Hydroptical Thermal Feedback: Spatial Thermal Feedback Using Visible Lights and Water

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Figure 1: Hydroptical Thermal Feedback works by shining visible lights onto the skin under water. We demonstrate its capabilities in psychophysical studies and physical measurements, showing that hydroptical thermal feedback is adjustable, spatial, and can offer a perceptual illusion that the water itself is warmer. We tested different light colors, including blue.

ABSTRACT

We control the temperature of materials in everyday interactions, recognizing temperature's important influence on our bodies, minds, and experiences. However, thermal feedback is an under-explored modality in human-computer interaction partly due to its limited temporal (slow) and spatial (small-area and non-moving) capabilities. We introduce *hydroptical* thermal feedback, a spatial thermal feedback method that works by applying visible lights on body parts in water. Through physical measurements and psychophysical experiments, our results show: (1) Humans perceive thermal sensations when visible lights are cast on the skin under water, and perceived warmth is greater for lights with shorter wavelengths, (2) temporal capabilities, (3) apparent motion (spatial) of warmth and coolness sensations, and (4) hydroptical thermal feedback can support the perceptual illusion that the water itself is warmer. We propose applications, including virtual reality (VR), shared water experiences, and therapies. Overall, this paper contributes hydroptical thermal feedback as a novel method, empirical results demonstrating its unique capabilities, proposed applications, and design recommendations for using hydroptical thermal feedback. Our method introduces controlled, spatial thermal perceptions to water experiences.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**.

KEYWORDS

Thermal display, Thermal feedback, Visible light, WaterHCI

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1 INTRODUCTION

Thermal sensation (*i.e.*, feeling warmth and coolness) plays a vital role in perceiving the environment, influencing our moods, and feeling intimacy. We might feel refreshed when swimming in the cool ocean or feel relaxed when bathing in a hot spring. The importance of thermal sensation is highlighted by how often we take actions to control it in everyday life: we choose our clothing for thermal comfort, we prepare our foods in specific temperatures to enjoy them, or we are encouraged/discouraged to go outside depending on the air temperature.

Despite the importance of thermal sensation, its applications in human-computer interaction (HCI) are relatively under-explored. This in part owes to the limited spatio-temporal capabilities, presentation area, and temperature range in existing thermal feedback methods. In other words, thermal feedback typically tends to change temperature slowly, be limited to a small area, and does not move around on the skin. Common methods for thermal feedback use direct contact of a thermally dynamic material touching the skin, leading to limited presentation area. The range of perceived warmth and coolness that a display can offer is also often limited. For example, commonly used Peltier modules [33] can provide both warmth and coolness in contact with skin by changing surface temperature, but cannot provide sudden thermal feedback and are not suitable for feedback on a large area.

Thermal feedback that can cover a large area with high spatio-temporal capabilities and wide temperature range is crucial for thermal interactions. If thermal feedback covers a large area, it gives us the sense of immersion that we have when experiencing ambient temperature of different weathers, times, or seasons [20]. If it moves, we can feel the warmth of human touch. If it is moderately responsive, we can experience the dramatic temperature changes when entering pools and hot springs and can use it in interactive applications [22]. Therefore, providing interactive, movable warmth and coolness over a large area opens up vast thermal interaction opportunities.

In this paper, we contribute a novel thermal feedback method, *hydroptical*. Hydroptical thermal feedback works by applying visible light to a person's skin under water, which makes the person perceive warmth (Fig. 2). When visible light is cast through water onto the skin, it directly heats the skin, providing warmth, and can be switched to cold by turning off the lights. Hydroptical thermal feedback is unique because it combines underwater, interactive, spatial characteristics. Spatial means the system can support warmth/coolness apparent motion, a sense of warmth or coolness moving along the skin. This method works on the entire underwater body part without any devices attached to the skin.

We demonstrate these characteristics of hydroptical thermal feedback through four studies. For each study, participants submerged their forearm underwater and experienced visible lights shining through the water onto their arm, while wearing a blindfold so they could not see the light. The studies show:

(1) Shining visible lights through water provides warmth by directly heating up the skin.
(2) Turning off the lights provides coolness.
(3) Hydroptical thermal feedback is interactive. It can change skin temperature quickly, so it offers a shorter reaction time than many non-contact thermal feedback systems.
(4) Hydroptical thermal feedback is spatial. Participants perceive continuous movements of warmth and coolness on their skin.
(5) Uniform hydroptical thermal feedback from surrounding light sources evoke illusory perceptions of water temperature changes. The user feels as if water gets warmer or cooler even though the actual water temperature stays the same.

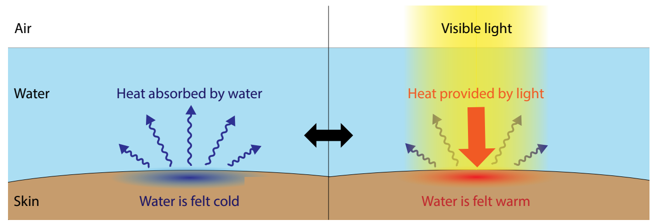

Figure 2: Mechanism of hydroptical thermal sensation. A body part is submerged in water and the water is below body temperature. (left) With lights off, the water is perceived as cool; this is how we normally perceive cool water in everyday life. (right) With lights on, visible light provides heat to the skin and so the water is felt as warm. The lights can be turned on/off to dynamically change the perception of warm/cool.

2 RELATED WORK

2.1 Thermal Perception

In developing and evaluating thermal feedback methods, device and experimental designs considering thermal perceptual characteristics are necessary [36]. This section introduces background on human thermal perception mechanisms and the associated thermal perceptual characteristics, providing background for discussing thermal feedback methods and their evaluations.

Changes in skin temperature are detected by warm and cold thermoreceptors. The density of these receptors varies depending on the body part, but in all areas, cold thermoreceptors have a higher density than warm thermoreceptors. Cold thermoreceptors are scattered closer to the skin surface [8] and have faster centripetal nerve conduction velocities [3] than warm thermoreceptors. Additionally, both types of receptors show static and dynamic responses to absolute temperature and temperature change rates. Moreover, when the skin temperature exceeds 45 °C or falls below 15 °C, nociceptors respond, leading to the sensation of pain. Within the warm and cold thermoreceptors, temperature stimuli are converted into electrical and chemical signals by ion channels called temperature-activated Transient Receptor Potentials (TRP). Among them, TRPV1 and TRPV2 are activated by warmth in the nociceptive (pain) range, TRPV3 and TRPV4 are activated by warmth outside that range, TRPA1 is activated by coldness in the nociceptive range, and TRPM8 is activated by coldness outside that range. Interestingly, TRPV1 is also activated by capsaicin, and TRPM8 is activated by menthol, thus these chemical substances can induce temperature sensations as well [2, 57].

Next, we describe the thermal perceptual characteristics reflecting the aforementioned perceptual mechanisms. Owing to the uneven distribution of thermoreceptors, thermal perceptual sensitivity varies by body part, with sensitivity to cold stimuli generally higher than to warm stimuli. For instance, when the skin temperature people between the ages of 18 and 28 changes from 33 °C, the detection thresholds for warm and cold stimuli are 0.17 °C and 0.09 °C for the thenar and 0.23 °C and 0.13 °C for the fingertip, respectively [72]. Moreover, as receptors respond to temperature change rates, humans perceive temperature changes based on a threshold of 0.1 °C/s. Skin adaptation temperature also affects detection thresholds; sensitivity to warm stimuli increases with adaptation to high temperatures, while sensitivity to cold stimuli increases with adaptation to lower temperatures [42]. Furthermore, human thermal perception exhibits spatial summation characteristics in response to weak temperature stimuli, where the intensity is supported by the area of temperature stimuli to maintain threshold values [23, 50, 74]. Therefore, even weak temperature stimuli can induce thermal perception when presented over a wide area. Conversely, due to spatial summation effects, the spatial resolution of human thermal sensation is lower compared to other tactile sensation. For example, people may not discriminate between two weak temperature stimuli 150 mm apart on the forearm [77]. Additionally, thermal perception also demonstrates temporal summation characteristics for stimuli lasting less than 1 sec, where duration and intensity are exchanged to maintain threshold values [73]. Another important temporal characteristic is reaction time to temperature stimuli, which increases which increases the further the skin is from the brain [14, 15]. Mean reaction times measured from the moment skin temperature reaches the perception thresholds are approximately 500 ms for cooling and 700 ms for warming on the hand [86]. Owing to this inherent delay in thermal perception, real-time applications necessitate the provision of thermal stimuli above the thresholds quickly and within a painless range. In evaluating thermal feedback methods, experimental designs considering the effects of the aforementioned thermal perceptual characteristics, such as standardizing stimulus location, area, and adaptation temperature, and applying stimuli lasting more than 1 sec to avoid the temporal summation, are necessary.

2.2 Thermal Feedback Methods

2.2.1 Contact-based thermal feedback. Thermal feedback methods are divided into contact and non-contact methods based on whether the user is in contact with the display / actuator or not. Contact methods are often used in wearable devices providing localized thermal feedback to the skin. Peltier modules are a prevalent contact method [26, 33]. By controlling the voltage, users can experience various temperature changes by directly touching the Peltier modules. For example, Dionisio [10] reproduced warmth in a virtual space with a Peltier module attached on the user's forearm. However, Peltier module's temporal responsiveness is insufficient to display sudden temperature changes. Some methods have been proposed to virtually enhance their responsiveness [6, 66].

Fluid-based heat conduction is often used when fast-switching thermal feedback is needed. It changes the skin temperature rapidly by changing the fluid temperature flowing through a thermal display unit in contact with the skin. A similar principle is used in liquid cooling for a central processing unit (CPU) of a computer. Liquid is widely used as the thermal medium [7, 9, 16, 18, 44, 47, 51, 65], while air is also used [5]. For example, Han *et al.* [22] controlled the water temperature flowing through a latex tube attached to the fingertip to provide rapid thermal feedback.

