Chemical Haptics: Rendering Haptic Sensations via Topical Stimulants

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Figure 1: We propose a novel haptics approach, which we call *Chemical Haptics*, based on delivering topical stimulants to the user's skin. Upon absorbing these stimulants, receptors in the user's skin are chemically triggered, rendering distinct haptic sensations. To explore our approach in interactive contexts, such as VR, we engineered a self-contained wearable that delivers liquid stimulants. Here, it allows this VR user to feel four haptic sensations: (a) *Sanshool* creates tingling, which renders electric sparks emitted from a "short-circuiting" touchscreen on the arm; (b) *Lidocaine* creates numbing, which renders a malfunctioning arm interface by reducing tactile feedback as the user taps the buttons; (b) *Menthol* creates cooling, which renders cold winter air on the face; finally, (d) *Capsaicin* creates warming, which renders the hot air on the face from a nuclear reactor on the brink of meltdown.

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ABSTRACT

We propose a new class of haptic devices that provide haptic sensations by delivering *liquid-stimulants to the user's skin*; we call this *chemical haptics*. Upon absorbing these stimulants, which contain safe and small doses of key active ingredients, receptors in the user's skin are chemically triggered, rendering distinct haptic sensations. We identified five chemicals that can render lasting haptic sensations: tingling (sanshool), numbing (lidocaine), stinging

(cinnamaldehyde), warming (capsaicin), and cooling (menthol). To enable the application of our novel approach in a variety of settings (such as VR), we engineered a self-contained wearable that can be worn anywhere on the user's skin (e.g., face, arms, legs). Implemented as a soft silicone patch, our device uses micropumps to push the liquid stimulants through channels that are open to the user's skin, enabling topical stimulants to be absorbed by the skin as they pass through. Our approach presents two unique benefits. First, it enables sensations, such as numbing, not possible with existing haptic devices. Second, our approach offers a new pathway, via the skin's chemical receptors, for achieving multiple haptic sensations using *a single* actuator, which would otherwise require combining multiple actuators (e.g., Peltier, vibration motors, electro-tactile stimulation). We evaluated our approach by means of two studies. In our first study, we characterized the temporal profiles of sensations elicited by each chemical. Using these insights, we designed five interactive VR experiences utilizing chemical haptics, and in our second user study, participants rated these VR experiences with chemical haptics as more immersive than without. Finally, as the first work exploring the use of chemical haptics on the skin, we offer recommendations to designers for how they may employ our approach for their interactive experiences.

KEYWORDS

chemicals, tactile haptics, fluidics, haptic feedback, virtual reality

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1 INTRODUCTION

Physical touch is a critical aspect of our experience, essential to interacting with our physical world. Thus, much emphasis has been put on engineering haptic devices that render physical sensations [27, 52, 58, 59], which is especially important for immersive experiences such as in Virtual Reality (VR). One promising approach is wearable devices that deliver tactile sensations directly to the skin [6]. This is primarily achieved by stimulating mechanoreceptors in the skin via actuators that *physically* create pressure [38], vibration [11], or skin stretch [35].

However, while these traditional cues (pressure, vibration, stretch) are undoubtedly important for rendering realistic sensations on the skin, these are **not the only sensations our skin can feel**. As such, in recent years, researchers started to explore how to render other sensations that our skin can feel, especially those with more nuanced and affective connotations, such as tingling [6], itching [53], temperature [24, 51, 52, 55], and pain [40].

Unfortunately, two key factors limit the application of these emergent haptic sensations that go beyond vibration/pressure: (1) most actuators capable of creating tingling/tickling/temperature are large (e.g., *ChillyChair* [18] requires desktop-sized actuators, *Therminator* [24] requires a large fluidics system) or consume a lot of power (e.g., Peltier elements [51, 52, 55]), rendering them unfeasible in a wearable form-factor; and, (2) most of these approaches are primarily based on mechanical actuation, and as such are unable to actuate many of the remaining skin receptors involved in these types of sensations, such as thermoreceptors and nociceptors.

In this paper, we introduce a new way to create haptic effects on the skin. We propose leveraging chemicals to create haptic sensations on the user's skin, we call this *Chemical Haptics*. With chemical haptics, the sensations are not created mechanically, but, instead, are created when the skin reacts to a particular chemical ingredient and responds by generating *a haptic sensation*. For example, when our device delivers cinnamaldehyde to the skin, it creates a long-lasting *stinging* sensation. Much like this example, all our haptic effects are possible because many of the receptors found throughout the skin can *also* be triggered *chemically* (in addition to mechanically triggered). By means of our engineering, explorations, and user studies, we found five skin-safe ingredients that can create five haptic sensations when applied to the skin: tingling via *sanshool*, numbing via *lidocaine*, warming via *capsaicin*, cooling via *menthol*, and stinging via *cinnamaldehyde*.

To demonstrate how chemical haptics can be used for untethered haptic experiences, such as the VR experience depicted in Figure 1, we engineered a self-contained wearable that can be worn across multiple areas of the user's skin. Implemented as a soft silicone patch, our device uses micropumps to push liquid stimulants through channels that are open to the user's skin, enabling stimulants to be absorbed by the skin as they pass through. In Figure 1, we illustrate how chemical haptics allows this VR user to feel four distinct haptic sensations on the arm and cheeks: (a) sanshool creates tingling, which renders electric sparks emitted from a "short-circuiting" touchscreen on the arm; (b) lidocaine creates numbing, which renders a malfunctioning arm interface by reducing tactile feedback as the user taps the buttons; (c) menthol creates cooling, which renders cold winter air on the face; finally, (d) capsaicin creates warming, which renders the hot air on the face from a nuclear reactor on the brink of meltdown.

To shine light on this novel way to achieve haptics, we validated our key hypotheses by means of two user studies. In our first study, we investigated the temporal profile of these chemically induced haptic sensations. We found that four chemicals provide distinct haptic sensations (cinnamaldehyde as stinging, sanshool as tingling, menthol as cooling, and capsaicin as warming), and another chemical, lidocaine, rendered an ambiguous sensation, which we suspected would benefit from a narrative and visual context to work as haptics. We used these insights to further refine our selection of chemicals and design five VR experiences. Then, in our second study we found that chemical haptics increased immersion for all these five experiences, including numbing via lidocaine.

2 WALKTHROUGH

To help readers understand the applicability of our device, we demonstrate it in a virtual reality (VR) experience with haptic sensations that are *all* rendered via our chemical-based device. The user is wearing two of our wearable devices: one device on the cheeks, between the user's face and the VR headset, and a second device worn as a forearm sleeve. These devices are self-contained (i.e., battery-powered and wireless), communicating with the VR headset via Bluetooth. To deliver chemical stimulants to the skin

our device uses pumps that push the stimulants through silicone channels on top of the skin; these channels are open at their base so that the liquids come in *direct contact* with the skin. Once a stimulant is absorbed by the skin it creates a haptic sensation. The chemicals used in this VR experience were sourced from off-the shelf, skin-safe, topical products (refer to *Implementation* for details). In this walkthrough, we demonstrate four of our chemically induced haptic sensations: tingling (sanshool), numbing (lidocaine), warming (capsaicin) and cooling (menthol).

At the start of this VR experience, users find themselves in a nuclear power plant on the brink of meltdown, their objective is to avert the disaster by shutting down the reactor.

