Douleur: Creating Pain Sensation with Chemical Stimulant to Enhance User Experience in Virtual Reality

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The imitation of pain sensation in Virtual Reality is considered valuable for safety education and training but has been seldom studied. This paper presents Douleur, a wearable haptic device that renders intensity-adjustable pain sensations with chemical stimulants. Different from mechanical, thermal, or electric stimulation, chemical-induced pain is more close to burning sensations and long-lasting. Douleur consists of a microfluidic platform that precisely emits capsaicin onto the skin and a microneedling component to help the stimulant penetrate the epidermis layer to activate the trigeminal nerve efficiently. Moreover, it embeds a Peltier module to apply the heating or cooling stimulus to the affected area to adjust the level of pain on the skin. To better understand how people would react to the chemical stimulant, we conducted a first study to quantify the enhancement of the sensation by changing the capsaicin concentration, skin temperature, and time and to determine suitable capsaicin concentration levels. In the second study, we demonstrated that Douleur could render a variety of pain sensations in corresponding virtual reality applications. In sum, Douleur is the first wearable prototype that leverages a combination of capsaicin and Peltier to induce rich pain sensations and opens up a wide range of applications for safety education and more.

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CCS Concepts: • **Human-centered computing → Virtual reality**; **Ubiquitous and mobile devices**.

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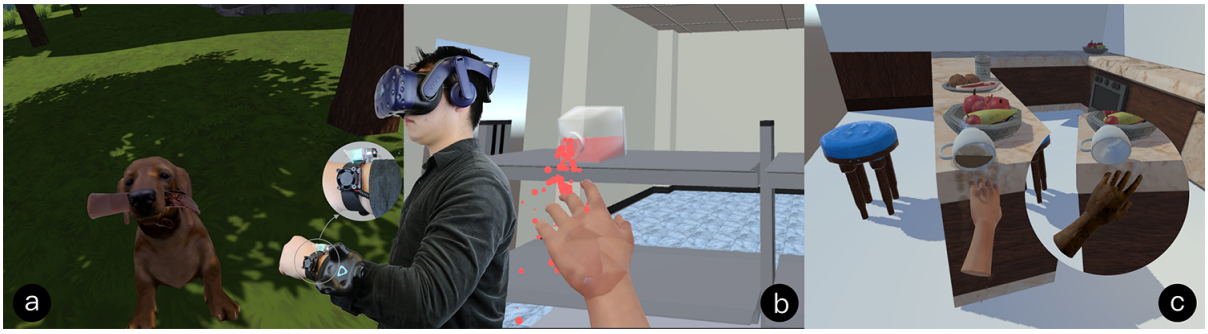

Fig. 1. Douleur is a wearable prototype that induces pain sensation of different intensity to enhance the immersion of realistic VR experiences: (a) The dog-biting scenario; (b) The corrosive liquid scenario; and (c) The spilled hot coffee scenario.

1 INTRODUCTION

Pain is a human instinct and plays an important role for safety. One common type of pain is the burning sensation and can be induced in several ways, including flame exposure, scald exposure, contact burns, radiation, chemicals, and electricity [60]. The accidents inducing burning sensation often cause injury, or even mortality. As reported by National Burn Repository [62], 40.60% of all burning cases were caused by fire/flame, 31.40% by scald, 9.10% by contact with hot objects, and 3.60% and 3.50% by electrical and chemical components. Unfortunately, potentially hazardous sources causing pain might go unnoticed due to people's lack of awareness or experiences with such hazard sources.

Virtual Reality (VR) is capable of engaging people with visual, audio and haptic renderings, and has been widely used in domains such as art, clinical, educational, and skill training. Inducing brief pain sensation in a VR environment can provide a safe and immersive way for people to experience the pain that is otherwise unavailable unless they unfortunately run into a real accident. Such simulated experience might help people better associate pain with potentially hazard sources, increase their safety awareness, and help them better avoid accidentally getting hurt in the future [27, 39, 75]. Furthermore, coupled with visual and audio feedback, such brief simulated pain sensation can also be helpful to improve VR users' immersive experiences.

Motivated by the potentials of simulated pain in safety education and VR applications, we present *Douleur*, a novel wearable haptic device that creates brief and adjustable pain sensations on the skin without causing injuries. Pain is mainly associated with the activation of receptors in the primary afferent fibers, such as C-fiber and Aσ-fiber [78]. These receptors are specialized peripheral sensory neurons known as *nociceptors*, which alert us to potentially hazardous stimuli on the skin. The burning pain sensation involves of the activation of such receptors in the skin, yet often comes with irreversible damage to skin tissues. For instance, burning sensation is typically caused due to scalding, burning by boiling oil or even burning by flames. There exist physical and electrical stimuli that create pain sensations [16], but they are much different from the burning pain as pain

sensations created by these physical and electrical stimuli are unsustainable. Once the power supply is cut off, the effect of such stimuli is stopped correspondingly. Besides, due to the limitation of the actuator size, the effective area is usually small and hard to scale. More importantly, the burning sensation is not able to be formed by physical or electrical stimuli due to different acting mechanisms. Instead, capsaicin is an ideal chemical stimulant for creating burning pain while causing no injury to the skin. It is commonly seen as an active component of chili peppers, and is irritant to humans when it contacts the skin or mucosa.

Informed by physiological principles of pain sensation and the prior knowledge on capsaicin usage, we leverage capsaicin stimulant in the design of Douleur. Specifically, Douleur comprises a badge-like microfluidic platform that precisely emits capsaicin onto the skin, and embeds Peltier to apply the heating or cooling stimulus to the affected area which plays a key role in adjusting different levels of pain on the skin. The device also includes a microneedling component to help the stimulant penetrate the epidermis layer to activate nociceptors safely and efficiently. To remove the effect, heavy cream, oleic acid and camphor can be used as analgesics [61, 65, 95]. Douleur is the first wearable device that integrates both a chemical stimulant and a temperate unit to render adjustable pain sensation and has the following unique properties unavailable in conventional electromechanical devices: i) the pain sensation can last for a long time without further stimulation or intervention; ii) it can adjust the pain intensity in an efficient way via thermal regulation; iii) it can generate pain sensation on a relatively large skin area due to liquid spreading.

We first conducted a user study with 12 participants to understand how capsaicin concentration, temperature, and time affect their perceived pain sensations when wearing Douleur. Results showed that Douleur delivered pain sensations on users' wrist immediately under specific conditions, e.g., with relatively high temperature or high capsaicin concentration. Pain intensity level increased significantly in the first 200-second window, followed by a stable pain intensity level, which lasted at least 6.5 mins on average without further stimulation or intervention. The higher the temperature and the capsaicin concentration level, the higher the induced pain intensity. What's more, the two most common types of pain perceived by the participants were shooting and hot-burning sensations. Interestingly, it was found that as capsaicin concentration and temperature increased, the percentage of hot-burning feeling increased while the percentage of shooting feeling decreased.

Informed by the results, we conducted the second user study. We asked another group of five participants to experience three VR scenarios that simulated *"the dog-biting"*, *"the corrosive liquid"*, and *"the spilled hot coffee"*, as shown in Figure 1, *with* and *without* pain sensation induced by Douleur. Results showed that Douleur played a positive role in safety alert by significantly increasing participants' immersive experiences with the induced pain sensation. Furthermore, our study revealed interesting directions for enhancing pain sensation for VR users.

In sum, we make the following contributions in this work: i) Douleur, a novel microfluidics and peltier module based wearable prototype that precisely controls the chemical and thermal stimuli to generate pain sensation; ii) An understanding of the effects of capsaicin concentration, temperature, and time on the intensity and the type of pain sensation induced by Douleur; iii) An initial exploration of Douleur's potentials in enhancing immersive VR experience by inducing brief pain sensation.

2 RELATED WORK

Creating haptic sensations is of special interest in recent years. Many examples exist that render haptic sensations including, but not limited to force, vibration, shape, weight, position, texture, wetness, and temperature [22, 24, 26, 51, 67, 89]. Here we review the work on studying abnormal sensations, wearable haptic device design, and induction of pain in gaming and virtual experiences.

2.1 Haptic Rendering of Abnormal Sensation

Sensations like burning, wetness, itching, electric shock, and needles are usually abnormal and unpleasant. They are usually caused by lesions of the nervous system, peripheral or central, spontaneous or evoked. Haptic rendering of such abnormal sensations is gaining attention in the interaction design domain. Peiris et al. [71] integrated five thermal feedback modules on a HMD to provide hot or cold feedback directly onto users' face. Later they looked into thermal feedback as a haptic feedback modality around users' wrist [70]. Niijima et al. [63] designed a haptic display with three tiny Peltier devices to provide different thermal feedback depending on the sensitivity of different body parts. Besides, Günther et al. [29] designed a thermal display that provides warm and cold on-body feedback in VR through flowing liquids with different temperatures, and investigated the interdependency of visual and thermal perception in VR. Blaga et al. [6] analyzed the effect of thermal visual cues on users' grasping actions without inducing actual thermal stimulus. Xu et al. [96] reported a non-contact cold thermal display using a vortex tube to generate ultra-low air temperature.

