Mouillé: Exploring Wetness Illusion on Fingertips to Enhance Immersive Experience in VR

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ABSTRACT

Providing users with rich sensations is beneficial to enhance their immersion in Virtual Reality (VR) environments. Wetness is one such imperative sensation that helps humans avoid health-risking conditions and adjust grip force when interacting with objects. Recently, researchers have begun to explore ways to create wetness illusion, primarily on face or body skin. In this work, we extended this line of research by creating wetness illusion on users' fingertips. We first conducted a user study to understand the effect of thermal and tactile feedback on users' perceived wetness sensation. Informed by the findings, we designed and evaluated a prototype—Mouillé—that provides various levels of wetness illusion on fingertips for both hard and soft items of varied weights when users squeeze, lift, or scratch it. We further presented demo applications that simulate an ice cube, iced cola bottle, a wet sponge, etc, to show its use in VR.

Author Keywords

Wetness illusion; virtual reality; prototype; user study

CCS Concepts

•**Human-centered computing** → **Human computer interaction (HCI);** *Haptic devices;* User studies;

INTRODUCTION

There has been an increasing interest in providing users with a rich set of sensations for VR environments. Recent research has explored ways to create spatial vibrotactile [9], motion [6], inertial [16], force [3, 17, 20, 21], thermal [5, 25, 27], and wind [26, 27] feedback. Although Wetness sensation is important to human, which helps people avoid health-risking conditions (e.g., feeling uncomfortable while wearing wet clothing [4]), researchers have only recently begun to understand its underlying mechanism [11, 12]. This has inspired researchers to explore ways to generate wetness sensation for VR, such as simulating showering experience on face and body skin [30, 24].

In addition to face and body skin, people commonly use their fingers to sense wetness and adapt their interactions with objects accordingly, such as adjusting grip force upon sensing wet surfaces [1, 2, 31, 28]). Therefore, it is important to understand what affects people's wetness sensation on their fingertips and then use it to guide the creation of wetness illusions on fingertips to enhance VR experiences.

In this paper, we first conducted a formative study with twelve participants to understand how the temperature, pressure, and friction affect users' perception of wetness on their fingertips. Results show that temperature is key to generating wetness illusion; and temperature and friction could potentially enhance such illusion.

Informed by the findings, we designed a prototype—Mouillé—that allows users to perceive objects with various levels of wetness and stiffness by changing its temperature and stiffness.

To understand whether Mouillé can provide wetness illusions on fingertips for VR users and whether it allows users to distinguish different levels of wetness, we conducted a user study, in which twelve participants interacted with four wet virtual objects of various stiffness in VR by squeezing, lifting, or scratching Mouillé with their fingers and reported their wetness perception on fingertips. Results show that all of them were able to perceive wetness on their fingers and they were also able distinguish three levels of wetness with at least 83% accuracy for five out of six test conditions. In addition, we also identified other factors that affected their wetness perception and discussed potential future directions.

We made the following contributions: i) an understanding of the effect of temperature, pressure, and fiction on simulated wetness perception on dry fingertips; ii) a portable prototype that allows users to feel different levels of wetness on their fingertips when they interact with VR objects of varied stiffness via touching, squeezing, lifting, or scratching;

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BACKGROUND AND RELATED WORK

Wetness Sensation Mechanism

Although previous research has identified anatomically the biological transducers of touch, pain, and temperature in human skin [22], no receptors have been found for sensing wetness [7]. Instead, previous research suggested that the wetness is perceived through the combination of specific skin thermal and tactile inputs, including information about skin cooling and rapid changes in touch, which are received primarily from thinly myelinated thermoreceptors and fast-conducting myelinated mechanoreceptors respectively [11].

Filingeri et al. conducted a study in which participants touched a wet surface and reported their sensation of wetness. By manipulating the temperature of the wet surface and asking participants to make a small movement on the surface, they provided the first experimental evidence that the combination of conscious coldness and mechanosensation could be the primary neural process allowing humans to sense wetness [12]. Recently, Shibahara and Sato extended their study to further evaluate the effect of static and dynamic touch on the perception of wetness [29]. They found that while users could perceive wetness via temperature alone in the static touch condition, they were only able to perceive wetness through the combination of temperature and the friction and roughness in the dynamic touch condition. In sum, these studies have provided evidence that the wetness sensation is produced by *thermal (i.e., heat transfer)* and *tactile (i.e., mechanical pressure and friction)* inputs.

While Filingeri et al. focused on the forearm and the index fingertip skin [13, 12] and Shibahara and Sato focused on the palm skin in their studies respectively [29], we sought to extend this line of work to better understand the effect of *thermal* and *tactile* inputs on users' *fingertips*, which would in turn inform interaction design that leverages the wetness sensation on fingertips.