Other contact methods include resistive heating [13, 55, 68, 70, 75, 81, 88], dielectric heating [45], direct contact to liquid [62], electrical stimulation [41, 64], chemical stimulation [48], thermal conductivity control [24], gel packs [35], and visual-thermal interactions [40].

2.2.2 Non-contact thermal feedback. Non-contact methods realize thermal interactions without actuators contacting the skin. They are particularly useful for casual, museum, public, shared, or large-scale settings, where users want to switch easily between the interactions and daily activities, when the users should encounter the interactions, or when they want to avoid infections. They are also suitable for switching between warming and cooling owing to the lack of actuator's residual heat. Contact actuators must undergo a transient period of cooling from high to low temperature when switching from warming to cooling, while non-contact ones can switch it instantly. For example, Peltier modules need to continuously lower their own temperature, while non-contact actuators can instantly switch the output to cooling. Infrared heating is a prevalent non-contact method [10, 30, 32, 34, 85]. Like people feel the warmth of the sunlight or a fireplace, users can experience various thermal sensations with infrared rays. In contrast to contact methods, users do not have to touch the device. For example, Lécuyer *et al.*[46] reproduced the warmth of the sunlight in virtual reality by controlling infrared lamps around the user.

To improve the temporal resolution (refresh rate) of this method, some studies mechanically controlled the infrared irradiance using shutters instead of controlling the source output [31, 79]. Recently, visible light, whose wavelength is shorter than infrared rays, were also used to provide fast-switching warmth remotely [84]. Additionally, Yamamoto *et al.*improved the spatial resolution of mid-air thermal sensation by using a double-layered array of rectangular mirrors [85]. Iwai *et al.*provided thermal sensation on the skin with a high spatial resolution with an infrared projector [34].

In contrast to the lights, liquid can provide both thermal and haptic sensations in a non-contact manner. Richter *et al.*shot water jets toward the fingertip touching a surface [62]. Gunawaradena *et al.*controlled water temperature in a water tank. [17]. Hoshino *et al.*controlled a shower nozzle output [29]. Han *et al.*used water drops to reproduce rain [20]. Although they make the skin wet, which potentially limits their applications, the accompanying haptic sensations of water offers unique experiences.

Other non-contact methods include heat medium transportation [12, 20, 49, 54, 69, 78, 82], humidity adjustment [25], ultrasound [39], mist vaporization [19, 53], laser [38], electric arc [71], chemical stimulation [2], and visual-thermal interaction [11, 80, 83]. For example, Nakajima *et al.* [54] blew cooling mist to the user's skin using an ultrasound phased array.

Hydroptical thermal feedback is a non-contact method because its actuator (light source) is not in contact with the skin. Many of the aforementioned non-contact methods provide either warming or cooling sensation. The current method achieves both by integrating visible light heating and passive cooling with water through which the heating light shines on the skin. As discussed earlier, contact and non-contact methods have different advantages and disadvantages (*e.g.*, contact methods require contact but generally achieves higher spatial resolutions, while non-contact methods can work on multiple users without making them touch the devices). These properties lead to unique applications. In section 6, we propose applications that take advantage of its unique characteristics such as non-contact, spatial, and immersive underwater properties.

3 HYDROPTICAL THERMAL SENSATION

Our water temperature perception depends primarily on skin temperature. When our skin is in contact with cold water, heat is transferred from our skin to the water resulting in a decrease in skin temperature until it reaches an equilibrium. This temperature change and the resulting temperature of the skin form our water temperature perceptions. Therefore, our water temperature perceptions can be mediated when our skin receives heat from sources other than water. For example, if the heat given to the skin from the outside is greater than the heat that cold water takes away from the skin, we may perceive the water as warm, or at least, we should perceive some warmth. And if the externally provided heat is gone, we may perceive the water as getting colder.

We hypothesize that the perceived water temperature (or simply thermal sensation) can be altered in both directions by controlling the external heat given to the skin in constant-temperature water, and will examine this hypothesis through studies. We evaluate visible light as a means of transferring heat. Because water absorbs most infrared, infrared via water will not reach the skin and only increase the water temperature, but since most visible light penetrates water, it is expected that the skin can be selectively warmed. In other words, we expect that visible light will shine through the water (not get absorbed by water) and warm the skin without warming the water. Section 4.1 will primarily test whether visible light can provide a sensation of warming on skin under water. In addition, because visible light has different absorption rates in water and skin depending on wavelength, section 4.1 will also compare visible light with various wavelength spectra in terms of skin and water temperature changes.

4 PSYCHOPHYSICAL STUDIES

We empirically evaluate the perceptual characteristics of hydroptical thermal feedback through a series of psychophysical studies. All studies were approved by our Institutional Review Board. For all studies: Participants were recruited via social media. Participants signed a consent form and received a $25 Amazon gift card. Participants wore a blindfold so that seeing the lights would not influence their responses. For the water tank in which we did hydroptical thermal feedback, the water temperature was monitored and maintained between 25.0 °C and 26.0 °C.

4.1 Study 1: Effect of Light Wavelengths on Perceived Warmth & Skin Temperature

We first investigate whether people feel thermal sensations when lights are cast on skin underwater and how lights in different visible wavelengths (*i.e.*, lights of different colors) affect the sensations. As shown in Figure 3, participants submerged their right hands in water and kept the palm 50 mm away from the LED. Once the LED was turned on and off, they rated the perceived warmth intensities.

4.1.1 Participants. The experiment involved 8 participants (4 self-identified males, 4 self-identified females; age: 4 in age range 18-19, 3 in 20s, 1 in 30s).

4.1.2 Apparatus. A Python program controlled the 100 W Chip-on-Board LED lights (CHANZON 1DGL-JC-100W[1]) via a micro-controller (Arduino Uno R3[2]) and motor drivers (ANMBEST FET-1[3]). An eye mask was used to block visual cues. A water tank was filled with 25 °C water. A laptop computer was used to fill the pre-experiment demographic questionnaire. Temperature sensors (Alpha Technics Thermistor) were used to measure water and skin temperatures. Their wires were coated with waterproof polymer, and their sensing parts were covered with aluminum tapes to prevent the direct heating by the light.

4.1.3 Conditions. In a pilot study, we examined the water and skin temperature as well as perceived warmth with seven LEDs with different spectra: 100 W LEDs of Warm-white (rated color temperature 3000-3500 K), Natural-white (4000-4500 K), White (4000-4500 K), Cool-white (6000-6500 K), Green (rated peak wavelength 520-525 nm), Blue (460-470 nm), and Royal-blue (440-445 nm). Based on this pilot study, we selected four LED lights to be examined in Experiment 1: Warm-white, Cool-white, Green, and Blue. This selection was made to reduce the number of conditions while ensuring the diversity in the spectra, measured skin temperature rises, and perceived warmth. Figure 4 shows the spectra of the selected lights measured through an empty water tank (*i.e.*, through two 5 mm low-iron glass walls) and the water tank filled with water (600 mm underwater travel distance). The LED was placed 50 mm away from the palm. The room temperature was maintained between 21.7 ℃ and 23.5 ℃ throughout this and the following studies.

4.1.4 Procedure. Participants stayed in the experiment room for ten minutes before the experiment started in order to adapt to the air temperature. While waiting, participants took a seat and were briefed on the experiment, procedures, data handling, risks, and rights and were instructed to sign a consent form if they agreed. Once they agreed, they filled the pre-experiment demographic questionnaire.

Practice trials were conducted before the experiment to reduce learning effects. The participants put the temperature sensors on the palm and wore eye masks, and the fit was adjusted as needed. They did four practice trials (one for each light condition).

After the practice trials, the main experiment started. The participants kept the temperature sensors and eye masks from the practice trial. The following procedure was repeated for each trial. The participants submerged their hands in water and waited for 20 sec to make sure their thermal sensations are adapted to the water temperature. Then, the light is turned on for 5 sec and turned off. They were instructed to report their thermal sensation in the provided scale (*i.e.*, 0: not at all - 3: significant). Once they reported it,

[1]https://a.co/d/0aI2WFKK
[2]https://docs.arduino.cc/hardware/uno-rev3/
[3]https://a.co/d/03igrCzm

Summary of Psychophysical Studies				
Study	**Independent Variable**	**Dependent Variables**	**Results Summary**	**Key Takeaways**
1	Light color (Blue, Green, Cool-White, Warm-White)	• Self-reported perceived warmth rating • Skin temperature • Water temperature	Cool-White and Blue have the greatest increase in skin temperature and highest warmth ratings, followed by Warm-White and Green.	**It works**; hydroptical thermal feedback is rated as warm by participants. Skin temperature increases. Water temperature remains constant.
2	Light illuminance	• Self-reported perceived warmth rating • Skin temperature • Water temperature • Reaction time to warm stimulus onset	More intense light increases skin temperature more and is rated as warmer. The relationship between skin temperature and perceived warmth can be modeled by Stevens' law. Reaction time was about 1.0-1.4s across all light intensity levels.	**It is interactive**; skin temperature was changed instantly and participants' reaction time in perceiving the warmth were shorter than or equal to the methods used in real-time applications.
3	Delay time of turning lights on/off at different locations (SOA, stimulus onset asynchrony)	• Self-reported continuity rating	Participants reported feeling continuity as the lights at different locations turned on/off in series. Depending on the sequence of lights turning on and off, participants could feel a sense of warmth or coolness moving along their arm. The optimal delay time for a continuous warmth movement is between 200 and 600 ms.	**It is spatial**; hydroptical thermal feedback can present warm/cool sensations that move smoothly on the skin.
4	Light illuminance	• Self-reported perceived water temperature	Perceived water temperature can be controlled by varying light intensity. The most intense light raised the perceived water temperature by 13 ℃ on average.	**It changes perceived water temperature**; uniform feedback across underwater skin is perceived as water temperature changes rather than warmth on the skin.

