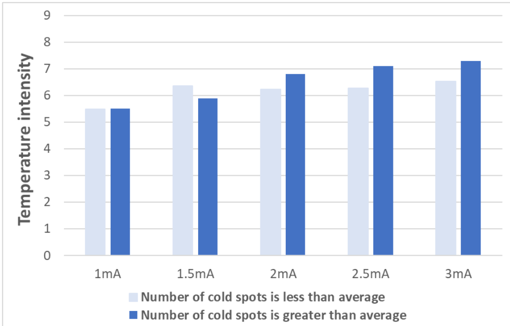

Figure 5: Temperature intensity due to differences in the number of cold points

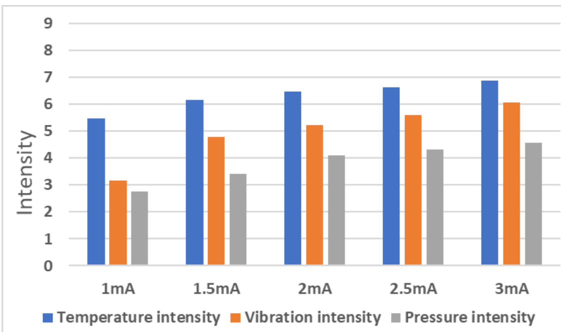

Figure 6: Overall mean (average of nine people)

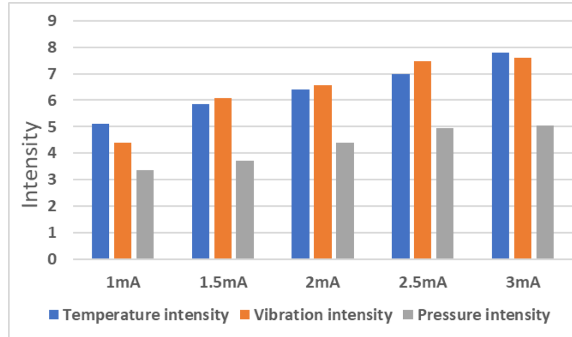

Figure 7: Upward trend (average of five people)

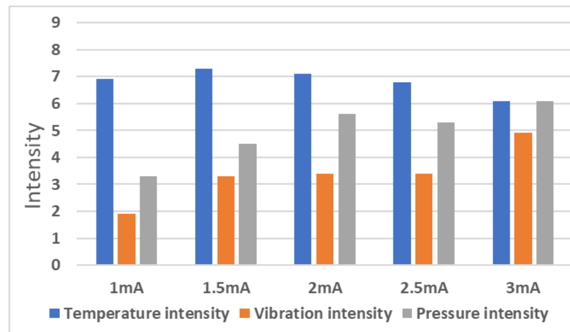

Figure 8: Downward trend (average of two people)

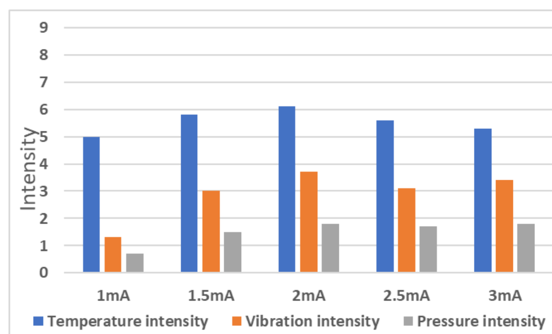

Figure 9: Upward and downward trend (average of 2 people)

also increased and then decreased as the current increased. The results of these three groups are shown in Figure 7, Figure 8, and Figure 9

Figure 10, Figure 11, and Figure 12 show the correlations of temperature intensity, pressure intensity, and vibration intensity with respect to the subjective evaluation of each value. The correlation coefficient between the temperature intensity and the pressure intensity was 0.792, indicating a strong positive correlation. The correlation coefficients between the temperature intensity and vibration intensity and that between the pressure intensity and vibration intensity were 0.362 and 0.463, respectively.

The comments from participants indicated that the cold sensation generated by electrical stimulation on the forehead was not felt as the spreading coldness of ice pressed on the forehead but felt as the localized coldness of the area like the needle was pressed.

5 DISCUSSION

The experiment was performed in two steps; the first step was to identify the point where the strongest cold sensation was elicited, and the second was to use the point for further investigation. With these steps, we confirmed that we could present a stable cold sensation, which was valid for nine out of ten participants. Therefore, the cold sensation generated by electrical stimulation to the forehead was confirmed. It is known that electrical stimulation is more likely to stimulate thick nerves and myelinated nerves than thin nerves and unmyelinated nerves [13], [14]. We consider that the cold sensation generated by electrical stimulation may be due to stimulation of A-delta fibers, which are myelinated nerves related to cold sensation [15].

