

Thermal and Tactile Integration in Human Liquid Perception Using Viscous Solutions and Visible Light

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Abstract—Human perception of liquid does not rely on dedicated wetness receptors but instead emerges from the integration of thermal and tactile cues. This study investigates whether perceived liquid sensation can be modulated by controlling these inputs on the skin. Participants immersed their hands in cool, viscous xanthan gum solutions to provide cooling while minimizing tactile stimulation, and visible light was applied to induce warming through thermal radiation. Across a series of psychophysical experiments, we systematically varied light intensity and solution viscosity. Results show that increasing light intensity consistently reduced the sensation of liquid while increasing perceived warmth. Higher solution viscosity also decreased liquid perception. These findings demonstrate that liquid perception can be systematically modulated through the control of thermal and tactile inputs, providing new insight into the sensory mechanisms of liquid perception and offering a novel approach for its active manipulation in haptic interfaces.

Index Terms—Liquid perception, thermal-tactile integration, psychophysics, haptic interface.

I. INTRODUCTION

Liquid perception is a fundamental sensory capacity that enables humans to detect and identify substances as liquids [1]. This ability is crucial for survival, allowing us to locate and consume water, prepare food, and maintain hygiene. Beyond its everyday relevance, understanding liquid perception carries both scientific importance and practical potential, with applications in haptic technology, virtual reality, and rehabilitation [2], [3]. Previous research has suggested that liquid perception depends primarily on uniformly distributed pressure and temperature cues [4]. Yet despite its importance, the mechanisms by which liquid perception can be systematically shaped or manipulated remain poorly understood.

To address this challenge, a promising avenue is to draw on insights from research on wetness perception. Although liquid perception and wetness perception are not identical, they are closely related and share fundamental mechanisms. According to Bentley’s classic experiments and subsequent neurophysiological studies, neither liquid nor wetness perception arises from specialized receptors; rather, both are constructed by

the central nervous system through the integration of thermal (temperature) and tactile (pressure) cues on the skin [4]–[6]. In particular, wetness perception has been shown to result from specific combinations of cold and tactile stimulation, and can even be evoked in the absence of actual moisture if these cues are appropriately synthesized [3], [4], [7], [8]. Similarly, Bentley demonstrated that the perception of liquid can be artificially reproduced by combining these sensory elements, even without true liquid present [4]. This close relationship suggests that knowledge developed for wetness perception can inform the study and manipulation of liquid perception. Since both perceptions are based on the integration of temperature and tactile cues, manipulating these inputs, as established in wetness perception research, provides a hint of actively modulating liquid perception. Therefore, in this study, we explore how liquid perception can be modulated through controlled thermal and tactile stimulation, guided by insights from wetness perception research.

Theoretical models and experimental findings on wetness perception indicate that under static contact, the absence of dynamic tactile input increases the relative contribution of thermal cues. In this context, skin cooling is frequently interpreted as a signal of wetness, even though the actual moisture level remains unchanged or is entirely absent [5], [6]. While this effect has been demonstrated for wetness perception [5], it remains unclear whether and how it applies to the broader perception of liquid. Therefore, in this study, we hypothesize that reducing the dynamic tactile input with viscous solutions, combined with manipulating the thermal input via liquid temperature and visible light, will actively modulate the perception of liquid. This approach allows us to systematically investigate how the integration of warm, cold, and tactile cues shapes the perception of liquid.

Our central research question is whether thermal input alone can modulate the perception of liquid when tactile cues are minimized. To investigate this, we utilized hydrooptical thermal feedback [9], a method that allows precise control of skin temperature while the hand is submerged in liquid. In this setup, when a hand is placed in cool water (e.g.,

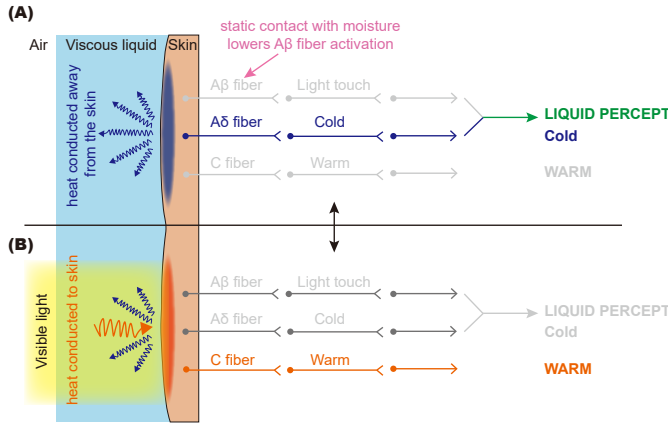


Fig. 1: Schematic of the proposed manipulation of liquid perception under two stimulus conditions. **(A) Skin in cool viscous liquid.** The viscous liquid reduces tactile inputs introduced by unconscious tremors while still provides cold stimulation (blue arrows), which gives “cold-liquid” perception **(B) Visible-light heating of skin.** Radiation heat from visible light provides warm stimulation, giving “warm-nonliquid” perception.

25 °C), the water feels cold if no light is present. However, when visible light is projected onto the submerged skin, it warms the skin but not the surrounding water, because its wavelength passes through water with minimal absorption. As a result, despite the water remaining cool, participants report a perceived water temperature of 31–38 °C, as if their hand were in hot water [9]. By varying the intensity of the visible light, it has been shown that higher light intensities produce more intense warm sensation [9]. This method allows us to induce cold or warm sensations on the skin while the hand is submerged, without altering the actual water temperature. In this way, we can manipulate skin temperature independently of liquid temperature, enabling a controlled examination of thermal contributions to liquid perception.

In this study, we replaced water with viscous solutions when applying hydroptical thermal feedback to minimize dynamic tactile input during hand immersion. We hypothesize that liquid perception can be modulated by independently controlling thermal input and liquid viscosity (see Fig. 1). When the hand is immersed in a viscous solution, tactile inputs caused by small involuntary tremors are reduced due to the medium’s higher resistance, leading to lower activation of mechanosensitive Aβ fibers. As tactile input decreases, the relative contribution of thermal cues to liquid perception becomes more prominent, allowing thermal input alone to more strongly shape the perceived liquidity of the stimulus.