Wetness Illusion in VR

Informed by the recent understanding of the wetness sensation mechanism [12, 29, 11], researchers have just begun to simulate wetness illusion for VR applications. LiquidReality integrates thermal and vibrotactile modules into a head mounted display to simulate a wetness sensation on the face while the user is interacting with a VR application [24]. Liquid-VR system adopts the same thermal and vibrotactile integrated head mounted display but extends it by placing additional vibrotactle modules on users' collarbone and feet to simulate a whole body wetness sensation [30]. Recently, Zhu et al. explored the possibility of generating spatial thermal patterns using smart rings embedded with multiple thermoelectric coolers [33]. The exploration so far has been limited to simulating wetness sensation for the face, the body parts (i.e., collarbone and feet areas), and on a ring [30, 24, 33]. Inspired by this line of work, we sought to create wetness illusion on users' fingertips to enhance the immersion of VR environments.

UNDERSTANDING WETNESS ILLUSION ON FINGERTIPS

To better understand the effect of temperature, pressure, and friction on the wetness illusion on fingertips, we designed a prototype that allowed us to control the parameters and then conducted a user study.

Apparatus

Figure 1: Experimental device (a: 40mm*40mm FSR sensor, b: 40mm*40mm TEC plate with a water-cooling equipment, c: printer plate with a finger holder) and (d) study setup (user separated from the experimental device by a board)

Figure 1 shows the experimental device and the experimental set. We retrofit a 3D printer to leverage its precise position control on three-axis slides. The printer is rotated 90°and placed on a table. One end of the original printhead is replaced by a *TEC plate*, which is connected to a water-cooling equipment. The *temperature* of the TEC plate is controlled by a TEC controller with an error of ±0.02 °C.

The other end of the printhead is attached with a 40*mm* × 40*mm FSR sensor*. A holder is positioned on the original printing plate to host users' fingers in the same position. The prototype moves the X-axis slide to drive the finger forward until it touches the TEC plate (ceramic surface). By measuring the pressure via the FSR sensor and adjusting the printing plate position in the X-axis, we can precisely control the *pressure* that the finger applies to the TEC plate. Similarly, by manipulating the movement of the TEC plate in the Y-axis back and forth, we can create different levels of *friction* sensation.

Participant

We randomly recruited twelve participants (3 females, 9 males) without sensory-related deficits from age 23 to 30 (M=24.25, SD=2.05) from a local university.

Design

Inspired by prior works that show temperature, pressure, and friction affect wetness sensation, we designed this study [13, 12, 10]. We evaluated the effect of five levels of temperature (2, 5, 7, 10 and 15°C below each participant index fingertip temperature, which would be referred to as temperature level 1 to 5) based on Filingeri et al.'s studies [13, 12]. We conducted pilot to select appropriate friction and pressure values with five participants. We recorded three different levels of pressure and two different levels of friction that can be clearly discerned by each participant first, and then selected the average of the overlapping values for each level of pressure and friction. Three levels of mechanical pressure are (The contact area between the finger and TEC plate is approximately 2 cm^2):3 kPa(0.6N/2*10^{-4} m^2, 6 kPa(1.2N/2*10^{-4} m^2, and 12.5 kPa(2.5N/2*10^{-4} m^2)), which will be referred to as low, medium, and high pressure. Two levels of friction are generated by horizontally moving the TEC plate at 2 Hz and 6 Hz, which will be referred to as low-frequency friction and high-frequency friction. In total, we applied 30 (5 + 5*3 + 5*2) cold-dry stimuli in a random order on each participant's index fingertip. Note that the temperatures of the stimuli were calculated on an individual basis, by measuring the fingertip temperature with an infrared thermometer.

Rating Scales

We asked participants to indicate their wetness perception on their fingertips between 0 and 4: 0 is the feeling of dryness, 4 is the feeling of putting a finger in water. As there was no clear discrete wetness levels, we encouraged participants to indicate their wetness sensation with any values between 0 and 4. Participants were asked to indicate their pressure and friction sensation between 0 and 4, with 0 meaning no pressure or friction at all, and 4 meaning the very strong pressure or friction that they had experienced in daily lives. To avoid priming participants with questions only asking their wetness feeling, we asked them to rate all these three tyeps of feelings after each trial. This setup ensured that participants did not know which of the three variables (i.e., temperature, pressure, and friction) was changed in each trial but focused on their real feelings.

Procedure

The study was conducted in a quiet office with room temperature of 21 ± 1°C and the relative humidity of $35 \pm 5\%$. Upon arrival, participants were asked to rest in the study room until their finger temperature reached a stable temperature, which was measured by infrared thermometer. During the study, the temperature and humidity of the study room was controlled constant. Participants were asked to immerse their finger into water at room temperature only once at the beginning of the study, allowing them to get a baseline wetness feeling. We dried their finger with tissue and waited until their finger returned to its original temperature (measured with infrared thermometer) before continuing the study.

Participants sat at a desk where the prototype was placed. Participants did not know the existence of the experimental device and were separated from it so that they could not see it. They did not know anything about how the stimuli were applied on their index fingers or the type and magnitude of the simulation to prevent any expectations. Stimuli included dry-stimuli of different temperatures with no pressure or friction, dry-stimuli of different temperatures with different levels of pressure, and dry-stimuli of different temperature with different levels of friction. Each stimulus confirmation was repeated three times during the study and the stimuli were applied in a random order.

For each trial, each participant positioned their index finger in the holder on the printing plate, which then automatically pushed the finger towards the TEC plate until the measured temperature, pressure and friction satisfied the configuration of the trial. Then the participant was asked to rate their wetness, pressure and friction sensation on their fingertip using scales in 3.4 section.