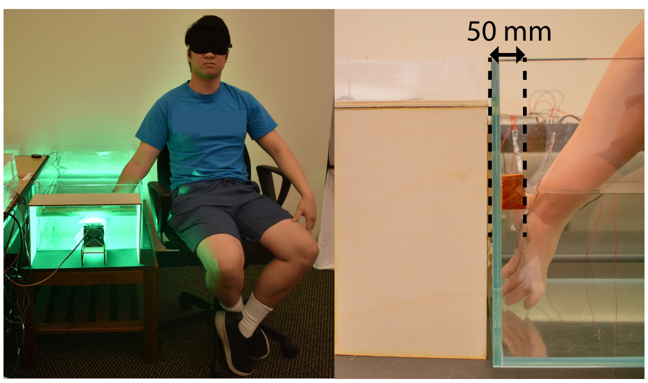

Figure 3: The experiment setup for study 1. A temperature sensor is attached on the participant's palm. The distance between the LED and the palm was fixed to approximately 50 mm with a wooden bar. The LED position was adjusted to the palm position for each participant.

water temperature was adjusted to 25.0 - 26.0 °C by replacing some water with cooler water. Then, the next trial started 20 sec after the adjustment to make sure their thermal sensations are adapted to the water temperature again. The trials were repeated in a randomized order for 48 times (*i.e.*, 12 trials for each light condition) for each participant.

After the final trial, semi-structured interviews were conducted for approximately five to ten minutes. The entire experiment lasted approximately 70 min.

4.1.5 Results. The measured changes in the skin temperature and water temperature for the tested lights are shown in Figure 5. The graphs show that the skin temperatures rose immediately after the lights are turned on and that the water temperature stayed constant for all the light conditions. These physical measurements suggest that visible lights can directly increase the skin temperatures under water. When compared in terms of the skin temperature, the Cool-White and Blue lights appear to raise the skin temperature more than the others. The Green light caused the smallest skin temperature rises.

The subjective warmth ratings results are shown in Figure 6. The percentages of trials where participants perceived warmth (*i.e.*, they rated thermal perception above 0) were 97.9, 82.3, 99.0, and 94.8 % for Blue, Green, Cool-White, and Warm White, respectively. These results suggest that visible lights evoke warmth perceptions on the skin in water. The semi-structured interviews also suggested that all the participants perceived warmth when the lights were turned on and coolness when the lights were turned off.

As these ratings data were nonparametric, we performed the Friedman test with the null hypothesis that there is no difference in warmth ratings between different light spectra. The Friedman test revealed significant main effects of light spectra on the warmth ratings ($\chi^2(3) = 18.3$, $p = .000$, Kendall's $W = .655$). Therefore, using the Holm-Bonferroni–corrected Wilcoxon signed-rank test, the post-hoc analyses were performed on the light spectra factor. The Blue light led to significantly higher warmth ratings than the Green ($p = .047$, cohen's $d = 2.711$) and Warm-White lights ($p = .047$, cohen's $d = 1.876$). The Cool-White light resulted in significantly higher warmth ratings than the Green light ($p = .039$,

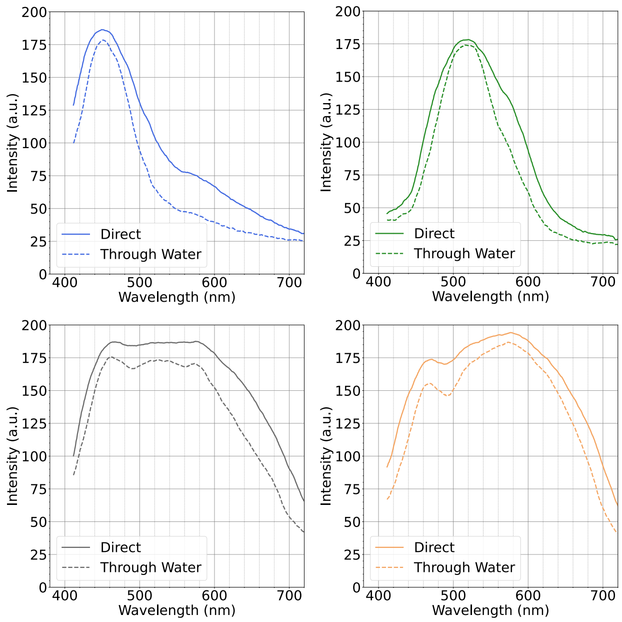

Figure 4: The spectra of different LED lights measured directly and through a 600 mm water tank: Blue (top left), Green (top right), Cool-white (bottom left), and Warm-white (bottom right). The vertical values are in an arbitrary unit and indicates relative intensities.

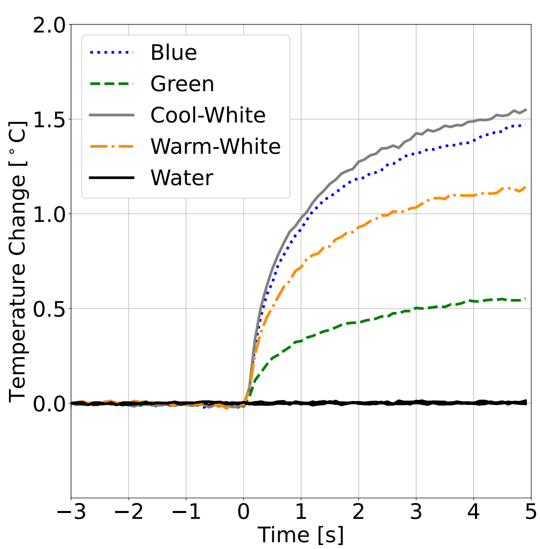

Figure 5: The temporal changes in the average skin temperature in Experiment 1. The lights were turned on at t = 0 [s]. The values are the temperature changes from t = -3 [s].

cohen's d = 2.931). The Warm-White light resulted in significantly

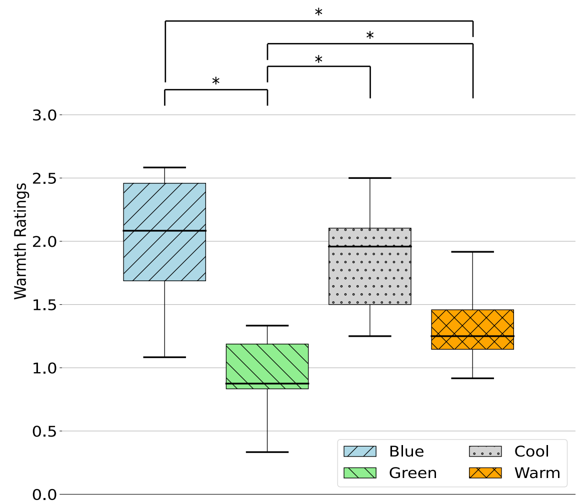

Figure 6: The warmth ratings for lights with different spectra. The * indicates a significant difference (p < 0.05).

higher warmth ratings than the Green light (p = .031, cohen's d = 1.189).

These results show that the Green light provides less warmth than the other lights. A possible reason for this poor performance of Green light is its relatively lower intensity in the whole visible light range as shown in Figure 4. The Green light LED may not convert the electric power to the light output as effectively as the other LEDs. The results also suggest that the Blue light leads to a stronger warmth than the Warm-White. There is no significant difference between the Blue and Cool-White lights. When compared in terms of light intensities in different wavelength regions (Figure 4), the Blue has higher light intensities than the other two in the 410-450 nm range, the Cool-White has higher intensities in the 460-530 nm range, and Warm-White has higher intensities in 530-700 nm range. The poorer performance of Warm-White implies that visible lights with wavelengths shorter than 530 nm provide heat more effectively to the underwater skin. As the Cool-White dominates the Blue in the light intensities in the 460 nm- range, the similar performances of Blue and Cool-White further suggest that visible lights with shorter wavelengths provide heat more effectively to the underwater skin even within the 410-530 nm range. These are consistent with the in-vivo absorbance measurement results from a previous study, where the absorbance dramatically increases for visible lights with shorter wavelengths on the dorsal arm and the upper inner arm regardless of skin tones [76]. It is also important to note that visible lights with shorter wavelengths become more effective as their underwater travel distance gets longer because water's light absorption rate gets lower for shorter wavelengths in the visible light range [60].

4.2 Study 2: Perceptual Intensity and Temporal Characteristics

In section 4.1, we showed that visible lights provide both warmth and coolness perceptions and that the Blue and Cool-White lights achieve it more effectively than the others. Since the Cool-White light has less intensities than the Blue light in the <450 nm wavelength range, it is considered to be safer for both eyes and skin. Additionally, Cool-White LEDs are more available and approachable than the Blue ones in the consumer market owing to its wide applications in daily lives. Thus, we focus on the Cool-White light in the following evaluations and applications of hydroptical thermal feedback.

In this section, we further investigate the intensities and temporal characteristics of the warmth perceptions caused by hydroptical thermal feedback with the Cool-White light.

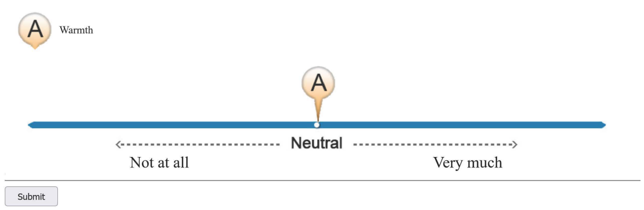

Figure 7: Visual Analogue Scale (VAS) used to rate the warmth in Experiment 2. Participants were instructed to move the slider in the range between "Not at all" and "Very much".

We investigate the intensities of perceived warmth for varied light illuminances through a within-subjects, repeated-measures psychophysical study. The Visual Analogue Scale (VAS) shown in Figure 7 was used to rate the subjective perceived warmth. The VAS was used instead of the 4-point Likert scale used in section 4.1 because our current focus is to investigate the warmth intensities at varied light levels rather than confirming the warmth perceptions. We also evaluated the temporal characteristics of the perception of hydroptical thermal feedback by measuring the reaction time of participants against the light.

4.2.1 Participants. The experiment involved eight participants (1 male, 7 females; age: 1 in 18-19, 7 in 20s). Participants also joined the following Study 3 in the same session, signing the consent form once and receiving one $25 gift card.

4.2.2 Apparatus. The apparatus from section 4.1 was used. The light illuminance on the hand was controlled by switching the pwm signals to the driver.