Building on this framework, we outline two hypothesized perceptual states that arise from different combinations of thermal and tactile contributions (Fig. 1). In the cold viscous liquid condition (Fig. 1. (A)), immersion in a cold, viscous solution is expected to preserve strong cold input via Aδ fibers while suppressing Aβ-fiber-mediated tactile input, resulting

in a “cold-liquid” perception. In contrast, in the visible-light heating condition (Fig. 1. (B)), visible light passes through the liquid and selectively warms the skin surface without altering tactile input, thereby increasing C-fiber activity. This condition is expected to evoke a “warm-nonliquid” perception, in which thermal input dominates and the experience of liquidity diminishes.

These hypothesized perceptual outcomes are empirically tested through two psychophysical experiments. We systematically controlled factors of light intensity and liquid viscosity to evaluate whether and how the fundamental perception of liquid could be altered, thereby providing new insight into the mechanisms and controllability of human liquid perception:

- **Light intensity** was adjusted to modulate the strength of warm stimuli cast on the skin to investigate influence of the temperature perception on the liquid perception.
- **Viscosity** was varied by altering the proportions of the viscous medium (xanthan gum solution) to modulate the solution’s viscosity.

II. GENERAL METHODS

A. Participants

A total of 11 participants (5 males, 6 females; mean age = 29.5 years, SD = 12.6) took part in both experiments. All participants provided written informed consent in accordance with the guidelines of the local Ethics Review Board. Recruitment for all studies was conducted via social media platforms.

B. Apparatus

1) *Hydroptical Thermal Display for Thermal Stimulation:* To systematically investigate the role of thermal input in liquid perception, we developed a hydroptical thermal display (Fig. 2), based on the apparatus introduced by Ichihashi et al. [9], [10]. This display is to present cold or warm stimulation to the skin while the hand is immersed in liquid.

The main setup consists of a transparent glass cylinder vase (H: 400 mm, D: 200 mm) used as a water tank. The tank is filled with 5 liters of circulating water, the temperature of which is regulated by a chiller (Poafamx Aquarium Cooler 60L Cooling and Heating). The chiller circulates the water and maintains a stable cool environment throughout the experiment. The thermistor that measures water temperatures has its sensing part covered in copper tape to prevent direct heating by the light.

Inside the water tank, a 3D-printed plastic ring bracket (H: 110 mm) is used to fix and support a smaller glass container (H: 115 mm, D: 90 mm) in the center of the tank. This arrangement ensures that the viscous liquid inside the small container is surrounded by circulating water, allowing for efficient heat exchange and stable temperature control. In addition, the ring bracket prevents the container with viscous liquid from tipping over.

The small glass container holds a xanthan gum solution, which serves as the viscous medium to minimize tactile inputs while maintaining liquid properties. Xanthan gum is chosen for its biocompatibility, optical transparency in the visible

spectrum, and tunable viscosity, allowing systematic control of tactile input to the skin (see Section II-B2).

Around the tank, six high-power Chip-on-Board LEDs (CHANZON 1DGL-JC-100W1, 100 W each) were arranged at a height of approximately 260 mm to deliver controlled visible light (460–530 nm) onto the submerged skin surface. The LEDs provide localized heating of the skin via thermal radiation. Each LED is equipped with a lens for focusing, a heat sink, and a fan for heat dissipation; airflow is isolated from participants by an external windscreen. A blackout cover and a pair of sunglasses were provided to prevent direct light exposure to participants' eyes.

LED intensity and timing are controlled by a microcontroller (Arduino Uno R3) and constant current drivers (ANMBEST FET13), with waterproofing and safety circuitry to prevent electrical hazards. A Python program coordinates the operation of the LEDs via the microcontroller. This hydroptical display thus enables independent, programmable presentation of cold (via the chiller-regulated liquid) and warm (via photothermal LED irradiation) stimuli to submerged skin.

To measure participants' liquid perception continuously, we developed a continuous Visual Analogue Scale (VAS). A variable resistor (75 mm straight slide type) records continuous 100-point liquid perception scores via a microcontroller (Arduino Mega). The far left side of the scale (0) indicates no liquid perception, while the far right (100) indicates the most intense liquid perception. Liquid perception scores are recorded at intervals of 0.1 seconds, capturing rapid perceptual changes.

By combining precise thermal control (using both chiller and LEDs) with a flexible choice of liquid medium, this system provides a robust platform for disentangling the contributions of thermal and tactile cues to human liquid perception.

2) *Xanthan Gum Solution as Viscous Liquid*: In this study, we used viscous liquid in order to minimize tactile input. Xanthan gum was selected to prepare viscous liquid for the reasons below:

Xanthan gum is a high-molecular-weight polysaccharide widely used in food, pharmaceutical, and industrial applications due to its unique viscoelastic and shear-thinning properties. Recognized as safe by the FDA and EFSA, it is non-toxic, non-allergenic, and biocompatible, making it suitable for studies involving human participants. When dissolved in water, xanthan gum forms a clear or slightly translucent solution (see Fig. 3. (A)). Its absorption of cool white light is negligible, with strong absorption only in the 250–350 nm range and near-zero absorption above 400 nm (cool-white has higher intensities in the 460–530 nm range, for reference, see [9]), rendering it almost transparent to visible light. Thus, light attenuation in xanthan gum solutions is dominated by scattering from macromolecular aggregates rather than absorption. In addition, xanthan gum enables precise viscosity control in aqueous solutions, even at low concentrations, producing homogeneous liquids rather than colloids. This allows for a wide range of viscosities suitable for experimental manipulation. Moreover, a key rheological feature is shear-thinning: viscosity decreases