Chemically-induced tingling to render electrical sparks. After being alerted about the imminent meltdown, the user walks down a corridor leading to the nuclear reactor core. The user opens doors using an interface anchored on their arm (which depicts a map and touch-buttons to open doors). Suddenly, after the user opens one door, a large explosion is heard and electrical sparks cascade down the walls as depicted in Figure 2 (a). When this happens, the user's control panel short-circuits as depicted in Figure 2 (b, c). Here, the user not only sees electrical sparks on their arm, but also feels them *tingling* their forearm as depicted in Figure 2 (d). This haptic sensation is not created by vibrations [11] or electrical-stimulation [34] but by delivering sanshool to the user's forearm—the molecule hydroxy-alpha sanshool reacts with receptors in the skin to induce a tingling sensation. This tingling sensation via sanshool is commonly experienced when eating food containing Sichuan peppercorns.

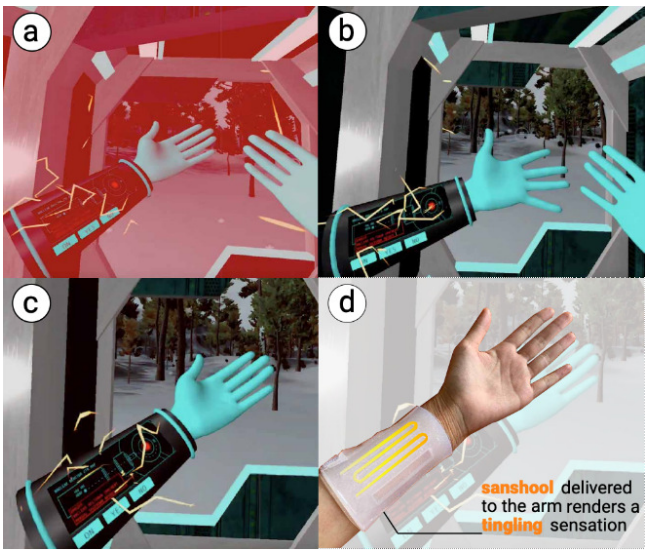

Figure 2: (a) While in VR, the user experiences an explosion that triggers electric sparks everywhere, (b, c) including on their arm interface. (d) As this happens, our device delivers sanshool to the user's skin, inducing a tingling sensation.

Chemically-induced cooling to render walking outside in the cold. To get to the nuclear power plant, the user keeps opening doors by touching their arm interface, which still functions despite the electrical sparks. As the user exits the last door of the corridor, they walk out to a snowy mountainous landscape (Figure 3). Here, our second device, renders the cold by passing a 10% solution of *menthol* across the cheeks—menthol is a chemical known to interact with thermoreceptors and cause a cooling illusion (for instance, it is why breath mints feel cold). As such the user slowly feels an increasing cold sensation as they cross this wintery landscape. After crossing it, the user enters the reactor's core facilities, and the cheek-device stops stimulating, letting the cooling sensation slowly fade away–similar to how our skin slowly warms up when entering a warmer room.

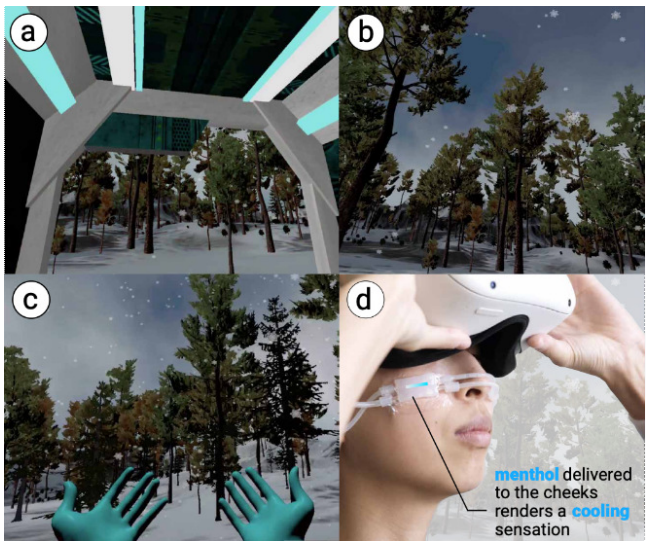

Figure 3: (a,b,c) As the user steps outside into a wintery landscape, they feel a cooling sensation on their cheek. (d) This is rendered via menthol pumped through attached silicone patches on their cheeks.

Chemically-induced numbing to render reduced haptic sensation. Finally, as the user reaches the reactor room's entrance, which requires authentication from the user's arm interface to enter, their VR arm interface starts to malfunction (Figure 4). While the display is still operational, buttons appear "grayed out" and the whole arm becomes transparent and starts to "glitch". As the user presses buttons to try to open the final door, they feel that their arm is *numb*. In other words, they feel less sensations on their arm because the virtual arm is "malfunctioning". Our device renders this *unique* haptic sensation (not achievable using existing haptics) by delivering 5% *lidocaine* solution to the user's arm. Lidocaine is a local anesthetic that blocks nerve signals, thus reducing touch sensation.

Chemically-induced warming to render rising temperatures. As the door to the reactor opens, hot steam slowly invades the room. Here, not only does the user see the steam coming from the core but they also slowly *feel the heat rising* as our cheek-device delivers a *0.025% capsaicin solution* to the user's face (Figure 5). Capsaicin is the active ingredient in chili peppers that triggers a sense of warmth when it binds with thermoreceptors in the skin (it is why

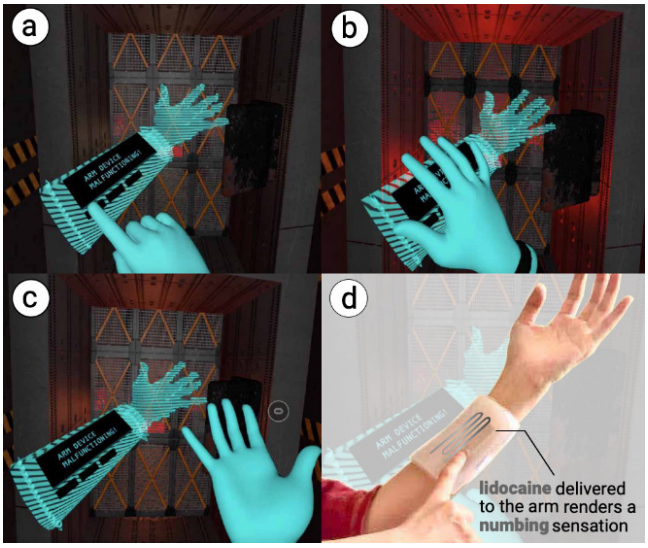

Figure 4: (a) The user notices their arm becomes holographic and starts to glitch. (b,c) When the user tries to press a button, they feel their arm is numb to the touch; (d) This is rendered via lidocaine being applied to the area.

chili peppers feel hot). Finally, the user pulls an emergency lever and prevents the meltdown. As the temperature slowly returns to normal, our device stops the capsaicin and the heat sensation slowly fades away.

