

# HydroRing: Supporting Mixed Reality Haptics Using Liquid Flow

Teng Han<sup>1,2</sup>

<sup>1</sup>Autodesk Research  
Toronto, Ontario, Canada  
{first.last}@autodesk.com

Fraser Anderson<sup>1</sup>

<sup>2</sup>University of Manitoba  
Winnipeg, Manitoba, Canada  
{hanteng, pourang.irani}@cs.umanitoba.ca

Pourang Irani<sup>2</sup>

Tovi Grossman<sup>1,3</sup>  
<sup>3</sup>University of Toronto  
Toronto, Ontario, Canada  
tovi@dgp.toronto.edu

## ABSTRACT

Current haptic devices are often bulky and rigid, making them unsuitable for ubiquitous interaction and scenarios where the user must also interact with the real world. To address this gap, we propose HydroRing, an unobtrusive, finger-worn device that can provide the tactile sensations of pressure, vibration, and temperature on the fingertip, enabling mixed-reality haptic interactions. Different from previous explorations, HydroRing in active mode delivers sensations using liquid travelling through a thin, flexible latex tube worn across the fingerpad, and has minimal impact on a user's dexterity and their perception of stimuli in passive mode. Two studies evaluated participants' ability to perceive and recognize sensations generated by the device, as well as their ability to perceive physical stimuli while wearing the device. We conclude by exploring several applications leveraging this mixed-reality haptics approach.

## Author Keywords

Haptics; mixed reality; ubiquitous interaction;

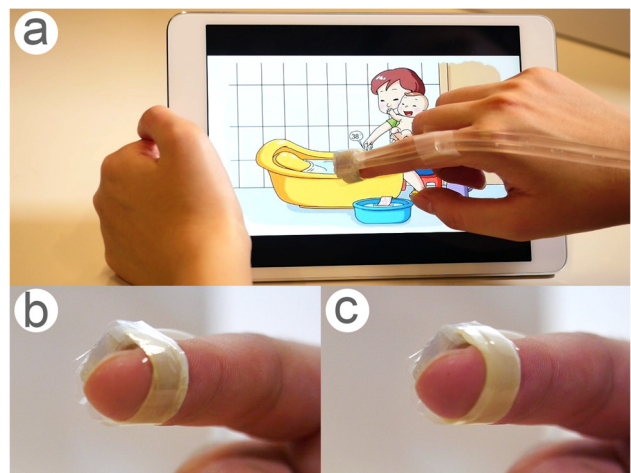
## INTRODUCTION

Hand-worn haptic devices have become prominent in recent years, as they can deliver compelling tactile sensations [10, 11, 18], even directly to the wearer's fingertips [1, 16]. Most of these haptic devices primarily serve applications with virtual objects, and impede the user's natural cutaneous sensations and dexterity for the benefits offered by the immersive haptic renderings. This tradeoff is largely a result of the often bulky mechanical structures and motors that are close to, or at the user's fingertips. However, in mixed reality or ubiquitous computing scenarios, the degree to which a user's fingertip is covered by rigid material directly affects how much they can interact with physical objects - to either hold them or to feel their texture for daily tasks. Very limited efforts have considered offering virtual haptic perceptions without the loss of original cutaneous sensation at the fingertips.

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In this work, we present HydroRing, a *mixed-reality haptic* device, which enables virtual haptic feedback without disturbing the user's natural tactile sensations of the physical world while wearing the device. Our prototype (Figure 1), is composed of a thin, flexible latex tube (0.1mm thick) that is lightly stretched over the skin, and provides the tactile sensations of pressure, vibration, and temperature on the fingertip via liquid flow. The sensations are delivered by modulating the temperature, pressure and flow rate of the liquid travelling through the device and across the fingerpad. The haptic device is non-obtrusive, and can readily switch between actively providing sensations, and being 'passive', i.e., supporting natural dexterity and allowing the user to sense and interact with the real world. This approach opens new opportunities for interaction, for example, allowing the user to seamlessly switch between physical and virtual sensations in mixed reality tasks, and provides a new channel for always-available notifications and other information. Our work envisions a future type of haptic display that can be always worn, or implanted on one's body with the support of artificial skins [21] and microfluidic devices [41].



**Figure 1. HydroRing, a mixed-reality haptics device shown a) augmenting a touchscreen with thermal feedback, b) not active c) active with liquid flow applying pressure.**

We present two studies evaluating the HydroRing device. The first examines a user's ability to learn and recognize different levels of temperature, pressure, and vibration produced by the device. We found that users could readily distinguish between five levels of each stimuli (>84% accuracy), though performance dropped at seven levels. The second study evaluates the extent to which HydroRing

impedes a user's natural touch perceptions of surface texture, pressure, temperature, and vibration while the device is worn in passive mode. Results indicated that users' perception of varying environment textures were minimally affected by wearing the device, with only a 4% reduction in the accuracy of perceived tactile sensations. Following these encouraging results, we explore several novel use cases that leverage mixed-reality haptics and discuss limitations and possible avenues of future work.

### RELATED WORK

This work is inspired by, and builds upon, prior research in wearable finger-based haptic devices, alternative approaches to haptics, and work that examines the use of pneumatic and hydraulic actuation for interactive devices.

#### Finger and Hand-worn Haptics

Finger-based wearable haptic devices have been well studied in recent years, as they have been shown to be effective in providing localized cutaneous stimuli [6] to, for example, fingertips that are most often used for grasping, manipulating and probing the environment. Pacchierotti et al. presented a comprehensive taxonomy of wearable haptic systems, including finger-worn devices [44]. Such devices are typically comprised of two structures - one structure that houses actuators on the back of the finger and another structure that is in contact with the volar surface of the fingertip. These devices can be categorized based on the cutaneous sensations they produce, including but not limited to, indentation, lateral force, and vibration.