This phase took roughly 20 seconds. After that, the TEC plate was set to the original temperature of the participant's finger to warm the finger back to its original temperature. This phase stopped when the participant indicated that the temperature of their finger was the same as that of the TEC plate. In each trial, the printing plate pushed the finger towards the TEC plate and then travelled back to its original position. We checked the TEC plate surface using Cobalt chloride test paper and ensured there was no condensation throughout the study. Participants repeated this process for all the trials. On average, the study took 135 minutes to complete. Each participant was compensated with $23.

Results

Ten out of the twelve participants had experienced wetness illusions on their fingers. The results of the rest two participants were treated as outliers because they were very insensitive to wetness perception, reflected by their wetness ratings (M: 0.06, STD: 0.01) compared to those of the rest of the participants (M: 0.48, STD: 0.27). As a result, in the following analysis, we focused on the data from the 10 participants who actually felt wetness to better understand how temperature, pressure, and friction affected wetness illusions. Figure 2 a, b, and c show the wetness perception ratings for different levels of temperature, pressure, and friction respectively.

Figure 2 (a) shows that the lower the temperature, the stronger the wetness illusion. We performed Friedman test and found that there was a significant difference for the ratings of different temperature levels ($\chi^2 = 39.82, p = 0.000, df = 2$). Pairwise comparisons indicated that the differences between any two levels were significant.

Figure 2 (b) shows that participants felt stronger wetness sensation without pressure than with any given levels of pressure. Friedman test found a significant difference ($\chi^2 = 8.28, p = 0.041, df = 2$) and pairwise comparisons indicated that there were significant differences between the no pressure condition and any of the three given pressure conditions, but there was no significant difference between the three pressure conditions.

Figure 2 (c) shows the ratings for all friction levels were very similar. Friedman test found no significant difference between the three frictions conditions ($\chi^2 = 4.00, p = 0.135, df = 2$).

Discussion

It is encouraging that eight-three percent of the participants (10 out of 12) were able to feel wetness illusions. Results in Figure 2 show that temperature was key to generating wetness illusions. Moreover, there was a clear trend between the temperature and the wetness illusions. Specifically, the lower the temperature, the stronger the wetness illusion. For example, when exposed to a lower temperature levels (e.g., T-10, T-15), P1 commented, *"I felt my finger was wrapped in a sponge full of water"*; P2 commented, *"it was like I just pulled my finger out of water."*; and P6 commented, *"it felt like touching a tin can in winter, or a ice pop in summer."*.

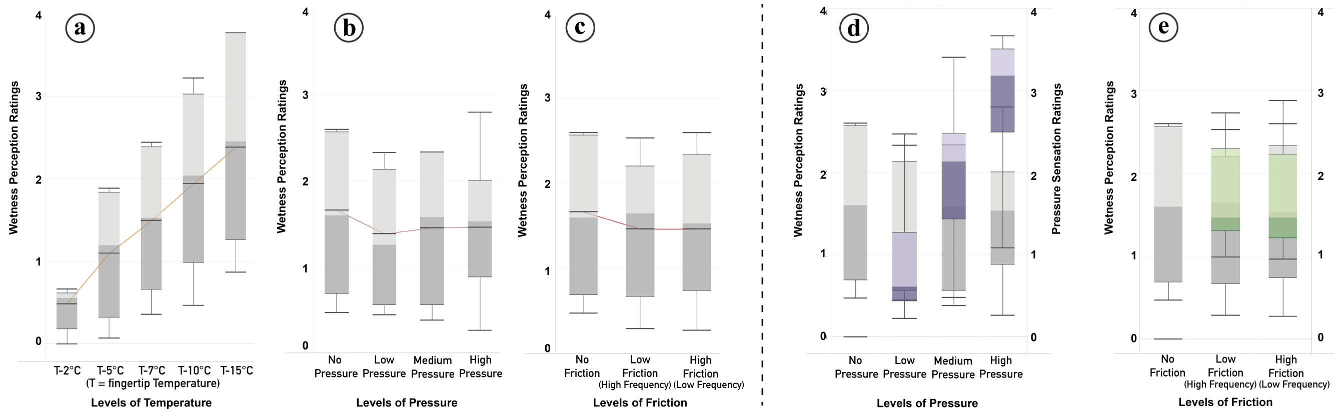

Figure 2: The effect of temperature, pressure, and friction on wetness perception: (a) temperature; (b) pressure; (c) friction.

Interestingly, participants tended to feel stronger wetness sensation when they touched on the surface without any external pressure or friction. The implication is that the wetness illusion can be triggered the moment when users touch a prototype without needing to apply extra pressure or friction.

To better understand how participants' perceptions of wetness and pressure changed in different pressure levels, we further plotted their ratings for wetness and pressure in Figure 2 (d). The grey and blue bars were the perceptions of wetness and pressure respectively. As the pressure become higher, participants tended to feel pressure sensation more than wetness sensation.

The implication for design is that if fingers would feel pressure when interacting with a device that generates wetness illusion, such as when lifting it, then the device should be designed to feel as close to the simulated object as possible. Because lifting a heavier object requires a higher grip force, which in turns requires users to apply higher pressure on the interaction surface. This could potentially reduce wetness illusion on their fingertips.