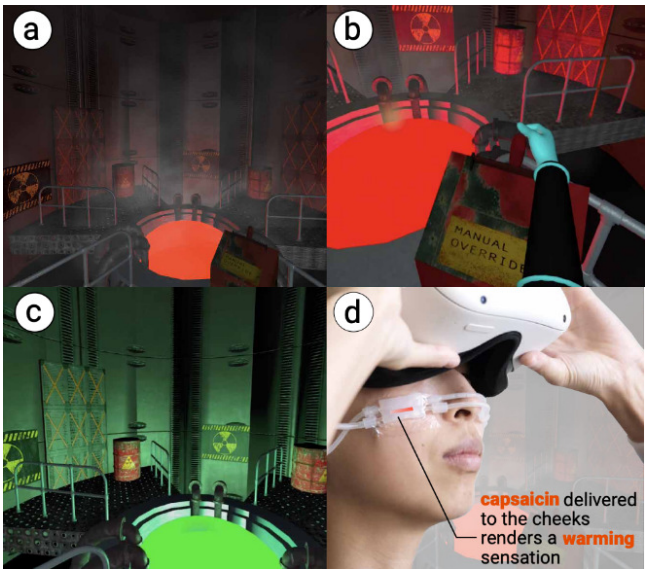

Figure 5: (a) In VR, the nuclear reactor glows red and is on the brink of meltdown. (b) The user finds the manual override and pulls the lever. (c) Doing so averts the meltdown. (d) The temperature of the hot room is rendered by capsaicin delivered to the cheeks.

3 BENEFITS, CONTRIBUTIONS, AND LIMITATIONS

Our key contribution is that we propose, explore, and engineer a new approach based on using liquid stimulants to induce haptic sensations on the skin.

Our approach provides three key benefits: (1) a new type of haptic device that uses chemicals rather than the more traditional mechanical approach (e.g., vibration motors or Peltiers), which we believe can inspire future work; (2) increasing the haptic design space with a unique *numbing* sensation, which existing haptic devices cannot render; (3) while our chemically-induced haptic sensations are, typically, slow-evolving they are also *long-lasting*; leveraging this, our device can create sensations lasting on the order of minutes with relatively low power—requiring only the power to move the liquid stimulant (0.52W to move two topical stimulants), rather than to create, for instance heat/cold, which require a lot of power (e.g., a typical Peltier uses 4-13W per Peltier [51, 55]); moreover, it is the fact that we recycle the chemical in a closed loop that decreases our power-consumption, i.e., the chemical will either be absorbed by the skin or evaporate slowly (too slow to be measured in a few days).

Our approach is limited in that: (1) the absorption of a chemical via the skin (the haptic stimulus onset) is influenced by the epidermal thickness, which might vary across individuals as well as across locations in the body [63]; while we have confirmed that our proposed set of chemicals induces haptic sensations, future research might shine more light on how these factors impact skin absorption; (2) likewise, chemical stimulation is a slow dissipating phenomena, thus, the haptic stimulus offset is also slower when compared to traditional haptic actuators. As such, this approach is best suited for slow changing haptic events (e.g., how the sting of a wound evolves over the first few minutes or rising heat) rather than rapidly changing discrete haptic events; and (3) as the first exploration into chemical haptics, we investigated only six ingredients that we found in over-the-counter medicine or food spices, resulting in five sensations, but we expect that more sensations will be possible as researchers build on this work by developing custom-engineered chemicals for haptics.

Finally, we are not proposing to replace existing haptics with chemical haptics, but rather enlarging the set of haptic techniques by also considering chemical stimulation of the user's skin and understanding what effects it can create; our paper lays the groundwork for this new technique.

4 RELATED WORK

The work presented in this paper builds primarily on the field of haptics, especially on-skin haptics.

4.1 Rendering vibration, pressure and skin stretch (traditional mechanical haptics)

As the skin is our largest sensory organ, it has received a great deal of attention with regards to haptics research. When it comes to inducing sensations on the skin, wearable haptic devices (i.e., ungrounded) are generally preferred over stationary devices (i.e., grounded) since they allow to *directly* deliver tactile sensations to the user's skin [12]. This is primarily achieved by stimulating

mechanoreceptors in the user's skin using actuators that *physically* create vibration [5], pressure [38], or skin stretch [31].

Vibration: One of the most popular and established approaches to skin haptics is vibration. Small vibration motors have enabled a large variety of wearable vibrotactile displays for haptic feedback [11, 38]. Depending on their frequency, these *mechanical* vibrations are sensed by our skin using a combination of its mechanoreceptors, such as the Meissner corpuscles and/or Pacinian corpuscles [12].

Pressure & skin stretch. The receptors that govern the perception of vibrations are not the only receptors that contribute to our tactile perception. Another significant area in skin haptics includes pressure and skin-stretch. Many have engineered tactile displays that deform the skin (i.e., stretching and dragging) [31] or render a certain texture [35]. Most of the these displays target slow adapting (SA) mechanoreceptors found in the skin, e.g., SA1 and SA2 afferents.

However, while these traditional haptic cues are undoubtedly important for rendering realistic sensations on the skin, these are *not the only sensations our skin can feel.* As such, in recent years, researchers started to explore how to render other sensations that our skin can feel, especially those with more nuanced and affective connotations, such as light touch (tickling, gentle stroking, etc.), tingling/itching, temperature, and pain.

4.2 Rendering affective types of touch (tingling, tickling, light-stroking, etc.) mechanically and electrically

When it comes to rendering a "light touch" sensation, which is linked to affective sensations such as tickling or tingling, researchers tend to resort to different actuators rather than vibration motors. One popular approach is to use actuators to stimulate the C-tactile neurons, which are rapidly adapting mechanoreceptors present in the root of the hair-cells, that respond preferentially to slow, stroking touch [12]. To achieve this, researchers often employ motors that move end-effectors along the user's skin, stretching and dragging to trigger the skin's directional sensitivity [31, 44, 59]. Similarly, *M-Hair* and its wearable counterpart, *MAGHair* requires a user to coat their body hair with magnetic paint, and then the system uses an X-Y gantry to move a magnet over the user's body, which much like the aforementioned mechanical actuators, cause the user's hair to move, resulting in a light-stroke, which mimics a tingling or tickling sensation [6, 7].

One alternative approach that also aims at stimulating the hair cells is using electrostatic forces. For instance, *ChillyChair* induces goosebumps by placing the user's arm between two large metal plates [18] and producing an electrostatic force between the two plates which raises the forearm's hair, causing a goosebump-like experience. Finally, electrical tactile stimulation has also been used to induce a large range of sensations, including itching [53] and pain [40].

4.3 Rendering numbing using additional haptic sensations that overpower tactile feedback

While most haptic interfaces focus on allowing users to feel *additional* sensations, our sensorial experiences are not always additive. For instance, when our arms and hands are exposed to strong vibrations for long periods (e.g., when manipulating powerful handheld tools such as a rock drill [9]), the tactile sensations in one's fingertips are decreased; this is known as hand-arm vibration syndrome [54]. While this effect has not been used in interactive systems, it has been used in HCI studies to minimize sensations. For instance, researchers in electrical muscle stimulation (EMS) use vibrations to minimize the tingling sensations that can alert participants to the EMS stimuli [36, 45]. Other researchers have explored mechanical ways to diminish tactile sensations. For instance, Ochiai et al. [48] utilized the squeeze air film effect, where surfaces feel smoother when a small ultrasonic vibration is applied, to interactively reduce texture sensations from real world objects. Unlike these, our chemical pathway allows for a real numbing effect because it blocks the sensory pathways involved in processing sensation.

4.4 Rendering temperature changes using thermoelectric elements

More recently, increased attention has been given to rendering a realistic sense of temperature [24, 51, 52, 55, 56]. One popular approach is adding thermoelectric materials in contact with the user's skin. The most popular actuator for temperature haptics is the Peltier, which is a thermoelectric material that creates a temperature between the side that is in contact with the user's skin and the opposite side when supplied with a strong electrical current. For instance, *ThermalBracelet* [51] used Peltiers attached to the user's wrist to explore eyes-free feedback; *ThermoVR* [52] used Peltiers added to the foam between the VR headset and the user's face; *Season Traveler* [56] used heating elements on the user's neck; and, lastly, *Thermotaxis* [47] added Peltier elements on the user's ears.