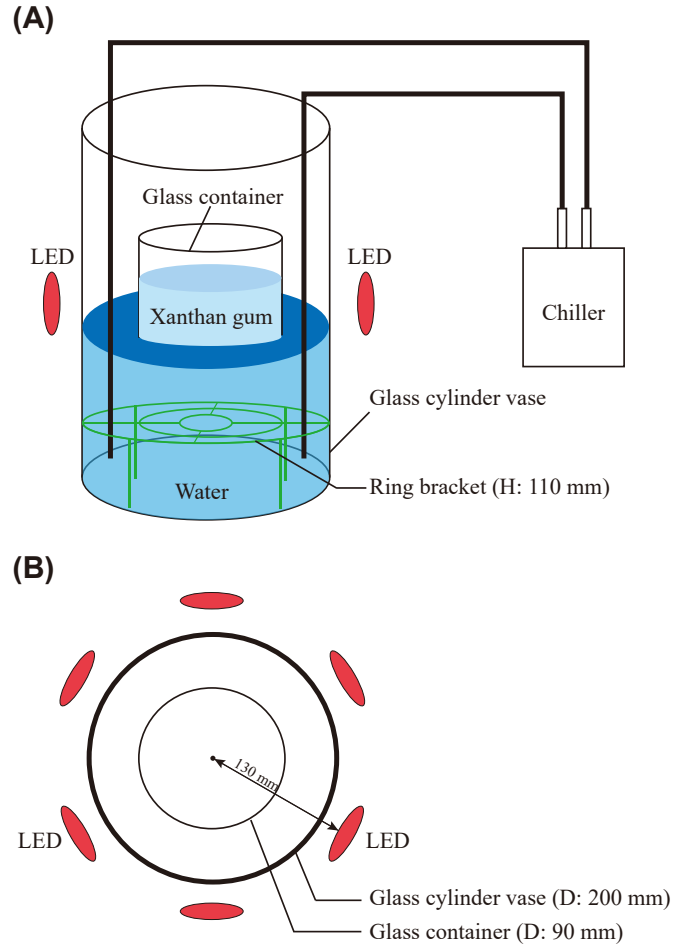
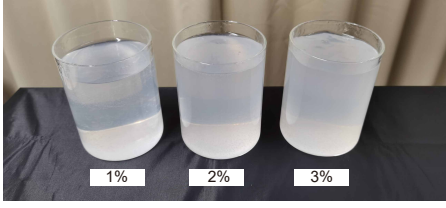


Fig. 2: Device used in this study. (A) A transparent water tank (H:400 mm D:200 mm) was used. A green ring bracket (H:110 mm) was placed in the water tank to support and fix the location of solution container. The water tank contains 5 liters of circulating water (driven by the water pump) to maintain the contact between the circulating water and the liquid container to the greatest extent possible without causing the liquid container to tip over. The solution container (H:115 mm D:90 mm) and was fixed in the center of vase by the green ring bracket. (B) 6 LEDs were arranged around the water tank to provide warm stimuli.

under shear stress and recovers when the stress is removed, which helps dampen hand micro-vibrations and stabilize tactile interactions during sensory testing. Xanthan gum solutions also maintain stable viscosity across broad temperature and pH ranges, ensuring consistent performance throughout experiments.

For the present study, xanthan gum solutions of varying viscosities were prepared in wide-mouth glass containers, which were then placed within a larger transparent water tank to maintain a constant temperature. The thermal stimulus was delivered by directing visible light through both the water and the xanthan gum solution, enabling rapid modulation of

(A)



(B)

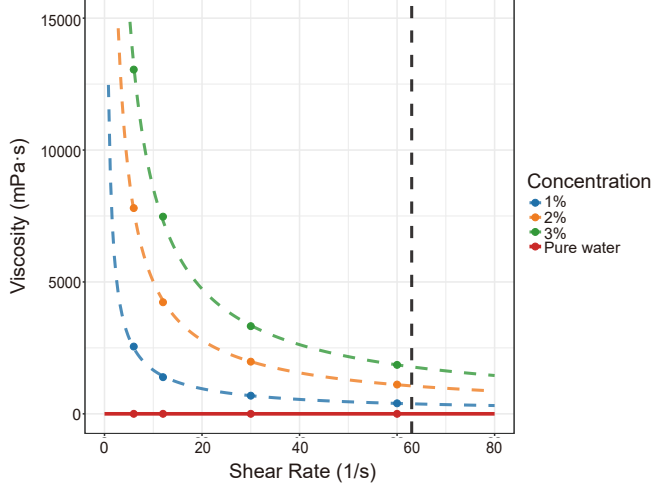


Fig. 3: Rheology of the xanthan gum solutions used in this study. (A) Visual appearance of the 1%, 2% and 3% samples. (B) Steady-shear flow curves (symbols) at 25 °C. Dashed lines are Ostwald-De Waele power-law fits. The fitting functions are $\eta_{1\%} = 1.05 \times 10^4 \dot{\gamma}^{-0.8004}$, $\eta_{2\%} = 3.50 \times 10^4 \dot{\gamma}^{-0.8444}$, and $\eta_{3\%} = 6.08 \times 10^4 \dot{\gamma}^{-0.8521}$ (mPa·s, $\dot{\gamma}$ in s^{-1}), indicating obvious shear-thinning behavior. For comparison, the viscosity of pure water at 25 °C is marked with a red line. The intersections with the black dotted line represent the shear stress on the finger in the liquid, describing the dynamic interaction between the finger and the liquid.

skin temperature without altering the bulk temperature of the liquid. This experimental setup allowed, for the first time, the active manipulation of human liquid perception by combining viscous static contact with dynamic thermal inputs.

3) *Preparation of Xanthan Gum Solution:* Xanthan gum solutions were prepared by weighing the powder to achieve 1%, 2%, and 3% concentrations, gradually dispersing it into distilled water with continuous stirring, and allowing the mixture to hydrate for 3 hours to ensure complete dissolution and homogeneity. Prepared solutions are shown in Fig. 3(A). Pilot results showed that xanthan gum solution can be stored for 5–7 days at ambient temperature (15 °C) and for longer in a 4 °C refrigerator, indicating strong stability and usability.