*Indentation:* Frisoli et al. [16] presented a fingertip wearable device to improve the curvature discrimination of virtual objects by placing a plate in contact with users' fingerpads at different orientations. Using this concept, many indentation haptic displays [9, 16, 44] have been developed which have various degrees of freedom (DOF) and levels of contact force to improve the haptic exploration of virtual objects. Such indentation displays have been successfully employed to convey pressure [27], and curvature [16].

*Lateral force:* Gleeson et al. [17] designed a fingertip-mounted tactile device that laterally stretches the skin of the fingerpad along any path in the plane to provide navigational cues. In Gravity Grabber [38], lateral force was applied to the fingertips to render gravity without proprioceptive sensations. It consisted of two motors and a belt that were in contact with the fingertip and provided vertical or shearing stress based on the rotational direction of the motors. Bianchi et al. [7] adopted the same two-motor approach to control the tension of fabric, with the resulting stiffness being used to convey the softness of a surface. LinkTouch [53] replaced the belt with a five-bar linkage mechanism to support contact and directional force perception.

*Vibration:* Another common cutaneous feedback actuator built into wearable devices are vibrotactile motors. As vibrotactile motors are very small, they can be embedded within wearable devices such as gloves [11, 18, 22].

Vibrotactile feedback applied to the fingertips can be used to simulate contact events [31], texture [5], etc. However, the rigidity of the vibrotactile actuators dampens the user's sensations of the real world.

In recent years, there has been a growing need to develop wearable haptic devices that are capable of conveying compelling interaction feedback with virtual objects, such as grasping, squeezing, pressing, lifting and stroking. This normally requires combining multiple cutaneous stimuli into one compact device. For instance, Schorr and Okamura [48] designed a fingertip wearable device that renders forces in multiple directions to investigate users' perceptions of mass, friction, and stiffness while manipulating virtual objects. Altered Touch [40] was a fingertip haptic device with a dual motor design and a Peltier module that provided shear and vertical force as well as thermal feedback. Gravity [10] demonstrated kinesthetic feedback with a handheld device to support grasping in VR, including virtual weight, inertia forces, and stiffness.

Common among these haptic devices, is that they are rigid, bulky, or obtrusive. In contrast, HydroRing was designed to enable its use in mixed-reality or ubiquitous scenarios, or during tasks requiring finger dexterity.

#### Mixed Reality Haptics and Reduced Form Factors

Some prior works on haptics have demonstrated non-intrusive wearable haptic devices, which support, to some extent, real world interactions while worn. Ando et al. [3, 4] mounted a vibration device on the fingernail, allowing users to perceive tactile feedback while keeping their fingerpad from interference by the device in the real environment. hRing [43] used a belt placed on the proximal finger phalanx instead of the fingertip. These configurations allowed a user to maintain the use of their fingertips for sensation and manipulation, but did not allow the system to render sensations directly on the fingertips. Other belt-based devices [38] may not dramatically impede the users' natural sensations, but they are difficult to compare to as they do not quantify the degree to which these devices impede natural sensations. The use of motors in this prior work may interfere with the user's normal hand activities (e.g., in wet or dirty environments), a key design goal in our work. One exception, AeroFinger [14], was designed with the goal of reducing the physical size of haptic devices. AeroFinger was a pneumatic device that consisted of four miniature airbags to provide force and tactile sensations to the fingertips. It is similar to HydroRing in that the device is not electromechanically actuated and thus can be submerged in water, however, the form-factor was rigid, impeding the finger's haptic sensation of the physical environment, and mixed-reality use cases were not explored.

Another way to reduce the form factor of haptic devices is to rely on non-(solid) mechanical principles. Mid-air haptic devices such as with air vortex [51] and ultrasound [8], take advantages of not requiring users to wear any physical devices. Lee and Lee [30] leveraged air flow and designed a

non-contact wearable tactile display. With HydroRing, we support haptic sensations without the need to instrument the environment with these specialized hardware devices.

Most recently, Lopes et al. [34] demonstrated the use of electrical muscle stimulation (EMS) to provide force feedback, and showed how this form of feedback could be particularly useful in mixed-reality environments. We extend this work to provide a richer set of haptic sensations on the fingertip (temperature, pressure, and vibration), without a substantial impact on the physical haptic sensations received in the areas where the device is being worn.

### Fluid-based Interactive Systems

Fluids have been explored in designing haptic and tangible interfaces, with research exploring both the use of liquids (hydraulics) and gases (pneumatics). For instance, Squeezeback [45] provides compression feedback on users' arm for sustained notifications. Vázquez et al. [55] designed physical controllers and programmatically manipulated the tactile response using pneumatic actuation. Pneumatic actuation has been widely used in designing interactive shape changing displays [28, 57].

Smart liquid material such as magnetorheological (MR) fluid, electrorheological (ER) fluid, and ferro fluid are often used in touch sensing devices [25, 32, 33, 52], which also provide unique touch feedback because of their non-rigid surfaces. Liquido [47] embedded liquid into 3D printed objects to detect tilting and motions via conductive sensing. Follmer et al. [15] explored how jamming of granular particles can be used in designing malleable, flexible and shape-changing interfaces. The state of material rigidity can be computationally controlled via either pneumatics or hydraulics. Niiyama et al. [42] demonstrated a weight changing device with liquid transportation. Using a water jet can create tactile feedback to fingers or hands with direct or indirect contact [36]. Game designers have brought liquid experiences into digital water-play [36, 46]. Furthermore, liquid metal has been explored in applications of deformable and tangible UIs [35].

These works demonstrated a wide range of haptic related applications using air/liquid fluid, but had different design goal from ours. With HydroRing, we leverage flowing water to produce sensations on the fingertip. By using a thin, flexible tube and leveraging the fact that the water can be pumped away from the finger when not needed, HydroRing is able to provide a mixed-reality haptic experience without impeding the user.