Moreover, alternative methods to generate temperature changes include hydraulics (i.e., moving cold or hot water by means of tubes that touch the user's skin) [24, 26], gel packs [33], or resistive heating [39, 62].

Finally, it is worth noting that while thermoelectric materials are more mobile than air-based devices (e.g., A/C units or heat lamps [17]) they consume an enormous amount of power (4-13 W per Peltier even considering only small Peltiers). In fact, the devices such as *ThermalBracelet* [51], *ThermoVR* [52], *Thermotaxis* [47], or resistive heating [39, 62] do not operate on battery because their lifespan would be drastically reduced and impractical.

While we have a variety of methods for temperature, all of these come with an added technical challenge: how to create temperature sensations on the user's skin *at low power.* One recent promising approach by Brooks et. al [8] used an illusion of temperature by stimulating the user's trigeminal nerve, inside the nose, *chemically* rather than using temperature. Their system works by emitting capsaicin or menthol, which the user breaths in as they inhale; these chemicals interact with the nose's nerves and create a sense of temperature. We take inspiration in this approach but expand it in two key aspects: (1) we explore chemical haptics in the skin rather than inside the nose; and (2) we propose achieving a range of sensations beyond just hot/cold. Moreover, while some of these other devices realize temperature by moving liquids in tubes *over* the skin, these liquids are *not in contact* with the skin. Instead, we

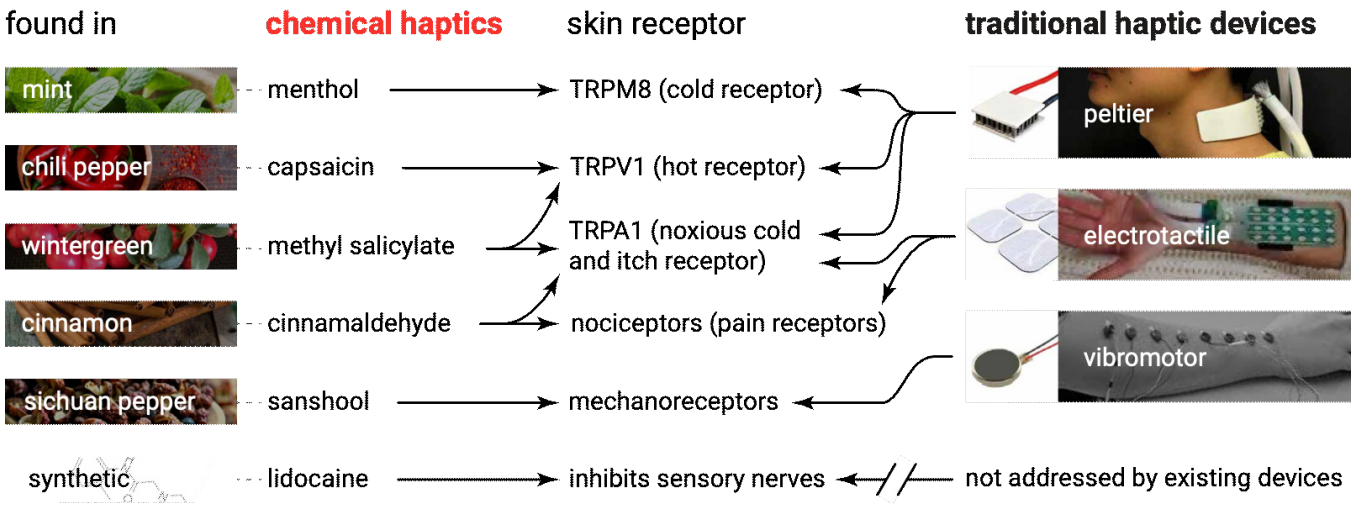

Figure 6: An overview of the six chemicals we explored in chemical haptics and the touch receptors they interact with. Also, a non-exhaustive depiction of some traditional haptics approaches for actuating these receptors.

implemented open channels to enable skin absorption and tap into chemically induced sensations.

4.5 Chemical interactions with skin neurons

While, to the best of our knowledge, our work is the first to articulate how to leverage chemical stimulation of the user's skin to achieve a range of interactive haptic sensations, the idea that chemical pathways interact with tactile innervated neurons is an active area of neuroscience research. Much research has been dedicated to mapping out the role of each tactile receptor, including those responsible for temperature changes (so called thermo-TRPs [5, 50]) and the receptors responsible for pain (so called nociceptors [13]). In the next section, we will discuss our approach of using chemicals for haptics and explain the biological mechanisms that each chemical interacts with. Moreover, in the next section, we will also complement our chosen chemicals with the neuroscientific evidence for their skin interactions.

5 OUR APPROACH: CHEMICALLY-INDUCED HAPTIC SENSATIONS

We propose to interactively deliver topical stimulants to the user's skin to induce haptic sensations. The first key challenge in our approach is to expand the palette of sensations that our devices can generate. To tackle this, we surveyed the literature of neurophysiology, cosmetics, and haptics to find candidate key ingredients to create haptic sensations. While there are several chemicals that trigger reactions on the human skin, there are also a few unsafe chemicals. As such, our literature analysis was filtered by skin-safety. In the end, we selected six topical stimulants at a skin-safe dosage, which we depict in Figure 6; these key active ingredients are commonly found across topical health products, skin cosmetics, and food products.

Many of these ingredients are used for the purpose of alleviating pain by producing counterirritation that distracts from pain (e.g., cooling gels with menthol), stimulating the release of a neurotransmitter making nerve fibers transmit less pain signals (e.g., theorized mechanism of pain relief from hot patches with capsaicin), or numbing to reduce sensation (e.g., lidocaine patches), while others are common in gastronomy (e.g., Sichuan peppercorns, spices, and mint in drinks or food). While these have everyday uses (medical or food), they are not seen as chemicals that trigger *interactive haptic sensations*—this is our focus. To help the readers understand the choice of topical stimulants and the biological mechanisms that each of these key ingredients triggers upon absorption by the skin, we provide an overview of our chosen topical stimulants.

5.1 Chemical Haptics Ingredient #1: *sanshool* creates a tingling sensation

Key active ingredient: Hydroxy-alpha sanshool is an organic molecule found in Sichuan peppercorns or uziza dried fruits; its chemical composition is $C_{16}H_{25}NO_2$. Sanshool is commonly associated with the tingling feeling Sichuan peppercorns leave in one's mouth and lips. **Biological skin mechanism:** Upon absorption by the lip skin, it reacts with sensory neurons, in particular with nociceptors and light-touch receptors [25]. Moreover, it reacts with mechanoreceptors in the lips, specifically, the tactile rapidly adapting channels that detect vibrations, which is why it feels as a tingling sensation similar to a mechanical 50Hz stimulus from a vibration motor [25, 42]. Others studies also attribute the tingling to activation of both TRPV1 and TRPA1 simultaneously [41, 43], which is why there is also a slight warming sensation. Unlike these previous psychophysics studies, we use sanshool not on the lips but on other skin areas, aiming to create tingling sensations beyond just intra-oral tingling. **How we obtained it:** We source this ingredient by soaking store-bought Sichuan peppercorns in Everclear (a grain-based alcohol). This method does not guarantee a

precise percentage of the sanshool, but it is easily reproducible without chemical lab equipment; alternative routes to acquire precise quantities are also available from chemical suppliers [30].