We measured the viscosity of the prepared xanthan gum solutions as the shear rate was increased and decreased. The measurements were conducted using a viscometer (Cgolden-wall NDJ-1). Each solution was loaded into the viscometer, which applied a controlled shear rate ranging from 20 to 60

(1/s). As the shear rate increased, the corresponding viscosity was recorded. The same process was repeated as the shear rate decreased. The average of the collected data was then plotted to generate the viscosity flow curve. The viscosity flow curve in Fig. 3. (B) reveals the shear-thinning behavior of xanthan gum solutions [11]–[13]. We applied the Ostwald-De Waele power-law, an established method for modeling the relation between viscosity and shear rate for non-Newtonian fluids [14]:

$$\eta = K \times \dot{\gamma}^{n-1} \quad (1)$$

, where η is the apparent viscosity of the fluid, $\dot{\gamma}$ is the shear rate, K is the consistency index, indicating how thick or viscous the fluid is, n is the flow-behavior index.

Green, yellow, and blue dashed lines in Fig. 3. (B) show the obtained models for the three concentration conditions. At low shear rates, the viscosity is high, indicating that the solutions resist flow. As the shear rate increases, the viscosity decreases, demonstrating that the fluid becomes easier to flow under higher stress. Fig. 3. (B) also highlights the impact of concentration on viscosity. At 1% concentration, the initial viscosity is relatively low, and the decrease in viscosity with increasing shear rate is noticeable. For the 2% solution, the initial viscosity is higher, and the shear-thinning effect is more pronounced. The 3% solution exhibits the highest initial viscosity and the most significant reduction in viscosity as the shear rate increases. This trend indicates that higher concentrations of xanthan gum enhance the thickening effect but also amplify the shear-thinning behavior.

To understand shear stress experienced by the skin arising from the physiological tremor when people's hand is submerged in different viscous liquids, it is important to distinguish between the shear rate as a parameter of the measurement device and the shear rate experienced at the skin interface during physiological conditions. In the viscometer, the shear rate is externally controlled to systematically characterize the fluid's rheological properties. However, when considering the interaction between the skin and the xanthan gum solution, the relevant shear rate arises from the physiological tremor.

In the context of skin-liquid interaction, the shear rate at the interface is determined by the frequency and amplitude of physiological tremor. These involuntary physiological tremor of the hand generate a specific shear rate of 10 Hz at the skin-fluid boundary [15], which, together with the fluid's viscosity, dictates the shear stress experienced by the skin. With a tremor frequency $f = 10$ Hz (thus angular frequency $\omega = 62.8$ rad/s) and amplitude $x_0 = 0.1$ mm [16], the shear rate at the interface can be estimated as $\dot{\gamma} = \omega x_0 / \delta \approx 63 \text{ s}^{-1}$, where δ is a characteristic length. Here, δ is taken as 0.1 mm, representing the effective thickness of the fluid boundary layer adjacent to the skin during oscillatory motion. Accordingly, the shear stress ($\tau = \eta \dot{\gamma}$) exerted by the fluid on the skin surface when the hand is submerged in pure water, 1%, 2%, and 3% xanthan gum solution is 1, 381, 1058, and 1781 mPa·s, respectively. As

the fluid becomes more viscous, it resists flow more strongly, further reducing tactile inputs.

C. General procedure

Prior to the experiment, participants were allowed a ten-minute acclimation period within the experimental environment. During this time, participants were seated and comprehensively briefed on the experimental protocol, including procedural details, data management protocols, potential risks, and participant rights. Those who consented were requested to sign an informed consent form. To mitigate potential learning effects, practice trials were conducted. Participants were equipped with sunglasses and instructed to immerse the fingers of their left hand into the experimental solution while simultaneously using their right hand to continuously rate liquid perception (see Fig. 4). Participants submerged their fingers of left hands except thumb in the solution. The distance between the palm and the LED is 100 mm.

Before the main experiment, participants were asked to verbally report their perceived warmth sensation on the left hand using a scale from 0 to 100 (0 = no warmth, 100 = maximum intensity) as a reference value. The standardized trial procedure was conducted as follows. Each trial began with an auditory cue accompanied by light extinction. After a 10-second interval, the light was turned on for 10 seconds, then extinguished again together with a second auditory signal. Throughout the 20-second trial, participants continuously rated their perception of liquidity using their right hand. Immediately afterward, they verbally reported their perceived warmth sensation and reset the variable resistor slider to its leftmost position. Between trials, participants immersed their hands in water for 20 seconds to restore thermal adaptation before the next trial.

The order of experimental conditions was randomized for each participant, and adaptation periods were included between trials to minimize carryover effects. All participants were instructed on the use of the apparatus and rating devices prior to the experiment, and were informed that they could withdraw from the study at any time.

III. EXPERIMENT 1: EFFECT OF LIGHT INTENSITY ON LIQUID PERCEPTION

In Experiment 1, we examined whether liquid perception can be influenced by the warmth generated by LED light projected onto the skin while the hand is immersed in a viscous solution. The intensity of LED was adjusted to various levels, and participants were asked to rate the perceived liquid perception continuously during the trial and rate the perceived warmth post trial.

A. Methods

In this experiment, we manipulated LED light intensity (100, 200, 300 klux) while keeping the distance between the LED and the hand at 100 mm. The selection of illuminance intensity was based on the results in pilot experiment so that the 3 levels are clear distinguishable; participants would

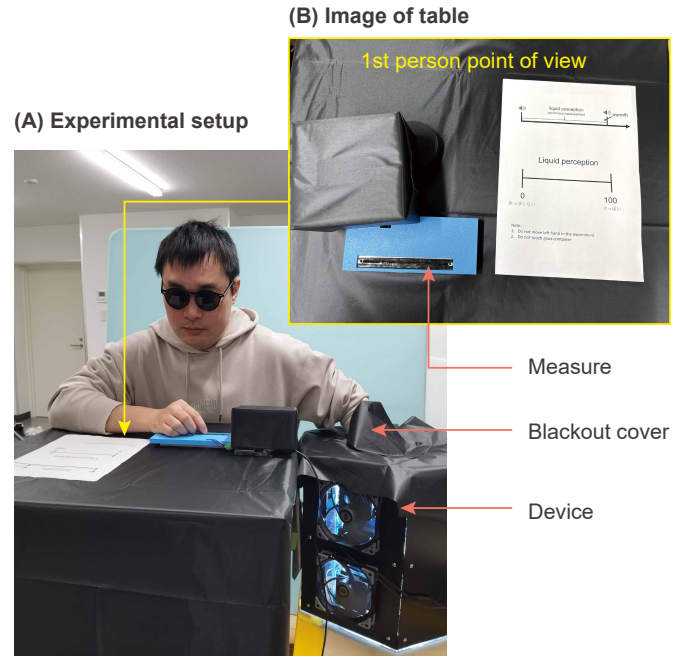


Fig. 4: (A) Experimental setup in the present study. During the experiment, participants were equipped with sunglasses and instructed to immerse the fingers of their left hand into the viscous liquid while simultaneously using their right hand to continuously rate liquid perception. A variable resistor was used as measure for continuous rate of liquid perception. (B) Image of table.