4.2.3 Conditions. We investigated the skin temperature change, subjective perceived warmth, and reaction time for Cool-White lights with three illuminances on the hand. The illuminances of 210, 433, and 635 klux were measured for the examined power levels of 1/3, 2/3, and 3/3. Their spectra are shown in Figure 8. These illuminance values are the average of that at the center of the light spot on the hand and that 0.05 m lateral to the center. As the hand is close to the light source (0.05 m from the lens), each illuminance value on the hand was obtained based on the measured values at the distances of 0.25, 0.30, and 0.35 m from the light source (the maximum coefficient of variation between the estimates from each distance was 6.84%). It is important to note that these were measured in the air. The setup is the same as Figure 3. The distance between the LED and the palm was 50 mm.

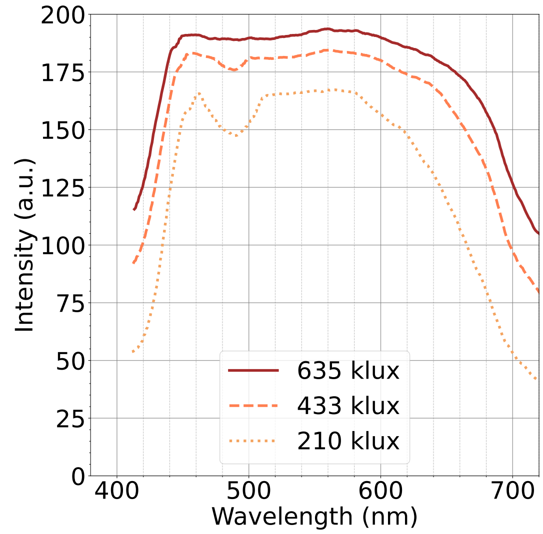

Figure 8: Spectra of the Cool-White LED light with varied illuminance: 210, 433, and 635 klux, corresponding to the 1/3, 2/3, and 3/3 pwm signals.

4.2.4 Procedure. The same pre-study procedure as section 4.1 was taken.

After the practice trials, the main experiment started. The following procedure was repeated for each trial. The light was turned on for 3 sec and turned off. They were instructed to press a space key on a keyboard in front of them as soon as they felt warmth on their hands. Then, the participants rated the warmth in the Visual Analogue Scale (VAS) on a laptop (not at all - very much) as shown in Figure 7. Water temperature was adjusted to 25.0 - 26.0 °C. The next trial started 20 sec after the adjustment to ensure thermal adaptation. The trials were repeated in a randomized order for 36 times (*i.e.*, 12 trials for each light condition) for each participant.

After the final trial, semi-structured interviews were conducted for approximately five to ten minutes. The entire experiment lasted approximately 40 min.

4.2.5 Results. The measured changes in the skin temperature for the tested illuminances are shown in Figure 9. It shows that different illuminances achieve different rates of skin temperature rise.

The subjective warmth ratings results are shown in Figure 7. As these ratings data were nonparametric, we performed the Friedman test with the null hypothesis that there is no difference in warmth ratings between different illuminances. The Friedman test revealed significant main effects of illuminances on the warmth ratings ($\chi^2(2) = 6.25$, $p = .044$, Kendall's $W = .298$). Therefore, using the Holm-Bonferroni–corrected Wilcoxon signed-rank test, the post-hoc analyses were performed on the light level factor. The 635 klux light led to a significantly higher warmth ratings than the 433 klux ($p = .047$, cohen's $d = 1.203$) and 210 klux lights ($p = .039$, cohen's $d = 2.028$). The 433 klux light resulted in significantly higher warmth ratings than the 210 klux light ($p = .047$, cohen's $d = 0.983$).

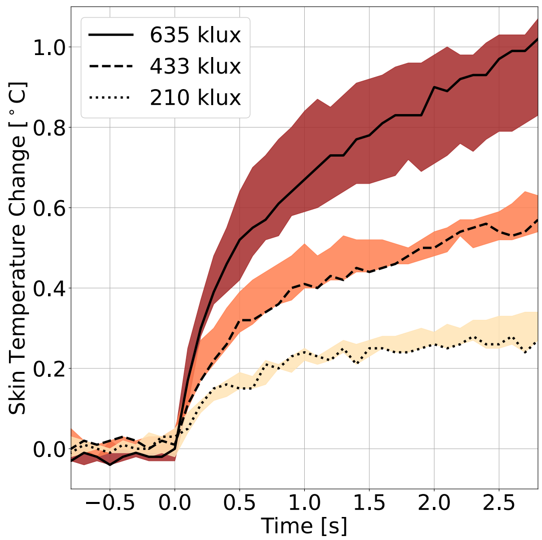

Figure 9: The temporal changes in the average skin temperature in Experiment 2. The values are averaged over all the trials in each condition for each participant. The shades show the ranges between the maximum and minimum values at each time step. The lines show the data for the participants with the most median values in t = 0.0 - 3.0 [s].

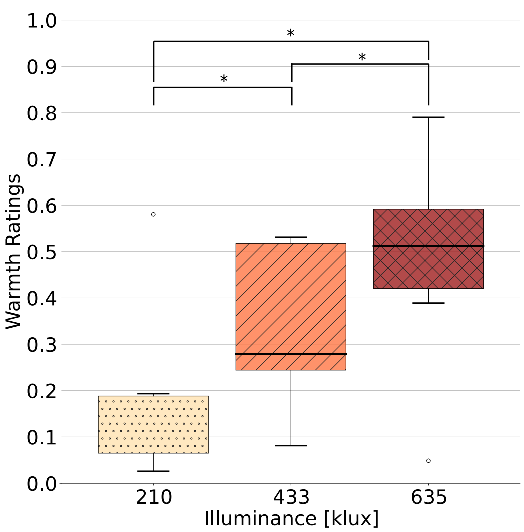

Figure 10: The subjective warmth ratings for the illuminances of 210, 433, and 635 klux. The * indicates significant differences (p < .05).

These results show that hydroptical thermal feedback can control perceived warmth intensities by varying light illuminances.

To analyze the relationship between the skin temperature rise and the perceived warmth, the perceived warmth ratings for each skin temperature rise 1.0 [s] after the light is turned on were plotted

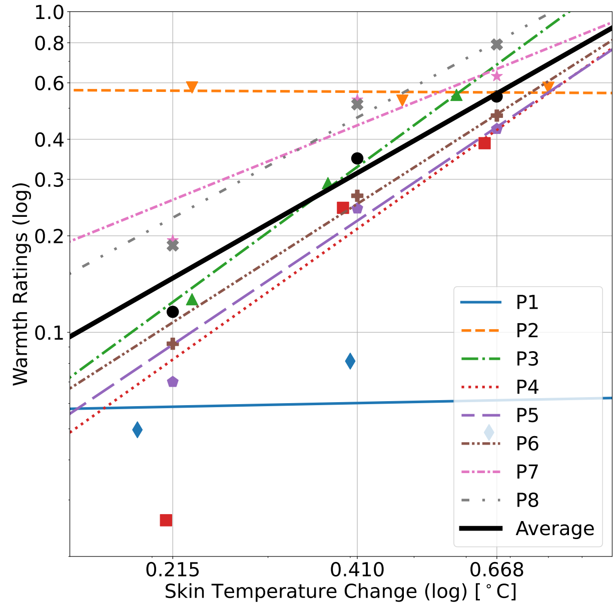

Figure 11: The points show the warmth ratings for the corresponding skin temperature rises (1.0 [s] after the 210, 433, and 635 klux lights are turned on). The lines are the fitted power functions.

in Figure 11. We apply the Stevens' law, an established method for modeling the relation between physical quantity and perceptual intensity:

$$\psi = k\phi^{\alpha} \tag{1}$$

, where ψ is the perceived intensity, ϕ is the physical quantity of the stimulus, α is the intrinsic power exponent for the perceptual modality, and k is a constant of scale. We fitted this function to each participant's data as well as the average data as shown in Figure 11. As the P1 and P2 appear to show different trends from the other participants, we excluded their data when obtaining the average. The resulting functions are the model for how the skin temperature rise relates to the perceived warmth intensity in hydroptical thermal feedback. The thick black line is the model fitted to the average responses. The similarities between the obtained models for the participants other than P1 and P2 imply that our results are reproducible for various participants. The obtained average model is as follows:

$$\psi = 0.890\ \phi^{1.169} \qquad (R^2 = 0.975) \tag{2}$$

The measured reaction time data for each illuminance is shown in Figure 12. The median reaction times were 1.38, 1.14, and 1.06 [s] for 210, 433, 635 klux lights, respectively. We performed the one-way ANOVA with the null hypothesis that there is no difference in reaction time between different illuminances. The one-way ANOVA showed no significant main effects of illuminances on the reaction time ($F(2, 95) = 0.51$, $p = .609$, $\eta_p^2 = .011$). These suggest that people can perceive and react to hydroptical thermal feedback within approximately 1.0 - 1.4 [s] for all the tested light levels.

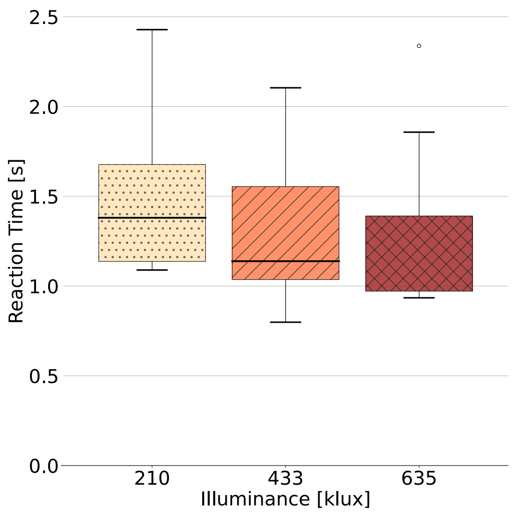

Figure 12: The reaction time of the participants to the warmth stimuli of hydroptical thermal feedback for the illuminances of 210, 433, and 635 klux.