Figure 2 (e) shows participants ratings of wetness and friction sensation for each friction level. Similarly, when friction was applied, higher friction also tended to generate slightly higher wetness ratings but the difference was not significant. Moreover, the wetness rating was higher without friction than with friction. The implication is that the frictions, as generated via vibrations as our experimental device did, did not significantly enhance wetness illusion. Future work should examine whether other ways of generating friction could potentially enhance wetness illusion on fingertips.

In sum, compared to Filingeri et al.'s recent work [11], our study has two key differences: 1) the wetness was simulated on a dry surface in our study while Filingeri et al.'s work used water wetted fabrics (cotton); 2) external pressures were passively applied to participants' fingertips in our study to make sure the applied stimuli were constant among users while active pressures were voluntarily applied by participants on a water wetted surface in Filingeri et al.'s work. While their study contributes a physiological understanding of real wetness, our study contributes an understanding of the effect of dry stimuli on simulated wetness on fingertips.

Based on our findings, we take the following two factors into consideration when designing our wetness illusion prototype—Mouillé: 1) temperature is key to generating wetness illusion and therefore. As a result, the prototype should be able to generate different levels of temperature; 2) pressure and friction are secondary factors that could help enhance wetness illusion. Therefore, the prototype should also allow users to apply pressure or friction, such as via squeezing or lifting, or not apply any pressure, such as scratching.

MOUILLÉ: CREATING FINGERTIPS WETNESS ILLUSION

Mouillé is a prototype that generates wetness illusion when users touch, squeeze, lift, or scratch its surfaces.

Theory of Operation

For producing the illusions of wetness, the same rendering mechanism was used as that of study 1, where the sense of wetness is induced by the rapid skin cooling. As Mouillé acts as an haptic proxy of virtual objects in VR and supports users to perform a variety of hand operations, pressure and friction are generated as a result of hand actions. Thus, we did not consider to include extra pressure and friction control in producing the wetness sensation.

Stiffness let users feel how hard the object are. Stiffness is important in helping users differentiate material that is rigid or soft. Here we employ two approaches to generate the sensation of stiffness: 1) the sensation of stiffness can be felt via a tunable spring, and 2) a rubber membrane can additionally add the stiffness sensation of flexible surfaces.

Implementation

The prototype is shown in Figure 4. It measures $75 \times 70 \times 145mm$ in length, width and height. It comprises of three parts, including the stiffness control components for rigidness and elasity, and the component that leverages the TEC plate to induce the rapid cooling on a copper plate, that serves as the contact surface with a user's fingers. There are two copper plates, one on each side for enabling grasping postures and support the rendering of wetness on all the fingers. The TEC

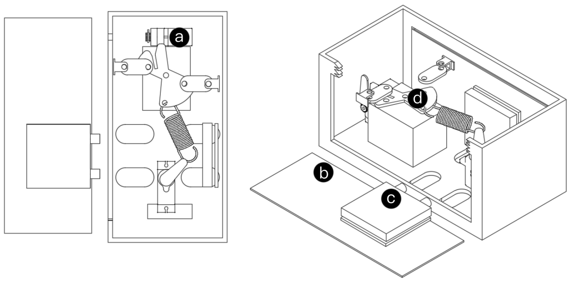

Figure 3: Mouillé scheme diagram: (a) stiffness control module (lock system); (b) brass plate; (c) TEC plate; (d) stiffness control module (spring system)

plates are attached with fluid cooler modules, that are tubed to a liquid reservoir.

The two copper plates are docked inside the prototype frame, and can slide in and out along the frame. To emulate different objects of various stiffness, the cooper plates are connected to a center wheel via linkage structures, whose rotary motion are restrained by a spring and a locking mechanism. This is to provide different stiffness sensations, as well as rigid ones. Two miniatured servo motors are used, to stretch the spring that enables the device to produces various levels of stiffness when fingers squeeze the copper plates, and to lock the center wheel to prevent any movements of the copper plates for representing rigid objects, respectively.

The device is driven by a TEC controller module that controls the TEC plates (same to the one used in Study 1), and an Arduino board to control the two servo motors. Altogether, the capabilities of Mouillé allows it to render sensations of wetness, as well as those rigid, flexible objects, and table surfaces as shown in Figure 5.

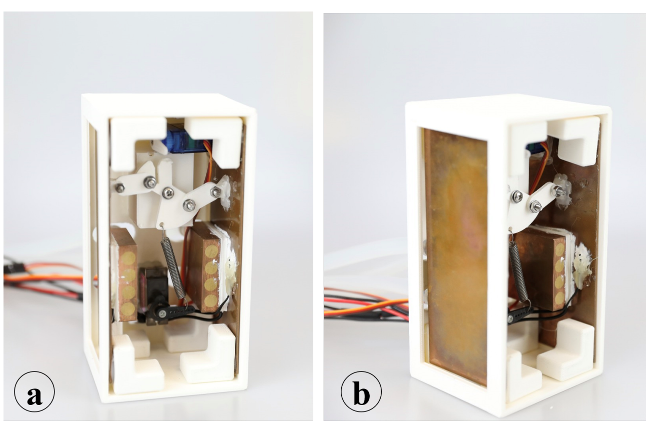

Figure 4: Mouillé: (a) shows the internal structure and (b) shows one interactive surfaces.