5.2 Chemical Haptics Ingredient #2: *lidocaine* creates a numbing sensation

Key active ingredient: Lidocaine is an engineered ingredient, which is commonly used as a local anesthetic and often found in the form of an off-the-shelf cream in drug stores; its chemical composition is $C_{14}H_{22}N_2O$. Due to its useful numbing effect it is considered one of the essential medicines by the WHO [49]. As with any ingredient of this nature, Lidocaine exhibits side-effects especially when applied intravenously, however, it rarely displays side-effects when topically applied under safe dosage [22]. **Biological skin mechanism:** Upon absorption by the skin, Lidocaine reduces tactile sensations by chemically binding to neuronal cell's channels and preventing these neuronal cells from firing to the central nervous system [3, 28]**. How we obtained it:** We source this ingredient from an off-the-shelf Ebanel spray, which contains a 5% lidocaine solution as its key active ingredient.

5.3 Chemical Haptics Ingredient #3: cinnamaldehyde creates an itching sensation

Key active ingredient: Cinnamaldehyde is an organic compound, which occurs naturally in the bark of trees that produce cinnamon and is what gives cinnamon its flavor and odor; its chemical composition is C_9H_8O. **Biological skin mechanism:** Upon absorption by the skin, it reacts with the sensory nerve's TRPA1 and induces an itching sensation [29]. It has also been showed to promote faster healing of infected skin wounds when applied as a topical medicine [15]. **How we obtained it:** We source this ingredient from the chemical manufacturer HiMedia (product GRM3277); this is then mixed at 5% with Everclear to ensure a skin-safe dosage.

5.4 Chemical Haptics Ingredient #4: capsaicin creates a warming sensation

Key active ingredient: Capsaicin is a colorless organic ingredient produced in chili peppers (or plants from the genus Capsicum), which is also the key ingredient of many off-the-shelf medicinal products (e.g., hot patches) as well as in food (hot peppers, paprika, etc.); its chemical composition is $C_{18}H_{27}NO_3$. Capsaicin is the ingredient that causes all these products and foods, such as chili peppers, to *feel* hot. **Biological skin mechanism:** Upon absorption by the skin, capsaicin reacts with sensory nerve's TRPV1, this temperature channel *also* reacts to hot temperatures above 42°C at the epidermal layer [50, 65]. **How we obtained it:** We source this ingredient from the off-the-shelf PainBloc24 topical roll-on product, which contains a 0.25% solution of capsaicin as its key active ingredient.

5.5 Chemical Haptics Ingredient #5: menthol creates a cooling sensation

Key active ingredient: Menthol is a mostly colorless organic compound made synthetically or obtained from the oils of mint-plants; its chemical composition is typically $C_{10}H_{20}O$. It is common in food/health products, where it is used as a tea or in off-the-shelf products (e.g., toothpastes or cold patches). **Biological skin mechanism:** Upon absorption by the skin, it interacts with the cold-sensitive TRPM8 receptor, which reacts to both chemical stimulations from compounds like menthol *and* to cold temperatures below 25°C at the epidermal layer [50]. This ability to chemically trigger the TRPM8 in the skin explains the well-known cooling sensation that menthol provides when inhaled or eaten [14]. Finally, while cooling is its main understood function, it also exhibits weak anesthetic properties (e.g., slightly reduces other sensations) and counterirritant qualities (e.g., assists in soothing an itch) [19]. **How we obtained it:** We source this ingredient from the manufacturer Nature's Oil (product: 23-0038-000). Unlike many of our other selected topical stimulants in our list, mint is typically solid at room temperature and requires a solvent to maintain a liquid form without needing to be heated; we mix it with Everclear at 10%.

5.6 Chemical Haptics Ingredient #6: methyl salicylate creates a mixed hot & cold sensation

Key active ingredient: Methyl Salicylate is also commonly found in many topical analgesics and can be found in wintergreen oil. It is a colorless organic compound, produced by many species of plants, particularly wintergreen; its chemical composition is $C_6H_4(OH)(CO_2CH_3)$. It is often added in the production of mint candies (as a flavoring agent) [32] or to fragrances. **Biological skin mechanism:** Upon absorption by the skin, it has been shown to stimulate as well as inhibit the TRPV1 channel (which also reacts to the aforementioned capsaicin) [23, 50] as well as the noxious cold TRPA1 channel [61]. Thus, it has previously been shown to elicit a combination of cool, warm, and burning sensations [23]. As such, we chose it as we were interested in understanding how a potentially mixed receptor stimulation might affect a user's haptic sensations. **How we obtained it:** We source this ingredient from the off-the-shelf product, Zim's MaxHeat (Kobayashi Laboratories, product 54273-001-01), which contains a 20% methyl salicylate as its key active ingredient.

6 HARDWARE IMPLEMENTATION

To help readers replicate our design, we now provide the necessary technical details. Furthermore, to accelerate replication, we provide all the code, chemical formulations, firmware, and schematics of our implementation[1].

The key components of our haptic device are the channels implemented using silicone (this is where chemicals are flowing and where they contact the user's skin), the pumps, and the electronics that regulate the flow. Our wearable device uses its pumps to circulate the chemical stimulants in a closed-loop manner, i.e., pulling them from their reservoirs, to the silicone channels, then to the open section in contact with the user's skin, then back into the closed channels, and, finally, back to their respective reservoirs.

[1] https://lab.plopes.org/#chemical-haptics

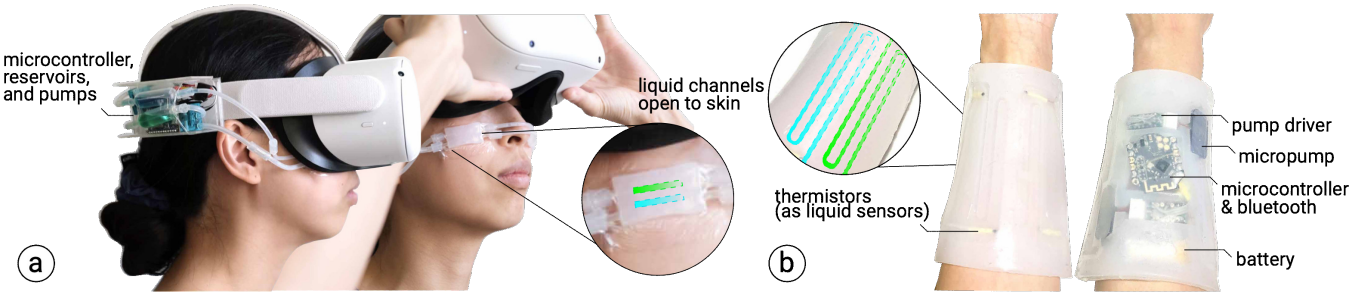

Figure 7: We designed two versions of our device to deliver liquid stimulants to two locations – the cheeks and the arm. These also showcase two engineered solutions for delivering our chemicals to the skin: (a) a central control & pump unit connected to silicone patch via tubing or (b) fully encased and self-contained silicone wearable, including microcontroller, pumps, and battery.