This measured reaction time is close to or shorter than that of the spatially-divided Peltier module [66], which is widely used in real-time thermal interactions [58, 59, 89]. This is consistent with the skin temperature shown in Figure 9 rising without much delay at t = 0.0 [s]. Therefore, these results suggest that hydroptical thermal feedback can control perceived warmth intensity by adjusting the light illuminance on the skin and that this method provides thermal feedback with the reaction time of approximately 1.0 - 1.4 [s].

4.3 Study 3: Spatial Characteristics

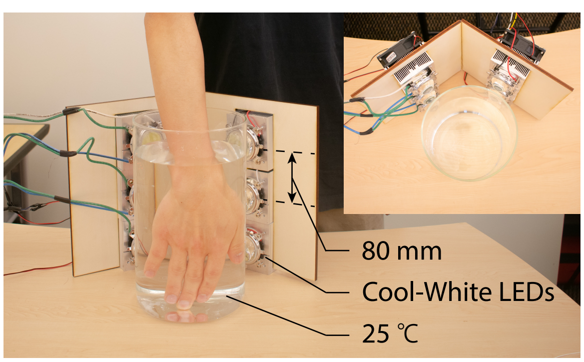

Figure 13: The setup for Study 3. The participant submerged their forearm in the water tank and reported the continuity of warmth/coolness movements from the bottom to the top along their skin.

We further investigated the spatial characteristics of hydroptical thermal feedback. In our pilot study using multiple light sources around the forearm, the participant could differentiate warmth applied on different regions on the forearm. They could also differentiate the cooling regions when a light is turned off. The participant also reported the possible apparent motions for both warmth and coolness. Apparent motion is a perceptual illusion, where people perceive continuous movements of sensations when two stimuli in a close proximity are applied with overlapping actuation times [4]. For example, people feel as if a vibrating point moved from the first vibration point to the next point continuously if two vibrators are actuated subsequently with some overlapping time. In our case, moving warmth was reported when two lights are turned on and off subsequently with overlapping times. Interestingly, moving coolness was also reported when two lights which were initially turned on were turned off and turned on with overlapping "off" times. To examine these potential apparent motions, we conducted another experiment using multiple light sources. It is important to note that this experiment does not study localization (*i.e.*, spatial resolution) of the thermal perceptions.

To evaluate the perception, we used a 7-point Likert scale on continuity of perceived warmth/coolness movements. This scale has been widely used to evaluate tactile apparent motions [27, 43, 56, 61, 87].

4.3.1 *Participants.*

The same eight participants as in Experiment 2 (1 male, 7 females; age: 1 in 18-19, 7 in 20s) were involved. One of them (female in 20s) participated only in the warmth apparent motion study.

4.3.2 *Apparatus.*

The experiment setup is shown in Figure 13. The same 100 W Cool-White LED was used. As the perceptions of warmth and coolness were stronger with two LEDs placed side by side in the pilot study, we used two LEDs for each row. The pairs of LEDs were placed in three rows with the vertical gap of 80 mm. The water tank diameter was 150 mm.

4.3.3 *Conditions.*

Stimuli duration and stimuli onset asynchrony (SOA), which is the time between onsets of subsequent stimuli, are the key variables determining the perceived quality of apparent motions [67]. As our primary goal is to confirm the warmth/coolness apparent motions, we fixed the stimuli duration to 1.0 [s] and investigated the perceived continuity of moving warmth/coolness sensations for different SOAs: 200, 400, 600, 800, and 1000 [ms]. For this study, the 635 klux light (*i.e.*, pwm = 3/3) was used. As the tank diameter is 150 mm, the distance between the LED and the skin is similar to 50 mm from above studies with some variability depending on the skin part and the forearm size. The temporal patterns of the heatings and coolings are shown in Figure 14. For the cooling trials, all the LEDs were initially turned on for 30 s to ensure the skin is adapted to the warmed state. Then, individual lights were turned off after each SOA.

4.3.4 *Procedure.*

Participants waited in the experiment room for five minutes after they completed Experiment 2 before this experiment started. While waiting, participants took a seat and were reminded of the procedures which were explained before Experiment 2.

The participants wore eye masks. If they had no problem with the fit, they did three practice trials (SOA = 200, 600, 1000 [ms]).

After the practice trials, the main experiment started. The following procedure was repeated for each trial. The water temperature was adjusted to 25.0 - 26.0 °C. In the warming trials, the lights were turned on with a specific SOA and were turned off after 1.0 [s]. In

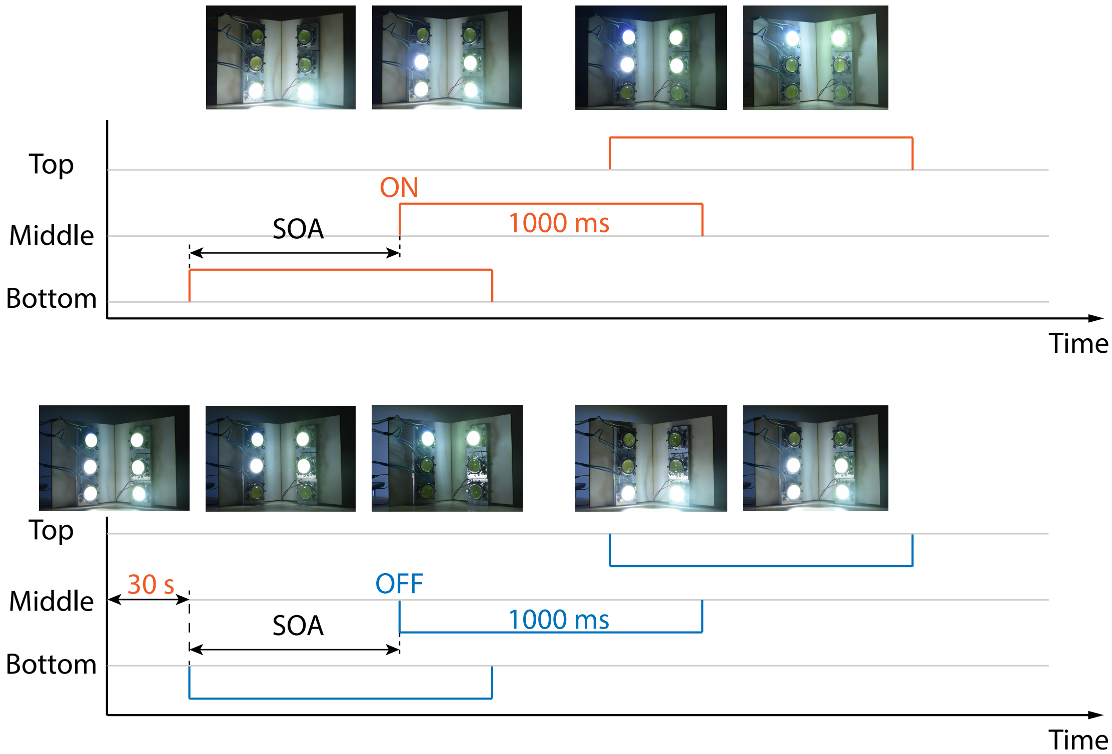

Figure 14: The light patterns used for warming (top) and cooling (bottom) spatial sequences in Study 3. To study the apparent motion of warming (top), the LEDs are turned on one by one in sequence from bottom to top. The delay between turning on one LED and turning on the next LED is called SOA (stimuli onset asynchrony). For cooling (bottom), the LEDs are turned off one by one in sequence.

the cooling trials, all the lights were turned on for 20 [s]. Then, the lights were turned off with a specific SOA and were turned on after 1.0 [s]. Once the thermal feedback is finished, participants were asked to verbally report the continuity of the warmth movement in the 7-point Likert scale (1: discrete or no movement - 7: perfectly continuous). The next trial started 20 sec after the adjustment to ensure thermal adaptation. The trials were repeated in a randomized order for 40 times (*i.e.*, 8 trials for each SOA condition). Once all the warming trials were completed, the cooling trials were started. After the final cooling trial, semi-structured interviews were conducted for approximately five to ten minutes. The entire experiment lasted approximately 40 min.

4.3.5 Results. In the semi-structured interviews, all the participants reported that they felt continuous warmth and coolness movements in some of the trials. This suggests that hydroptical thermal feedback can present warmth/coolness sensations that move smoothly on the skin. Two participants reported that they felt tingling sensations in some of the warming trials. This could be thermal grill illusions, where humans feel illusory tingling sensations when warming and cooling points are close to each other. When the SOA is 1.0 s, the second LEDs are turned on when the first LEDs are turned off, possibly resulting in simultaneous warming and cooling points in close proximity on the skin. However, we could not confirm which SOA condition caused these sensations because they reported it after finishing all the trials.

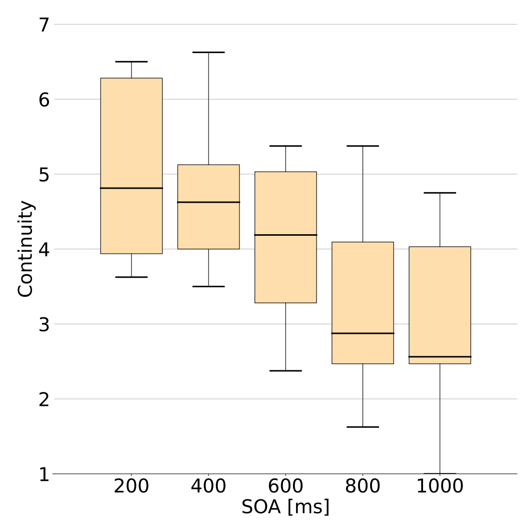

Figure 15: The continuity ratings of subsequent warmth feedback with varied SOA (stimuli onset asynchrony) times.