Lee et al. [45] explored a non-contact wearable tactile display using airflow, and compared it with a vibrotactile display in information transformer performance. Shim et al. [79] combined wind and vibration to make a multimodal tactile display that created "colored" tactile sensations on wrists. Lopes et al. [53] presented a small impact device to render haptic sensation of hitting and being hit, using a solenoid and electrical muscle stimulation. Spelmezan et al. [83] stimulated fingertips with touchable electric arcs to provide users in-air tactile feedback. Han et al. [33] studied how temperature, pressure and friction stimulus resulted in the perception of wetness. Besides the cutaneous sensations, researchers also looked into other sensory channels to create, for instance, scent stimulus via a near nose olfactory interface [92]. Recently, Brooks et al. [7] demonstrated emitting certain scents to create temperature illusion via stimulating the trigeminal nerve. This work is similar to ours in the way that both consider using chemical stimulants. Differently, Douleur emits the chemicals with microfluidic channels and microneedling, and with adjustable temperature, it is able to adjust the intensity level of pain sensation.

2.2 Wearable Haptic Device Design

Wearable haptic devices have been well studied and shown to be effective in providing localized tactile sensations on body [4]. There is a recent trend in device design towards being compact, lightweight, and flexible. Many works are designed on fingertips as their contact with virtual objects is usually involved in hand operations. Examples include AeroFinger [20], HydroRing [31], and SPA-Skin [82], which provided miniature end effectors and actuated the devices with liquid or air flow. Tacttoo [94] demonstrated the feasibility of using thin-layered tactors to build ultra-thin tactile interfaces on fingertips. HapBead [32] was made thin and flexible, leveraging a microfluidic channel and oscillating a bead to provide tunable vibration sensations on fingertip.

There are lots of work on designing haptic devices worn on hand or held within hand. Dexmo [28] tracks the user's motion and provides force feedback. Combined with 3D graphics rendered environment, user can enjoy a realistic sensation of grasping an object in virtual reality. Hinchet et al. [35] applied braking force resulted from modulating the electrostatic attraction between flexible elastic metal strips to rapidly render on-demand kinesthetic feedback. Choi et al. [11] achieved similar functionalities via Leveraging low-power brake-based locking sliders. Tsai et al. [88] presented a device to provide continuously changing resistive force and instantly occurring impact upon the user's hand using elastic band. A more comprehensive review examining existing force feedback gloves and exoskeletons can be seen from Wang et al. [91]. Handheld haptic devices are getting popular and have been thoroughly researched, e.g., to simulate the sensation of weight, grasp, touch, contact, texture and compliance [10, 12, 46, 52, 85, 93].

Besides, researchers also paid attention to applying haptics on users' wrist. This was very much motivated by the need of enriching haptic feedback for smartwatches or smartbands. Lee et al. [47] evaluated wrist-worn wearable vibrotactile displays that provided easy to perceive alerts for on-the-go users. Liao et al. [50] designed a

system of spatiotemporal vibration patterns for delivering alphanumeric characters on the back of a watch-like device. Gupta et al. [30] investigated a device that generated squeezing sensations on wrist using shape memory alloys. Zhu et al. [100] provided fabric-based sleeves to render compression, skin stretch, and vibration by controlling pneumatic pressure inside. Pece et al. [69] developed a flexible haptic interface based on latching electromagnetic actuators integrated in flexible straps. Douleur is a wrist worn device serving for enriching haptic experiences in VR applications such as safety education. Similar to the previous work, Douleur also takes a compact-sized structure and embeds microfluidic channels in a flexible platform for i) emitting precisely a small drop of the capsaicin solution to the skin, ii) be comfortable and lightweight to wear or attach onto the body. With the use of small size Peltier, temperature change can be precisely controlled.

2.3 Inducing Pain Sensations

Inducing the sensation of pain is non-trivial for safety and ethical reasons. However, it was shown that pain helps improving emphatic experiences in VR, such as being hit or punched. Lopes et al. [53] combined mechanical actuators and EMS to create an immersive experience for users to perceive the sensation of being hit. Similar technical approach was used on a user's face/eyes to manipulate her eyelids (e.g., to close her eyes), and it managed to induce fear or pain with visual and such artificial blink reflex [43]. Although it was shown that electrical stimulation can elicit strong tactile/pain sensations without damaging the skin, it is inferior in terms of naturalness [57]. Other methods to induce pain in VR were described as using thermal stimulus. For instance, Niijima et al. [63] reported that a user could perceive heat and pain when touching Peltier devices using a sensitive part such as lips or forearm. Other than VR, instrument inducing pain feedback was designed as a game component, such as in PainStation [59], where possible feedback effects include heat impulses, an electric shock and an integrated miniature wire whip. Different from these, Douleur explores the feasibility and effects of leveraging chemical stimulant - capsaicin to create pain sensations on skin without causing injuries. Capsaicin was used in Brooks et al. [7], but their purpose was to create hot temperature illusion by emitting chemical stimulants to the air close to the user's nose. Sabien et al. [90] used high-concentration topical capsaicin to study whether the changes in thermal sensitivity induced by the capsaicin can be explained entirely by desensitization of capsaicin-sensitive afferents. They did not study the effects of different concentration levels and temperatures on induced pain. Donald et al. [80] studied the effects of different capsaicin solution concentrations, from 0.0001% to 1%, on the pain intensity and found that the area and duration of mechanical hyperalgesia and the area of flare increased with the dose of capsaicin. However, they ignored the effects caused by temperatures and time.

3 DOULEUR PROTOTYPE

3.1 Theory of Operation

The forming of pain sensation is associated with the activation of nociceptors [19, 37], such as Aσ-fiber and C-fiber. The brain requires the perception of a series of sensory events to detect pain and produce a response towards the threat [81]. Fundamentally, the basic pain mechanism undergoes three events including transduction, transmission and modulation when there is a presence of noxious stimuli [97].

Pain is widely considered as both distressing sensation and emotional experience. Pain is mainly associated with the activation of the receptors in the primary afferent fibers, such as C-fiber and Aσ-fiber. These receptors are specialized peripheral sensory neurons known as nociceptors, which alert us to potential damaging stimuli at the skin, such as extreme temperature, pressure, and injury chemicals. These stimuli, transduced by nociceptors into long-ranging electrical signals, are relayed to higher brain centers, which causes pain sensation [18, 87, 97]. Contrasted to the sensitivity of visual, auditory, olfactory, taste, and somatosensory organs to their stimuli, the sensation of nociceptors is often sensitive to the stimuli that exceed a threshold range. For each nociceptor there is a threshold range of activation, beyond which the nociceptor can be activated. In order to form pain sensations,

nociceptors must be activated by noxious chemical stimuli or extreme temperature above or below the threshold range to induce abnormal and unpleasant sensation[18]. TRPV1, as one of the transient receptor potential cation channels (TRP channels) that expressed on C-fiber, can be activated by capsaicin and temperature higher than $43°C$ to form pain sensation. Besides, TRPV (2-4) and TRPM3 can also be activated by different chemicals and temperature [60], TPRV2 is activated by Cannabidiol and temperature higher than $52°C$, TRPV3 and TRPV4 are activated when temperature is higher than 33-39$°C$ and 27-34$°C$ separately, TRPM3 is activated by the agonist such as CIM-0216 and temperature higher than $30°C$ [56], which also form pain sensation. The activation of these channels causes the release of calcitonin gene-related peptide (CGRP) from the primary sensory nerves, which in turn results in the elevation of intracellular Ca^2+ levels [60].

In particular, capsaicin lowers the temperature threshold of TRPV1 activation, so that it is activated at room temperature, which forms pain sensation that is of same intensity level at much higher temperature without damaging skin structure [13]. Though seems different, the mechanism of pain sensation induced by accidents such as being burned by boiling water or hot oil, erosion by corrosive chemicals, burned by scalding is similar, only through the application of capsaicin and less extreme temperature. Therefore, safety education can be conducted via combining VR scenarios and pain feedback created by Douleur, which therefore requires a highly precise prototype for pain feedback creation.

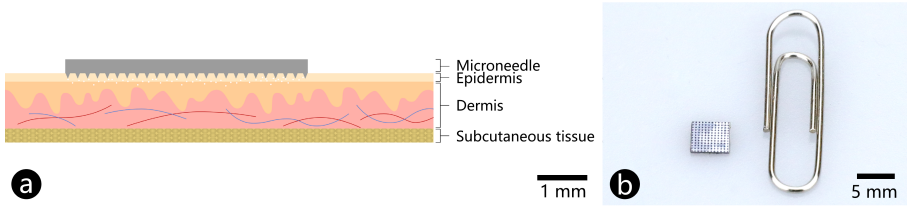

Fig. 2. Microneedling: (a) Transdermal of microneeedling; (b) Real size of microneedling.