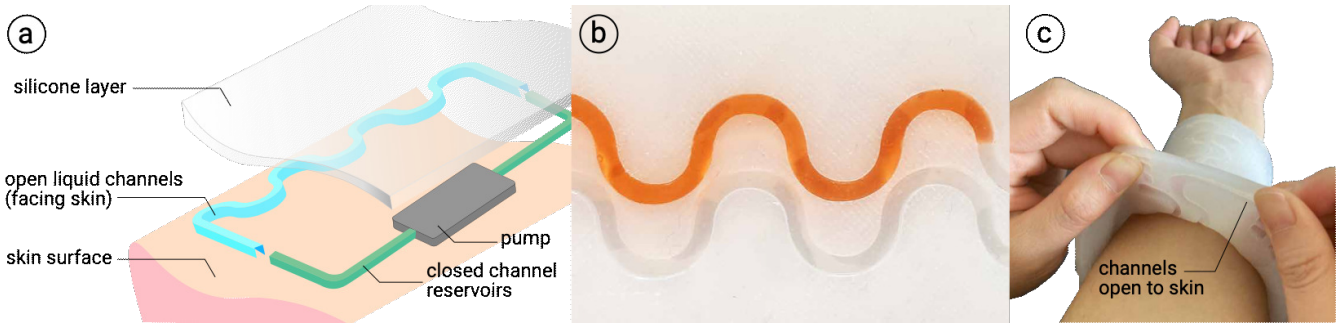

Figure 8: (a) Material stack of our device, (b) close-up of the sleeve's open channels, and (c) close-up of channels touching the skin.

Figure 7 shows two of our devices, one worn on the cheeks as a mask, and one worn on the forearm. The mask device showcases how we created a central control and pump device connected via tubing to silicone patches adhered to the skin, enabling delivery to difficult locations like the cheeks. The sleeve showcases how we created a self-contained device generic enough to be used on different limbs, such as arms or even legs.

6.1 Fluidic channel design

We used Dragon Skin FX-Pro silicone to implement our patches with channels open to the skin as seen in Figure 8. This open area of the channels, which allows any chemical flowing through it to contact directly with the user's skin, measured 8.75 cm^2 in the arm device and 0.96 cm^2 in the cheek device.

The sleeve's reservoirs hold 1.2mL of liquid, enabling approximately 20 minutes of actuation (in our study 2, only 3 minutes was enough for desired effect). While we have measured minimal evaporation within the silicon (<20% in 24h), the silicone is not hermetically sealed, and long-term storing works best in sealed containers (which is what we used for studies).

For sealing the devices to prevent leakage of the chemicals, we adhered the cheek patches using a waterproof skin adhesive tape and rely on the compression of the Oculus headset to form a seal with the user's cheek skin. For our sleeve device, we rely on the tightness achieved from the silicone's compression to ensure a good seal with the skin surface. While this method allows some variability in forearm size, we still recommend measuring forearm size prior to fabricating these patches to ensure a robust fit. We also made a sleeve that closes via Velcro (study 2) allowing one sleeve to be used across participants. With the mp6 pump, we recommend channels no wider than 3mm in width but otherwise can take any form as our pumps can overcome even a 180 degree turn.

As silicone can be cured to take many forms, our device can be molded for many skin regions. In addition, silicone is a breathable material, allowing for some minor airflow to the user's skin [64]. Lastly, in our self-contained arm device, we also added compartments in the silicone for reservoirs, electronics, and battery.

6.2 Electronics and Pumps

At the core of our devices is a ATmega328 microcontroller, which communicates with external applications (such as VR experiences running in an Oculus Quest) via Bluetooth LE (chipset CC2540) and is responsible for the orchestrated control of two micro pumps and four thermistors, which act as liquid sensors.

Pumping and absorption. For each channel, we use a MP6 piezoelectric micropump to push a topical stimulant from its reservoir to the channel. The fluidic circuits are closed, which allows us to recycle the stimulant for a long time. We set the pump to pulse at 10ms intervals establishing a flow rate of 0.07 ml/sec (4 ml/min).

When pumping across a 119 mm^2 of skin for 10 minutes, we measured an average absorption of 0.66mL (capsaicin: 1mL, menthol: 0.8mL, sanshool: 0.6mL, methyl salicylate: 0.8mL, cinnamaldehyde: 0.6 mL, lidocaine: 0.2mL, water: 0.48 mL, everclear: 0.8mL). This is a worst case as some liquid is inevitably lost in ways other than skin absorption (e.g., stays in the channels).

Sensing the liquids. The thermistors are sensitive temperature-based resistors, which makes them useful as liquid sensors. We leverage the fact that a liquid moving by a thermistor (which is in contact with the liquid as it pokes into our channels) will introduce a change in temperature, since the fluids are more thermally conductive than air (present when the channel is empty). We took inspiration from the fact that this approach is used to sense water in large hydraulics systems (e.g., RS offers an industrial liquid sensing system based on this principle [67]). We measure temperature by using one thermistor in a voltage divider and sampling the resulting output voltage with our microcontroller. This enables our device to use one thermistor at the start and end of the channel region that is open to the user's skin to sense if liquid is present. This information is all our device needs for its logic. As such, when the device receives a haptic command, it starts cycling the liquid through the channels. Conversely, when it receives a stop command, it will turn off the pumps as soon as the thermistors indicate no liquid in the open channel region. This enables the chemical to be stored for future use without any contact with the user's skin.

Power consumption. Our complete prototype uses only 0.52W of power at full intensity (two channels). In contrast with other devices such as Peltier elements (commonly used for thermal feedback), which use at least 4-13W per small Peltier [51, 55], our prototype is approximately 10 times more efficient. Moreover, a device that combined Peltier elements, vibro-motors, electrical stimulation, or other haptic actuators to induce feelings of temperature, tingling, itchiness, and numbing as this device delivers would likely be less efficient than our design.

Latency. The end-to-end latency of our device is around 800ms. This latency includes: the Bluetooth latency (~40ms), microcontroller latency (<10ms), and the physical action of the micropump as it pushes a liquid from its reservoir until its first contact with the user's skin on the open region of the channel (~750ms).

6.3 Form-factor trade-offs

While our two wearable devices (one that stimulates the arm and another that stimulates the cheeks) could be integrated as one, we opted for separating these in order to showcase the versatility of each of our two designs, as each form-factor has inherent advantages and limitations. First, the self-contained sleeve unit is highly wearable but harder to adapt for different skin locations as it requires the device to wrap around a limb and relies on the stretchability of the silicone to prevent leaks. Conversely, the centralized unit, which we used to distribute chemicals to patches on the user's cheeks, enables more flexibility since it can deliver chemicals to more challenging locations (as long as a patch can be adhered to this location). However, this centralized approach is less wearable as it relies on distributing the chemicals via tubes from the central pump to the peripheral patches—these tubing connections will limit freedom of body movement.

Moreover, the choice of skin locations was also a factor in our designs. We chose the cheeks because: (1) they are a strong candidate for ambient sensations that are often associated with the face (e.g., warming/cooling of the face), and (2) they illustrate the ability of our system to enable haptics in hard-to-reach areas. Meanwhile, the forearm was chosen because (1) they depict an ideal candidate for sensations related to arm UIs (which are popular in VR [4, 66]), and (2) our sleeve design can be adapted also to other body areas (e.g., legs, neck, and so forth).

7 USER STUDY 1: REVEALING THE HAPTIC SENSATIONS INDUCED BY TOPICAL STIMULANTS (IN ISOLATION)

In our first study, we explored how the chemicals induced sensations on the skin in isolation, aiming to gain a deeper understanding of how chemical haptics can be utilized.

To assess this, we employed the *Temporal-Check-All-That-Apply* design (TCATA [10]), which is often used to test sensory experiences where the effect of a product is tested over time, e.g., for how a taste of a new ingredient develops over the first minutes of eating [2] or how a texture of a liquid develops after the first sip [10, 37].

In this study, participants' goal was to verbalize which sensations they felt as the topical stimulant contacted their skin. Participants were able to choose from a list of pre-existing descriptors. The TCATA study design is extremely powerful because not only does it capture which sensations participants feel but also how these sensations develop over time (i.e., when they start feeling each sensation, when they stop feeling it, etc.).

