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# Coldness Presentation Depending on Motion to Enhance the Sense of Presence in a Virtual Underwater Experience

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Ethics Committee of the University of Tokyo.

**ABSTRACT** In virtual reality (VR), there is consumer demand for underwater world experiences. To address this demand, previous studies have presented coldness to enhance the sense of presence in virtual underwater experiences. We considered that we could further improve the sense of presence and the experiential quality of underwater VR simulations by making the coldness presentation more realistic. We also considered that methods of presenting coldness continuously would have a wider application range. In this research, with reference to actual water behavior, we propose a method that presents coldness depending on whether it is moving. We conducted an experiment comparing the sense of presence between the steady-state temperatures of 24.9 ± 1.9 °C / 27.8 ± 2.7 °C and the proposed method, the temperature of which moves between the aforementioned temperatures as the user moves and stops. The results show that the proposed method yielded higher scores than the higher steady-state temperature in ''closeness of overall sensation'' and ''closeness of thermal sensation''. For the lower steady-state temperature, the proposed method achieved the same sense of presence improvement while removing less heat. This extends the experiential duration. Meanwhile, for those who noticed the temperature change, the proposed method yielded higher scores than the lower steady-state temperature in ''realness'' and ''closeness of thermal sensation''. To further improve effectiveness of the proposed method, it is important to not only change the temperature but also to notice the temperature change. This method is suitable for several virtual underwater applications, such as education and training.

**INDEX TERMS** Haptic interfaces, multimodal, presence, thermal display, virtual reality.

## I. INTRODUCTION

There is a social and consumer demand for the experience of underwater worlds in virtual reality (VR) for education, training, and other applications. Therefore, there has been considerable research on underwater simulation. For example, Licia *et al.* [1] developed a VR game to teach sustainable behavior while diving. Jain *et al.* [2] provided an immersive scuba diving experience with various actuators to train divers before they go to the ocean.

Notably, humans accept multiple forms of sensory information and take a weighted average of each sensory signal [3]. In VR, previous research have shown that multiple sensory stimuli enhance the sense of presence. In particular, simulated haptic sensation is a key component used to enhance the sense of realism in virtual environments [4]. Researchers have utilized various modalities to enhance the sense of presence, such as friction [5], wind [6], [7], pressure [4], vibration, and shaking [8].

Researchers have also utilized thermal stimuli to improve the sense of presence or the quality of the experience of VR applications, such as images indicating temperature, snow, rain, and heaters [7], [9]–[12]. In research on communication and emotional experiences, they have added thermal stimuli to messages and music to enrich affective experiences [13]–[16].

In a virtual underwater environment, previous research have successfully enhanced to enhance the sense of presence by coldness presentation. Maeda *et al.* [17], [18] developed a cold-presenting device that is small and can be worn on

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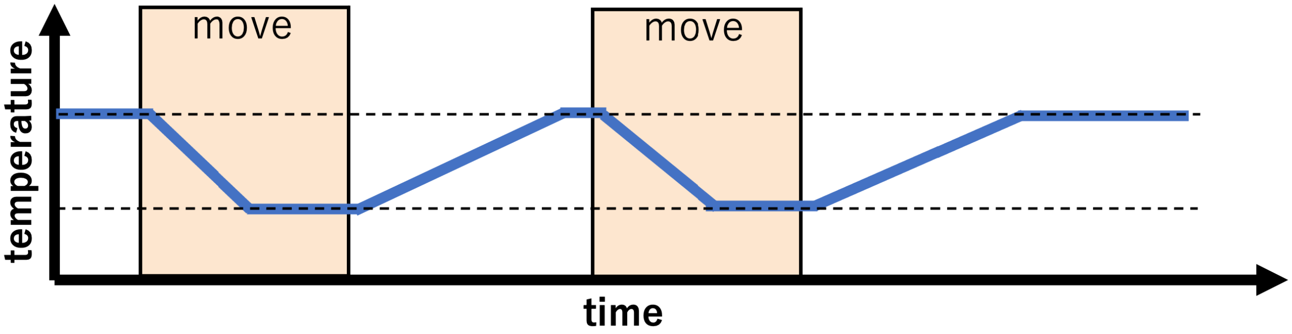


**FIGURE 1.** Schematic of the proposed method, which presents coldness depending on whether a user is moving.

multiple body parts. Peiris *et al.* [19] developed a head-mounted display (HMD) integrated with thermal and vibrotactile modules. They presented coldness in synchronization with the playback of images of the underwater environment. These studies showed that the coldness presentation significantly enhanced the sense of presence.

We considered that we could further improve the sense of presence and the quality of experience by making the coldness presentation more realistic. In actual water, the temperature changes interactively depending on human motion with the fluid. To the best of our knowledge, this study is the first to consider such a design.

We also considered that a method to present coldness continuously would have a wider range of virtual underwater applications. Previous research [17]–[19] have presented a continuously falling temperature, so they were only useful for very short experiences. For example, Peiris *et al.* [19] presented a continuous cooling temperature of −3.0 °C/s for 1 s. Owing to the performance of the thermal module and safety issues, it is difficult to extend the duration of this method, and thus, the experience time is limited.

To make the coldness presentation more realistic and enable a continuous presentation of coldness, we propose a method that presents coldness depending on the motion concerning the phenomenon in actual water (see Figure 1). In a cold swimming pool, one typically feels less cold when stationary, and feels colder when moving. This occurs due to the thinning of the boundary layer that is caused by movement. We hypothesized that reproducing this phenomenon would enhance the sense of presence compared to the presentation of a steady low temperature, where adaptation is concerned. We also considered that reproducing this phenomenon would enable coldness presentation for longer durations than in previous research [17]–[19].

The research question is whether the proposed method enhances the sense of presence compared to the method that does not present any coldness and to the method that presents a steady low temperature. To clarify this question, we conducted an experiment to evaluate the sense of presence between several thermal conditions. The temperature change depending on motion also occurs in warm water. In this study, we utilized the coldness because human perception of cold is generally more sensitive [20].

## II. RELATED WORK

### A. UNDERWATER VR WITH ACTUAL WATER OR HARDWARE

Researchers have been investigating ways to augment underwater experiences for a wide variety of applications in entertainment and training, among other fields. Yamashita *et al.* [21] developed a computer-augmented swimming pool with an immersive three-dimensional projection environment, such as CAVE [22]. This research allowed users to swim in artificial computer-generated landscapes, such as coral reefs and outer space. This research aims to improve motivation for swimming, which is one of the best exercises for maintaining health. In another study, Osone *et al.* [23] and Zhang [24] engineered an HMD for underwater use. Blum *et al.* [25] and Quarles [26] developed entertainment and rehabilitation applications using HMDs. Jain *et al.* [2] developed a virtual scuba diving system that uses a suspension device to lift the user and present buoyancy and resistance forces. These studies found ways to augment underwater experiences, but the hardware systems developed are often cost prohibitive and difficult to implement.

### B. SIMULATING UNDERWATER ENVIRONMENT VIRTUALLY

Therefore, some studies have attempted to make it possible to use an underwater environment through virtual reality simulations. Along these lines, some works aimed to reproduce the resistance force through visual inputs. Kang *et al.* [27] and Lee *et al.* [28] improved the visual effect of a simulation by varying the mapping ratio of displayed to real-world motion [29]. Other researchers made use of tactile stimuli. Chang *et al.* [4] engineered an HMD with an integrated pulley system to generate normal forces that expressed water pressure on the face. Wang *et al.* [5] proposed the generation of a two-dimensional skin-stretching feedback on the legs. They showed that these techniques increased the realism of the experience of walking with legs immersed in virtual water.