### MIXED-REALITY HAPTICS USING LIQUID FLOW

Based on our review of previous work, there have been little efforts to design haptic devices that can also support a user's ability to perceive physical sensations. We use the term *mixed-reality haptics*, to describe devices that can enable virtual haptic feedback without impeding the user's haptic sensations of the physical world on the same location of the body (i.e. fingertip) while worn. Such devices are akin to

mixed-reality displays [37], which support a user's ability to view both physical and virtual imagery. Before describing our specific device, we outline two main design considerations when constructing the prototype - the use of liquid flow, and the form factor.

### Liquid Flow

A challenge of mixed-reality haptics is to design a device that allows the skin to perceive both virtual and physical stimuli. Any mechanical or rigid device that covers the skin would thus not be suitable. One possibility is to use a retracting device to stimulate the skin on demand, and retract when not in use. However, such an approach would require significant power and accuracy and the miniaturized motors would likely be rigid and bulky. The use of liquid and liquid flow, has several beneficial properties that lend well to providing mixed-reality haptics.

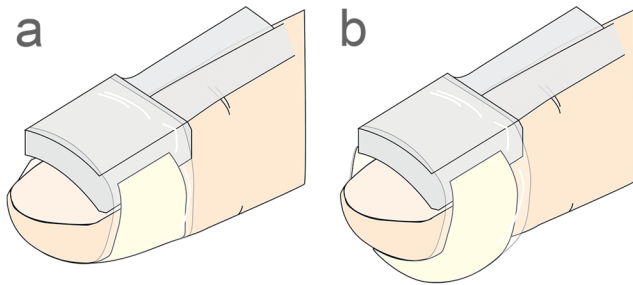
Liquid flow has a variety of states that can be described with physical and transport properties such as pressure, velocity, viscosity, (in)stability, and temperature. By dynamically adjusting the properties of liquid flow inside a tube, a range of haptic feedback sensations can be created. Due to the nature of liquid flow and the design of the system, some of these haptic sensations can be applied independently or simultaneously. For instance, a user could sense changes in both temperature and vibration at the same time as the temperature of the flowing water changes, and the flow is restricted and released quickly to provide the vibration.

The use of liquid to deliver haptic sensations also allows the end-effector that delivers the sensations to be located away from the equipment that drives the flow of the liquid. As liquid is incompressible, the latency for many sensations (e.g., vibration, pressure) can be relatively low, despite there being long distances between an end-effector and its associated equipment. For other properties (e.g., temperature), the distance to the end effector can impact the latency, but, when using liquid, this can be mitigated through the use of higher flow rates and thinner tubing. If a sealed end-effector is located away from the equipment controlling the flow, it can also be used in a variety of environments (e.g., under water, in dirty or oily environments, and so on). Lastly, if the majority of the end effector is made of flexible tubing, it would be robust to daily usage and small impacts. Even if components become damaged, they could easily be replaced with passive plastic and rubber parts. In comparison, the small, rigid electromechanical actuators associated with traditional haptics damage relatively easily and are often costly and difficult to repair.

### Form Factor

With strategic tube routing, liquid flow could potentially be used to provide haptic sensations on any area of the body. In our implementation, we focus on a finger worn device. The fingertip is particularly sensitive to haptic stimulation [19], making it a suitable target area. Demonstrating mixed-reality haptics on the fingertip will also allow us to explore usage

scenarios which require dexterous use of the hands or fingers, which traditional haptic devices impede.



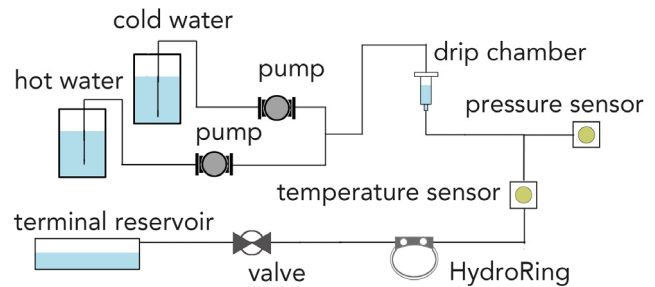
**Figure 2: Diagram of HydroRing as worn on the finger; a) non-active state; b) applying pressure to the finger by pumping water into the latex tube.**

In our implementation, we deliver fluid to the fingertip using a dedicated hydraulic circuit running through a latex tube (Figure 2). One potential implementation of liquid-flow haptic feedback is to offload the hydraulic circuit to existing hydrostatic or hydrodynamic systems the user is already wearing. Exoskeletons, while once part of science fiction [13], have recently become a reality, with both industry and medicine [2, 59] testing their utility. It is possible that these existing fluid-based exoskeletons could be modified to include the ability to provide haptic feedback to the fingertip in addition to their regular assistive function.

There is also potential for future liquid-flow haptic devices to be implemented using active microfluidics [41, 56]. Using very thin films, micropumps, and microvalves, it may be possible to deliver haptic sensations directly to the fingertips using low volumes of liquid. This approach shows potential, as it is low powered, very small, and may be able to be implantable directly under the skin in the distant future [21].