Our hypothesis was that each chemical would exhibit distinct sensations. Furthermore, to ensure that these haptic sensations are due to interactions with the chemicals, we introduced a baseline topical stimulant (water) for comparison. Moreover, we did not reveal any ingredient labels or names to participants during the trials (i.e., blind trials, participant had no knowledge of the stimulant used in each trial). Our study was approved by our Institutional Review Board (IRB20-0290).

7.1 Stimulants

We selected seven topical stimulants: **capsaicin**, **methyl salicylate**, **menthol**, **lidocaine**, **sanshool**, and **cinnamaldehyde**; and, lastly, **water** as a baseline. To ensure safety, the key ingredients were sourced from: three topical products obtained as off-the-shelf (Zim's Max Heat, PainBloc24, Ebanel Numbing Spray); one product marked as safe for food consumption (Szechuan peppercorns soaked in Everclear); and two liquid stimulants at concentrations deemed safe in previous studies (Cinnamaldehyde at 5%, Menthol at 10%) [29, 60]. Additionally, due to safety concerns regarding COVID-19, all studies were conducted remotely over video-conferencing with experimental devices and (unlabeled) stimulants mailed directly to our participants.

7.2 Apparatus

Participants were given: a manual version of our device and pipettes pre-filled with stimulants for each study round (with anonymized labels, such as "A", "B" rather than "capsaicin", "menthol") as seen

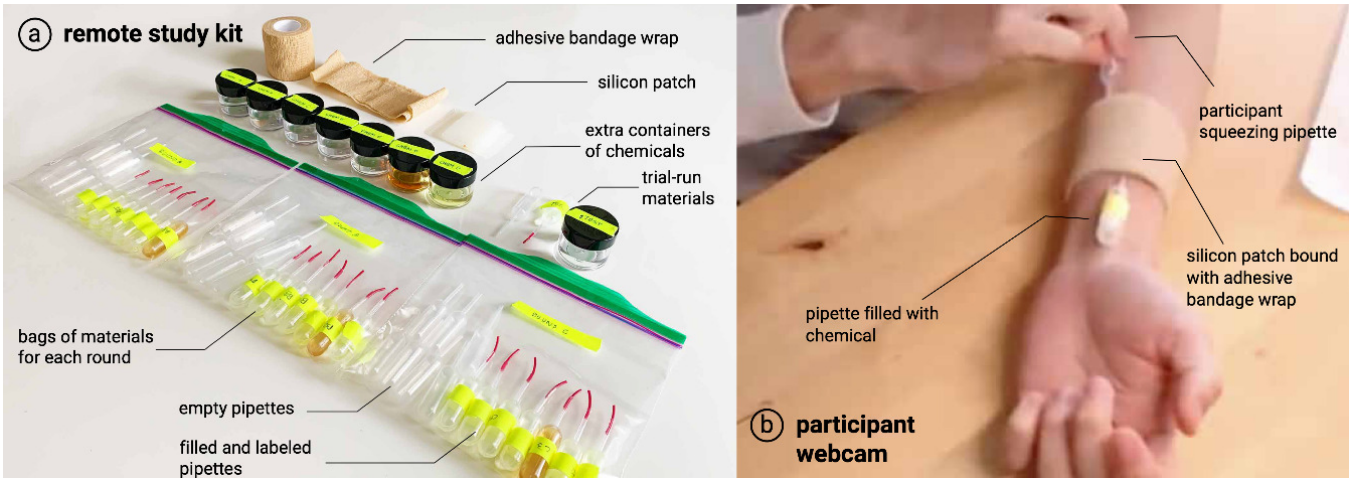

Figure 9: (a) Overview of the materials included in one study kit that was mailed to a participant (b) Participant in study over Zoom.

in Figure 9. The manual version of our device, which participants wore throughout all trials on their non-dominant forearm, was designed to be as similar as possible to our sleeve device, except that it uses a manual method of actuation (i.e., participants squeezing the pipettes) rather than relying on pumps, to prevent any technical setup (pumps, Bluetooth, battery replacement) from interfering with the study outcomes, which were focused on the elicited sensations and not on the hardware.

To facilitate data collection according to the *Temporal-Check-All-That-Apply* (TCATA) design, we implemented a web-interface that allowed participants to indicate when they started/stopped feeling a particular sensation. Moreover, it is worth noting that TCATA allows a participant to indicate that they feel a particular sensation, but not label its associated intensity [10]. Moreover, for speeding up replication of our work we provide our TCATA web interface as open-source[1]. This interface of our TCATA experimental software was shared with participants over Zoom so that participants could see experimenters check and uncheck sensations as verbally communicated. This interface also provided a visual and audio metronome that served as a cue to remind participants to compress the pipettes, which actuates the liquid back and forth inside the silicone channels (in contact with the participant's skin); but also reminded participants to tap their arm every ten seconds, to assess any numbing/excitation effects.

7.3 Task and Procedure

Total trials. Each participant performed a total of 21 trials: 7 topical stimulants (six chemical haptic stimulants and water as a baseline) x 3 repetitions.

Setup: Prior to each trial, participants were instructed by the experimenter of which pipette to load in the haptic device (all labels were anonymized, i.e., "A" or "B" rather than "capsaicin "or "menthol"). Loading a topical stimulant into the silicone patch was simply done by pushing one pipette, pre-loaded with the stimulant, and an empty pipette into two openings. During the trials, participants squeezed the pipettes in sequential order (i.e., first squeeze the one with the liquid, then the other, repeat), which causes the liquid to move back and forth on top of their skin.

Task. A single trial was comprised of experiencing 10 minutes of stimulation with one topical stimulant; followed by 10 minutes of no-stimulation (without applying any topical stimulant on the skin). During both the stimulation and no-stimulation phases, participants were asked to verbalize when a new sensation arose or vanished. The experimenter checked/unchecked each sensation according to the participant's verbal indications, which generated a timestamp for when the sensation started/ended—this is the key behind the TCATA study design [10]. Furthermore, because we are also investigating numbing sensations, we asked participants to also tap their non-dominant arm every five seconds, and after each tap, verbalize if they feel any change (either suppression or excitation) in tactile perception. At the end of the trial, they chose which sensation they felt as the most dominant.

Haptic descriptors: We used nine haptic descriptors inspired by [1, 16, 21, 23, 29, 43]. Descriptors included *burning, painful, tingling, warm, stinging, itching, pressure, cool*, and nothing (by not choosing any). Furthermore, we added *numbness* as well as *increased* and *decreased sensation* to encode for tactile sensitivity to touches.

Procedure. We randomized the order of the trials. Participants were never aware of which topical was being applied. Once a trial was done, participants were required to wait at least 30 minutes before starting another trial.

Participants. Seven participants (four self-identifying as female, three as male, 26.29 ± 5.77 years old) were recruited from our city (including outside our research institution) and received a 50 USD compensation. No participant reported any known allergies to our chosen ingredients.