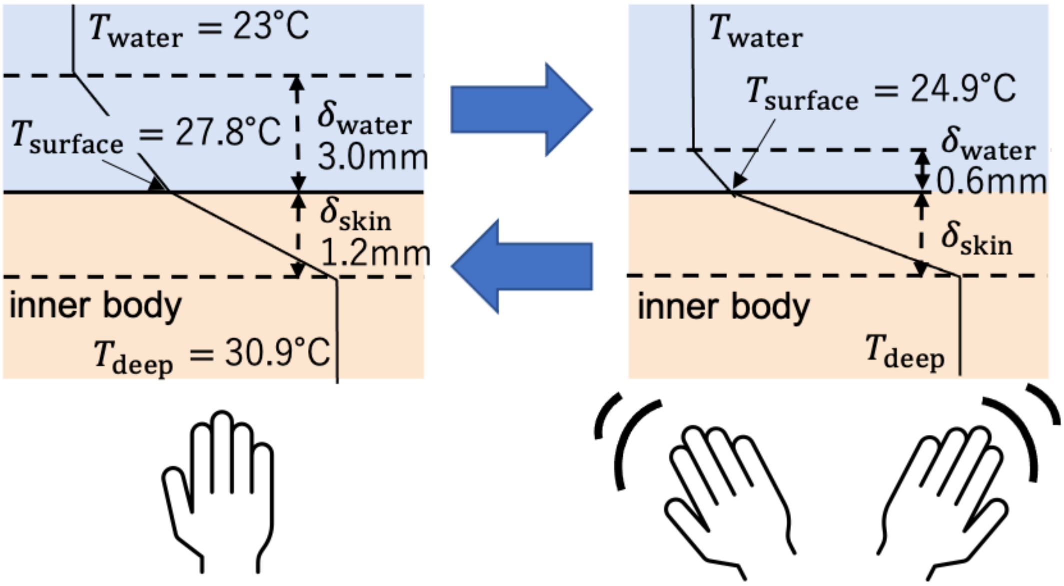


**FIGURE 2.** Schematic diagram of the temperature change when stationary and when moving. The figures on the left and right are when the user is stationary and moving, respectively. The specific values in the figure are only examples. Heat exchange is assumed to occur only in the boundary layer, where the temperature changes linearly. When the speed of movement is high, the thickness of the thermal boundary layer $\delta_{\text{water}}$ becomes smaller, and the skin surface temperature $T_{\text{surface}}$ decreases.

In contrast, Maeda *et al.* [17], [18] and Peiris *et al.* [19] presented coldness to enhance the sense of presence in a virtual underwater experience. As mentioned in the introduction, the present work aims to further improve the sense of presence and the quality of experience by increasing the realism of the presentation of coldness.

### C. PHYSICS-BASED TEMPERATURE PRESENTATION

In solids, there is a phenomenon that the temperature differential sensed in touching differs depending on the material. Some studies simulated the temperature change after touch for material recognition of virtual objects touched in a virtual environment [30], [31]. In liquids, there is a phenomenon in which the temperature change depends on whether people are moving or stationary relative to the water. In this research, we aimed to improve the sense of presence by devising a new coldness presentation method with reference to the phenomenon that occurs in actual water.

## III. TEMPERATURE CHANGE OF VIRTUAL WATER

In this study, we propose a method of presenting coldness depending on motion enhance the sense of presence in a virtual underwater experience by considering the temperature changes that occur during actual motion in a swimming pool. To design the temperature presentation, we constructed a model that calculated temperature using a model of forced convection heat transfer and one-dimensional heat conduction. We need to emphasize that the purpose of the experiment is to determine "whether the coldness presentation depending on motion enhances the sense of presence in a virtual underwater experience". This work is not necessarily intended to accurately reproduce physical phenomena or to discover the optimal coldness presentation method. We focused on physical phenomena as a guideline for "coldness presentation depending on motion or lack thereof," which is not represented in the relevant literature, to be used in the experiments described below.

Figure 2 shows a schematic diagram of the temperature change when stationary and when moving. Heat exchange is assumed to occur only in the boundary layer, where the temperature changes linearly. Given our aims and focus, a relatively simplified physical model of temperature producing a rough approximation was considered sufficient accurately to reflect human experiences of coldness or the lack thereof.

The specific values that appear in the following are the parameters of the experimental design, as described in the next section. The virtual water temperature $T_{\text{water}}$ was determined to be 23 °C for two reasons. Given that humans feel pain at skin temperatures less than 15 °C [32], we set the temperature with a margin of safety. Decreases in temperature are signaled most vividly at around 25 °C. By later calculations, the skin surface temperature $T_{\text{surface}}$ while moving would be approximately 25 °C.

The deep skin temperature $T_{\text{deep}}$ was measured after the temperature-regulating task (1st time) described below. The mean $T_{\text{deep}}$ in the experimental participants was 30.9 °C, with a standard deviation of 2.3 °C.

In the model of forced convection heat transfer used in this study, the forearm and hand were approximated as cylinders of diameter $d$ ($d = 0.1$ m). The thickness of the thermal boundary layer in the one-dimensional heat conduction model was defined as $\delta_{\mathrm{water}}$ for the water side and $\delta_{\mathrm{skin}}$ for the skin side. $\delta_{\mathrm{water}}$ varies with the speed of movement (see below for the calculation), and $\delta_{\mathrm{skin}}$ was determined to be 1.2 mm based on the sum of the thicknesses of the epidermis and dermis [33].

Based on the model of forced convection heat transfer, we calculate $\delta_{\mathrm{water}}$. First, from $T_{\mathrm{water}}$, the density $\rho$ [34], viscosity $\mu$ [35], thermal conductivity $\lambda_{\mathrm{water}}$ [36], and specific heat $C_p$ [37] were calculated, from which the Prandtl number $Pr$ is calculated using (1).

$$Pr = \frac{\mu C_p}{\lambda_{\mathrm{water}}} \tag{1}$$

Next, considering the speed of motion as $u$, the Reynolds number $Re$ can be calculated using (2). In this experiment, $u$ was set to 0.2 m/s while moving and 0.01 m/s while stationary (if the speed is set to 0.00 m/s, the thickness of the boundary layer becomes infinite).

$$Re = \frac{\rho u d}{\mu} \tag{2}$$

The Nusselt number $Nu$ can be expressed in two ways, as shown in (3) ($C$ and $m$ are coefficients determined by $Re$). By solving (3), the heat transfer coefficient $h$ is calculated.

$$Nu = \frac{hd}{\lambda_{\mathrm{water}}} = C Re^m Pr^{1/3} \tag{3}$$

$\delta_{\mathrm{water}}$, the thickness of the thermal boundary layer on the water side is calculated using (4).

$$\delta_{\mathrm{water}} = \frac{\lambda_{\mathrm{water}}}{h} \tag{4}$$

The faster the speed of motion $u$, the smaller $\delta_{\mathrm{water}}$ becomes.

The skin surface temperature $T_{\mathrm{surface}}$ is calculated by solving (5) for the heat flux exchanged between the water and skin.

$$\lambda_{\mathrm{water}} \frac{T_{\mathrm{surface}} - T_{\mathrm{water}}}{\delta_{\mathrm{water}}} = \lambda_{\mathrm{skin}} \frac{T_{\mathrm{deep}} - T_{\mathrm{surface}}}{\delta_{\mathrm{skin}}} \tag{5}$$

$\lambda_{\mathrm{skin}}$ is the thermal conductivity of the skin (0.37 W/m/°C [38], [39]). The mean $T_{\mathrm{surface}}$ while moving in the experimental participants was 24.9 °C, with a standard deviation of 1.9 °C, the mean $T_{\mathrm{surface}}$ while stationary in the experimental participants was 27.8 °C, with a standard deviation of 2.7 °C. $T_{\mathrm{surface}}$ calculated by this model was used as the indicated temperature to be sent to the controller of the coldness presentation device while moving and stationary.