3.2 Capsaicin & Microneedling

Utilizing chemical stimulants for haptic rendering is a novel concept that little knowledge can be referred to about selection of the stimulant. We considered several candidates including Histamine, Acetylcholine, strong base and strong acid which are off the shelf. Capsaicin was chosen for its accessibility and thorough research of toxicity [36, 86]. Compared to other stimulants, capsaicin, which extracted from pepper, is more acceptable mentally by users as human has a much longer contact history with it. Histamine is not chosen in this project so as to prevent allergy and immune system disorders, which also forms itch sensation that may interfere the sensation of pain [99]. Compared to strong acids, capsaicin is less harmful for not damaging skin structure. Acetylcholine is highly hazard, which is even applied in chemical weapons, that is not suitable to be utilized in this project. Strong Base is also corrosive compared to capsaicin. Besides, capsaicin selectively activate trigeminal nerve, especially TRPV1, which is highly effective in rendering pain sensation [23]. The preparation procedure of capsaicin solution is as follows: Capsaicin powder was weighed at first and then put in a flask. Next, the solvent (deionized water: ethanol = 1:1) was weighed and added into the flask. Then, the solution was strongly stirred by a glass rod, which accelerated the dissolution of the capsaicin powder. Finally, after vacuum filtration, the capsaicin solution was kept in the reagent bottle for utilization.

As studied [17, 73, 76], the time required for capsaicin solution to take effect under normal circumstances is fairly long, owing to the fact that the absorption of capsaicin by skin is slow. To solve the problem, we took the approach of microneedling, which is typically a dermaroller procedure that uses small needles to prick the skin

at only surface-level deep [5, 41, 54, 72]. It creates microscopic punctures in the skin and thus can accelerate the absorption to offer immediate results under specific conditions, e.g., relatively high temperature or high capsaicin concentration. Traditional transdermal drug delivery method includes topical cream and hypodermic needle. The former only delivered 10-20% of total drug loaded due to the requirement of passing the stratum corneum barrier, which also needs relatively longer time. The latter goes deep into the dermis where pain receptors are present, which decreases the influence of capsaicin. Microneedling, however, bypasses the stratum corneum barrier and delivers the drug directly into the epidermis or upper dermis layer, which avoid the stimuli of pain receptors and remains high drug delivery efficiency. We integrated a commercially certified microneedling array as shown in Figure 2 with a side of 4.9 mm and thickness of 0.40 mm which comprises micro-fine needles in diameter of 0.10 mm and height of 0.12 mm [1]. The final microneedling component used in our experiment was obtained after removing the plastic shell.

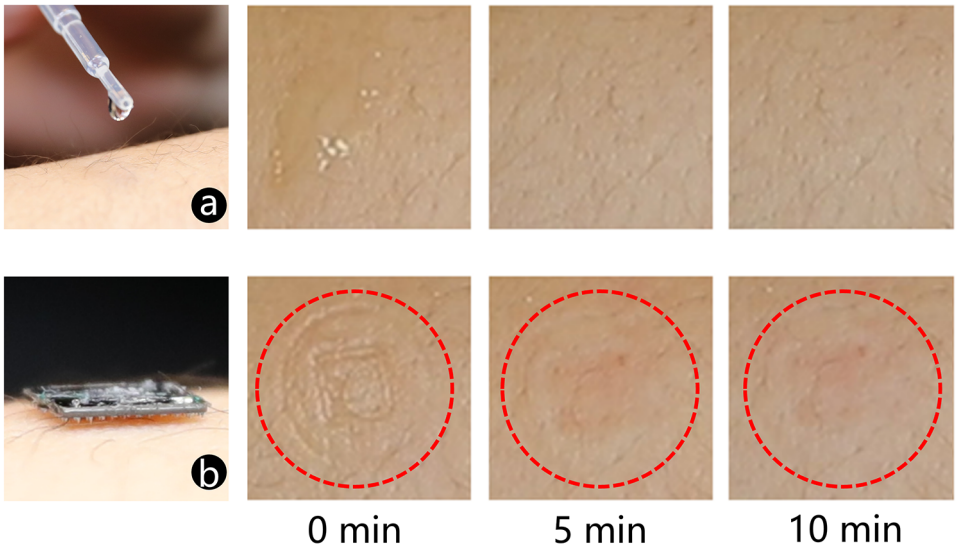

Fig. 3. Flare on skin induced by microneedling-assisted application of capsaicin: (a) Without using microneedling; (b) With using microneedling.

3.3 Toxicity & Side Effect

Capsaicin injection was conducted in the area of medicine and biology in several previous research. Due to transdermal injection of chemical stimuli, the toxicity and side effect should be thoroughly studied. Fortunately, it was extensively investigated by researchers in previous study related to capsaicin. In Sabien et al.'s study [90], participants showed flare response immediately after capsaicin patch remove. They described the sensation induced by topical capsaicin as "warm", "pricking", "burning", "itching", and "unpleasant". For the study of James et al. [58], the injection of 10–25 μl of 10 mg/ml capsaicin solution leads to spontaneous pain intensity and zones of hyperalgesia and allodynia, which takes 15 min to disappear. As shown in Figure 3, it can be seen that without using microneedling, capsaicin solution vaporized, causing little effect to the skin. With the use of microneedling, capsaicin solution penetrated into the skin, with the appearance of side effect as flare on the skin.

[1]Dr. Pen Replacement Cartridges Disposable Needles, Square Nano, https://drpen.com.au/collections/cartridges

For long history, capsaicin with concentration of 1% and higher, such as 8% capsaicin cream, was used for analgesia. Toxicity of capsaicin is highly dose-dependent, the LD50 in humans has been estimated at 0.50-5.00 g/kg. LD50 is a lethal dose that causes death in 50% of treated human or animal, which commonly regarded as a measure of acute toxicity. Chemicals are considered highly toxic when LD50 is small and practically non-toxic when the value is large. Neither the U.S. EPA nor the International Agency for Research on Cancer (IARC) has published a cancer rating for capsaicin. Besides, No human data was found on the teratogenic or reproductive effects of capsaicin [49].

3.4 Form Factor

Douleur comprises a plate structure (Figure 4), measured 25.6 mm in radius and 18.40 mm in thickness, that embeds the microchannels for dose emitter and water flow based temperature change, respectively. In the middle of the plate anchors the microneedling component, which is only 0.10 mm in height and 0.4 mm in side length. The device is lightweight (measured 42.8 g) and with a flexible layer that contacts skin, measured 2.60 mm in thickness, and can be worn tightly on a user's body. The main RF-Nano control board wirelessly transmits data using RF 2.4 GHz. In our case, we demonstrate and evaluate Douleur on a user's wrist.

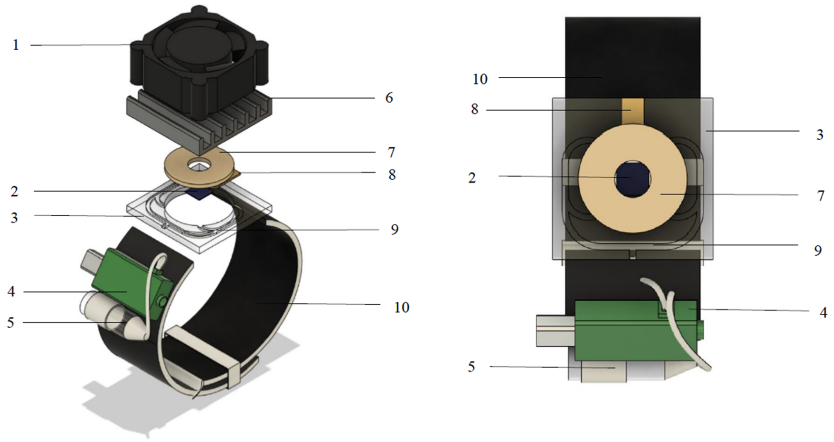

Fig. 4. Design of Douleur: 1 - Fan; 2 - Microneedling ; 3 - Microfluidic Channel ; 4 - Micropump ; 5 - Reservoir ; 6 - Heat Sink ; 7 - Peltier ; 8 - Temperature Sensor ; 9 - Chemical Delivery Layer ; 10 - Wristband.

3.5 Microfluidic Channel

As shown in Figure 5, microfluidic channel was fabricated by PDMS, after curing for 2 hours at $65°C$. The relatively soft interface makes Douleur more comfortable to wear. The design of the microfluidic channel, especially these four symmetrically placed exits, are used to ensure the uniform distribution of capsaicin solution after its emission.