#### HYDRORING PROTOTYPE

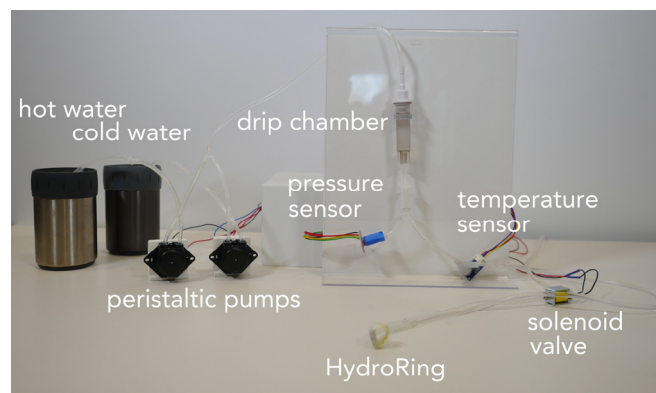
The HydroRing prototype consists of a purpose-built hydraulic circuit (Figure 3) connected via flexible PVC tubing to a fingertip-worn ring (Figure 2). The hydraulic circuit controls the flow of the liquid, to provide sensations of pressure, temperature, and vibration. Pressure and temperature sensors attached to the tubing monitor the state of the liquid and provide input to the system to ensure that accurate sensations are being rendered. We use water as the liquid medium due to its availability, inert nature, and low cost, although other liquids could potentially be substituted, potentially altering the sensations which are received. While the current form-factor is relatively small and unobtrusive, it does require a dedicated hydraulic circuit and tubing running to the fingertips. In the future, we foresee this approach becoming less cumbersome and more easily integrated.



**Figure 3: Schematic of the HydroRing system. Water is pumped from the hot and cold water reservoirs, through the drip chamber, and passes through the latex tube within the HydroRing before emptying into the terminal reservoir.**

#### Hydraulic Circuit

The hydraulic circuit that drives the movement of the water through the ring was custom built to efficiently deliver haptic sensations to the fingertip (Figure 3-4). Water is stored in two reservoirs, one contains hot water, the other cold. Each reservoir has a peristaltic pump [23], which draws water from the reservoir at a controlled speed, computed from the desired pressure, vibration, or temperature. The water flows from the pumps and is combined in a drip chamber [58]. This drip chamber not only mixes water that is at two different temperatures, but also dampens the pressure fluctuations introduced by the peristaltic pump. The water travels from the drip chamber, through the PVC tubing (inner radius: 1mm) to the finger-worn ring before passing through a controllable solenoid valve [60] that stops the flow of water. This allows HydroRing to increase pressure or produce vibration sensations. When the valve is open, the water flows into a terminal reservoir to be later recycled. The latex tube empties when the pump stops and the valve is open, or maintains constant pressure when the valve is closed. Currently, the reservoirs are manually emptied and refilled, but with a more complex system, the water could be recycled within a closed circuit.



**Figure 4: Overview of the prototype system showing the hydraulic circuit and HydroRing.**

The two peristaltic pumps are controlled using an Arduino Uno with an attached Motor Driver board [24] that allows the speed of the pump to be dynamically controlled. The same Arduino UNO also controls the solenoid valve that

modulates the flow of liquid to the terminal reservoir. A second Arduino oversees the pressure and temperature sensors (pressure sensor - MS5803-14BA [61] and infrared thermometer - MLX90614 [62]) that monitor the current state of the ring. Both Arduinos are connected to a single PC which contains the logic that monitors user input and sensor values and controls the flow rates and valve states.

### Ring

The ring is comprised of a small custom 3D printed plastic structure (12 x 12 x 4 mm) worn on the back of the finger, and a thin latex tube that is 9mm wide which wraps around the fingertip and connects to the rigid structure behind the finger on either side of the fingertip. As latex is very flexible, any increases in pressure will cause the latex to expand both toward, and away from, the actuated finger. To constrain the expansion toward the finger, a thin film of clear Low-Density Polyethylene (LDPE) was wrapped around the latex tubing and finger. As LDPE is not as elastic as latex, this constrains the expansion of the latex tubing toward the finger-pad, increasing the pressure felt on the finger and reducing the overall size of the actuated device.

### Software

Custom software written in Java monitors the sensors and coordinates the control of the pumps and valves. The software is run on a desktop PC, and communicates with the Arduinos over USB.

### Haptic Sensations

An advantage of using a fluid is that it can produce a range of haptic sensations. Below we describe how the device is used to render vibration, pressure, and temperature.

#### Vibration

To render vibration, the terminal solenoid valve is opened and closed in rapid succession as the water is pumped through the system. By varying the incoming flow rate as well as the frequency at which the solenoid valve opens and closes, the system is able to control both the frequency and amplitude of the vibration.

The system is able to render vibrations from 1Hz to 50Hz while running a single pump at 12VDC constantly. Beyond 50Hz, the water does not circulate fast enough through the system and pressure builds up. It is worth noting that the vibration amplitude decreases as the frequency increases, while the absolute amplitudes are also determined by the water flow rate (as affected by pump speed, tube size, etc.). The latency to activate the vibration sensation is less than 200ms.

#### Pressure

Pressure is produced by closing the terminal solenoid valve and preventing the water from flowing back into the terminal reservoir. As the volume of water increases, the pressure within the tubing does as well. Because the latex tubing is the most elastic component within the prototype, this volume of water causes the latex tubing to expand towards the finger,

yet still be constrained on one side (by the LDPE), causing the user to feel the sensation of pressure on their fingertip.

The system can produce pressures ranging from 0.1N to 2.6N (measured with a force sensor [63] put in between the fingertip and the latex tube). The minimum pressure (0.1N), represents the pressure felt from wearing the ring in its relaxed form. We observed a linear relationship between water pressure inside the tube via the pressure sensor reading and the measured force applied to the fingertip. Thus the inner water pressure sensor is used to monitor and adjust the rendered pressure sensation. As the water takes some time to reach and fill the latex tube, there is some latency in achieving high pressures. Currently, the device takes approximately 3 seconds to change from no pressure to maximum pressure, with smaller changes taking less time. With a stronger pump, this time to reach the desired pressure may decrease, but the accuracy in controlling the pressure may be reduced.