## IV. EXPERIMENTAL DESIGN

The research question is whether the coldness presentation depending on motion enhances the sense of presence in a virtual underwater experience compared to methods that do not present any coldness and that presents a steady low temperature. To clarify this question, we conducted an experiment to evaluate the sense of presence of a virtual underwater experience between several thermal conditions. We also used actual water in an aquarium to compare the sensation with that of touching actual water.

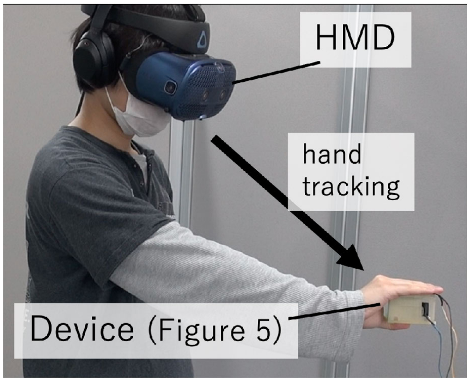


**FIGURE 3.** Experimental Setup. The participants held the coldness presentation device, which is shown in Figure 5, in their right hand. The HMD displayed the virtual underwater scene shown in Figure 4. They moved their right hand horizontally or kept it stationary according to the scene instructions.

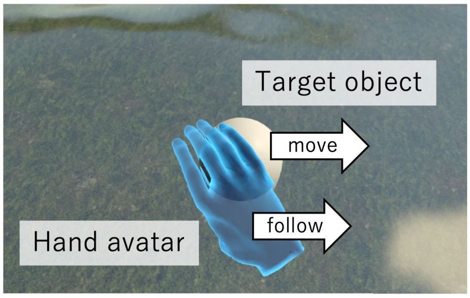


**FIGURE 4.** Capture of a virtual underwater scene displayed on an HMD. Participants were instructed to move the hand avatar to follow the moving virtual target object.

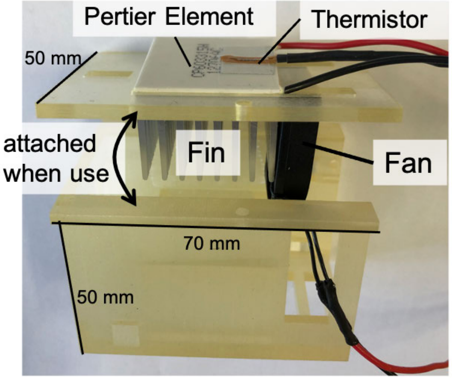


**FIGURE 5.** Coldness presentation device. Peltier element removed heat from the fingers. Thermistors monitored the temperature to control. A fin and fan vented the heat transferred by the Peltier element. The housing was divided into upper and lower parts, and plastic screws were attached to them when they were used in the experiment.

### A. EXPERIMENTAL SETUP

First, we describe the items used to make the virtual underwater environment. The experiment was conducted in a room where the room temperature was set to 25 °C. We used an HTC Vive COSMOS HMD (refresh rate of the image was 90 Hz) with the VIVE Hand Tracking SDK to track

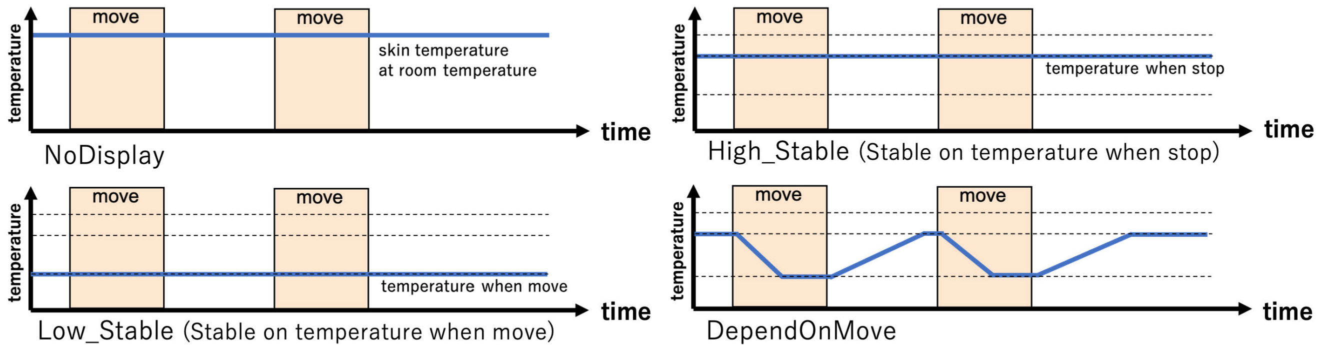


**FIGURE 6.** **Experimental Conditions. The top dotted line represents skin temperature at room temperature. The middle dotted line (in High_Stable, Low_Stable, and DependOnMove) represents temperature when stationary calculated by the model described in Section III. The bottom dotted line (in High_Stable, Low_Stable, and DependOnMove) represents temperature when moving calculated by the model described in Section III.**

the location of participants' hands. The participants held a coldness presentation device in their right hand (see Figure 3). We set the simulation area to "stationary experience" because the participants did not walk through the virtual environment. The image was rendered by a gaming computer (Mouse G-Tune H5-CML) with 16GB of RAM and an Intel i7-10870H CPU (rated clock rate was 2.20 GHz). A Ndivia Geforce RTX 3070 Laptop GPU with 8GB memory was used as the graphics processor. The virtual underwater scene (see Figure 4) was created with the Unity engine. Participants wore Sony WH-1000XM3 noise-canceling headphones to help them concentrate, which played white noise on repeat.

The coldness presentation device (see Figure 5) used in the experiment consisted of a Peltier device (CP603315H CUI Devices), a fin (YH-3020A Ainex), a fan (TKNECKCO 5V 2006 detached from TK-NECK2-BK THANKO), and a thermistor (TSA-103JT-1R5-B KURAG ELECTRONICS) in a housing made using a 3D printer. The thermistor and Peltier elements were attached with double-sided heat-dissipating tape (HF-S43 Sunhayato). By holding the device, as shown in Figure 3, coldness is presented to the fingers. The housing was divided into upper and lower parts, which were attached with plastic screws when used in the experiment. A Peltier device, which is an electronic component that controls cooling and heating by transferring heat from one side to the other, was used for the coldness presentation. The Peltier device was selected for the following two reasons. First, Peltier devices are compact and lightweight for coldness presentation. Moreover, Peltier devices can present coldness with a lower delay than other coldness presentation methods and can easily maintain the temperature within a safe range for skin contact. A fin and fan were installed to vent the heat transferred by the Peltier element to cool the participants' finger. The temperature measured by the thermistor was sent to a Peltier controller PLC-24V10A (KURAG ELECTRONICS), which controlled the cooling to a specified temperature or kept it at a steady temperature. The vibration of the device generated by the fan was 4.31 $m/s^2$, 14.8 Hz. This vibration was always constant, regardless of the presentation temperature.

We also used actual water in the pot to control the deep skin temperature by immersing the hand. We used an aquarium with 900 mm × 450 mm × 450 mm with actual water to allow the participants to remember the sensation of interacting with it. A Sony LSPX-P1 portable ultra-short throw projector was used to display instructions in the aquarium (details of the instructions are described below).

### *B. EXPERIMENTAL CONDITIONS AND DETAIL OF THERMAL STIMULI*

We conducted an experiment to evaluate the sense of presence of a virtual underwater experience under the following four conditions (see Figure 6). Cooling methods that present continuous falling temperatures used in previous studies [17], [19] were excluded because they were difficult to present for more than 10 s because of the performance of the device.