3.6 Driving Unit

The Douleur prototype was driven by a dedicated microfluidic pumping unit connected with a reservoir of 3.50 ml of capsaicin solution. When the reservoir is full, 50 pain events can be generated, as shown in Figure 4 as 4 and 5 (i.e., Kamoer[2], KMPP-D3.7). Controlled by the main microcontroller (RF-Nano), the microfluidic pumping

[2]http://www.kamoer.com/product/product538.html/

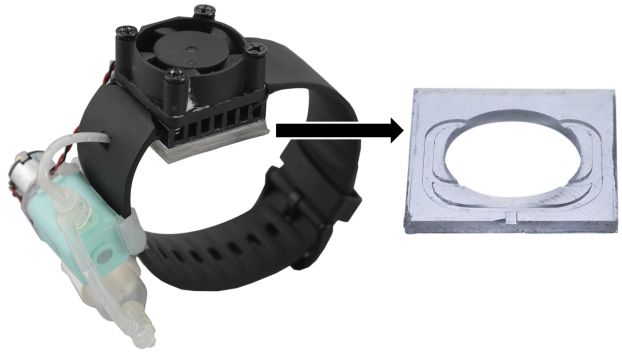

Fig. 5. Douleur prototype and the microfluidic channel.

unit is programmable and can precisely drive the liquid flow inside the microchannels. The size of the peristaltic pump is 35 mm * 24 mm * 20 mm, which makes it available to be installed on wristband.

3.7 Temperature Control System

In order to produce various levels of temperatures and ensure fine control, Peltier was utilized and installed with cooling fin equipped with fan as shown in Figure 4 as 1, 6 and 7. Microneedling as 2, is installed under the inner ring of Peltier, while the microfluidic channel as 3, is located under the outer ring of Peltier. The temperature sensor TTF-103 fixed under the Peltier outer ring can quickly respond to temperature changes. The main microcontroller (RF-Nano) computes the PWM signal, and the DC motor driver controls Peltier temperature through the PWM signal. Four LiPo batteries (3.7V, 3400mAh) are divided into two groups to power the temperature control system and the other systems. They are connected through a custom PCB. Taking into account the weight and wearing comfort of the device, we group the batteries, the main microcontroller, and drivers with a customized PCB into an elastic band so that users can easily wear it on the arm.

3.8 Evaluation of the Prototype

Challenges remain as whether the prototype can precisely emit a specific volume of the capsaicin solution and whether it can precisely control the temperature on the application area. As shown in Figure 6, experiments were conducted to measure the accuracy of the capsaicin solution emission volume and the temperature adjustment. After 30 trials of the experiment, with every trial consisting of 10 emissions, we found that our prototype was highly precise in capsaicin solution emission. The average volume of each trial was 0.51 ml (SD=0.01), which meant an average of 0.05 ml liquid per emission. As for temperature adjustment, three experiments were conducted for each temperature, we found that our prototype also performs efficiently at each temperature, 15°C (M=15.23, SD=0.54), 20°C (M=19.74, SD=0.45), 25°C (M=24.89, SD=1.00), 30°C (M=30.97, SD=1.65), 35°C (M=35.56, SD=1.77), and 40°C (M=39.74, SD=1.75). This device can maintain a constant thermal stimulus of 40°C for 1.5 hours. As for the power consumption, our prototype costs 10 W when using the Peltier, the fan, and the micro-pump together.

3.9 Removal of The Effect

We have explained the key principle, mechanisms, and benefits to apply capsaicin solution directly on the skin and create pain sensations for VR applications. A remaining challenge is to remove the pain sensation. Different from conventional methods that provide cutaneous tactile feedback via end effectors that are on or above the skin surface, Douleur requires chemical absorption in the skin. Although it is in the surface-level deep and causes

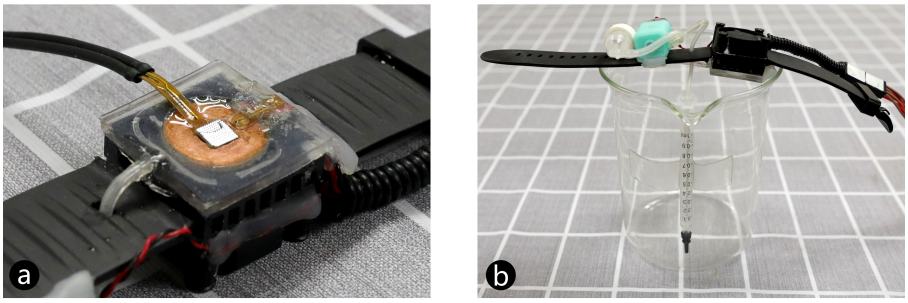

Fig. 6. Evaluation of Douleur: (a) Evaluation of temperature control; (b) Evaluation of capsaicin solution control.

no real harm, the absorption is irreversible. One possible way is to induce chemical neutralization to remove the pain effect. Xu et al. reported that Camphor as topical analgesic, can rapidly and completely desensitize TRPV1 [95]. Another report from Andrew et al. [15], a series of 6-aryl-7-isopropyl-quinazolinones TRPV1 antagonists were developed for deactivation of TRPV1. Carolina et al. [25] and Charrua et al. [9] also developed active TRPV1 antagonists for pain relief. As for more practical methods, applying oleic Acid, whole milk, skim milk, and heavy cream [61, 65] after given rinsing the influenced area can largely decrease the effect by capsaicin. This was verified in our pilot study. However, the application of the above chemicals was not integrated in our prototype at the current stage.

4 USER STUDY 1: EFFECTS OF THREE FACTORS ON PAIN INTENSITY AND TYPE

In this study, we sought to understand the effects of *capsaicin solution concentration*, *temperature* and *time* on induced pain intensity and type.

4.1 Ethics Approval

All studies were approved by the ethics review board at our university's medical school. We had the following ethical and safety considerations: 1) Capsaicin is a naturally occurring Alkaloid and is a TRPV1 agonist that does not hurt dermis—a layer of the skin, 2) Microneedling pricks the skin only at the surface level and does not cause any damage to Epidermis, 3) People with any allergies were excluded from the recruitment, and 4) We would stop the studies and call medical service immediately if participants claimed any discomfort. In practice, none of our participants reported any discomfort.

4.2 Independent Variables

Our study has three independent variables (IVs): *capsaicin solution concentration*, *temperature* and *time*. We included the first two IVs because they were controlled by Douleur. We included time as an IV because induced pain sensation would change over time once capsaicin solution is applied on the skin. We conducted an informal *pilot study* with ten volunteers to collect their feedback and determine the appropriate levels for each IV.

4.2.1 Capsaicin solution concentration. When choosing the concentration levels, we referred to the prior literature [34, 80] and also considered whether the concentration levels would induce pain sensation in a few seconds for interactive VR applications. In the end, we chose three concentration levels: 0.1%, 0.01% and 0.001%. According to participants' feedback, these concentration levels were able to induce pain sensation promptly (e.g., in just seconds), and the intensity of the pain was safe.

We dissolved 0.001g, 0.01g, and 0.1g of capsaicin separately into 100g of 50:50 Ethanol/H2O. After stirring the solution and waiting 30 minutes for sedimentation, we vacuum filtrated the solution to get rid of any sediment and then collected the final solution.

4.2.2 Temperature. Because capsaicin's effect is influenced by the temperature, Douleur includes a temperature control unit (i.e., a Peltier) to modulate the induced pain at each given capsaicin concentration level. We chose five temperature levels: $15°C$, $20°C$, $25°C$, $30°C$, $35°C$, and $40°C$. These levels were chosen based on participants' feedback.

4.2.3 Time. Our pilot study feedback found that the perceived pain intensity changed quickly in the first few minutes. Thus, to capture this feeling at a high granularity, we chose 30 seconds as the interval to ask for participants' feedback. Our pilot study also showed that pain sensation induced by different temperatures and concentrations became stable within 10 minutes. Thus, we set the maximum duration as 10 minutes.

4.3 Dependent Variables

The primary dependent variables (DVs) were the *pain intensity rating* and *pain type*.

4.3.1 Pain Intensity Rating. We adopted the widely used Numerical Rating Scale (NRS) [21, 40]. Specifically, at every 30-second interval after capsaicin solution and temperature were applied, participants were asked to rate their pain intensity level between 0 and 10: 0 refers to no sensation of pain, 10 is the highest pain intensity level that they can imagine.

4.3.2 Pain Type. We adopted the widely used McGill pain questionnaire [55], which is a short version of the original McGill pain questionnaire used for measuring the types of pain sensation. The short-form McGill pain questionnaire includes 11 types of pain sensations: *throbbing*, *shooting*, *stabbing*, *sharp*, *cramping*, *gnawing*, *hot-burning*, *aching*, *heavy*, *tender*, and *splitting*. After participants reported pain intensity at every 30-second interval, they were also asked to choose one or more words from these 11 types of pain sensation that best described their feelings at the moment. Participants were only asked to report pain type if they felt pain.