#### Temperature

Temperature output is produced by controlling the speed of two pumps that draw water from insulated reservoirs. One reservoir contains hot water held at 55-60°C, while the other contains cold water held at 1-2°C. To control the ratio of hot to cold water, a PID controller [49] monitors the water temperature via an infrared temperature sensor [64], and controls the relative speed of each pump. Manual tuning of the PID parameters ensured that the temperature reached the target value as quickly as possible, but did not overshoot (so as not to expose the wearer to temperatures that are too hot or too cold). The PID parameters also ensured the stability of the flowing water at the target temperature, to reduce undesired oscillations.

Using this approach, the system is able to deliver water in the range from 2°C – 55°C, but we limit the output to 15-40°C to ensure users' comfort. Because the temperature change requires the liquid to travel from the reservoir to the fingertip, and the priority of not overshooting and maintaining temperature stability, its latency is higher than the pressure and vibration stimulus generation. The system takes approximately 6 seconds to change the temperature by 5 degrees. This latency could be reduced with a stronger pump, or by shortening the tubing connect the fingertip device to the reservoir.

#### Squeeze Input

In addition to haptic output, HydroRing can also support pressure-based input through the use of the pressure sensor connected to the tubing. When the pressure applied by the ring is held constant by the system, squeezing the tube will cause a discernable increase in the pressure measured by the sensor. Empirically, we found that increases in pressure of 40% over the target pressure can be attributed a wearer pinching the tube shut.

With a single finger instrumented, such squeeze input can be used for single degree of freedom input, enabling common



gestures such as press, double-press, and press-and-hold. With multiple fingers, or a thumb and forefinger instrumented, the system could additionally determine if the user is pressing a surface with a single finger, or pinching their thumb and forefingers together, allowing for more expressive set of input.

### STUDY 1: RECOGNITION OF HYDRORING SENSATIONS

Two user studies were conducted to evaluate HydroRing. The objective of the first study was to determine how well users could differentiate different levels of rendered tactile sensations produced by HydroRing after a brief training period. This study serves to validate that the prototype is able to reliably generate haptic sensations and to evaluate users' ability to perceive and recognize the sensations.

#### Participants

Twelve participants (8 male) between the ages of 22 and 36 years participated in the study and were reimbursed \$50.

#### Apparatus

The experiment was performed using the HydroRing prototype previously described to render the sensations. A traditional desktop computer ran the experimental software, showed feedback to participants, and controlled HydroRing.

Three HydroRing sizes were available: the best fitting ring was chosen by using the largest ring where the latex tube would lightly stretch over the fingertip of the dominant hand while the finger was in a resting state.

#### Experimental Design

This experiment evaluated participants' ability to recognize stimuli using the three modalities that HydroRing is capable of rendering (i.e., pressure, temperature, vibration). For each modality, the functional range of stimuli that the ring could provide was divided into three, five, or seven levels of granularity (values for stimuli at 7 levels is shown in Table 1). Participants completed 3 repetitions of each of the three granularity levels for each of the three modalities for a total of 135 testing trials per participant (i.e., 3 levels of granularity  $\{3 \text{ trials at level 3} + (5 \text{ trials at level 5}) + (7 \text{ trials at level 7}) = 15 \text{ trials}\} \times 3 \text{ repetitions of each stimulus} \times 3 \text{ modalities \{pressure, temperature, vibration\} = 135 \text{ testing trials per participant}\}$ ).

The presentation order of modalities was counterbalanced amongst participants using a Latin square, as was the presentation order of each granularity level. Within each block of trials, the presentation order of stimuli was randomized.

Sensation	Levels	Unit
Pressure	0.3, 0.39, 0.50, 0.64, 0.83, 1.07, 1.4	N
Vibration	2, 3, 4, 7, 12, 20, 31	Hz
Temperature	15 19 23 27 31 35	°C

**Table 1: Levels of each stimulus rendered by HydroRing for the 7 level condition.**

### Procedure

After being outfitted with HydroRing, participants began the first block of the experiment, for the first assigned modality. In each block, participants were shown a training set of stimuli corresponding to the current granularity level (i.e., in the 3 levels of granularity condition they were shown the stimuli from 1 – 3, in order; in the 5 levels of granularity condition, they were shown the stimuli from 1 – 5 in order; etc.). They were then shown this training set of stimuli again. Then, they were shown a testing set of stimuli, which was one of the stimuli from the current granularity level, and were asked to indicate, using a keyboard, which level the stimuli corresponded to. This process was repeated for all remaining stimuli in the current granularity level. Once all the testing set stimuli were presented, the participant was shown the training set of stimuli again and completed another testing set of stimuli. This process was repeated until the participant had been exposed to a total of three sets of testing stimuli (with additional two sets of training stimuli interspersed). Once a block was completed, the participant then moved onto the next granularity level and modality.



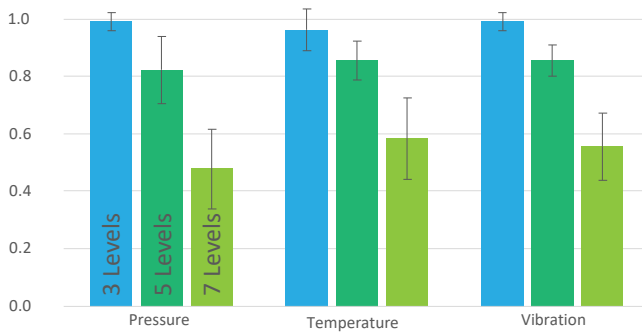
**Figure 5: Apparatus for evaluating HydroRing. The user's view of the device is occluded, and they wear headphones to mask the noise of the pumps and valves.**

Each time a granularity level was presented during a training set, HydroRing would render the stimuli and the computer monitor would display the number associated to the current granularity level of the stimulus (i.e., in the 7 level condition, the numbers 1 – 7 would be displayed; in the 5 level condition the numbers 1 – 5 were displayed; in the 3 level condition the numbers 1 – 3 were displayed).