NoDisplay denotes a condition in which the device is only held, and no coldness is presented. High_Stable and Low_Stable are conditions in which a steady temperature lower than the skin temperature prior to the participating in the experiment is presented. $T_{\mathrm{surface}}$ was calculated from the participants' deep skin temperature ($T_{\mathrm{deep}}$) using the model described in Section III. High_Stable represents the temperature when participants were stationary ($u = 0.01$ m/s). The mean $T_{\mathrm{surface}}$ at High_Stable among the experimental participants was 27.8 °C, with a standard deviation of 2.7 °C. Low_Stable represents the temperature when participants were moving ($u = 0.2$ m/s). The mean $T_{\mathrm{surface}}$ at Low_Stable among the experimental participants was 24.9 °C, with a standard deviation of 1.9 °C. DependOnMove denotes the proposed method, which presents the temperature at High_Stable or Low_Stable depending on whether the participant is moving. The total amount of heat removed by the various methods was in the order of Low_Stable > DependOnMove > High_Stable > NoDisplay.

We describe the details of the time series of the indicated temperature in DependOnMove (see Figure 7). It is unclear how the user perceives temperature changes when the forearm is moved in actual water. In a pilot questionnaire, which asked

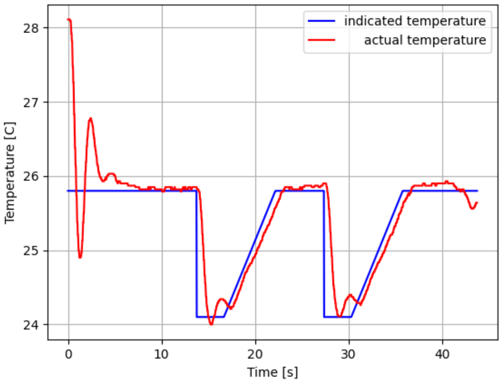


**FIGURE 7.** **Time series graph of the indicated temperature and actual presented temperature in DependOnMove for one participant. Blue line denotes the indicated temperature. Red line indicates the actual temperature presented to the finger.**

participants how they felt a change in temperature when they moved their forearms after holding them stationary in actual water at 23 °C, all 6 participants answered that they felt a rapid cooling sensation. Therefore, when participants moved their forearms in virtual water, the indicated temperature was designed to be directly dropped to $T_{\text{surface}}$ at Low_Stable. The Peltier element functions to provide rapid cooling. The actual temperature change rate when lowering the temperature was −0.80 °C/s on average.

It is unclear how the user perceives temperature changes even after the arm is moved and then stopped in actual water. In a pilot questionnaire, which asked participants how they felt a change in temperature when they stopped moving their forearms in actual water at 23 °C, most (5 out of 6) participants answered that they could feel that they were becoming gradually warmer. Based on this result, we considered that it is necessary to present a noticeable temperature change after the participants stop moving their forearms in the virtual water. Therefore, when participants stopped moving their forearms in virtual water, the indicated temperature was designed to increase to $T_{\text{surface}}$ at High_Stable at 0.3 °C/s. A rising temperature of 0.3 °C/s is considered to be a noticeable temperature change in [20]. The actual temperature change rate with increasing temperature was 0.27 °C/s on average.

Configuring proportional-integral-derivative (PID) control parameters is difficult. After careful tuning, we were able to achieve the above temperature change rate with as little delay and temperature oscillation as possible. The parameters set were proportional coefficient Kp=180, integral coefficient Ki=3.00, and derivative coefficient Kd=150. These were input to the Peltier controller.

### C. PARTICIPANTS

This study was conducted with a within-subject design. Participants were recruited under the theme "Research on interaction with water in VR" to avoid the expectation effect. The participants were not informed of the experimental conditions in advance. 32 healthy participants (26 males and 6 females) were recruited for the experiment (31 of whom were right-handed). Although gender differences are a subject of discussion in the study of thermal perception, Wilson *et al.* [40] states that there are no gender differences in the perception of temperature. The mean age was 25.9, with a standard deviation of 5.2 (4 people did not provide their age). There were 20 participants with VR experience. The Ethics Committee of the University of Tokyo has approved the experiments in this paper. We acquired a written consent form from all participants.

### D. PROCEDURE

First, we provide an overview of the experimental procedure (see Figure 8). A total of five blocks were conducted. The first block was a practice block to familiarize the participants with each task. In the second to fifth blocks, each condition shown in Figure 6 was presented in the VR task. The order of the experimental conditions was counterbalanced across participants.

Each block consists of a sequence of five tasks described below.

1) Pot task: control the deep skin temperature
2) Aquarium task: remember the sensation of interacting with actual water
3) Pot task: control the deep skin temperature
4) VR task: experience a virtual underwater environment
5) Questionnaire: measure the sense of presence of each condition

After completing all the blocks, participants filled out another questionnaire about the entire experiment. The entire experiment took about 60 minutes. For the questionnaire in the practice block, the participants were asked to read the text of each question to understand the questions beforehand.

#### 1) POT TASK

A pot containing 28 °C water was used to control the deep skin temperature by immersing the hand. Participants placed their right hand in the water and remained still for one minute. They were instructed to put their right hand in the water up to the back of their right hand and not to touch the bottom of the pot.

This task was performed before aquarium task and before VR task, respectively. In the questionnaire, the participants had to answer by comparing the sensation of the actual water they touched in the aquarium task with the sensation they felt in the VR task. Therefore, the skin temperature must be controlled before each of them.

$T_{\text{measured}}$ was set as the skin temperature measured after the second pot task in the practice block. $T_{\text{deep}}$ used in the model described in III was calculated in the same manner as in III (5).

#### 2) AQUARIUM TASK

We used an aquarium with actual 23 °C water to induce the participants remember the sensation of interacting with

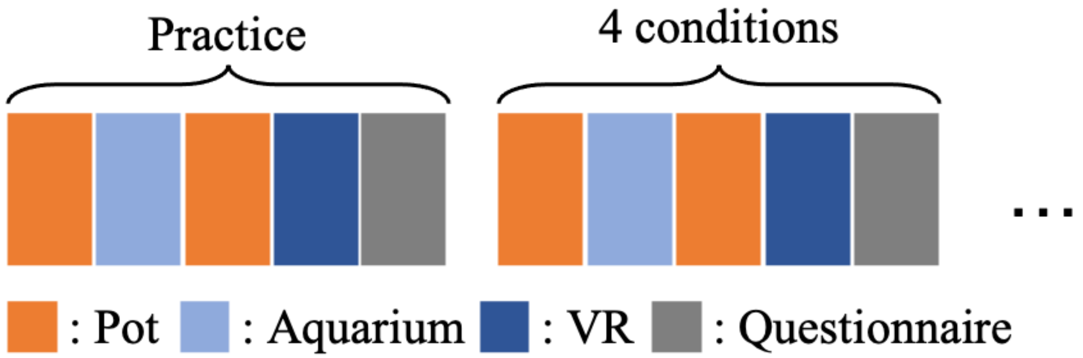


**FIGURE 8.** Experimental Procedure. One block contained four types of tasks. The participants controlled the skin temperature in pot task. They memorized the sensation of actual water in the aquarium task. After controlling the skin temperature in pot task again, they experienced virtual underwater simulations in the VR task. Finally, they answered a questionnaire about VR task. The first block was a practice block to familiarize with each task. In the second to fifth blocks, each condition shown in Figure 6 was presented in the VR task.

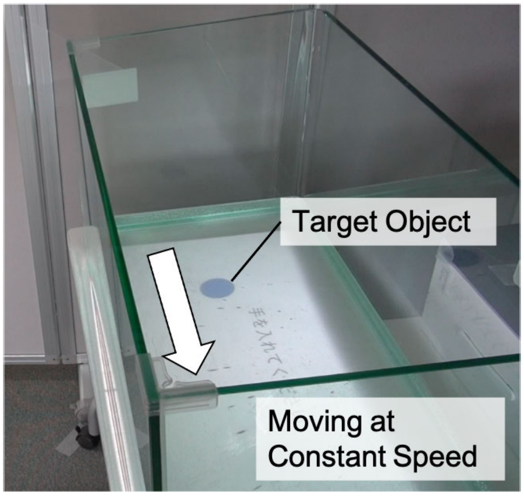


**FIGURE 9.** Video projected onto aquarium. The target object repeatedly moved horizontally and held stationary. Participants placed their right hand in the water and followed the target object.

water before VR task. The participants stood in front of the aquarium and placed their right hand in the water according to the instructions on the projected video (see Figure 9). Similar to the pot task, they were instructed to put their right hand in the water up to the back of their right hand and not to touch the bottom of the aquarium. The participants repeatedly made horizontal movements and held static positions following the target object projected onto the water. The workflow of this task was the same as the workflow of "evaluation time period" of the VR task (see Figure 10).