4.4 Task and Procedure

The study was conducted in a quiet laboratory with the room temperature of $25 \pm 1\ °C$ in three consecutive days. We informed participants that they could stop the study any time without giving any reasons (no participant terminated the study). For each day, participants were tested with one of the three capsaicin concentration levels, which normally took 1 hour. We arranged one-day gap between two study sessions to allow the participants to fully recover from the effects of the study session on the previous day. The three concentration levels were randomized. The experiment for one participant was 3.5 hours in total, including 0.5 hours for set-up and experiment preparation. For each test, one pain stimulus was given. Therefore in total 18 sets of capsaicin concentrations and temperatures, each participant took pain stimuli for 18 times. Each microneedling was only used for once and discarded after the experiment of each set of temperature and capsaicin concentration level. In total, 18 microneedlings were consumed by one participant. Moreover, before each test, microneedling was thoroughly disinfected by ethanol (99%) so as to avoid potential infection, and the contacting area between Douleur and skin was also washed by deionized water followed by thorough disinfection by ethanol (99%) after each set of test.

Upon signing the consent form, the participants were asked to sit at a desk, rest their arms on the desk, and wear the Douleur on their preferred forearm. Figure 7 shows the study set up. In each trial, Douleur applied the capsaicin solution and then the micro-needles. This allowed capsaicin solution to flow into the dermal layer through microscopic funnels created by micro-needles and bind with TRPV1 to form pain sensation. Subsequently,

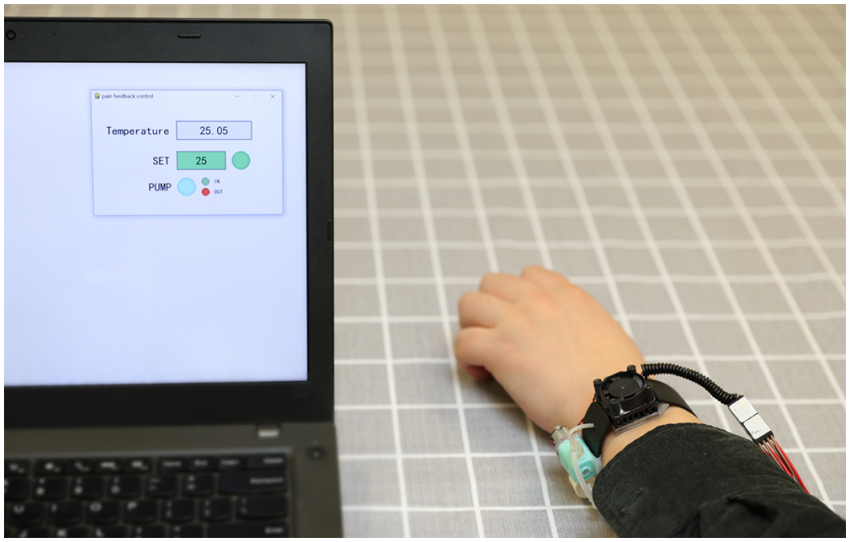

Fig. 7. The study setup: the experimental software controls the temperature change and pumps the capsaicin solution. When temperature reached a target level and was stable, participants were asked to rate their perceived pain intensity and type.

Douleur changed the temperature to one of the six levels. Then, the participants were asked to rate their pain intensity level using NRS and the pain type using short-form McGill pain questionnaire.

Each trial lasted for 30 seconds. After each trial, the Peltier was set to the original temperature and the test skin area was rinsed. Participants rested until their pain intensity level return to 0, which took around 5 minutes. The temperature levels were randomized. Every combination of concentration and temperature was applied to participants for 10 minutes in total. In sum, there were 20 pain intensity ratings and pain type reports. Noted that before each test, temperature stimuli of $15°C$ and $40°C$ were given so as to avoid misjudging the pain as being formed by high temperature induced abrasion rather than the synergy of capsaicin and temperature.

At the end of the study session, Oleic acid and heavy cream were applied separately on the capsaicin application zone after thorough rinse. After one-day break, participants returned to continue the study with a different concentration level. On average, the study took 90 minutes each day and happened in five days including two days of break between the three study sessions.

4.5 Participants

Twelve participants (age range: 20 to 27; mean age: 24.25, 6 females and 6 males) were recruited from our local institution. No participants reported any allergies. To avoid misjudgment of pain intensity level, participants were excluded if they used any analgesic within 48 hours prior to taking the study or if they had a recent history of chronic analgesic use. Each participant was compensated with $22.

4.6 Results

Next, we present the results of participants' perceived pain intensity levels and pain types, which were measured with two standard questionnaires. Details of the questionnaires were explained in Sec. 4.3.

4.6.1 Pain Intensity. We conducted a three-way repeated-measure ANOVA to compare the effects of the three IVs: the capsaicin solution concentration, temperature, and time. We found significant main effects of the

three IVs on the perceived pain intensity: capsaicin concentration ($F(2, 20) = 20.42, p < 0.001$), temperature ($F(5, 50) = 99.50, p < 0.001$), and time ($F(20, 200) = 47.53, p < 0.001$).

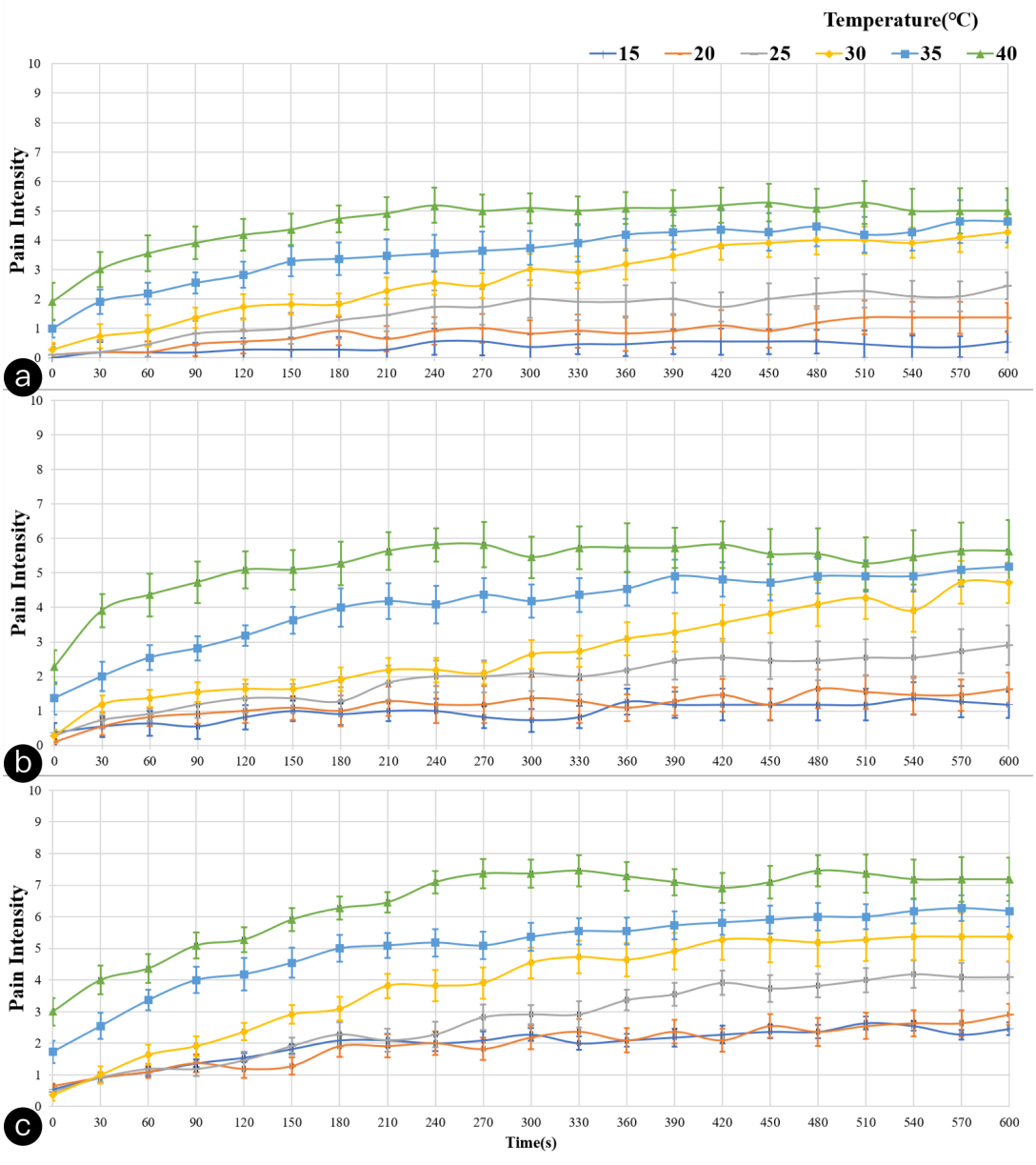

Fig. 8. Pain intensity level induced at various capsaicin concentration levels and temperatures in time series: (a) 0.001%; (b) 0.01%; (c) 0.1%.