not feel pain under exposure of intense LED light. Each participant completed 10 trials per condition, with conditions presented in randomized order. Before each trial, participants orally reported their perceived warmth sensation on the left hand using a scale from 0 to 100. The trial started with an auditory cue and simultaneous light extinction. After a 10-second interval, the light was activated for 10 seconds. The light was subsequently extinguished, accompanied by another sound signal. Throughout the trial, participants continuously rated liquid perception of the skin part submerged in the liquid. Finally, they orally reported their perceived warmth sensation. “Liquid perception” was defined as the subjective liquid perception and fluid flow on the skin, while “perceived warmth” referred to the participants’ subjective experience of temperature.

To prevent fatigue, participants were permitted to withdraw their hand, dry it, and take a brief 1-minute rest after every 10 trials. The entire experimental session lasted approximately 30 minutes.

B. Results

We used the raw data of liquid perception rating and warmth rating to analyze experimental results in Experiment 1. Fig. 5 illustrates the average liquid perception over time for three conditions: intense (black), middle (dark gray), and weak (gray). The vertical axis represents the liquid perception

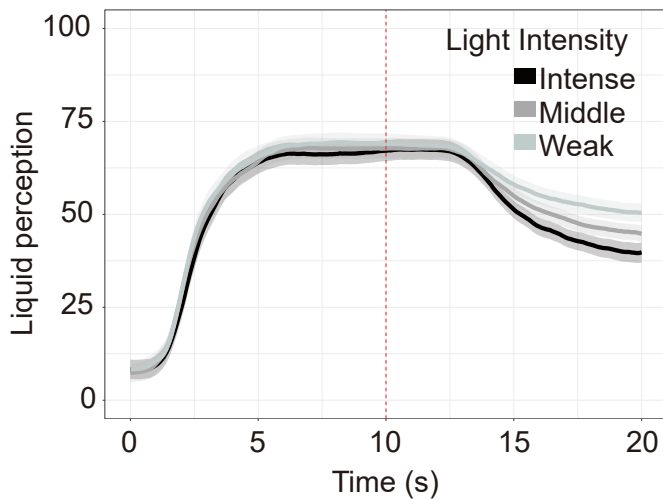


Fig. 5: Average liquid perception over time for light intensity conditions (intense, middle, and weak). The light gray shades represent the standard error. The red dashed line at 10 seconds indicates the point where the light was turned on. Liquid perception scores (0 = no perception of liquid at all, 100 = the most intense liquid perception imaginable) increased similarly across conditions before the light was turned on, followed by declines after light activation.

scores, where 0 indicates “no perception of liquid at all” and 100 indicates “the most intense liquid perception you can imagine”. The horizontal axis represents time in seconds, and the red dashed line at 10 seconds marks the transition point where the LEDs were turned on. All three conditions showed a gradual increase in scores over time during the adaptation period. The increase was similar across conditions, with no significant separation between the intense, middle, and weak conditions during this phase. This is because the LEDs were turned off and all other factors were the same. Liquid perception scores took about 5 seconds to reach asymptote. After the light was on, liquid perception score began to decrease about 2.5 seconds and declined over time for all conditions. However, the rate of decline differs across conditions. The intense condition shows the steepest decline, indicating a rapid reduction in perceived liquid. The weak condition showed the slowest decline, maintaining the highest liquid perception scores throughout this phase. These results suggest that the LED light reduces liquid perception for all three conditions. In addition, higher light intensity leads to more reduction in perceived liquid.

The data from the final timing of the LED OFF and ON was used for further analysis. Fig. 6 indicates the average liquid perception ratings on a 0-100 scale during the period when LEDs were turned off (black bars) and the period when LEDs were turned on (gray bars). A linear mixed model examined the effects of light intensity (strong, middle, weak) and light status (off, on) on participants’ liquid perception ratings, with participants included as a random effect. The analysis revealed a significant main effect of light status ($p < .001$), indicating

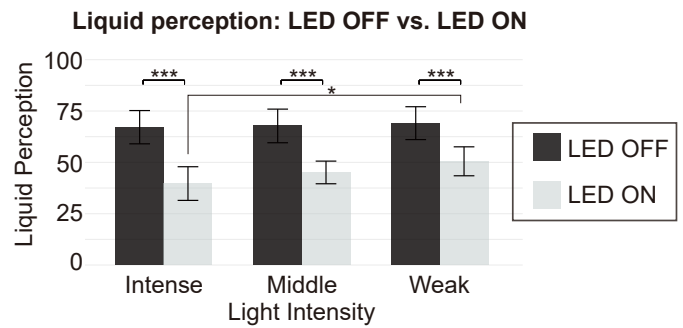


Fig. 6: Liquid perception (0-100 scale) before (black) and after (gray) LED exposure for Intense, Middle, and Weak light intensity conditions in Experiment 1. Error bars represent standard error. * $p < .05$; *** $p < .001$.