### Results

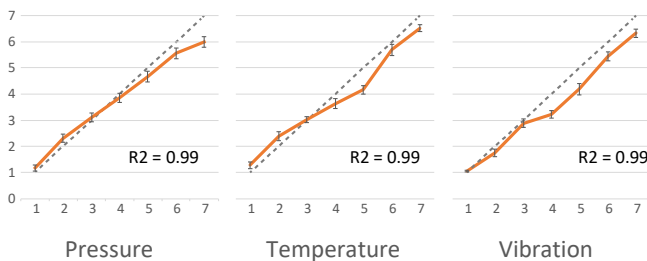
Response accuracy was analyzed using a 3 (*Modality*: pressure, temperature, and vibration)  $\times$  3 (*Granularity Level*: 3, 5, and 7) repeated measure ANOVA, with Bonferroni corrected paired t-tests for post-hoc pairwise comparisons. No *Modality*  $\times$  *Granularity Level* interaction ( $p > .05$ ) or effect of *Modality* was found ( $p > .05$ ), but a main effect of *Granularity Level* was significant ( $F_{2,22} = 170.9, p < .01$ ). Post-hoc pairwise comparisons demonstrated that it was easiest to discriminate between 3 levels ( $M = 98.1\%$ ),

followed by 5 levels ( $M = 84.4\%$ ), and by 7 levels ( $M = 53.8\%$ ) (all  $p < .01$ ).



**Figure 6: Mean recognition accuracy per modality. Error bars show standard error of the mean.**

A further analysis on the responses with 7 levels demonstrates that while accuracy levels may be low (around 50%) across all modalities, the participants were often close to the correct answer. Comparing the mean responses against the baseline (Figure 7) shows that participant responses tended towards the ground truth, with strong correlations for all modalities.



**Figure 7: Mean perception of each stimuli, compared to the ground truth. Error bars show standard error of the mean.**

## Discussion

The results demonstrated that HydroRing was able to reliably produce haptic sensations at different levels. Participants could accurately distinguish among 3 levels of haptic stimuli on each sensation, and performed relatively well even with 5 levels. However, if accurate perception of the stimuli is needed, subdividing the space into more than 5 levels is not practical.

The results suggest that designers could consider including 3 or 5 items or notification levels, that are associated with different levels of haptic stimuli. However, applications should allow users to receive enough training to become familiar with, and learn the stimuli. Two participants (P4, P9) noted that re-training was beneficial as it helped strengthen their memory and improved their confidence in subsequent trials. It remains a challenge as to how best to design interactive training sessions within applications.

When deciding between many levels of haptic feedback (e.g., 7 levels) with HydroRing, users were likely to under-rate their perceived stimuli. Despite this, it was easier for them to distinguish between values at the extreme ends of

what HydroRing could generate versus those that were similar. Such information could be useful for designing feedback like haptic progress bars that do not require users to perceive absolute values but could indicate a general direction or relative magnitude.

The study design has some limitations that were observed or elicited through participant feedback, which designers should consider. First, participants' perception of pressure, vibration and temperature were likely influenced by the last stimuli they had encountered. For instance, participants may have felt a stimulus was warmer if the previous stimuli was cold. This suggests that the relative change in stimulus level should be considered, not just the absolute stimulus. Second, although participants could rest during the study, some felt that they lost some ability to sense stimuli accurately towards the end of the study due to the repeated trials.

## STUDY 2: IMPACT ON PHYSICAL SENSATIONS

A second study was conducted to assess the degree to which HydroRing impedes the wearer's natural tactile sensations. Four common tactile sensations that could be impacted by the use of HydroRing were evaluated: *pressure*, *vibration*, *temperature*, and *texture*.

### Participants

The same twelve participants from the first study participated in the second study, they were reimbursed \$25 for their participation.

### Apparatus

Several purpose-built devices were constructed to render different levels of each of the desired stimuli (**Error! Reference source not found.**).

*Pressure* was produced via a small platform which was constrained to move along a single dimension (normal to the fingertip). The finger was placed underneath the platform with the fingerpad facing upwards. Different masses ranging in weight from 0.3–4.8N were placed on top of the platform to produce a range of pressures. The masses had the same appearance so participants could not visually determine which weight was being added, but differed in the amount of weight that was contained inside.

*Vibration* was produced with a small vibrotactile motor that could be actuated between at 80 and 250 Hz. The motor was fixed onto a table and participants rested their finger on the tactor. The frequency of the vibration was controlled by regulating the voltage that powered the device.

*Temperature* was rendered using a  $20 \times 20$ mm Peltier module with a heatsink to provide stimuli between 14°C and 42°C. The module and heatsink were affixed to a table and participants were instructed to place their finger on the pad. The temperature of the module was controlled by regulating the current flowing to the device, and participants were instructed to place their finger on their module only after the module had reached the desired temperature.

*Texture* was rendered using five different 3D-printed texture samples. Each texture sample was created by embedding different sized spheres on top of a solid to create a grid of bumps. The bumps ranged in size from 0 mm (flat and smooth) to 2 mm (rough, bumpy surface). All texture samples had the same overall dimensions of 50 mm × 50 mm × 2 mm.

### Experimental Design

Participants completed the within-subjects study under two conditions, a *baseline*, where they used their bare index finger to perceive the stimuli, and an *augmented* condition, where they perceived the stimuli using their index finger while wearing the HydroRing in its passive state.