At the beginning, the message "Please insert your hand" was displayed. 6 s later, the target began to move. A countdown sound was played from 2 s before the target began to move. The target object took 3 s to complete its 0.6 m horizontal movement from the left to the right direction. After resting for 11 s, it then reversed its direction along the same path, and participants were instructed to follow it. 9 s after the second move, the message "It is over" was displayed, and then the participants lifted their right hand out of the water. This sequence of actions comprised a single trial and requires 32 s.

### 3) VR TASK

After the aquarium task, the participants again performed the pot task to align their deepskin temperature with that of before the aquarium task. Participants wiped their hands after completing the pot task and then performed the VR task. The participants wore the HMD and performed the VR task with the cold presentation device on their right hand (see Figure 3). HMD presents a virtual underwater environment (see Figure 4). The noise-cancelling headphone plays a white noise on repeat to make them concentrate on the task.

The workflow of this task is shown in Figure 10. After wearing the equipment, participants were instructed to wait in the state shown in Figure 3 and close their eyes until the signal was sounded. After this task, the participants were instructed to answer a questionnaire about their experience after the signal was sounded, and their eyes were opened. This instruction was especially carefully and repeatedly given. The Peltier device was cooled to a predetermined temperature during the closing of the eyes.

After the signal was sounded, participants were instructed to open their eyes and control the hand avatar to follow the target object (see Figure 4). The target object was initially located in front of the left side of the participant. 6 s after the signal, the target began to move. Countdown sounds and character displays were played from 2 s before the target began to move. The target object took 3 s to complete its 0.6 m horizontal movement from the left to the right direction. After resting for 11 s, it reversed its direction along the same path at the same speed. Participants were also instructed to follow it. 9 s after the second move, the color of the target object changed from white to red to indicate the end of the task.

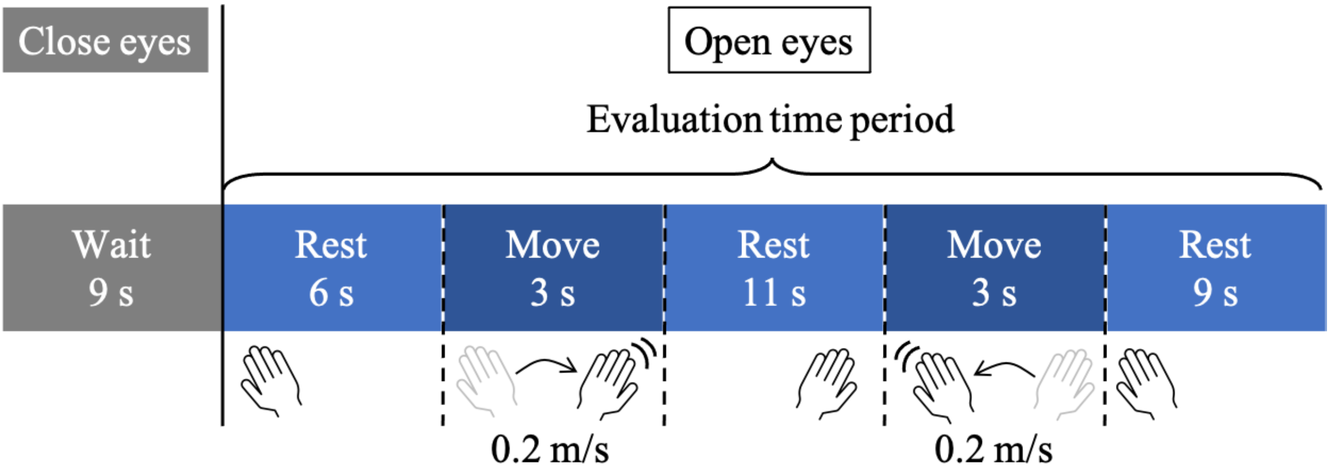


**FIGURE 10.** **Workflow of the VR task. The Peltier device was cooled to a predetermined temperature during the closing of the eyes. In move section, the target object moveed horizontally at 0.2 m/s. Participants answered the questionnaire only about the evaluation time period.**

This sequence of actions comprised a single trial, and took 41 s. The coldness presentation itself was performed for a total of 41 s, but the scope of evaluation in the questionnaire was 32 s.

For safety reasons, the PID parameters of the Peltier controller were chosen to emphasize stability rather than responsiveness, and the surface temperature of the Peltier element was programmed so as not to fall below 20 °C and not to exceed 40 °C. Furthermore, the surface temperature of the Peltier element was continuously monitored by the experimenter during the VR task, and the experiment was aborted when it was judged that the heat dissipation could not be maintained. Aside from thermal reasons, if participants felt any symptoms of VR sickness, the experiment was aborted.

#### 4) QUESTIONNAIRE TASK

We measured the sense of presence via Igroup Presence Questionnaire (IPQ) [41] (The Japanese translation is [42]). IPQ is measured on a 5-point Likert scale.

Furthermore, we added two questions that compared participants' experience of the VR task (after opening their eyes) and the aquarium task in which they interacted with actual water. These two questions were added to measure how well our method simulates the underwater environment more directly than the IPQ. This questionnaire was based on the questionnaire used in the study by Kang *et al.* [27].

This questionnaire consisted of the following two questions.

1) (sensation closeness) How close was the sensation you received throughout the VR experience to the sensation of water you felt in an aquarium?
2) (thermal closeness) How close was the temperature you felt in your hand to the sensation of the water you touched in the aquarium?

This questionnaire was measured with a numerical value ranging from 100, indicating "the same as the actual water sensation", to 0, indicating "no such sensation at all." To avoid expectation effects, the questionnaire also included dummy questions such as "How close were the vibrations you felt in your hands to the sensation of water you felt in the aquarium?". At the end of the questionnaire, we asked a free response question on the VR task.

## V. RESULT AND ANALYSIS

### *A. RESPONSES OF ALL*

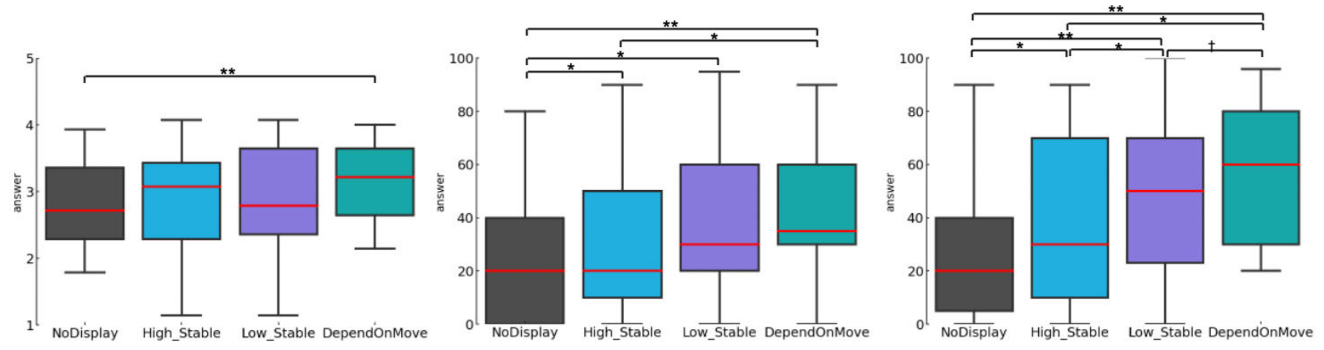
The experiment was conducted with 32 participants, but we were not able to present the target temperature to some of them. The reason for this is likely to be that the heat dissipation was insufficient, or that the parameters were not optimal due to individual differences in skin characteristics. Only participants who met all three of the following requirements were included in the analysis.