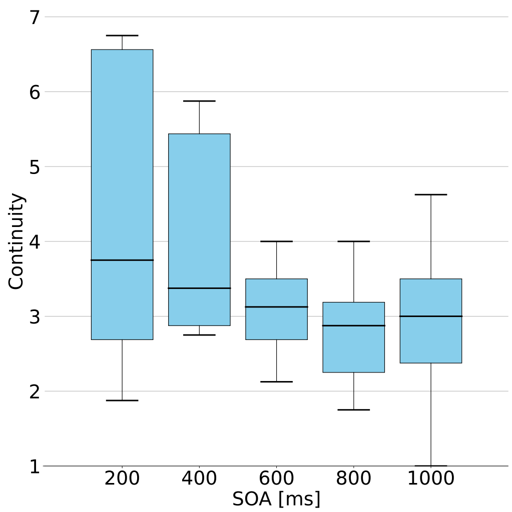

Figure 16: The continuity ratings of subsequent coolness feedback with varied SOA (stimuli onset asynchrony) times.

The obtained continuity ratings for the warming trials are shown in Figure 15. We performed the Friedman test with the null hypothesis that there is no difference in continuity ratings between different SOA conditions. The Friedman test revealed significant main effects of SOAs on the continuity ratings ($\chi^2(4) = 17.36$, $p = .002$, Kendall's $W = .620$). Therefore, using the Holm-Bonferroni–corrected Wilcoxon signed-rank test, the post-hoc analyses were performed on the SOA factor. However, no significant difference was found between any pairs of the SOA conditions. A possible reason for the high p values are the Holm-Bonferroni corrections for five conditions. Thus, we report the pairs with large effect sizes (cohen's $d > 0.800$) and discuss the influence of SOAs on the perceived continuity based on them. The continuity ratings for the SOAs of 200, 400, and 600 [ms] were likely to be higher than those for the SOAs of 800 (200: cohen's $d = 1.581$, 400: cohen's $d = 1.510$, 600: cohen's $d = 1.091$) and 1000 [ms] (200: cohen's $d = 1.820$, 400: cohen's $d = 1.762$, 600: cohen's $d = 1.338$), respectively. These results imply that hydroptical thermal feedback achieves smoother warmth apparent motions with a SOA shorter than 600 [ms] when individual lighting duration is 1.0 [s].

The obtained continuity ratings for the cooling trials are shown in Figure 16. We performed the Friedman test with the null hypothesis that there is no difference in continuity ratings between different SOA conditions. The Friedman test revealed no significant main effects of SOAs on the continuity ratings ($\chi^2(4) = 4.53$, $p = .339$, Kendall's $W = .162$). However, Given the large variation in continuity ratings for the 200 [ms] SOAs (inter-quartile range = 4.37) and the small number of participants (N=7), we cannot argue whether the perceived continuity does not vary across all SOAs tested.

Overall, Experiment 3 confirms that hydroptical thermal feedback can present apparent motions of warmth/coolness on the forearm. It is important to note that we did not evaluate the spatial acuity (*i.e.*, the ability to localize thermal sensation) of the method.

4.4 Study 4: Illusory Water Temperature Perception

The previous studies' results empirically demonstrate that the hydroptical thermal feedback method achieves smoothly-moving thermal feedback with various intensities. One participant's report during our pilot study implied one more unique perceptual experience of our method: illusory water temperature. When uniform thermal feedback is applied over the entire underwater body part (*i.e.*, the forearm), the participant felt as if their hand were in warm water even though the actual water temperature stayed around 25 ℃. In this final perceptual study, we investigated the felt quality of this water temperature illusion and the relationship between the perceived water temperature and the light illuminance on the skin.

We used the psychophysical staircase method (1-up 1-down), an established method for studying perception [37]. How we used the staircase method is detailed in section 4.4.4. At a very high level, participants had one arm in a bath of reference water with no hydroptical thermal display, and the other arm in the hydroptical thermal display. The temperature of the reference water was gradually manipulated until both baths of water seemed to be about the same temperature to the participant. So, for a given light illuminance of hydroptical thermal feedback, we can estimate how warm it makes the water seem.

Figure 17: The experiment setup for Study 4. Each participant put their right hand in the hydroptical thermal display water bath and their left hand in the reference water.

4.4.1 Participants. The experiment involved 6 participants (6 males, 2 females; age: 1 in 18-19, 4 in 20s, 1 in 30s). This experiment took approximately 70 min to complete.

4.4.2 Apparatus. The experiment setup is shown in Figure 17. The same 150 mm diameter water tanks from Study 3 were used for both hydroptical thermal feedback (right hand) and the reference water (left hand). 2 rows of 6 LEDs (100 W x 12) were used to provide uniform thermal feedback over the forearm. The water temperature of the hydroptical thermal feedback tank was kept between 25-26 ℃.

4.4.3 Conditions. The light levels we examined were the same ones from section 4.2 and section 4.3: 210, 433, and 635 klux at the 50 mm distance.

4.4.4 Procedure. We used the staircase method to find the threshold at which participants could no longer detect any difference between the temperature of two different water baths; *i.e.*, when both water baths were perceived as about the same temperature by participants.

In general terms, how we used the staircase method is that participants were repeatedly asked which water bath felt warmer, the 'reference water' or the 'hydroptical water'. The hydroptical water was constant between 25 and 26 ℃ and the light illuminance was constant. The reference water's temperature was slowly adjusted until the point at which participants perceived the reference water and hydroptical water as about the same temperature. So, for that particular illuminance in water at 25 ℃, it creates a perceptual illusion of water at that particular temperature. This is repeated for different illuminance levels, to estimate the relationship between illuminance and perceived water temperature.

In more specific terms, what the staircase method means is: When the participant reports that the reference water feels warmer than the hydroptical water, the reference water's temperature is 'stepped down' (decreased) by 1 ℃. Then the two water baths are held constant for 30 sec so the participant can experience them. Then, the participant is again asked to report which water bath feels warmer. If they continue reporting that the reference water is warmer, then the reference water is stepped down in 1 ℃ increments. Eventually after enough 'steps down', when the participant reports that the reference water feels cooler than the hydroptical water, then the reference water is 'stepped up' (temperature increased) by 1 ℃. If the step-downs and step-ups start to alternate (*i.e.*, a series of reversals), this indicates that the reference water and hydroptical water are perceived as about the same, or that the hydroptical water's perceived temperature is somewhere between those two steps. This 'stepping down' and reversals are shown in black in Figure 18. Similarly, if the participant first reports that the reference water feels cooler than the hydroptical water, then the reference water temperature is 'stepped up' by 1 ℃ until the reversals indicate perceived temperature equality between the two water baths, shown in red in Figure 18.

From this, we computed the water temperatures of subjective / perceived equality (where participants thought both water baths were about the same temperature) for each participant as the average of the reference water temperatures of the last 4 reversals. We ignored the first two reversals because it takes a few reversals for participants to converge towards their threshold levels [37]. The experiment concluded after six reversals.

4.4.5 Results. Responses in ascending and descending series for one of the participants are shown in Figure 18. We computed the

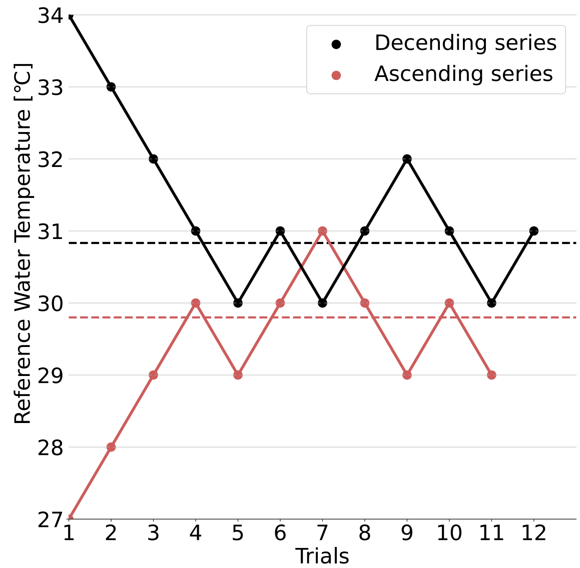

Figure 18: The resulting ascending and descending staircases for one of the participants. The horizontal dashed lines show the values of subjective equality obtained by taking the average of the last four reversals in each series.

water temperature of subjective equality (perceived water temperature) by taking the average of the last four reversals. The results are shown in Figure 19. We conducted one-way repeated-measures ANOVA with the null hypothesis that there is no significant difference in perceived water temperatures for different illuminance conditions. The ANOVA revealed a significant main effect of light levels ($F(2,71) = 43.16$, $p = .000$, $\eta_p^2 = .549$). The post-hoc analysis was conducted using the paired t-test with Holm-Bonferroni correction. The 635 klux light resulted in a significantly higher perceived water temperature than the 433 klux ($t(5) = 6.99$, $p = .002$, cohen's $d = 3.894$) and 210 klux lights ($t(5) = 8.99$, $p = .001$, cohen's $d = 4.955$). The 433 klux light resulted in a significantly higher perceived water temperature than the 210 klux light ($t(5) = 6.64$, $p = .001$, cohen's $d = 1.575$). Therefore, the perceived water temperature was different depending on the illuminance. To identify the relationship between the illuminances and perceived water temperatures, we fitted the following logarithmic curve.

$$T_{water} = a \ln(E_V + b) - a \ln b + 25.0 \tag{3}$$

, where T_{water} [℃] is the perceived water temperature, E_V [klux] is the illuminance, and a and b are constants. A logarithmic curve was used because the amount of perceived temperature rise should decrease as the illuminance goes up and the temperature difference between the skin and surrounding water increases, resulting in more heat dissipation. This specific logarithmic curve was selected because the perceived water temperature T_{water} should be 25 ℃ when there is no light ($E_V = 0$). The fitted logarithmic curve (shown in Figure 19) is as follows:

$$T_{water} = 9.870 \ln(E_V + 222.334) - 28.339 \quad (R^2 = 0.844) \tag{4}$$

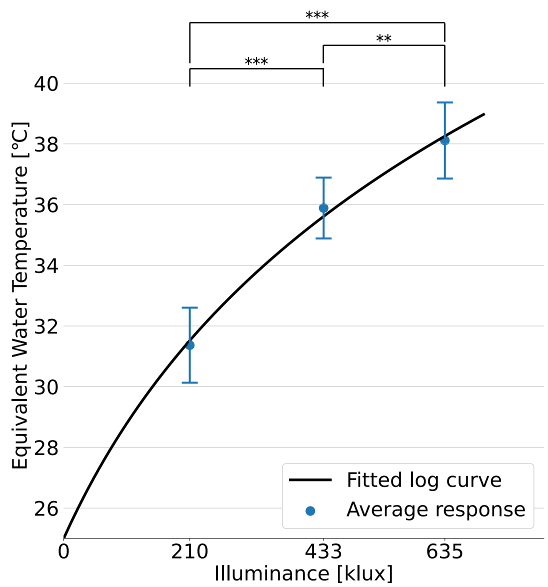

Figure 19: Water temperature of subjective equality (*i.e.*, perceived water temperatures) for different light illuminances on the skin. The error bars show standard deviation. The logarithmic curve is a fitted model of the relationship between the light illuminance and the perceived water temperature in 25 ℃ water. The ** and * indicate p < .01 and p < .001, respectively.**

This equation is used to present specific water temperature in section 6. Although Equation 4 is applicable only for the current light setup with the base water temperature of 25 ℃, a similar procedure with fewer trials can be taken to calibrate control functions for thermal displays using the hydroptical method.