To better understand the effects of the IVs, we plotted out the perceived pain intensity level at each temperature and each capsaicin solution concentration level in Figure 8 and conducted Bonferroni post-hoc tests. Firstly, post-hoc test results showed significant differences between 0.01% and 0.1% ($p < 0.05$) and between 0.001% and 0.1% ($p < 0.05$). This result suggests that the 0.1% concentration level induced significantly higher pain intensity levels than the other two concentration levels (0.01% and 0.001%); no significant difference between the two low concentration levels (0.01% and 0.001%). Secondly, post-hoc test results also showed significant differences between any two temperature levels except for a few adjacent temperature levels: 15°C and 20°C (p = 1), 15°C and 25°C (p = 0.08). This result suggests that in general the higher the temperature, the higher the pain intensity level. Lastly, post-hoc test results also showed significant differences between any two times before 210 seconds. This result suggests that the pain intensity levels increased significantly during the initial 210-second period and then became stable.

As Figure 8 shows, the lowest and highest pain intensity levels for all concentration levels were at 15°C and 40°C respectively. However, the lowest pain level for 0.1% concentration level (1.80 ± 1.42) was much higher than that for 0.01% (0.90 ± 1.20) and 0.001% (0.36 ± 0.62); and the highest pain level for 0.1% concentration level (6.39 ± 2.31) was also much higher than that for 0.01% (5.22 ± 2.18) and 0.001% (4.601 ± 1.74). These results confirm with the results of the statistical test that the concentration level 0.1% induced significantly higher pain intensity levels than the other two concentration levels.

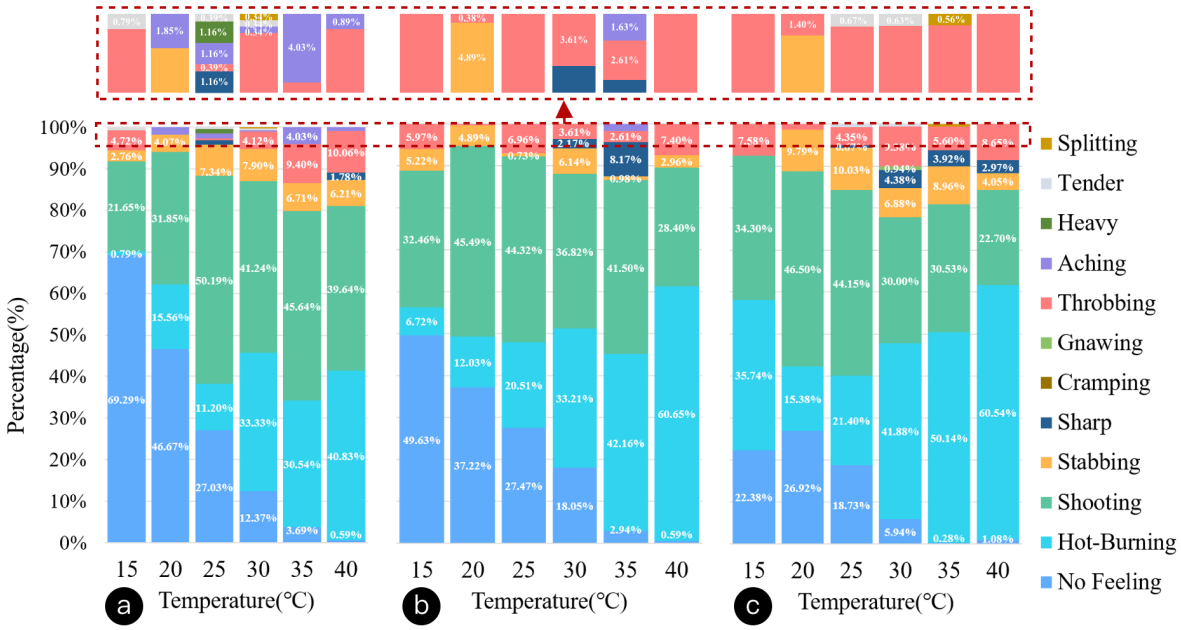

Fig. 9. Pain types induced at various capsaicin concentration levels and temperatures: (a) 0.001%; (b) 0.01%; (c) 0.1%.

4.6.2 Pain Type. Participants reported their perceived pain type at each sampling point along with their perceived pain intensity. Figure 9 shows the percentage of reported pain types at different temperatures and capsaicin

concentration levels. The main findings were as follows: 1) the two main pain types were *shooting* and *hot-burning*; 2) as the temperature increased, participants felt hot-burning more often than shooting; 3) similarly, as the capsaicin concentration level increased, participants felt hot-burning more often than shooting; 4) higher temperatures induced more other pain types in general; 5) in addition to shooting and hot-burning, the three most frequently mentioned other pain types were: *stabbing*, *throbbing*, and *sharp*; 6) with a higher concentration level (e.g., 0.1%), more participants started to feel various pain types at a lower temperature (e.g., $15^{\circ}C$).

4.7 Discussion

Our results show that the capsaicin concentration level of 0.1% can induce significantly higher intensity levels of pain compared to the other two lower concentration levels (0.01% and 0.001%), and there were no significant differences in induced pain intensity levels between the two lower concentration levels. The implication is that we can adjust induced pain intensity levels by adjusting the capsaicin concentration levels.

As the temperatures increased, participants felt higher levels of pain intensity regardless of the concentration levels. This suggests that we can tune the perceived pain intensity by controlling the temperature change. This is important because changing temperatures is much easier than changing the capsaicin concentration level during usage. What's more, the significant differences in the induced pain intensity between different temperatures show that it is possible to adjust induced pain intensity promptly and precisely. For applications that require quick changes in induced pain intensity, changing the temperature can be considered prior to changing the capsaicin concentration level.

Interestingly, our results also show a significant effect of time on induced pain intensity. Specifically, the perceived pain intensity increased significantly in the first 210-second period and then became stable. The implication is that if a VR application requires to induce stable pain intensity, then its design should expect that such stable pain intensity will not arrive until roughly after this 210-second window. On the other hand, if a VR application expects to provide a rapidly changing pain intensity, then its design should leverage the first 210-second window.

Furthermore, we found that some participants were more sensitive to pain sensation than others. For example, P1, a 21 year-old female, reported feeling three to four types of pain at $30^{\circ}C$ and $35^{\circ}C$ for the capsaicin concentration level of 0.1%, while others in same condition typically only felt one or two types of pain. P1 explained her feeling that *"I really felt those types of pain and also the changes from one type to the other."* Moreover, the pain intensity reported by her was also relatively higher than the others. We found her not only sensitive to pains, but also to temperature changes when different temperatures were applied to her. In contrast, another participant, P2, a 26 year-old male, reported relatively lower pain intensity in all tests except for the test of each concentration at $40^{\circ}C$. The average pain intensities at 0.1%, 0.01% and 0.001% were 3.43, 2.43 and 2.42 respectively, while the numbers for P1 were 6.33, 5.24 and 4.57 respectively. Data showed that pain intensity levels and pain types reported by participants were significantly different, and the reasons for the difference were various, such as their personal sensitivity of pain and different personal judging standards. That said, it remains an open question of how best to design pain sensation to cater different individuals' sensitivity levels.

Our results show that shooting and hot-burning are two most common pain types. As temperature increased, hot-burning was felt more frequently and shooting less frequently. What's more, as temperatures increased, more pain types were perceived in general. The implication is that with higher temperatures, users are more likely to feel a wider range of pain types. Thus, if applications need users to have more uniform pain sensation, lower temperatures should be chosen; however, if applications expect users to feel more diverse pain types, higher temperatures should be preferred. It is worth noting that even at a low temperature, participants still felt different pain types. Thus, it is still challenging to induce a particular type of pain. More research is needed to understand how to induce a particular type of pain. Furthermore, as we only asked participants to choose the pain types that

they felt but did not ask them to rate the intensity for each pain type, we cannot infer the effects of temperature and capsaicin concentration level on the intensity of each type of pain.

Apart from the two most common pain types, other pain types are also worth further investigation. At the same capsaicin concentration level, the percentage of throbbing decreased with the increase of temperature at first, and after specific temperature the trend rebounded. However, this interesting phenomenon did not apply for other pain types. Though mentioned by Anaïs et al[44] that with the change from a cold environment to a warm one, the throbbing pain of teeth is triggered, which seems to be only triggered by large temperature changes between outdoor and indoor environments in autumn and winter. However, their results did not study whether pain types could be affected with small temperature changes, such as the ones we studied. What we have found is that as the temperature increased, the throbbing pain change did not follow a monotone increasing trend but rather a parabolic trend. It may be because that the mild temperature between 20°C and 30°C is not a temperature range that these TRP channels can be activated efficiently. As different TRP channels have different activation thresholds, such as TRPV1 (higher than 43°C), TRPV2 (higher than 52°C), TRPV3 (higher than 33-39°C), TRPV4 (higher than 27-34°C), TRPM3 (higher than 30°C), and TRPM8 (lower than 17°C), it is possible that throbbing pain may follow this law, which also applied for burning sensation at the capsaicin concentration level of 0.1%.

Another interesting phenomenon is that there were more types of pain in the middle of the temperature range than at the two ends of the range. While more research is needed to understand the reasons behind this phenomenon, one takeaway for VR designers is that the temperate needs to be carefully considered so as to induce either a diverse set of pain types or a particular pain type.