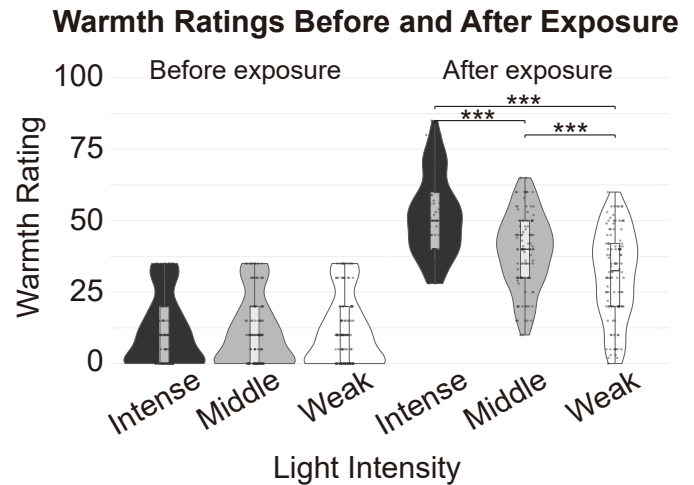


Fig. 7: Subjective warmth ratings (0–100 scale) before and after exposure to light intensity conditions (Intense, Middle, Weak) in Experiment 1. Data are presented as violin plots overlaid with box plots (median line, interquartile range box) and individual participant ratings (dots). *** $p < .001$.

that the liquid perception rating was markedly lower when the light was on. A significant interaction between light intensity and light status was found for the weak-intensity condition ($p = .019$). To further examine this interaction, simple-effect analyses were conducted under the light-on condition. Mean liquid perception ratings increased progressively from strong to weak light intensity ($\approx 39.6 \rightarrow 45.0 \rightarrow 50.4$). Pairwise comparisons showed that the weak-intensity condition was rated significantly higher than the intense-intensity condition ($p = .019$), whereas the middle-intensity condition did not differ significantly from either. These results suggest that LED light generally reduced perceived liquid intensity. Participants experienced stronger liquid perception when the light intensity was low, indicating that the effect depends on light intensity—the higher the light intensity, the greater the reduction in liquid perception.

Fig. 7 shows the subjective warmth ratings reported by par-

ticipants before and after exposure to three light intensity conditions. Before light exposure, the median warmth ratings were consistently low across all three conditions (11). This result suggests that participants had comparable baseline perceptions of warmth regardless of the condition. After light exposure, warmth rating was increased across all three condition. The median warmth rating in the intense condition was highest (52), followed by the middle condition (39), and finally the weak condition (31).

A two-way repeated measures ANOVA was conducted with light status (on/off) and light intensity as within-subject factors and warmth rating as the dependent variable. The analysis revealed significant main effects of both light status ($F(1, 644) = 2207.49, p < .001, \eta_p^2 = .77$) and light intensity ($F(2, 644) = 89.65, p < .001, \eta_p^2 = .22$), as well as a significant interaction between these factors ($F(2, 644) = 89.65, p < .001, \eta_p^2 = .22$).

Post-hoc comparisons using Bonferroni correction showed that participants rated the warmth significantly higher when the LEDs were on compared to off ($p < .001$). For the main effect of light intensity, all pairwise comparisons were significant ($p < .001$).

The interaction effect was further examined through simple effects analyses. When the LEDs were off, no significant differences were found between intensity conditions (all $p = 1.000$). However, when the LEDs were on, intense light produced higher warmth ratings than middle light (mean difference = 12.18, $p < .001$) and weak light (mean difference = 20.35, $p < .001$), and middle light produced higher warmth rating than weak light (mean difference = 8.17, $p < .001$). These results demonstrate that light illumination enhances warmth perception.

IV. EXPERIMENT 2: EFFECT OF SOLUTION VISCOSITY ON LIQUID PERCEPTION

In Experiments 1, we examined the effects of light intensity on the perception of liquids and warmth. In this experiment, we shifted focus to explore how liquid perception is influenced by solutions with varying viscosity, aiming to understand how viscosity of liquid influence perception of liquid. We hypothesized that solutions with higher viscosity would reduce the perception of liquid due to decreased dynamic contact between fingers and water.

Participants submerged the fingers of their left hands (excluding the thumb) into glass containers filled with solutions of three predefined viscosity levels (low, medium, and high). The solutions were maintained at a constant temperature of 18 °C to control for thermal variation. Participants were asked to rate their perceived warmth and liquid sensation.

A. Methods

The apparatus and general procedure were identical to those described in Section II. Participants immersed their left-hand fingers (excluding the thumb) into xanthan gum solutions at three concentrations: 1%, 2%, and 3%. These levels correspond to “low,” “medium,” and “high” viscosity,

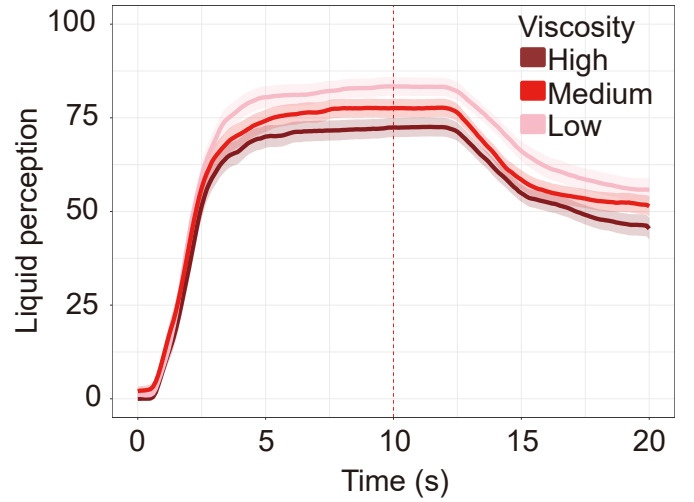


Fig. 8: Average liquid perception over time for viscosity conditions (high, medium, and low). The light pink shades represent standard error. The red dashed line at 10 seconds indicates the point where the light was turned on. Lower viscosity condition showed higher liquid perception scores.

respectively, based on the Japanese Dysphagia Diet 2013 (JDD2013) guidelines. All solutions were maintained at 18 °C. LED light intensity was set as 300 klux.

B. Results

We used the raw data of liquid perception ratings and warmth ratings to analyze experimental results in Experiment 2. Fig. 8 shows the results under different viscosity conditions. When the trial started, liquid perception scores took about 5 seconds to reach asymptote. After the light was on, liquid perception score began to decrease about 2.5 seconds and declined over time for all conditions. The low viscosity condition maintained the highest liquid perception scores across all time points, indicating that participants perceived more liquid. Contrary to this, the high viscosity condition consistently exhibited the lowest liquid perception scores throughout the trial, indicating that participants perceived less liquid.