Application Scenarios

To demonstrate how Mouillé can be used to enhance users' experience when interacting with wet virtual objects, we designed four application scenarios (Figure 5). In these scenarios, users could experience wet virtual objects with different levels of stiffness by squeezing, lifting, or scratching Mouillé, which acts as a proxy for those virtual wet objects. To simulate a ice cube (5 (b)), the lock system (highlighted in green circles) is locked so that the two vertical side surfaces cannot be squeezed. To simulate a Coke bottle (5 (c)), the lock system is unlocked so that the two vertical side surfaces can be squeezed. To simulate the rigidness of the coke bottle, the bottom motor (highlighted in red circle in Figure 5) rotates 180°and pulls the spring down, which in turn pulls the two side surfaces into the body of Mouillé so that the two side surfaces can only travel a small distance. Similarly, to simulate sponge (5 (d)), the lock system is unlocked and the bottom motor only rotates 90°so that the two sides surfaces can travel longer distances and therefore produces a spongy effect. To simulate a wet glass table ((5 (e))), we rotate Mouillé 90°so that one of its vertical side surface faces upward so that users can scratch it. Similar to the ice cube, the lock system is locked to produce a complete rigid surface feeling.

EVALUATION

Study Design

We conducted a user study to answer two research questions:

- **RQ1:** whether and to what extent Mouillé can simulate wetness illusions that people commonly experience in their daily lives?
- **RQ2:** whether and to what extent Mouillé can simulate different levels of these wetness illusions?

To answer RQ1, we simulated four daily items covering three levels of stiffness: 1) *hard*: ice cube, table surface; 2) *medium*: coca-cola bottle; and 3) *soft*: sponge. Because people interact with these items differently, we tested three common types of interactions: *squeeze*, *lift*, and *scratch*. Specifically, we asked users to squeeze and lift the simulated ice cube and cola bottle, to squeeze the simulated sponge (we did not ask users to lift the simulated sponge due to the prototype's weight constraint), and to scratch the simulated table surface. In total, there were six combinations of the simulated items and their corresponding interactions. For each combination, we further included three temperature levels to test their effect on users' wetness perceptions. As a result, there were 18 (6*3) test conditions. For each test condition, participants wore an HMD, which renders the corresponding item, and were asked to interact with the item with the corresponding interaction for roughly 5 to 7 seconds. Afterward, they were asked to rate on a 5-point Likert scale *"I felt that I just touched [the item]"* (0: not at all; 4: exactly the same). We repeated the 18 test conditions three times and therefore each participant tried 54 (18*3) trials. We shuffled the order in which the trials were administered and allocated a time gap and fingertip rewarming between any two adjacent trials to avoid potential carry-over effect.

To answer RQ2, for each of the aforementioned 6 combinations, we first asked users to interact with Mouillé with three parameter settings corresponding to three wetness levels sequentially; we then repeated the same three parameter settings and asked users to choose their perceived wetness level from