The levels of each stimuli were selected to represent a range of levels frequently encountered in daily life, while remaining inside the range of comfort for a given sensation (Table 2). Each level of the stimuli was repeated 5 times, resulting in 5 levels × 3 repetitions × 2 conditions (*baseline*, *augmented*) = 30 trials for each sensation. The presentation order of the conditions, as well as the type of sensation was counterbalanced between subjects using a Latin Square design. Within each stimulus, the presentation order of the levels was randomized within each block of trials.

Sensation	Levels	Unit
Pressure	0.3, 0.6, 1.2, 2.4, 4.8	N
Vibration	80, 110, 150, 200, 250	Hz
Temperature	14, 21, 28, 35, 42	°C
Texture (Bump size)	0, 0.5, 1.0, 1.5, 2.0	mm

Table 2: Levels of each sensation used in the study.

### Procedure

Before beginning the study, participants were informed of the nature of the study. Depending on the condition, they were then outfitted with the HydroRing prototype.

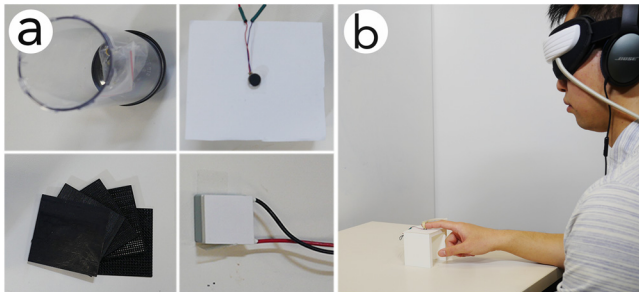


Figure 8: Apparatus for testing tactile perception capability; a) the four devices used to produce the sensations of pressure, vibration, texture, and temperature; b) the participant assessing the vibration stimulus while wearing the HydroRing.

Each sensation was tested independently, and all trials were completed for that sensation before beginning a new sensation. For each sensation, there were two blocks, with the ring and without the ring. The order of the blocks was

counterbalanced among the users. Users received 5 minutes of training before beginning the trials for each sensation to get familiar with the five levels of the stimuli. During the test, the presentation order of the stimuli were selected randomly. The stimuli were presented to the user (their hand was guided towards the stimuli), and they were asked to verbally report which level of the stimuli they believed they had felt.

### Results

A two-way 2 (*Condition: baseline, augmented*) × 4 (*Modality: pressure, temperature, vibration, texture*) repeated measures ANOVA was conducted, with Bonferroni-corrected paired t-tests for post-hoc pairwise comparisons. There was a significant effect of Condition, ( $F_{1,11} = 16.60$ ;  $p < .01$ ); as well as Modality ( $F_{3,33} = 4.31$ ;  $p = .01$ ). There was no interaction effect ( $F_{3,33} = 1.08$ ;  $p = 0.37$ ). Wearing the ring significantly impacted the user's ability to identify the sensations, with accuracy dropping from 0.876 with the bare finger to 0.839 with the ring. The only significant difference between modalities was between vibration ( $M = 0.90$ ) and texture ( $M = 0.81$ ,  $p < 0.01$ ); all other comparisons within Modality were not significant ( $p > 0.2$ ).

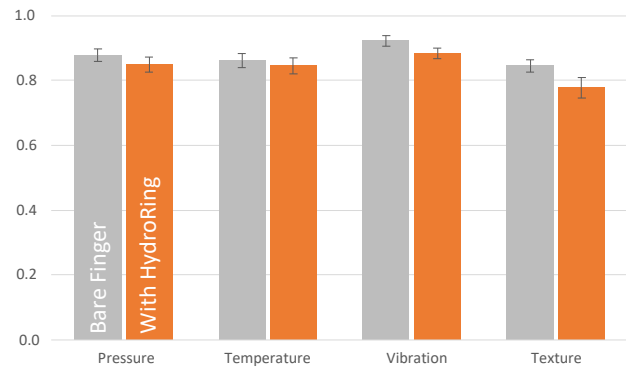


Figure 9: Accuracy in perception recognition with and without wearing the HydroRing prototype. Error bars show standard error of the mean.

### Discussion

While the difference in accuracy while wearing the ring was significantly less than without the ring, the actual effect was quite small at only 3.7%. From this small effect, we can conclude that while the device has some impact on the user's perception, the effect is quite minimal. Additionally, some modalities were relatively unaffected (e.g., temperature, pressure), while texture was most impacted. This is likely due to the higher frequency textures being dampened by the latex tubing. Further evaluation is necessary to determine exactly what components of the perception are altered to better characterize how the perception is affected [29].

### SAMPLE USAGE SCENARIOS

While always-available, unobtrusive haptic devices could have many different applications and use cases, here we



outline three general uses of such technology that were prototyped in a Wizard-of-Oz approach.

### Usage in Daily Activities

The ring form factor makes it suitable for an always-available notification and low-bandwidth information channel. Vibration, pressure and thermal feedback can be used to enrich the information received by the users from a notification. Using the pressure input channel, users can provide simple input using the same channel they received the notification from, providing a tight coupling between input and output. As the actuation of the device results in very little visible movement, the notifications could be quite subtle, and non-disruptive to others around the wearer.

As the device is designed not to be obtrusive, users can continue doing their normal daily activities without worrying that the device will impede their dexterity or tactile sensations. Additionally, as the actuating component of the device is sealed and flexible, the user does not have to worry about damaging the device through normal activities. Users can use the device in messy or wet environments, and while performing fine manipulation or assembly tasks [20].



**Figure 10:** Sample scenarios where mixed-reality haptics could be used; a) while operating existing technology b) performing activities in wet or dirty environments c) performing activities that require manual dexterity.

### Augmenting Physical Objects

Mixed-reality haptics could be used to augment existing static objects and structures. They could provide feedback to augment the real world with haptic information, or deliver new haptic sensations. For instance, if the hand were tracked in 3D space and the structure of the room was known, by running your finger over a wall the ring may increase in pressure to indicate where wiring or framing structures are located behind the wall.