1) (High_Stable and Low_Stable) The temperature was not higher than the target temperature by more than 1 °C during the evaluation time period.
2) (DependOnMove) The minimum temperature became at least 1 °C lower than the temperature at the start of the movement and not greater than the indicated temperature calculated by the model described in III by 1 °C.

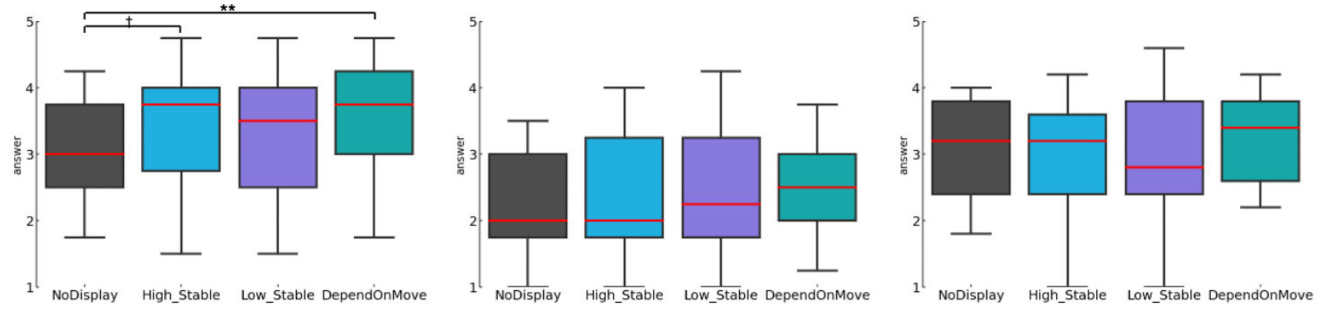
As a result of this screening, the answers of 21 participants were included in the analysis.

Figure 11 shows the responses to IPQ and additional two questions. The Igroup Presence Questionnaire consists of involvement, realism, spatial presence factors, and the total of these three factors represents presence. The results of the Shapiro-Wilk test showed that some scores were not normally distributed.

A non-parametric statistical test, the Friedman test, was performed to evaluate the difference in scores between the four conditions. For IPQ presence (see Figure 11 (a)), this test revealed that there were significant differences between the



(a) IPQ presence (b) sensation closeness (c) thermal closeness



(a-1) IPQ involvement (a-2) IPQ realism (a-3) IPQ spatial presence

** : p<.01, * : p<.05 † : p<.10

**FIGURE 11.** Responses to the Igroup Presence Questionnaire and two additional questions The IPQ is measured on a 5-point Likert scale. Two additional questions were measured with a numerical value ranging from 100 to 0. The median, interquartile ranges, maximum, and minimum values and the result of the Wilcoxon signed-rank test with Holm-Bonferroni correction are shown.

conditions ($\chi^2(3) = 8.56, p < 0.05$). Because the Friedman test revealed significant differences, the Wilcoxon signed-rank test was conducted as a post hoc test. Because this test is a six-fold multiple comparison, the Holm-Bonferroni correction was applied to the Wilcoxon signed-rank test. There was a significant difference between NoDisplay and DependOnMove ($Z = 3.04, p < 0.01$).

We analyze each factor of IPQ below. For IPQ involvement (see Figure 11 (a-1)), the Friedman test revealed that there were significant differences between the conditions ($\chi^2(3) = 10.46, p < 0.05$). The post hoc Wilcoxon signed-rank test with Holm-Bonferroni correction revealed that there was a significant difference between NoDisplay and DependOnMove ($Z = 3.24, p < 0.01$). There was also a marginal difference between NoDisplay and High_Stable ($Z = 2.43$, $p < 0.10$).

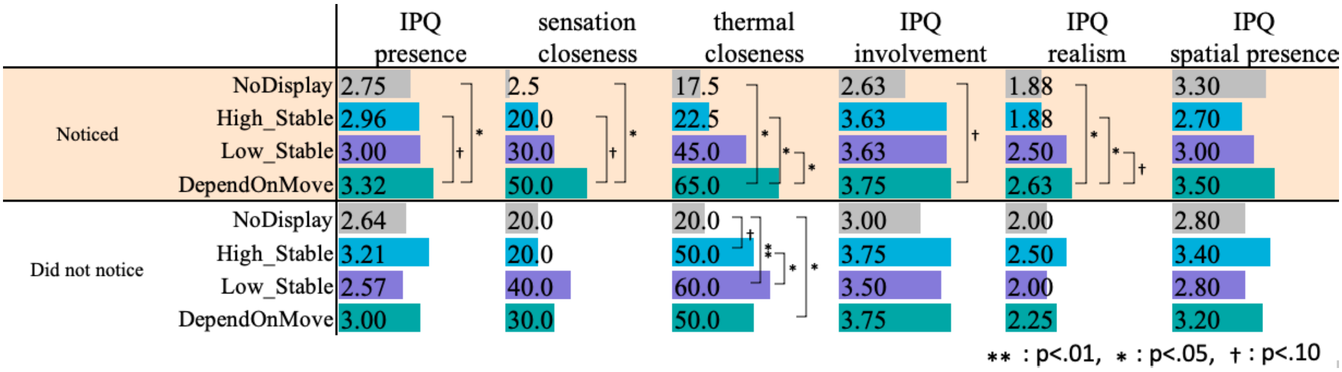
For IPQ realism (see Figure 11 (a-2)), the Friedman test revealed that there were significant differences between the conditions ($\chi^2(3) = 8.40, p < 0.05$). post hoc Wilcoxon signed-rank test with Holm-Bonferroni correction revealed that there was no significant difference between any pair ($p > 0.10$).

For IPQ spatial presence (see Figure 11 (a-3)), the Friedman test revealed that there was no significant difference between the conditions ($\chi^2(3) = 5.97, p > 0.10$).

We analyze about additional two questions below. For sensation closeness (see Figure 11 (b)), we posed the question "How close was the sensation you received throughout the VR experience to the sensation of water you felt in an aquarium?" The Friedman test revealed significant differences between the conditions ($\chi^2(3) = 19.03, p < 0.01$). post hoc Wilcoxon signed-rank test with Holm-Bonferroni correction revealed that there were significant differences between NoDisplay and High_Stable ($Z = 2.36, p < 0.05$), between NoDisplay and Low_Stable ($Z = 2.90, p < 0.05$), between NoDisplay and DependOnMove ($Z = 3.46$, $p < 0.01$), between High_Stable and DependOnMove ($Z = 2.79, p < 0.05$).