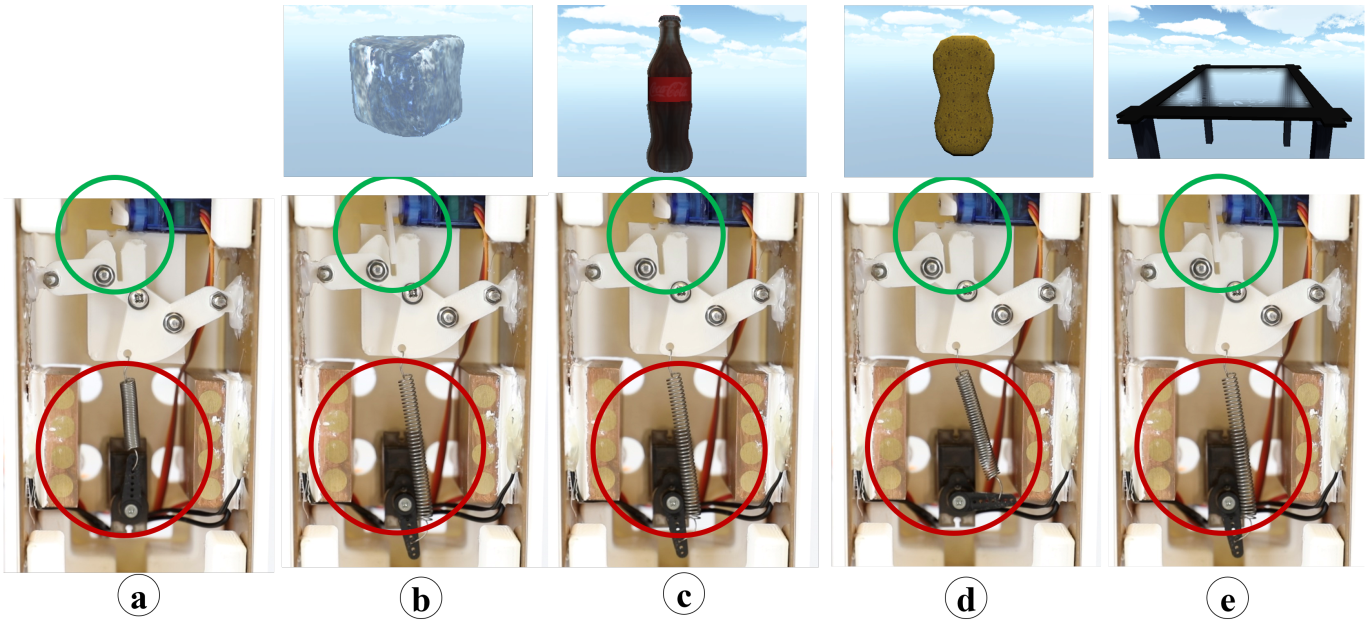

Figure 5: Four simulated items and Mouillé's corresponding internal structures for : (a) Mouillé in the idle state; (b)ice cube (green: lock, red: more stretched); (c) cola bottle (green: unlock, red: more stretched); (d) sponge (green: unlock, red: less stretched); (e) glass table (green: lock, red: more stretched).

the three levels (i.e., least wet, middle wet, and most wet) for each of the three parameter settings. We repeated the three test trials for each of the 6 combinations one more time. In total, users interacted with Mouillé 54 (6*(3+3+3)) times, in which there were 18 trails to experience all three wetness levels and 36 (6*(3+3)) test trials. Similar to RQ1, we also shuffled the order in which the trials were administered and allocated a time gap between any two adjacent trials.

Participants
Twelve local university students with no sensory-related diseases (3 females and 9 males, aged 25-28) participated in the study (M=25.83, SD=1.03).

Design Procedure
The study was conducted in a quiet office with room temperature of 21 ± 1°C and the relative humidity of $35\pm5\%$. Participants were asked to wear the HMD (HTC VIVO Pro). Figure 6 (a) shows the study setup. They then were able to see the corresponding item rendered in VR and interact with Mouillé, which acts as an proxy to allow them to interact with four wet virutal objects as described in Figure 5. Figure 6 (b), (c) and (d), (e) illustrate how Mouillé allows users to squeeze and lift an ice cube and a coke bottle respectively. Figure 6 (f) and (g) show how Mouillé allows users to squeeze a sponge and scratch a glass surface. During the study, they were presented with these six interaction scenarios in a random order. After seeing each scenario and interacting with the virtual wet object, they were asked to answer the corresponding questions in VR.These scenarios were repeated three times.

During the study, participants were not allowed to see the Mouillé prototype but could request a rest time whenever needed. The study took 120 minutes on average to complete. They were compensated with $ 23.

RESULTS

RQ1: Wetness perception of simulated wet objects
To answer RQ1, we computed and plotted the distribution of users wetness ratings for the three test temperature levels (i.e., T-5°C, T-10°C, and T-15°C) for all the six test conditions (i.e., ice cube & Squeeze, ice cube & lift, coke bottle & squeeze, coke bottle & lift, sponge & squeeze, and glass table & scratch). The results in Figure 7 indicate consistent trends across all the six conditions that participants' perceived wetness sensation became stronger when the temperature became lower.

We performed Friedman test on users' wetness ratings for each of the six conditions. The results show that there were significant differences in the wetness sensation ratings for different temperature levels were significant for all six conditions: Ice cube & squeeze ($\chi^2 = 17.24, p = 0.0002, df = 2$); Ice cube & lift ($\chi^2 = 23.53, p = 0.0000, df = 2$); Coke bottle & squeeze ($\chi^2 = 20.47, p = 0.0002, df = 2$); Coke bottle & lift ($\chi^2 = 21.83, p = 0.0000, df = 2$); sponge & squeeze ($\chi^2 = 14.22, p = 0.0008, df = 2$); and glass table & scratch ($\chi^2 = 17.52, p = 0.0002, df = 2$).

We further performed post-hoc pairwise comparison for each condition and the results show that: for the Coke & lift, Coke & squeeze, Ice & lift, and sponge &squeeze conditions, the differences between any two temperature levels were significant; and for the Ice & squeeze and glass table & scratch conditions, the difference between the low temperature (T-5°C) and the lower temperature (T-10°c) and that between the