The data from the final timing of the LED OFF and ON was used for further analysis. Fig. 9 shows the average liquid perception ratings (0-100 scale) when LEDs were ON and OFF for the High (3%), Medium (2%), and Low (1%) viscosity conditions. A linear mixed model examined the effects of solution viscosity (high, medium, low) and light status (off, on) on participants’ liquid perception ratings, with participant included as a random effect. The analysis revealed significant main effects of light status ($p < .001$) and viscosity ($p = .0007$). Participants reported lower liquid perception ratings when the light was on, and higher ratings for low-viscosity solutions compared with high-viscosity ones. No significant interaction was observed between viscosity and light status, indicating that the effect of viscosity on liquid perception remained consistent under both lighting statuses (off, on).

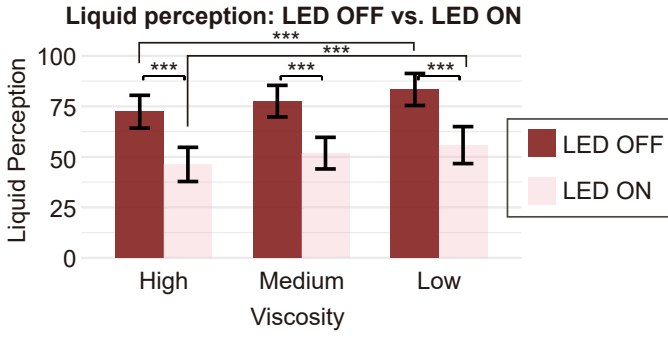


Fig. 9: Liquid perception (0-100 scale) before and after LED exposure for High, Medium, and Low concentration conditions in Experiment 2. Error bars represent standard error. *** $p < .001$.

Fig. 10 illustrates the perceived warmth ratings, measured on a 0–100 scale. To examine the effects of both liquid viscosity (high, medium, low) and light status (off/on) on warmth perception, a two-way repeated measures ANOVA was conducted. The analysis revealed significant main effects of viscosity ($F = 38.07$, $p < .0001$) and light status ($F = 2286.71$, $p < .0001$), as well as a significant interaction between viscosity and light status ($F = 19.23$, $p < .0001$). Post hoc pairwise comparisons with Bonferroni correction further revealed that light was off, warmth ratings did not differ significantly between viscosity conditions (all $p > 0.05$), indicating minimal baseline influence of viscosity on perceived warmth. However, when light was on, the high viscosity condition showed higher warmth ratings compared to both the medium viscosity (mean difference = 10.55, $p < .0001$) and low viscosity conditions (mean difference = 11.10, $p < .0001$), while no significant difference was observed between the medium and low viscosity conditions (mean difference = -0.56 , $p = 1.0$). These results demonstrate that both higher liquid viscosity and the presence of light robustly enhance perceived warmth, and that their effects interact: high viscosity amplifies the warming effect of light exposure.

V. DISCUSSION

In the present study, we demonstrated that the warmth brought by the visible light reduces liquid perception. Higher intensity of light generates more heat within a certain period of time, leading to more reduction in perceived liquid (Experiment 1). Liquid viscosity influences perceived liquid as well (Experiment 2), with higher viscosity causing more reduction in perceived liquid. Our findings provide systematic evidence that human liquid perception is a flexible, multisensory construct, arising from the integration of thermal and tactile cues at the skin. By manipulating thermal inputs (via visible light intensity) and tactile inputs (via viscosity of liquid) [17], we demonstrated that liquid perception can be manipulated (Fig. 1).

The findings from Experiment 1 provide strong evidence that the warmth from visible light reduces perceived human

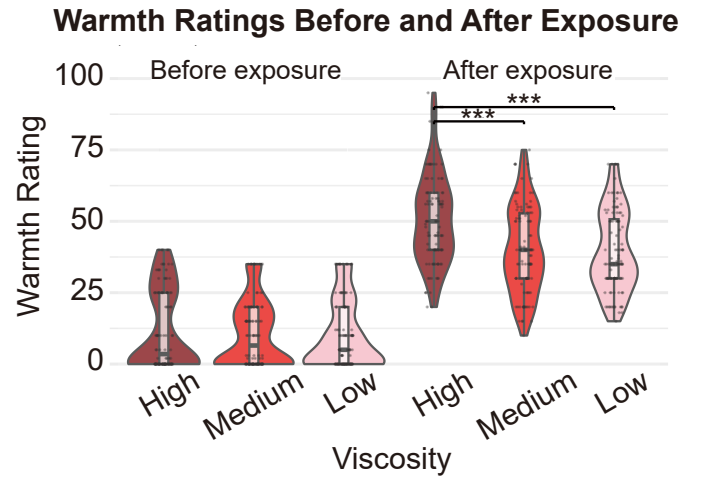


Fig. 10: Subjective warmth ratings (0–100 scale) before and after exposure under viscosity conditions (High, Medium, Low) in Experiment 2. Data are presented as violin plots overlaid with box plots (median line, interquartile range box) and individual participant ratings (dots). *** $p < .001$.

liquid perception. The inverse relationship between warm perception and liquid perception suggests that as the skin receives more heat, the brain interprets as “less liquid perception”. This finding aligns with previous study that the perception of liquid is an integration of sensory inputs [4]. However, for the first time, we artificially manipulate the liquid perception in the liquid environment. Some participants even reported that they cannot feel the liquid surrounded by their fingers at all when they receive warm inputs from visible light. Thus, our finding forms an interesting reverse process of Bentley’s approach that creating perception of liquid without real liquid, greatly advancing our understanding of manipulation of liquid perception.