The results of the experiment suggest that there is a correlation between the intensities of pressure and cold sensations. Although the correlation diagram includes all experimental results at different current values, it may include pseudo-correlation caused by the increase in general sensation due to the increase in current. This point needs to be carefully investigated in the future. Nevertheless, pressure and cold sensations are the only pairs that gave strong correlation. Here, we discuss the possible causes of the relationship between the pressure and cold sensation intensities.

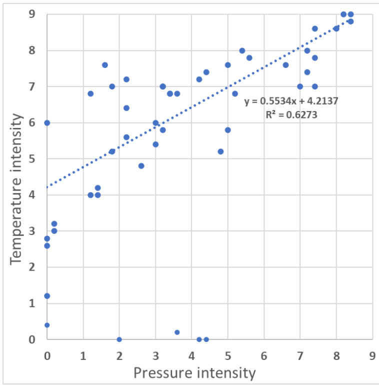

Figure 10: Correlation between temperature intensity and pressure intensity

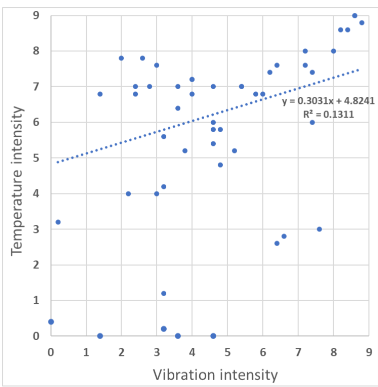

Figure 11: Correlation between temperature intensity and vibration intensity

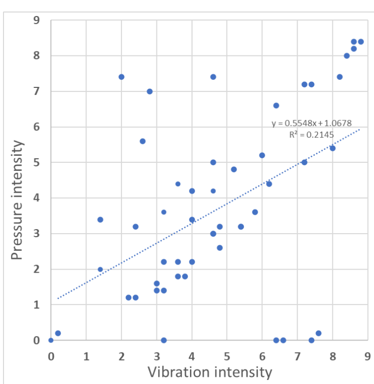

Figure 12: Correlation between pressure intensity and vibration intensity

First, it is known that the pressure sensation is strongly affected by temperature [16], while the low-frequency vibration sensation of approximately 30 Hz is barely affected by temperature [17]. In addition, the weight of a cold object is felt heavier than the actual weight [18]. This suggests that there may be a psychological interaction between the two senses, temperature and pressure. However, while it is well known that "cold objects are perceived heavy", to the best of our knowledge it is not known that "heavy objects are perceived cold". Therefore, the cold sensation that occurred this time is not considered to be an illusion accompanied by a pressure sensation.

In electrical stimulation, there is a relationship between the polarity of the stimulus current and the sensation generated. Pressure sensation is dominant over vibration sensation in cathodic stimulation, and vibration sensation is dominant over pressure sensation in anodic stimulation [19], [20]. In this experiment, we used cathodic stimulation because a preliminary investigation showed that cold sensation tends to occur during cathodic stimulation. This suggests that the properties of the electrically stimulated nerve (e.g., nerve axon orientation and/or electrical conditions of the nerve terminals) may be similar in cold and pressure sensations.

In this experiment, it was observed that the number and location of cold sensations and the temperature intensity differed greatly in each person, which is possibly due to differences in the thickness of the skin on the forehead and the number of cold spots. In addition, there were three trends in the variation of temperature sensation with the increase in electric current. In general, the sensation tends to increase monotonically with the current in electrical stimulation, but in other cases, the temperature sensation may be masked by other pressure or vibration sensations.

Currently, our method has several limitations; First, electrical stimulation of temperature sensation inevitably accompany vibration and pressure sensation. In addition, electrical stimulation requires calibration, and it is necessary to investigate the location where the cold sensation occurs in advance. In the future, we will investigate the method of presenting cold sensation by quickly locating the cold point for cold sensation presentation and presenting warm sensation to forehead by electrical stimulation.

6 CONCLUSION

We confirmed that cold sensation was generated by electrical stimulation on the forehead, with individual differences in the number and location of cold points and electrical stimulation conditions. It was also suggested that there was a correlation between the intensities of pressure and cold sensations. We also found that there were individual differences in the point where cold sensation was generated by electrical stimulation. Therefore, it is important to calibrate the point where the temperature sensation is generated in order to present the temperature sensation by electric stimulation. Our future work will include finding a method to locate the cold point quickly and to discover the cause of individual differences. In addition, we will integrate the electro-tactile display into the HMD and use it in a VR environment.

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