For thermal closeness (see Figure 11 (c)), we posed the question "How close was the temperature you felt in your hand to the sensation of the water you touched in the aquarium?", The Friedman test revealed significant differences between the conditions ($\chi^2(3) = 31.81, p < 0.01$). post hoc Wilcoxon signed-rank test with Holm-Bonferroni correction revealed that there were significant differences between NoDisplay and High_Stable ($Z = 2.44, p < 0.05$), between NoDisplay and Low_Stable ($Z = 3.32, p < 0.01$), between NoDisplay and DependOnMove ($Z = 3.68$, $p < 0.01$), between High_Stable and Low_Stable ($Z = 2.30$, $p < 0.05$), between High_Stable and DependOnMove

**TABLE 1.** Responses to IPQ and two additional questions divided between those who noticed the temperature change of DependOnMove and those who did not. Shown are the median. The upper row shows the results of the responses of the 10 people who noticed the temperature change. The bottom row shows the results of the responses of the 11 participants who did not notice the temperature change. The asterisk in each pair represents the p-value of the Wilcoxon signed-rank test with the Holm-Bonferroni correction.



| | | IPQ presence | sensation closeness | thermal closeness | IPQ involvement | IPQ realism | IPQ spatial presence |
|---|---|---|---|---|---|---|---|
| Noticed | NoDisplay | 2.75 | 2.5 | 17.5 | 2.63 | 1.88 | 3.30 |
| | High_Stable | 2.96 | 20.0 | 22.5 | 3.63 | 1.88 | 2.70 |
| | Low_Stable | 3.00 | 30.0 | 45.0 | 3.63 | 2.50 | 3.00 |
| | DependOnMove | 3.32 | 50.0 | 65.0 | 3.75 | 2.63 | 3.50 |
| Did not notice | NoDisplay | 2.64 | 20.0 | 20.0 | 3.00 | 2.00 | 2.80 |
| | High_Stable | 3.21 | 20.0 | 50.0 | 3.75 | 2.50 | 3.40 |
| | Low_Stable | 2.57 | 40.0 | 60.0 | 3.50 | 2.00 | 2.80 |
| | DependOnMove | 3.00 | 30.0 | 50.0 | 3.75 | 2.25 | 3.20 |

** : p<.01, * : p<.05, † : p<.10

($Z = 2.84$, $p < 0.05$). There was also a marginal difference between Low_Stable and DependOnMove ($Z = 1.81$, $p < 0.10$).

## B. DIVIDING BY THOSE WHO NOTICED TEMPERATURE CHANGE OR NOT

After completing all tasks (see Section IV-D), we asked the participants, "Did you notice that out of the four VR tasks, there was only one condition where the temperature changed when you moved your arm?" Ten participants out of 21 answered "Yes," and 11 answered "No." Let us analyze and compare the results of the questionnaire between these two groups.

Table 1 shows the responses to IPQ and additional two questions, divided between those who noticed the temperature change of DependOnMove and those who did not. In the responses of those who noticed the temperature change (Noticed below), DependOnMove was rated the highest for all items. On the other hand, in the responses of those who did not notice the temperature change (Did not notice below), the DependOnMove condition was not the highest (except for IPQ involvement).

As in Section V-A, the Friedman test and the post hoc Wilcoxon signed-rank test with Holm-Bonferroni correction were performed. For IPQ presence, among people who responded "Noticed," the Friedman test revealed that there were significant differences between the conditions ($\chi^2(3) = 9.88, p < 0.05$). The post hoc Wilcoxon signed-rank test with Holm-Bonferroni correction revealed that there was a significant difference between NoDisplay and DependOnMove ($Z = 2.70, p < 0.05$). There was also a marginal difference between High_Stable and DependOnMove ($Z = 2.31, p < 0.10$). In people who "Did not notice", there was no significant difference between the conditions ($\chi^2(3) = 1.69, p > 0.10$).

We analyze each factor of IPQ below. For IPQ involvement, in the Noticed group, the Friedman test revealed marginal differences between the conditions ($\chi^2(3) = 7.57$, $p < 0.10$). The post hoc Wilcoxon signed-rank test with Holm-Bonferroni correction revealed that there was a marginal difference between NoDisplay and DependOnMove ($Z = 2.37, p < 0.10$). In the "Did not notice" group, there was no significant difference between the conditions ($\chi^2(3) = 3.55, p > 0.10$).

For IPQ realism, in the Noticed group, the Friedman test revealed that there were significant differences between the conditions ($\chi^2(3) = 14.35, p < 0.01$). The post hoc Wilcoxon signed-rank test with Holm-Bonferroni correction revealed that there was a significant difference between NoDisplay and DependOnMove ($Z = 2.67$, $p < 0.05$) and between High_Stable and DependOnMove ($Z = 2.52, p < 0.05$). There was also a marginal difference between Low_Stable and DependOnMove ($Z = 2.17$, $p < 0.10$). In the "Did not notice" group, there was no significant difference between the conditions ($\chi^2(3) = 6.03$, $p > 0.10$).

For IPQ spatial presence, in the Noticed group, Friedman test revealed that there were marginal differences between the conditions ($\chi^2(3) = 7.06, p < 0.10$). The post hoc Wilcoxon signed-rank test with Holm-Bonferroni correction revealed that there was no significant difference between any pair ($p > 0.10$). In the "Did not notice" group, there was no significant difference between the conditions ($\chi^2(3) = 1.04$, $p > 0.10$).

We analyze the additional two questions below. For sensation closeness, in the Noticed group, the Friedman test revealed that there were significant differences between the conditions ($\chi^2(3) = 13.53, p < 0.01$). The post hoc Wilcoxon signed-rank test with Holm-Bonferroni correction revealed that there was a significant difference between NoDisplay and DependOnMove ($Z = 2.52, p < 0.05$). There was also a marginal difference between High_Stable and DependOnMove ($Z = 2.37, p < 0.10$). In the "Did not notice" group, the Friedman test revealed that there were significant differences between the conditions ($\chi^2(3) = 8.11, p < 0.05$). post hoc Wilcoxon signed-rank test with

Holm-Bonferroni correction revealed that there was no significant difference between any pair ($p > 0.10$).

For thermal closeness, in the Noticed group, the Friedman test revealed that there were significant differences between the conditions ($\chi^2(3) = 17.97, p < 0.01$). The post hoc Wilcoxon signed-rank test with Holm-Bonferroni correction revealed that there was a significant difference between NoDisplay and DependOnMove ($Z = 2.67, p < 0.05$), between High_Stable and DependOnMove ($Z = 2.67, p < 0.05$), between Low_Stable and DependOnMove ($Z = 2.52, p < 0.05$). In the "Did not notice" group, the Friedman test revealed that there were significant differences between the conditions ($\chi^2(3) = 18.69, p < 0.01$). The post hoc Wilcoxon signed-rank test with Holm-Bonferroni correction revealed that there was a significant difference between NoDisplay and Low_Stable ($Z = 2.93, p < 0.01$), between NoDisplay and DependOnMove ($Z = 2.50, p < 0.05$), between High_Stable and Low_Stable ($Z = 2.52, p < 0.05$), There was also a marginal difference between NoDisplay and High_Stable ($Z = 2.24, p < 0.10$).

### C. FREE RESPONSES ABOUT VR TASK

In addition to the IPQ and two additional questions, we also asked a free response question about the VR task at the end of the questionnaire. 7 participants out of 21 responded favorably to the proposed DependOnMove method (11 participants gave no answers to the free response questions).

- The temperature of the water was felt more in DependOnMove than in the other conditions.
- DependOnMove was the closest sensation to reality among the four trials. This was probably because the temperature change of the device followed the movement of the hand well.
- DependOnMove had a sensation closer to the actual water in terms of temperature change and vibration, but it was not felt as much in the High_Stable and Low_Stable.
- The coldness of the water was quite realistic in DependOnMove.

Meanwhile, two participants answered that they preferred a steady-state temperature presentation (Low_Stable).

- I thought that Low_Stable was very good at reproducing the temperature.
- Low_Stable seemed to be as realistic as DependOnMove. In particular, I think the coldness of water was well reproduced.

Both responses were from people who did not notice the temperature change depending on whether they were moving or not.

In addition, there were several comments on the implementation of hardware and software.

- In the aquarium task, I was concerned about the temperature of not only the palm of my hand, but also the back of my hand and my wrist. However, in the VR task, the temperature change was only on the palm of my hand, so I felt that the VR experience was not as good as the reality.
- The wires of the device were a bit disturbing.

## VI. DISCUSSION

### A. RESPONSES OF ALL

From the responses of all participants, DependOnMove provided a significantly higher sense of presence than NoDisplay in IPQ presence, sensation closeness, and thermal closeness. DependOnMove yielded significantly higher scores than High_Stable in sensation closeness and thermal closeness. This condition also yielded a marginally higher score than Low_Stable in thermal closeness. The median values of DependOnMove were the highest for all question items (see Figure 11). This result suggests that coldness presentation depending on motion enhances the sense of presence in a virtual underwater experience.