Our results indicated that the liquid perception score began to decrease approximately 2.5 seconds after the stimulus onset. This result suggests that the time required to judge liquid perception is relatively long, a finding that is strongly corroborated by existing scientific literature. This extended time frame likely reflects that liquid perception is not an immediate sensation but a complex, interpretive process synthesized by the brain. The 2.5-second delay for perceiving liquid is long compared to more direct sensory modalities. Indeed, liquid perception is nearly 10 times slower than simple auditory (284 ms) [18] or visual (331 ms) reaction times [18]. This time delay reflects that perceiving a liquid is a fundamentally different and more involved cognitive event than merely reacting to a sound or a flash of light. The brain actively integrates inputs from different modalities of information (thermal and tactile) to form a judgment [19].

Experiment 2 demonstrate that increasing the viscosity of the solution leads to a marked reduction in perceived liquid sensation. Participants consistently reported lower liquid perception ratings as the xanthan gum concentration increased

from 1% to 3%, supporting our hypothesis that higher viscosity reduces the dynamic tactile cues that are essential for liquid perception. Furthermore, these results highlight the importance of tactile cues in the perception of liquids. When the solution is more viscous, human has less tactile inputs on the skin, leading to a reduction in liquid perception. This finding aligns with the original knowledge that liquid perception comes from the integration of thermal and tactile signals at the skin [4]–[6].

Interestingly, while the reduction in liquid perception was robust across all viscosity levels, the effect of viscosity on perceived warmth was less pronounced. Only the highest viscosity condition (3%) produced a significant increase in warmth ratings after light exposure, compared to the lower viscosity conditions. Someone might consider it results from optical transparency of the xanthan gum solutions. However, xanthan gum solutions are nearly transparent to visible light in the 460–530 nm range [20], the thermal energy from the LED illumination was able to reach the skin surface efficiently, regardless of viscosity. Thus, the high warmth rating under high viscous condition was not because more light was absorbed by the solution. There is another possibility that increased warmth sensation in high concentration solutions results from reduced heat capacity. In high-concentration xanthan gum solutions, the relative amount of free water decreases. Because water has a high specific heat capacity, substituting part of it with polymer reduces the overall heat capacity of the solution. Consequently, for the same thermal input, high-concentration solutions exhibit a larger temperature increase than low-concentration solutions. However, it has been found that in high-concentration xanthan gum solutions, the heat capacity is increased [21], leading to smaller temperature change for the same thermal input than low concentration solutions. Thus, heat capacity may not be able to interpret the increased warmth sensation in the high-viscosity condition. A possible explanation is thermal conductivity of the xanthan gum solution. There is no bulk fluid flow in our exp conditions, therefore the heat transfer mode should be conduction, instead of convection. Recent research measurements indicate that at room temperature, the thermal conductivity coefficient of a 0.5% xanthan gum solution ranges from 0.598 to 0.679 W/m·K [22]. This value is very close to the thermal conductivity coefficient of pure water at the same temperature. While as a polymer solution, xanthan gum solution adheres to the general physical properties of polymer solutions—namely, that increasing concentration typically leads to a slight decrease in thermal conductivity [23]. Therefore, we can infer that the thermal conductivity of the xanthan gum solution used in this experiment is lower than that of water and decreases with increasing concentration. Lower thermal conductivity leads to less heat flowing from the warmer skin to adjacent layers of the stationary fluid via molecular interactions. As a result, more intense warmth is perceived.

These findings extend the neurophysiological model of wetness perception [5], [6], [24], which posits that wetness is a construct arising from the combined activity of cold-sensitive A δ fibers, warm-sensitive C fibers, and mechanosensitive A β

fibers [5], [24], [25]. Our results suggest that it is the same for the liquid perception and the inputs of thermal and tactile cues can be dynamically shifted by external manipulation. The observation that spatial origin of thermal input (palmar vs. dorsal) did not differentially affect liquid perception, despite differences in warmth ratings, implies that spatial information is largely lost during central integration. This supports the view that liquid perception is dominated by the overall thermal state rather than by precise spatial localization.

Despite providing new insights into the multisensory basis of liquid perception, the present study has several limitations that should be addressed in future research. Our experiments only tested perception in viscous xanthan gum solutions while did not include direct comparisons with pure water. As a result, it remains unclear how the liquid perception changes in pure water environment. Future work should systematically compare responses in viscous liquids and pure water to clarify the extent and boundaries of the effect of viscosity on perceived liquid.

The current study primarily manipulated thermal and tactile cues, while intentionally minimizing visual cues through the use of sunglasses and blackout covers. However, previous research has suggested that visual inputs can also influence wetness perception [26]–[28] or liquid perception [29]. Further studies should explore how visual information, such as seeing the liquid, may shape or interact with thermal and tactile contributions to liquid perception.

From an applied perspective, our findings have direct implications for the design of haptic interfaces and multisensory feedback systems. The ability to modulate liquid perception through controlled thermal and tactile cues could enable more realistic rendering of liquid sensations in virtual and augmented reality, teleoperation, and rehabilitation contexts [30], [31]. For example, hydroptical thermal feedback could be used to simulate liquid or dryness without the need for actual liquid, expanding the repertoire of tactile illusions available to haptic designers.

In summary, this work demonstrates that human liquid perception is an actively constructed, multimodal experience that can be flexibly manipulated by controlling the integration of thermal and tactile cues. These insights advance our understanding of somatosensory integration and open new avenues for the development of haptic technologies capable of simulating complex tactile experiences.

VI. CONCLUSION

This study demonstrates that human liquid perception is not a fixed property. Instead, liquid perception results from flexible sensory integration, which can be actively modulated by the integration of thermal and tactile cues. Through systematic manipulation of thermal input and tactile input, we showed that liquid perception can be diminished or altered without changing the physical presence of liquid. Notably, increasing illumination intensity of visible light reliably reduced the liquid perception, while higher solution viscosity suppressed tactile cues, further decreasing liquid perception. These results

indicate the manipulability of human liquid perception. Our findings provide new insights into the mechanisms of somatosensory integration and open avenues for the development of haptic technologies capable of rendering liquid perception in virtual environments and human-computer interaction.

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The preferred spelling of the word “acknowledgment” in America is without an “e” after the “g”. Avoid the stilted expression “one of us (R. B. G.) thanks ...”. Instead, try “R. B. G. thanks...”. Put sponsor acknowledgments in the unnumbered footnote on the first page.

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