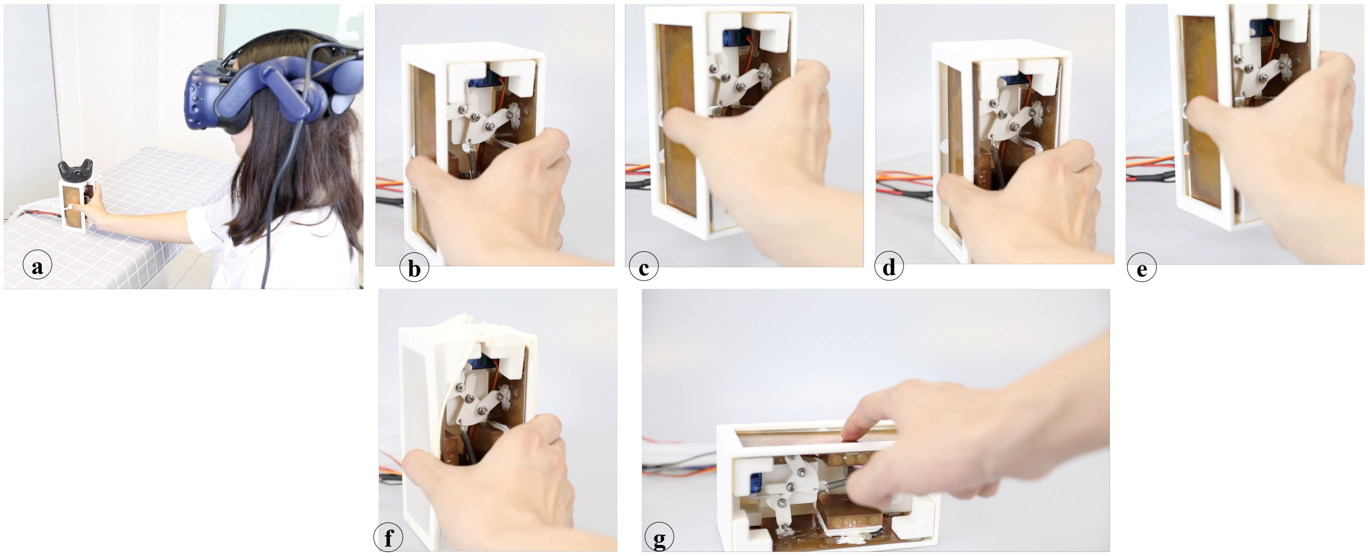

Figure 6: (a): Study 2 setup; and prototype configurations: (b): ice cube (squeeze); (c): ice cube (lift); (d): coke bottle (squeeze); (e) code bottle (lift); (f) sponge (latex films attached to the external surfaces); (g) glass table (device rotated 90°).

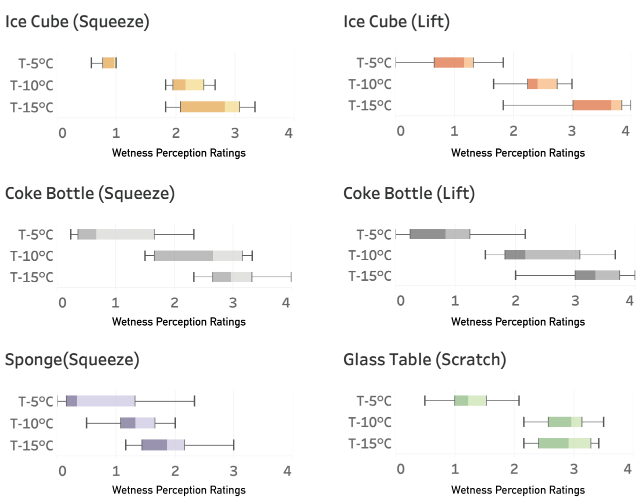

Figure 7: participants' wetness ratings for six conditions: coke bottle (squeeze); coke (lift); ice cube (squeeze); ice cube (lift); glass table (scratch);sponge (squeeze)

low temperature (T-5°C) and the lowest temperature (T-15°C) were significant.

RQ2: Recognition of correct wetness levels

To answer RQ2, we computed how accurate participants recognized the correct levels of wetness for the six test conditions and the results are shown in Table 1. We found that: 1) participants were able to distinguish three levels of wetness for coke bottle and sponge with at least 89% average accuracy (the fourth and fifth lines in the Table 1); 2) participants had achieved higher average accuracy in distinguishing wetness levels for the ice cube when they lifted them up than squeezing them on the table (the first and second lines in the Table 1);

Table 1: The accuracy of recognizing correct wetness levels for the six conditions(in $\mu(\sigma)$). T refers to the temperatures of the participants' fingertips.

Condition	**T-5°C**	**T-10 °C**	**T-15 °C**
Ice cube (squeeze)	0.83 (0.38)	0.94 (0.23)	0.57 (0.50)
Ice cube (lift)	0.97 (0.17)	0.97 (0.17)	0.94 (0.23)
Coke bottle (squeeze)	1.00 (0.00)	0.83 (0.38)	0.94 (0.23)
Coke bottle (lift)	0.97 (0.17)	0.97 (0.28)	0.94 (0.42)
Sponge (squeeze)	0.97 (0.74)	0.89 (0.51)	0.89 (0.82)
Glass table (scratch)	0.69 (0.33)	0.47 (0.32)	0.58 (0.42)

3) Comparison between T-15°C and the other temperature levels for the ice cube & squeeze condition (the first line in the Table 1) seemed to suggest that lower temperature could have a negative affect the wetness sensation when users squeeze Mouillé; 4) Participants had lowest accuracy distinguishing the wetness levels for the glass table condition (the last line in the Table 1) .

Qualitative feedback

All participants were able to feel wetness on their fingertips. Ten out the 12 participants tried to rub their fingers to dry them during the study. All participants thought there was a wetness generator and three of them even constructed a mental model of the wetness generator, which consists of a water sprayer or a water drop generator, a dryer, and a stiffness generator.