**Figure 11:** Example scenarios using mixed-reality haptics to add feedback to existing objects and devices. a) a user moves their finger over a wall, and feels vibration feedback as her hand passes over wiring hidden behind the wall. b) a user touches an interactive children's book, which provides thermal feedback corresponding to the on-screen content.

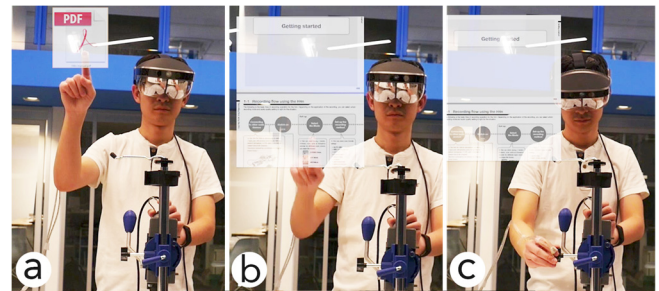
The feedback could also be used to enhance existing technology that does not have haptic output capabilities. For

instance, when reading a children's book on a tablet, the device could respond and provide haptic feedback corresponding to the elements in the book. For instance, if the book has scenes of a desert, the ring may heat up when the book is touched – if the book has bees, the ring could vibrate to emulate the buzzing. Such sensation may also be used to aid low-vision users [50].

### Mixed Reality Interaction

Current augmented reality devices and applications are largely focused on visual augmentations of the real world, with other sensations left un-augmented. By leveraging mixed-reality haptics, the virtual elements in a scene can not only have a visual representation, but a tactile representation as well. The haptic device can provide contact sensations, as well as vibration and thermal information to enrich the user's perception of the virtual aspects of the augmented scene.

Additionally, because the device does not substantially impede the user's natural sensations, they can seamlessly switch between interacting with real objects and interacting with virtual objects.



**Figure 12:** Example scenario of adding tactile feedback to an augmented-reality instruction manual. As the user selects items on the display and navigates the content, vibration and pressure provide real-time feedback on their actions (screens are simulated).

### LIMITATIONS AND FUTURE WORK

The user studies and sample applications demonstrate the viability and utility of the use of liquid flow to produce tactile haptic sensations. There are, however, a few challenges that must be overcome before this approach could become a commonplace modality.

*Liquid vs. electromechanical actuation:* HydroRing demonstrated the viability of using liquid flow to deliver various haptic sensations to the end-effector (e.g., fingertip). Its capability of switching between being passive and being active due to liquid transportation fulfills the need of mixed reality scenarios. The non-electromechanical actuation allows the device to be used in, for instance, wet or dirty environments. These benefits are not present with the previous electromechanical approaches. On the other hand, the latter takes the advantage of being more rigid, accurate, and ubiquitous. Additionally, the low latency and high bandwidth (e.g., high frequency vibration) allow electromechanical devices to render a wider variety of haptic sensations.

*Technical limitations and practicality:* The current HydroRing prototype utilizes hardware such as valves, pumps, and temperature-controlled reservoirs that require a considerable amount of space. Additionally, after flowing through the ring, the water flows into a reservoir which must be manually recycled back into the system. Further work is needed to develop a prototype that is more self-contained and would allow the water to be recycled. Such a prototype could quickly adjust the temperature of liquid on-the-fly using high-power Peltier modules. Additionally, we anticipate that further hardware developments, particularly in the area of microfluidics [12, 39, 54] will result in hardware devices such as valves and pumps that are smaller, require less power, and can be more readily integrated into wearables.

Full, independent control of all three tactile sensations is not possible with the current implementation of the hydraulic circuit. For instance, increasing pressure requires restricting the flow rate, which prevents different temperatures of water from reaching the ring. Alternative approaches to the design of the hydraulic circuit, and different hardware to drive the flow of liquid, may be able to achieve more seamless and responsive integration of the stimuli. For instance, a higher-powered pump, a variable terminal valve, and a more complex control loop may be able to provide more flexibility to combine sensations.

The current design of HydroRing lightly stretches the latex tube around the fingerpad and secures rigid connector to the nail. This is to keep the most of the fingertip free of occlusion from rigid structures. Such a design brings unique characteristics of the feedback as users would experience the rendered sensations over a fixed area on the fingertips. Some applications may require a more precise and controllable location to apply the feedback. This can be done by fabricating latex tubes with uneven distributed elasticity, allowing the pressure, vibration sensations to affect smaller areas. Such an approach could also eliminate the use of LDPE around the finger by having one-sided elastic tubes. Mixing different thermal conductive material while fabricating the tube can refine the area/position of the temperature feedback.

One exciting area of future work is the notion of ‘pass-through’ augmented haptics. By mounting tactile sensors to the outside of more traditional, rigid haptic devices, users may be able to ‘feel’ the real world by having the device render what it is sensing, similar in nature to how camera-based augmented reality works [26].

Lastly, even though the finger’s natural sensations were not drastically affected by the presence of the ring, there are still some improvements that could be made to further reduce any interference. The use of a thinner latex tube or other form factors aside from a simple ‘band’ around the finger may provide a better balance between novel sensations and natural perception.

## CONCLUSION

Mixed-reality haptics enables new interactions and applications that are unavailable with traditional haptic devices. We developed a prototype device, HydroRing, that uses flexible materials and liquid to render the various sensations of pressure, temperature and vibration. Through two user studies we demonstrate that by delivering tactile sensations to the fingertip via liquid flow, the user can experience novel sensations of pressure, vibration and temperature without drastically impacting their fingers’ normal sensations. Mixed-reality haptics offer benefits for applications that require both our ability to sense physical objects and perceive haptic augmentations.

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