We considered each factor of IPQ. There were significant differences in involvement and realism, with DependOnMove being the most highly evaluated. There was no significant difference in spatial presence, but this study did not manipulate factors associated with spatial perception.

Based on the summary of the responses of all participants, the proposed method enhanced the involvement and reality of the underwater VR experience, which contributed to the enhancement of the sense of presence.

### B. A REASON FOR THE EFFECTIVENESS OF THE PROPOSED METHOD

We discuss why the proposed method enhanced the sense of presence.

In terms of how close was the temperature felt on their right hand to that of actual water (thermal closeness), DependOnMove was rated as the closest to the actual water that was touched in the aquarium. In the responses of the participants, there were comments such as "The coldness of the water was quite realistic in DependOnMove." and "DependOnMove was the closest sensation to reality among the four trials. This was probably because the temperature change of the device followed the movement of the hand well." These results suggest that the presentation of temperature changes in response to movement, which is similar to that of actual water, helped improve the sense of presence in a virtual underwater experience.

Kim *et al.* [43] stated that when people wear thermal display gloves and receive visual stimuli and thermal stimuli, the brain processes these two stimuli as if they were real situations, and they can experience a sense of presence. Humans accept multiple modalities of sensory information and take the weighted average of each sensory signal to understand the surrounding world [3]. Based on these factors, it can be said that the more modal the input information, the more clearly people can perceive the surrounding environment and the higher the sense of realism. Furthermore, similar to physical phenomena, coldness arrives synchronously with proprioceptive information and is considered to enhance the sense of presence because it matches the user's actual experience.

### C. ADVANTAGES OF THE PROPOSED METHOD COMPARED TO A STEADY LOW TEMPERATURE

Because DependOnMove < Low_Stable in terms of total amount of removed heat, DependOnMove successfully obtained the same (or better) effect of improving the sense of presence while reducing the amount of removed heat compared to Low_Stable. To sustain cooling, the heat dissipation is required, but if the temperature is kept low for a long time, the heat dissipation may not be able to keep up. In this experiment, 11 out of 32 participants were not included in the analysis due to screening (see V-A), 9 of which were not fully cooled in Low_Stable condition.

### D. COMPARING THOSE WHO NOTICED THE TEMPERATURE CHANGE AND THOSE WHO DID NOT

On the other hand, nearly half of the participants did not notice the cooling in response to the movement. Only 3 out of 21 people did not notice a temperature change in the actual water (all of them also did not notice the temperature change of the device). Comparing the results of the questionnaire between those who noticed the temperature change and those who did not (see Table 1), it may be observed that the trend of the results was different between those two groups. The different results of the Friedman test and the Wilcoxon signed-rank test for each group also support this.

For those who noticed the temperature change, DependOnMove was found to provide a significantly higher sense of presence than the other conditions including Low_Stable in terms of sensation closeness and IPQ realness.

For those who did not notice the temperature change, the median values of Low_Stable were the highest in sensation closeness and thermal closeness (see Table 1). As mentioned in IV-B, the total amount of heat removed by the various methods was in the order of Low_Stable > DependOnMove > High_Stable > NoDisplay. The total amount of removed heat was simply correlated with the sense of presence. For those who noticed the temperature change, DependOnMove was rated the highest even though the total amount of heat that was removed was lower than Low_Stable. From these results, it can be concluded that to further improve effectiveness of the proposed method, it is important to not only change the temperature but also to notice the temperature change.

### E. REASONS WHY SOME PARTICIPANTS DID NOT NOTICE THE TEMPERATURE CHANGE

We discuss why nearly half of the participants did not notice the temperature change.

There is the possibility that the range of the temperature change was simply too small. In particular, the fact that the coldness was presented to the fingertips, which have relatively low thermal sensitivity, may have had an effect. However, we consider that this is not the only reason why they did not notice temperature changes. In this experiment, the range of change must have been at least 1 °C (because of the screening mentioned in V-A). Stevens *et al.* [44] found that participants definitely noticed when their fingertips were cooled by 1 °C.

Meanwhile, it is possible that this was due to the fact that the movement was performed, and the proprioceptive information influence was dominant. This phenomenon is called tactile suppression [45], which refers to a reduction in tactile perception that occurs during movement.

### F. LIMITATION AND FUTURE WORKS

In this study, some parameters were determined heuristically. For example, the PID parameter was determined after careful tuning. The PID parameter affects the responsiveness and stability of temperature change. Temperature change rate when raising the temperature was also determined by pilot questionnaire. In addition, we focused on the physical phenomena that the thickness of the thermal boundary layer changes depending on the speed of motion. However, all the motions performed by the participants in the experiment were uniform at 0.2 m/s. Therefore, the effect of temperature change according to the movement speed was not confirmed.

Some participants answered that "the temperature change was only on the palm of my hand, so I felt that the VR experience was not as good as the reality," in free response section. We consider that this is not a problem for the elucidation of the research question, whether the proposed method enhances the sense of presence, because the conditions are aligned. However, if the findings of this study are to be applied to augment virtual underwater experiences, it may be necessary to consider changing the presentation body part and improving the device. The studies by Maeda *et al.* [17], [18] would be helpful for hardware design.

The proposed method can be used for various types of underwater worlds in VR applications, such as entertainment, rehabilitation, and training. In particular, it is expected to be useful for diving education [1] because it has been shown that skin sensory stimulation increases the learning effect in VR training [46].

Furthermore, to improve the effectiveness of the proposed method, this method should be modified so that more people notice the temperature change. We consider that introducing more exaggerated temperature changes to induce more people to perceive the temperature change could improve it. In a study that induced people to perceive the drag force of water by visual manipulation [27], it was found that the virtual drag force should be presented 4.05 times larger than the model based on physical phenomena. This is because the drag force was presented only to a limited part of the body and because it exhibited less modality (visual, audio, and virtual force). In this study, the coldness was presented only to the fingertip, and it presented less modality (visual, audio, and coldness). Therefore, as in [27], an exaggerated temperature change presentation may be effective.

In addition, the proposed method can also be used to present the sensation of virtual hot water, and this method is expected to be applied to relaxation in virtual hot springs. In the case of warm water, there is a concern about the lower sensitivity of warm sensations compared to cold sensations, but this may be solved by exaggerated temperature changes. Moreover, this method may be integrated with other systems that stimulate other modalities to further improve the sense of presence. Drag force presentation by visual manipulation [27], [28], buoyancy presentation by suspension systems [2], [47] can be integrated.

## VII. CONCLUSION

In this study, we have proposed a method that presents coldness depending on whether participants were moving their limbs. To provide a more realistic sensation, a temperature presentation model based on the physical phenomenon (thinning of the thermal boundary layer due to movement) was created. We conducted an experiment that compared the sense of presence between the steady-state temperatures of 24.9 ± 1.9 °C (Low_Stable) / 27.8 ± 2.7 °C (High_Stable) and the proposed method, the temperature of which moves back and forth between the aforementioned temperatures as user moves and stops. The results showed that the proposed method provided higher "closeness of overall sensation" and "closeness of thermal sensation" than High_Stable. This method also achieved the same improvement in the sense of presence as Low_Stable, while removing less heat. This extends the duration of the experience. Meanwhile, for those who noticed the temperature change, the proposed method was found to provide higher "realness" and "closeness of thermal sensation" than Low_Stable. To further improve effectiveness of the proposed method, it is important to not only change the temperature but also to notice the temperature change. This research provides a more concrete method for enhancing the sense of presence of virtual underwater experiences through coldness presentation. It is expected to satisfy the demands for such virtual experiences of underwater worlds in VR at a higher level.

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