Most participants felt that the wetness sensation for the coke bottle and the table surface were more realistic than that for the ice cube or the sponge. One reason perhaps was that the texture feeling of the ice cube or the sponge was much more different from that of Mouillé, compared to the texture feeling of the coke bottle or the table surface. For example, an ice cube was expected to melt after being touched and the sponge was expected to be deformed after being touched. Moreover, some reported that the sponge was more like a wet fabric. Pressure and friction also helped enhance the wetness illusion. For exampled, participants mentioned that they felt stronger wetness when lifting cola bottle up, which would generate pressure and friction on the touching surface.

Although lower temperature tended to generate stronger wetness sensation, participants sometimes felt coldness more than wetness when exposed to lower temperatures.

DISCUSSION

Our evaluations indicate it is possible to create different levels of wetness illusion on fingertips by modulating the temperature, pressure, and friction on the touch surface when participants interacted with virtual objects through HMD by squeezing, lifting, or scratching the prototype—Mouillé. Some participants felt their fingers so wet that they asked the experimenter to wipe their fingers (as they were not allowed to see and dry their fingers themselves).

We also found that lower temperature, higher pressure, or higher friction could potentially increase wetness illusion as participants felt stronger wetness when the temperature was lower and when they were lifting Mouillé up than squeezing it on a resting platform. Participants needed a time to reset their wetness sensation after they interacted with Mouillé each time, which was the reason why we set a time between any two adjacent trials. The implication for VR application design is that user interactions should be designed to encourage users to reset their fingers after interacting with Mouillé and the length of each interaction with Mouillé should also be kept to a minimum.

It is worth noting that the wetness illusion disappears once the stimulus no longer applies to participants' fingertips. As some participants reported, it felt strange that their fingers dried so fast, which was contradictory to their common knowledge. It is a challenge for interaction designers to take into consideration. Our participants suggested that if they were tricked to believe there was a dryer helping with drying their fingers, they would have been convinced the fast disappearing wetness sensation. However, future work should examine how to provide persistent wetness whenever desired.

We chose Mouillé's parameters based on all participants' data in the first study. While these values worked in general, two out of the twelve participants could not feel wetness illusion well with the experimental device. This finding and the variations in the wetness ratings in Figure 2 suggests that individual difference in their ability of perceiving wetness exists and should be considered when creating wetness illusion, such as choosing appropriate parameters or perhaps examining other types of stimuli if changing temperature does not work for these users. One potential way to search for an optimal set of parameters is to continually change the set of parameters while allowing users to provide their perceived wetness sensation. However, because users need a time to reset their wetness sensation from previous interaction with Mouillé, searching through the vast parameter space could take a long time. Future work should examine a better approach to identify optimal parameters for an individual.

We chose not to ask users to lift the simulated sponge because Mouillé was much heavier than a real piece of sponge. However, matching Mouillé's weight with the simulated VR item might potentially enhance users' wetness illusion. This could be realized by connecting Mouillé through a pulley system to a weight-adjustable counterweight. With appropriate counterweight, users might be able to feel the corresponding VR item's weight when they lift Mouillé up.

In addition to the different levels of stiffness and types of interactions that Mouillé supports, the roughness of the interaction surface could potentially affect wetness illusion [23]. Integrating texture-generating prototypes (e.g., [8]) into Mouillé would allow for a better understanding of the effect of surface roughness on wetness illusion.

In the evaluaton of Mouillé, we designed the two questions to understand if participants could distinguish different types of wetness (e.g., coke, sponge) and if they could distinguish three wetness levels for each type of wetness respectively. In future work, it is interesting to understand the effect of Mouille on enhancing virtual presence and embodiment using questions proposed in the literature, such as Witmer and Singer's questionnaire [32] and Gonzalez-Franco and Peck's questionnaire [15, 19].

In addition, the evaluation of Mouillé focused on users' wetness perception when interacting with the prototype, where it was challenging to control the pressure and friction. This is because in the proposed scenarios, participants actively applied pressure on Mouillé's surfaces, and friction was implicitly determined by the pressure and Mouillé's weight (when lifted). Therefore, we opted to only control temperature instead of pressure and friction in the evaluation. Future work should examine ways to better measure and control the active pressure [14, 18] and friction that users apply when they actively use Mouille in VR tasks.

CONCLUSION

In this work, we first conducted a study to understand how temperature, pressure, and friction affect people's wetness perception on fingertips using simulated dry-stimuli. We then designed and implemented a prototype—Mouillé—that allows VR users to experience wetness on their fingertips. We conducted a user study in which VR users interacted with four wet virtual objects that were of different stiffness by squeezing, lifting, and scratching Mouillé. Results show that users were able to feel wetness with different levels of temperatures and ways of interaction. Moreover, they were able to distinguish three levels of wetness for each VR object (i.e., ice cube, coke bottle, sponge, and glass table). We found that temperature is key to generating wetness illusion and pressure and friction can further enhance such perception if only they are carefully designed to not override wetness sensation. Mouillé took a step further to enhance VR users' immersive experiences by providing them with simulated wetness sensation to their fingertips. We have discussed factors (e.g., weight and surface textual of the prototype, duration of the wetness illusions, individual difference) that should be examined to enhance wetness experience in VR.

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