In the semi-structured interviews where participants were asked to explain their perceptual experiences, all participants reported that hydroptical thermal feedback made the water itself feel warmer. This suggests that the illusory water temperature can be controlled with uniform lights over the underwater skin surface. It is reasonable to think that human water perceptions are formed by combining water haptic sensations and thermal sensations. Therefore, this illusory changes in water temperature could be caused by altering the thermal sensations while keeping the water haptic sensations. It is important to note that some participants stated that they could feel the actual cold water temperature when they move their fingers. For example, while they were moving their fingers, they felt as if the water around the fingers got colder. This disruption of the illusion could be caused by the increased heat dissipation into water owing to the faster water movements around the finger. If water takes more heat, it feels cooler. Although the illusion occurs again once the movement stops, the application of this illusory water temperature perception may be limited to the interactions without frequent user movements.

Overall, we confirmed the illusory changes in water temperature, identified the perceived water temperature at three illuminances, and obtained the relationship between the illuminance and perceived water temperature. **Hydroptical thermal feedback changes perceived water temperature without changing the actual water temperature, which has never been achieved in previous studies to our knowledge, or even in our everyday perceptions of the physical world.**

5 DISCUSSION

5.1 Perceptual Characteristics of Hydroptical Thermal Feedback

Through a series of experiments in section 4, we have shown various perceptual characteristics of the hydroptical thermal feedback method. In section 4.1, all the participants reported perceiving both warmth and coolness provided by hydroptical thermal feedback. The skin temperature measurements and subjective ratings results revealed that the lights with shorter wavelengths (*i.e.*, Blue and Cool-White) raised skin temperature more and evoked stronger warmth. Study 1 confirmed that hydroptical thermal feedback does successfully convey actual and perceived warmth without changing water temperature.

Then in Study 2 (section 4.2) we investigated the perceived warmth intensity, skin temperature and reaction time using a Cool-White light at varying illuminances. Results showed that, with hydroptical thermal feedback, participants had short reaction times (1.0-1.4 s) and perceived stronger warmth with more intense light. This shows that hydroptical thermal feedback can evoke **varying intensities** of thermal sensation in a short period of time. The results of section 4.3 further suggest that hydroptical thermal feedback can not only provide warmth and coolness sensations but also move them smoothly by controlling adjacent lights subsequently. In other words, hydroptical thermal feedback offers **spatial** thermal feedback. Finally, section 4.4 revealed that hydroptical thermal feedback can reproduce various water temperature perceptions without changing the actual water temperature by applying uniform light with the LEDs surrounding the body part. Overall, **hydroptical thermal feedback provides interactive, spatial warmth and coolness perceptions, as well as illusory changes in water temperature.** These unique capabilities of hydroptical thermal feedback expand the design space of thermal interactions in HCI.

5.2 Integrating Active Warming and Passive Cooling

Non-contact warming and cooling has been integrated by Xu *et al.* [84] using visible light and cold air flow actively heating and cooling the skin. They turned on light and turned off cold air when warming, while they turned off light and turned on cold air when cooling.

In contrast, the hydroptical method does not actively cool the skin. Instead, it uses ambient water as a passive cooling medium through which warming light passes. As the thermosensory system reacts to temperature changes (*e.g.*, a skin temperature drop suppresses warm receptor firings and increases cold receptor firings, causing cold sensation), skin temperature drops owing to light dimming and cold surrounding water is perceived as cooling. Thus, the current method achieves both warming and cooling sensations by integrating active warming and passive cooling. Owing to the passive nature, the current method requires warming before presenting a cooling sensation.

Xu *et al.*'s method [84] is suitable for long-term and/or wind-related thermal experiences. It can keep providing thermal feedback for a long time as the cooling medium (*i.e.*, cold air) can be constantly produced, while the hydroptical passive cooling gets less effective over time as water temperature gets closer to the skin temperature. The accompanying wind haptic sensation of the former method will enhance wind-related thermal experiences.

The hydroptical method is suitable for immersive, intense, and/or underwater thermal experiences. As the active air cooling requires an air compressor even for a small presentation area, it is challenging to scale it for a larger skin area. By contrast, passive water cooling does not require huge equipment and is easy to be scaled to a larger skin area for more immersive thermal experiences. In addition, although the cooling capability of our method is not evaluated in this study, the passive water cooling could also provide a more intense cooling sensation than active air cooling. Water has a higher thermal effusivity and a greater heat capacity than air, resulting in more effective cooling. The potential larger presentation area also contributes to the perceived intensity owing to the spatial summation mentioned in section 2.1. Instead of using a transparent water tank surrounded by LEDs as in the current study, we can use a waterproof light source to utilize pre-existing bodies of water (e.g., pool and ocean) as the cooling medium for the hydroptical thermal feedback.

Therefore, the current method changed the cooling material of the previous work [84] from actively controlled air flow to static cold water to make it more scalable and intense while replacing wind haptic sensation with water haptic sensation and potentially limiting the operation time. Following these points, future work should investigate which non-contact thermal interactions are best suited for each method's benefits and limitations.

5.3 Design Considerations for Hydroptical Thermal Feedback

Based on our study results, we suggest several design considerations for thermal displays using our method and their applications.

5.3.1 Light spectrum. As shown in section 4.1, light spectra affect the extent of skin temperature rise and resulting perceived warmth intensity. Our study suggests that light with shorter wavelength components achieves stronger thermal sensations. These results come from Study 1, which had participants of diverse skin tones. This is also consistent with previous skin light absorbance measurements [76]. After comparing different light colors in Study 1, we found that Cool-White light worked well and used this for the remaining studies.

5.3.2 Safety. Although shorter wavelengths may support stronger thermal sensations, because hydroptical thermal feedback uses strong lights, we also recommend using visible lights with a peak wavelength longer than 450 nm to avoid potential tanning. Furthermore, people with skin sensitivity to strong light or sensitivity to extended exposure to water should consider not using this display. As hydroptical thermal feedback emits bright lights, we recommend enclosing the water tank with a cover or protecting everyone's eyes with sunglasses, eye masks, or HMDs. If multiple people use the water bath, the water should be changed regularly to keep the water transparency and to avoid potential infections.

5.3.3 Base water temperature. The water temperature affects the thermal sensations of hydroptical thermal feedback. After some informal testing, we set it to 25 ℃ to achieve both warmth and coolness by switching lights on and off. If the water temperature is much lower than 25 ℃, the intensity of warmth will be lower for the same light intensity. As long as the LEDs can provide enough light intensity, lowering the base water temperature will improve the dynamic range of thermal feedback (*i.e.*, the range between maximum perceived warmth and coolness). If the water temperature is much higher, the intensity of warmth will be higher, but the coolness intensity will be lower. Therefore, we recommend setting the water temperature to the lowest value with which users can perceive enough warmth to achieve a wide dynamic range while ensuring both warmth and coolness feedback capabilities. It is also important to note that larger water tanks can keep the water temperature constant for a longer time. Thus, we recommend using larger water tanks for hydroptical thermal displays used for a long time. If the room temperature is significantly different from the base water temperature or the tank is small, the water temperature may need to be actively monitored and maintained.

5.3.4 Individual differences. Throughout our studies, we have observed individual differences in subjective ratings. Therefore, we recommend designing thermal displays that can accommodate people with various thermal sensitivities and preferences. The light intensity can also be calibrated before first usage, and other features such as recalibration, settings, adjustments can support the desired range of warm and cool sensations for different users in different contexts and application scenarios.

6 APPLICATIONS

Based on our studies, we identified unique thermal experiences that hydroptical thermal feedback provides: illusory changes in water temperature, smoothly-moving warmth and coolness, and interactive thermal feedback accompanied by water haptic sensation. Here, we propose the applications taking advantage of these unique perceptual qualities: aquatic virtual reality, shared water experiences, and therapeutic cooling and warming.

6.1 Aquatic Virtual Reality

As hydroptical thermal feedback involves direct engagement with water, many of its applications belong to WaterHCI [52], which is a growing field exploring interaction possibilities with water. One WaterHCI application that hydroptical thermal feedback opens up is aquatic virtual reality as shown in Figure 20. Conventional methods, such as water temperature control [17] have reproduced some of the water thermal experiences that we have in the physical world. The illusory water temperature perception from section

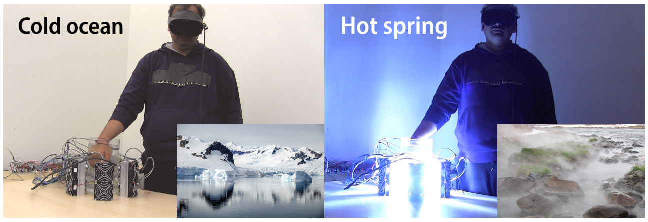

Figure 20: Hydroptical thermal feedback can change perceived water temperature to reproduce thermal haptic water experiences in VR.