5 USER STUDY 2: EFFECTS OF DOULEUR IN VR APPLICATIONS

To understand the potentials of Douleur in improving immersive user experience of VR applications, for example, for safety education purpose, we conducted the second user study. Next, we present the design of three application scenarios first and then the details of the study. Based on Study 1's results, 40°C and 0.1% capsaicin concentration level can generate a strong pain intensity in the shortest amount of time. Thus, we used these two parameters for Douleur in this study to provide participants with the most responsive pain feedback.

5.1 Application Scenarios

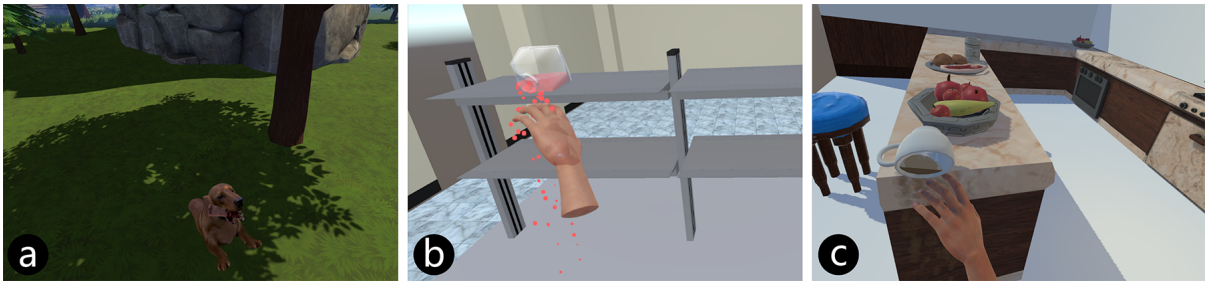

Fig. 10. Three VR application scenarios: (a) The dog-biting scenario; (b) The corrosive liquid scenario; (c) The spilled hot coffee scenario. Participants experienced these scenarios with and without Douleur in a random order during the study.

We created three VR application scenarios to simulate conditions that a person might experience pain. Figure 10 shows the scenarios: (a) The dog-biting scenario; (b) The corrosive liquid scenario; (c) The spilled hot coffee scenario.

5.2 Participants

Five participants (age range: 21 to 26; mean age: 23.60, 3 females and 2 males) were recruited from our local institution. The same inclusion criteria as Study 1 were applied. Each participant was compensated with $22.

5.3 Study Procedure

The study was conducted in a quiet laboratory with the room temperature of 25 ±1 $^{\circ}C$. Upon signing the consent form, the participants were asked to sit at a desk so as to lay their arms. The researchers helped participants wear Douleur on their preferred wrist and Vive Tracker[3] on the forearm of the same side as Douler. Vive Tracker was used to track the motion of the participant's hand, which was used to control the virtual arm in VR. Participants then wore the VR helmet[4]. Next, the three application scenarios were presented in a random sequence.

In the "dog-biting scenario", participants were asked to pet a strange dog with their hand worn Douleur and Vive Tracker. This action will then trigger an attack from the dog. The moment when the dog bit the participant, Douleur released the capsaicin solution with the temperature increase to induce pain sensation. In the"corrosive liquid scenario", participants were asked to get a bottle of chemical materials on a shelf. Once their virtual hand was about to grab the bottle, the bottle fell and the liquid poured out to the virtual hand. At the same time, Douleur emitted capsaicin solution with the temperature increase to induce the pain sensation. In the "spilled hot coffee scenario", participants were asked to grab a cup of coffee sitting at the edge of a table. Once the virtual hand touched the cup, the cup fell and the hot coffee poured out on the virtual hand. At the same time, Douleur emitted capsaicin and increased the temperature to induce pain sensation.

Participants experienced the three scenarios with and without Douleur in a random order to help them compare their experiences. After experiencing each scenario either with or without Douleur, participants were asked to rate how much they agreed with the following statement on 7-point Likert scale (7 = totally agree, 1 = totally disagree): *"I felt the experience was immersive."* After experiencing all scenarios, participants were asked to provide feedback about their experiences.

5.4 Results

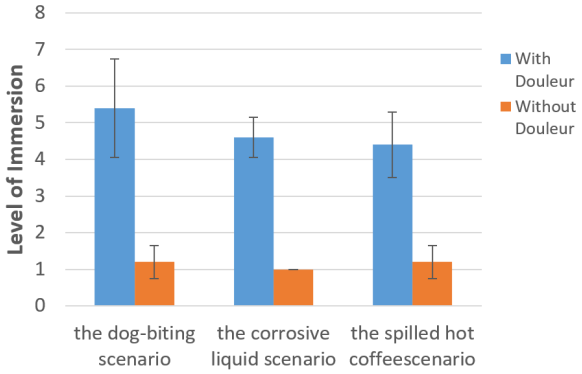

Fig. 11. The ratings of immersion for three application scenarios with Douleur and without it.

Figure 11 shows participants' ratings of immersiveness with and without using Douleur. Wilcoxon signed rank tests found significant differences between with and without using Douleur in all three application scenarios: "the

[3]https://www.vive.com/us/accessory/vive-tracker/
[4]https://www.vive.com/cn/product/vive-pro/

dog-biting scenario" (z=-2.06, p=0.04), "the corrosive liquid scenario" (z=-2.07, p=0.04), and "the spilled hot coffee scenario" (z=-2.04, p=0.04). Four out of five participants felt that the "dog biting" experience was the most realistic and immersive scenario among the three scenarios. P1 commented that the high immersion of the "dog biting" scenario was because the visuals in VR and the pain feeling induced by Douleur were highly synchronized. P3 remarked that *"the immediate pain intensity increase [induced by Douleur] was similar to the reality and significantly enhanced the dog biting feeling."* P4 argued that the "corrosive liquid" scenario was immersive because of the burning and stabbing sensation as well as the feeling of the flow of liquid.

In contrast, the "spilled hot coffee" scenario was not as immersive as the other two. One reason was that participants expected a larger area of their skin would be affected when the hot coffee spilled. P2 explained that, *"it could be more immersive if the area of pain sensation was much larger."* It remains an open question of how to generate a larger area of pain sensation to simulate the spilled liquid scenario in which a part of the skin feels pain while other parts do not. One possible solution might be creating an array of Douleur prototypes and controlling the on and off of certain ones based on how the virtual liquid is spilled.

Regarding the form factor of Douleur, P3 commented that the form factor of Douleur was even better than a smartwatch due to its small size and light weight: *"The only drawback was the weight of power supply system. The prototype, however, is light enough and effective enough for me"*. During the study, we tightened the power supply of Douleur on participants' upper arm, which included four AA batteries. The heavy weight of power supply was due to the requirement of the long duration of the study. When using for a relatively short time, the power supply can be reduced. Nonetheless, future research should explore ways to reduce the weight of the power supply system so that it would be light enough to be integrated with the main part of Douleur.

Furthermore, P5 mentioned that in order to create more immersive experience, multi-channel haptic feedback should be integrated. For example, for the dog-biting scenario, the hot air from the dog's mouth, the pressure caused by the dog's teeth, and the feeling of the dog's saliva could further enhance the immersion in addition to the pain sensation. More efforts should be devoted to understand how to simulate these multi-channel sensations with a wearable device form factor.

6 DISCUSSION

Though it is seen that pain sensation could help establishing immersive and controlled virtual scenarios for safety education and training, inducing pain is non-trivial. Aside from ethical considerations, mechanical, electrical and thermal stimulus have been attempted in previous work but they are inferior in terms of naturalness. In this work, we paid attention to the burning pain, involved in many types of accident that cause injury to skin. To avoid the skin injury, we took an alternative approach and leveraged capsaicin as a chemical stimulant to induce the pain. Our approach took advantage that capsaicin is not unusual, which stimulates the same nociceptors under skin as those real injuries do. We verified that capsaicin's effect on skin is safe, controllable and removable. This makes it an ideal candidate to be used for developing interactive pain inducing scenarios.

Douleur has tackled several key challenges. First, it leveraged microfluidic channels to precisely deliver the solution on the skin. As shown in the study, concentration of the solution is directly associated with the pain intensity felt by the users, thus guaranteeing precise control of the stimulant delivery is of importance. Second, matched with our prior knowledge, it takes time ranging from seconds to minutes, for the capsaicin to take effect and for us to feel the pain. This is not practical to use in interactive applications. Douleur mitigated the problem by using a microneedling method, which helped the solution penetrate the epidermis while not hurting the skin. Study 1 showed that with certain concentration and temperature conditions, the participants can feel the pain immediately after the capsaicin solution was applied on the skin. Third, compared with adjusting the concentration on the go, it is more doable to control the thermal stimulus. Douleur integrated a thermal module to dynamically adjust the pain intensity, and its effect was quantitatively evaluated in the study.