4.4 can augment our virtual thermal experiences beyond those of everyday life. For example, it has been impossible to present the thermal sensations in the teleportation between cold aquatic environments (*e.g.*, deep ocean or winter rivers) and warm ones (*e.g.*, hot springs or tropical ocean) because physical water does not change its temperature suddenly. However, it can happen in a digital world and hydroptical thermal feedback can "reproduce" this unrealistic thermal experiences to potentially enhance the sense of realism. Hydroptical thermal feedback reimagines WaterHCI by turning water into an interactive medium.

6.2 Shared Water Experiences

Figure 21: People with different thermal preferences sharing a footbath. Thanks to the hydroptical thermal feedback on the right side of the bath, the person on the right enjoys a footbath warmer than the other person is experiencing. The enclosure of the lights is removed for visibility in the figure.

Hydroptical thermal feedback contributes to shared water experiences by synchronizing or personalizing water thermal experiences. One of the challenges in WaterHCI is that people often have different water exposures that can inhibit shared water experiences [52]. Our method enables computers to manipulate perceived water temperature, synchronizing water thermal experiences for social WaterHCI applications. For example, if two remote users sing together while sharing a bath experience, one can use the hydroptical thermal display to recreate the other's bath experience.

On the contrary, our method can also personalize water thermal experiences when people share water bodies. In a public bath or foot bath, people enjoy shared thermal haptic experiences of water that evoke the sense of connections and facilitate intimate communication. However, conventional baths have the same water temperature for everyone. Thus, people could not personalize their water thermal experiences even when it is too hot or cold for them. As a result, these shared thermal experiences were only available for people sharing similar thermal preferences. Hydroptical thermal feedback breaks the wall between people with different thermal preferences by enabling water to virtually have multiple temperatures in a single bathtub. In Figure 21, the person on the right prefers a warmer footbath, therefore, hydroptical thermal feedback is applied on the right side. Therefore, the current method turns water into a material that can have heterogeneous temperatures while mediating others' presences through waves and flows for communal immersion.

6.3 Therapeutic Cooling and Warming

Many athletes use icing and warming tools, including pouches filled with ice or warm water, after practice to shorten the muscle recovery period. For example, some athletes alternate between warm towels and ice packs on areas frequently used during play. Because those tools directly touch various body parts, many athletes have to do it themselves, which is time-consuming and labor-intensive. Hydroptical thermal feedback can alter these conventional manual icing/warming practices that might offer time-saving convenience for athletes.

Additionally, hydroptical thermal feedback can realize therapeutic experiences for a larger population. In some regions including Nordic countries and Japan, people alternate between hot and cold baths repeatedly as a general wellness therapeutic experience. The illusory changes of perceived water temperature from section 4.4 could enhance these practices by enabling people to enjoy both hot and cold baths without switching a bathtub. The apparent warmth/coolness motions from section 4.3 also enriches the bathing experience.

6.4 Spatio-Temporal Control of Virtual Water Temperature

While not currently implemented, the spatio-temporal control of water temperature can have diverse applications beyond human experiences. In cooking, specific ingredients can be heated more than the others while being boiled. The heating intensity can also be quickly changed without waiting for the water temperature changes.

In aquariums, perhaps fish from different climates could coexist in the same water tank. Unlike traditional setups that require selecting fish from similar environments, our method may allow tropical and Antarctic fish to coexist in the same tank by optimizing fish skin temperatures.

7 LIMITATIONS & FUTURE WORK

7.1 Thorough Perception & Application Studies

The current study is limited by the lack of exploration on some perceptual aspects, as well as the lack of application evaluations.

Spatial Characteristics. We expect future studies to investigate the spatial characteristics other than the apparent motion studied in section 4.3, such as the minimum skin area to evoke thermal perceptions and the ability to localize the thermal stimuli. The minimum skin area can be measured by using a stencil in water that blocks light for other skin regions. Understanding this will help define the display size limitations of the current method.

Coolness Perception and Effect of Light Source-Skin Distance. We only looked into the subjective intensity and reaction time of warmth perception in section 4.2. They should be studied on the coolness perception in the future. We also did not investigate the effect of light-source–skin distance on the skin temperature changes. Thus, future study is expected to measure skin temperature changes at varied distances. A suitable light color (*i.e.*, spectra) might be different depending on the distance.

Effect of Skin Tone. Future work should continue to evaluate our method with a diverse range of skin tones because the method utilizes visible lights. Skin color is known to impact other visible-light based technologies such as photoplethysmogram (PPG) pulse measurement [1] and photography [63]. Applications leveraging properties of visible light must be proactively built so that they calibrate to, adjust to, and work well for diverse skin tones.

Other Body Parts. We also expect future studies to focus on other body parts beyond the arm or hand. As this study is the first to propose hydroptical thermal feedback, we studied its perceptual characteristics on the hand, where the thermal sensitivity is higher than most of the other parts. However, non-contact methods like ours are applicable to various body parts, expanding the thermal display applications as mentioned in section 2.2. Therefore, further studies should build and evaluate hydroptical thermal displays for other body parts based on our general design considerations in section 5.3 and our results.

Number of Participants. The current study is also limited by the small number of participants. Although we set the number of participants for statistical power of 0.80 or more, the number should be increased in future studies.

Application Evaluation. Another limitation is the lack of evaluations of the applications. Although we proposed some applications that leverage the unique characteristics of our method, we did not conduct any user studies on them. Thus, future studies to evaluate the sense of immersion in VR, the intimacy and emotions in shared water experiences, and the effect of the therapeutic feedback are expected.

7.2 Limitations of Hydroptical Method & Potential Improvements

Current limitations of hydroptical thermal feedback and their possible solutions are discussed. Possible extensions of the method are also proposed.

Pre-Heat for Cooling Feedback. One major limitation is that the skin needs to be warmed before presenting a cooling sensation as mentioned in section 4.3 and section 5.2. We expect future work exploring ways to present coolness without evoking warmth. A potential approach is to use the neutral illuminance light as the default state and let the skin adapt to that temperature. From this state, cooling sensation can be evoked without warmth perceptions by dimming the light. For a repetitive or continuous cooling feedback, the skin temperature should be raised back to this default state at the rate below the perceptual threshold [84].

Water Tank Alternatives. The water tank setups in our studies restrict movement. Options to address this limitation include using larger tanks (e.g., foot baths or pools), which offer the space for broader movements but necessitate directing light to the skin either through body tracking [17] or by attaching lights directly to the body. Alternatively, sealed water pouches placed between the skin and lights can free up hand movement and eliminate haptic sensations from water movement, making them potentially suitable for non-aquatic applications.

Power Consumption. Our method is currently limited by the power consumption of each LED (100 W). Future efforts could focus on using reflectors, lenses, and highly transparent liquids with better thermal conductivity to enhance efficiency and facilitate miniaturization. Additionally, incorporating chemicals like capsaicin and menthol [48] into the water could help evoke desired effects with smaller skin temperature changes.

Water Temperature Rise. Passive water cooling results in water temperature rise. Although this rise is gradual owing to the high heat capacity of water, it eventually gets close to the skin temperature, making it challenging to control cooling sensation over time, especially for miniaturized setups like water pouches. Potential solutions include an additional cooling mechanism to maintain the water temperature, water-temperature–based light control, and a hardware design enabling quick and easy water replacements. The relationship between the rate of water temperature rise, light power, and water volume should also be studied.

Disruption of Illusory Water Temperature Perception. Future study is expected on the control algorithm. Dynamically controlling the light levels based on underwater body movements may resolve the disruption of illusory water temperature perception caused by finger movements in section 4.4.5 in the current setup.

Light Emission. The leaked light from the device needs to be either blocked by an enclosure or incorporated into the interaction. It can be used to visually communicate user thermal perceptions to other people [28] or to add abstract artistic expressions.

Spatial Resolution. The spatial resolution can be improved by using reflectors and lenses or by replacing the Chip-on-Board LED with a laser. As the spatial resolution of human thermal perception is limited as mentioned in section 2.1, these measures may not improve the spatial resolution of thermal experiences. However, it can cause pain sensation (*i.e.*, thermal grill illusions), which was possibly experienced by some in section 4.3.

Combining Other Methods. Future studies could combine our method with other haptic feedback methods. Similar to Singhal *et al.* [69], the spatial resolution can be improved through thermal referral with haptic feedback. For example, our method can be integrated with other liquid-based haptic feedback, such as water jets [9, 29, 62] and flows [21]. Another potential extension is chemical haptics [48] as mentioned in the power consumption paragraph. If chemicals are mixed in or replaces water of our method, they will improve thermal sensations or add other qualities. Their unique absorption spectra should be considered when selecting the light.

8 CONCLUSION

We contribute *hydroptical* thermal feedback, a spatial thermal feedback method that works by applying visible lights on body parts in water. We did a series of psychophysical studies and physical measurements providing empirical evidence of the characteristics of hydroptical thermal feedback.

Our results show that (1) It works. Humans perceive thermal sensations when visible lights are cast on the skin under water, and perceived warmth is greater for lights with shorter wavelengths, (2) It supports participants' reaction times of about 1.0-1.4 sec. (3) It supports apparent motion of warmth and coolness sensations, demonstrating spatial capability when LEDs in different locations are turned on/off. (4) It can also support the perceptual illusion that the water itself is warmer, when the LEDs shine light evenly across all the submerged skin. The combination of characteristics (4) and (2) is very unique: Hydroptical thermal feedback supports the sensation that the water surrounding one's body part is suddenly changing temperature in about one second, a sensation that to our knowledge has not been achieved in prior thermal displays research or in everyday life.

Leveraging these unique characteristics, we propose WaterHCI, such as aquatic VR and shared water experiences, and therapeutic applications. The VR application reproduces the transitions between varied ambient water temperature for a compelling immersive experience. The shared water experience offers synchronous water thermal experiences to remote people and personalized water thermal experiences to co-located people.

Overall, this paper contributes hydroptical thermal feedback as a novel method, empirical results demonstrating its unique capabilities, proposed applications, and design recommendations for using hydroptical thermal feedback.

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