While Douleur was shown to be effective to induce pain sensation, it can be improved in the following ways. First, the prototype consists of a microfluidic system and a temperature control system. The microfluidic system is used to transport capsaicin solution and control the solution's application area via restricting the flow area of the solution. However, when stretching after wearing, conformation may occur. This could induce subtle leakage of capsaicin concentration and may lead to unwanted pain feedback out of the application area. To solve this problem, we introduced a tighter belt into Douleur, that ensured the microfluidic channel cling to the skin.

The utility of microneedles decreased the initiation time of capsaicin when working with the microfluidic system. We used a commercially available microneedling component, which had relatively high permeation rate and was more suitable for VR system. In order to make the induction of pain sensation always hygienic and efficient, replacement of microneedling and following sterilization are needed every time when using Douleur. Though troublesome, safety issues should come first, and therefore it cannot be omitted. Fortunately, Douleur can induce continuous pain feedback with only one emission, which does not affect an intact VR experience. One solution to the troublesome replacement is to design Peltier that allows easy installation and dismantling of microneedling, such as designing a slot which microneedling can be easily inserted into and removed from. Peltier, also regarded as TEC plate, was utilized for temperature control along with a thermal sensor. The temperature control system could be improved in the following ways: 1) choosing a smaller Peltier with lower energy consumption and lower heat dissipation capacity requirement; 2) choosing heat sink with better thermal conductivity to dissipate the heat more efficiently; and 3) reconstructing the whole heat dissipation system to achieve higher heat dissipation efficiency.

To address the concern that wearing Douleur for a long time was tiring, we estimated the pain events and the time of pain sensation based on the VR scene. This helped choose different battery capacities to control the weight of the entire device. For instance, 1.5-hour continuous operation at $40^{\circ}C$ requires four LiPo batteries (3.7V 3400mAh). On the one hand, the less time the operation takes, the less powerful batteries are needed, which are commonly lighter. Further, due to the limited energy efficiency of the Peltier that we used, it consumes a large amount of energy. To reduce power consumption, we can choose a smaller Peltier and improve the heat dissipation capacity of the hot end to make it more efficient for heat pumping.

Our study revealed two groups of pain types with different qualities and temporal features. The first group of pain types includes lancinating, stabbing, or pricking. The second group of pain types includes burning, throbbing, cramping, and aching, which happened more often [74]. In our study, the change between these two groups of pain types was mentioned by participants. P4 reported that, "I felt shooting and pricking at first, and then it is warmer and hotter, which to me the sensation turned to burning sensation." P8 said, "In the same test, burning sensation was replacing the sensation of shooting gradually." P11 explained that "Shooting occurred earlier at the beginning. I cannot say it's totally disappeared, but later I felt more like burning sensation". In general, we found that shooting occurred at the beginning. As the time passed, burning sensation occurred. As participants mentioned, the intensity level of burning sensation was dominant later, which showed a gradual replacement of shooting sensation.

The habituation of pain may also lead to inaccuracy of pain feedback formed by Douleur. As mentioned by Victor et al. [19], high concentration and repeated dose of capsaicin induced an analgesia after initial pain sensation, due to the desensitization of TRPV1 receptors and even the inhibition of receptor function [8, 14, 48, 68]. Experiments were conducted to investigate the influence of capsaicin concentration and the frequency of application on its desensitization effect. Topical capsaicin (0.075%) applied four times a day for 3 weeks caused nerve fibers degeneration [64]. Topical capsaicin patch (8%) formed a significant decrease in pain for 12 weeks [2, 38]. One patient reported 80% reduction of neuropathic pain after the use of 8% capsaicin patch after 18 months' application [3]. Although the mechanism of desensitization of TRPV1 receptors has been studied, it is still not entirely understood. Nonetheless, studies suggest that the desensitization of capsaicin occurred not only in oral

[77] and nasal [84] areas but also after injection of capsaicin into skin [90]. Therefore, the concentration of capsaicin should be considered when using Douleur to avoid desensitization.

Furthermore, it is also worth paying attention to the interval of stimulus which is another factor that affects the pain intensity created by capsaicin. Sufficient time should be allocated between two usages, whose effect is trivial for safety education due to its disposable use. The rest time between two applications should be more than 5 minutes at least according to our previous study. Otherwise, the test result may be influenced by last test. While using for VR games that require multiple-time stimuli within a relatively short period, desensitization should be considered as one factor that may influence the effect of Douleur.

Our research shows that inducing pain feedback that synchronizes with visual feedback can increase immersion of VR applications. It is worth exploring how best induce pain feedback for more hazardous sources, such as boiling oil in kitchen, wild animals in forests, and hot motorcycle exhaust pipe. Pain feedback in these scenarios could be designed as education modules to help people gain tangible experiences of these hazardous sources and develop better awareness of avoiding such sources. Toward this goal, it remains unknown how best design such applications and whether such VR experiences with induced pain feedback would create a long-lasting memory for safety education.

Moreover, pain feedback could also be used for hazard warning. Traditionally warnings are delivered through visual or audio channels, such as earthquake early warning [42], flood alert [1], and operation warning [98]. When audio and visual feedback is unavailable or not preferable such as a cluttered and noisy workplace, pain feedback could be an effective alternative warning.

Lastly, in the area of medicine, pain feedback induced by Douleur could be used to simulate the pain sensation of certain operations before they decide to perform the operations, in particular those involving acute pain, e.g.: Electromyography (EMG), Colonoscopy, and Gastroscope. Such simulation would help patients understand how painful an operation might be. If the patients could endure the pain, they could proceed to take the operations. Otherwise, they may choose alternative treatments.

7 LIMITATION AND FUTURE WORK

One challenge with using chemical-induced pain sensation is that it takes time to remove the pain sensation. In our studies, we rinsed participants' skin and applied oleic acid, which took 30-45 minutes to remove the induced pain sensation for most participants. This was because it took time for oleic acid to bind with TRPV1 and reduce the open probability of the channel (Po), which renders it resistant to stimulation by capsaicin [66]. This was not an issue for our educational scenarios because there was no need to remove the pain sensation immediately. Indeed, having the pain sensation lasting for some time probably would be better for such educational scenarios. However, the long time needed to remove the induced pain would be a limitation for interactive applications that require immediate removal of induced pain. Future work should investigate how to remove pain feedback promptly for more interactive applications. One possible solution, based on the results of our study 1, would be to use a low capsaicin concentration level that does not induce any pain at a low temperature (e.g., 15 $^{\circ}C$ or lower), increase the temperature quickly to induce pain sensation and drop the temperature quickly to reduce the pain sensation.

Another challenge is that people have different pain sensitivity. A set of capsaicin and temperature parameters works well for one user does not necessarily work for another one. Our current prototype does not provide customized experiences for each individual. It is worth exploring ways to customize the parameters to induce best pain experiences for different individuals. Toward this goal, a calibration process might be needed. During calibration process, users could be exposed to a few parameter combinations and report their feedback. Based on the feedback, the system could infer the best parameters. However, more research should be conducted on how to design an effective calibration process that would minimize the number of trials users have to go through.

Furthermore, it also remains unknown whether the best parameters remain unchanged for the same user or whether the best parameters are scenario-dependent.

Finally, in addition to pain sensation, chemicals might be utilized to induce multi-channel feedback, such as temperature, itching, and even anesthesia of a specific part of body. In addition to the applications of safety education, hazard warning, and VR games, chemicals-induced multi-channel sensations could also be used in medical training and treatment, such as surgery experience training. However, it remains as a challenge how best to make chemical-induced feedback more controllable.

8 CONCLUSION

Pain plays a critical role in human lives. In this work, we present the design and evaluation of a wearable device—Douleur—that is worn around the wrist and can induce pain sensation. Douleur emits capsaicin with the assistance of microneedling and changes the temperature to modulate the effect of the induced pain. We conducted a study with 12 participants to understand the effects of different capsaicin concentration levels and temperatures on the perceived pain intensity and type over time. Our results show that: 1) different capsaicin concentration levels can induce different pain intensity; 2) the higher the temperature, the higher the perceived pain intensity; 3) regardless of the capsaicin concentration level and temperature, the pain intensity increases significantly during the first 210-second window and then becomes stable; 4) the two most common types of pain are shooting and hot-burning sensation; 5) the higher the temperature, the more likely users would feel hot-burning sensation than shooting; 6) the higher the temperature, the more diverse types of pain users can feel. To further understand whether Douleur would improve VR users' experiences, we conducted a second study with five participants to understand their immersion with and without the pain sensation induced by Douleur in three application scenarios: the dog-biting scenario, the corrosive liquid scenario, and the spilled hot coffee scenario. Our results showed that participants felt the scenarios more immersive with Douleur-induced pain sensation. They felt that the dog-biting scenario was most immersive due to the synchronization of the visual and pain feedback. As a first step toward introducing pain sensation into VR via a wearable form factor, our work opens up more research questions regarding how best to enable multi-sensory feedback to enhance user experience.

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