7.4 Results

We collected data from 147 trials (7 topical stimulants x 3 repetitions x 7 participants), where each trial's data provides us with: the dominant sensation (chosen by the participant at the end of each trial) and start/end timings for each sensation over time (derived from

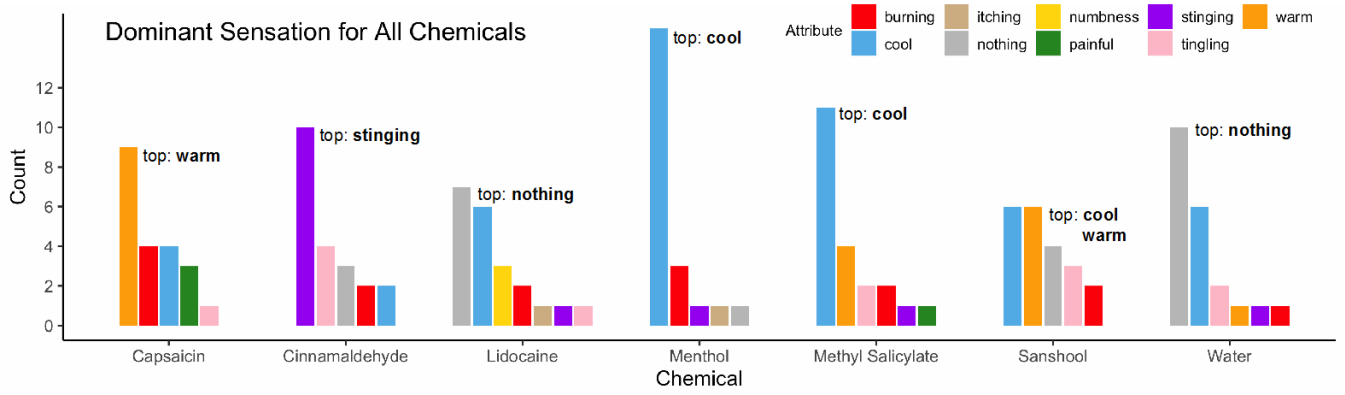

Figure 10: Dominant sensations chosen by participants, as felt after 10 minutes of experiencing a topical stimulant on skin and 10 minutes without it. Note that there was no additional stimulus, e.g., no VR, interactive applications, etc.

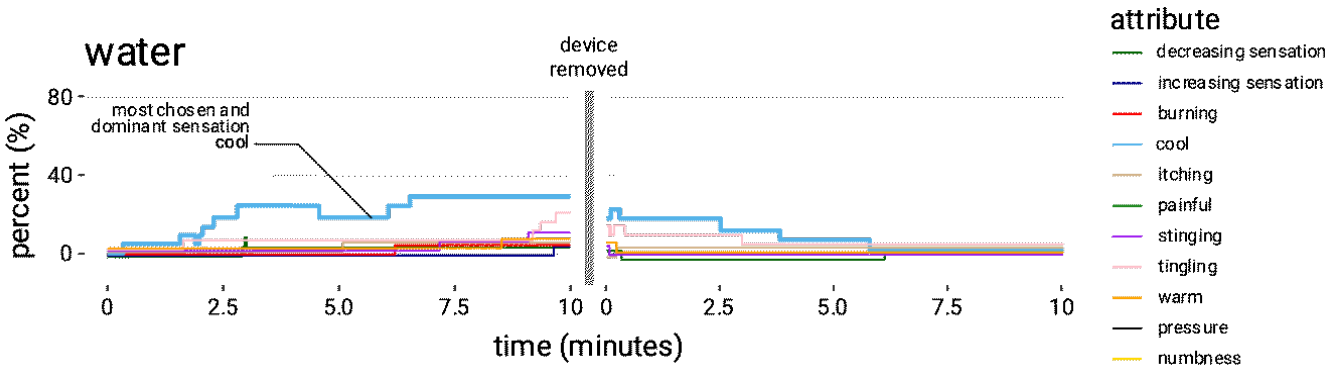

Figure 11: For water, the most felt sensation were "cool", but rarely felt.

the TCATA design). To facilitate replication and future research, we provide all our data in [1].

Dominant sensation. Figure 10 depicts the most dominant sensations chosen by participants after each trial.

All stimulants, except water (baseline) and lidocaine, elicited a clear haptic sensation. Capsaicin was felt as predominantly warm (and, secondly, also burning); cinnamaldehyde was felt as predominantly stinging; menthol was felt as predominantly cool; methyl salicylate was felt as predominantly cool; and sanshool was felt as predominantly cool or warm. However, as we will see in our temporal analysis, these dominant sensations forced a participant to *collapse a rich 20 minutes of varying sensations down to one descriptor*; thus, it does not capture: (1) which sensation arose first, (2) how sensations develop over time; and (3) how sensations fade in the absence of the stimulus. Moreover, as participants did not know the stimulant, the cold sensation of the liquid reaching one's skin at first, always leaves a tactile impression, which led many to choosing "cool" as a descriptor. But, as revealed in our temporal analysis and comments, chemicals deemed as cool actually felt more diverse and unique than cool. To showcase this, we plotted how much a sensation was experienced over time (in %), which was calculated by the number of times a sensation was reported divided by total trials with each chemical.

Water (baseline). In Figure 11, we start our analysis of the temporal profiles with the baseline to demonstrate how its sensations were "bland" compared to all other stimulants. P1's comment illustrates what most participants felt with water: "I can feel the liquid moving but don't feel (. . .) anything, it is probably warmed up to my body heat".

Menthol. In Figure 12, we depict the temporal profile of menthol. To give the reader a sense of how varied and rich haptic sensations with chemicals can be, contrast menthol's temporal profile to water's (baseline) profile. For menthol, the sensations felt most often were "cool" and, secondly, "tingling". Notably, "cool" was felt almost throughout the entire time. We also observed that cool sensations arise much quicker than any other sensation, sometimes within mere 10s of the application. Moreover, cool tens to fall over a longer period of several minutes but decreases rapidly when not applied. Participants comments clearly echoed these sensations, such as "this is really blasting cold, wow" (P7) or "This is a lot more intense (. . .) immediately feel cool" (P6). This suggests that **menthol is a strong chemical haptics candidate for cool sensations.**

Capsaicin. In Figure 13, we depict the temporal profile of capsaicin. the primarily sensations felt were "warm"; closely followed also by "burning" (which is also a "heat"-related descriptor), "stinging", and "tingling". These sensations developed most linearly with

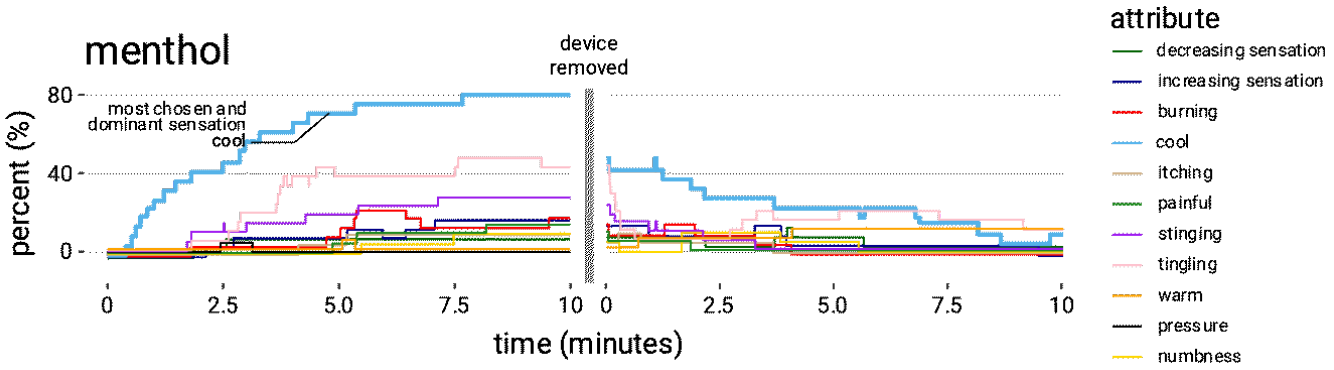

Figure 12: For menthol most felt sensations were "cool" and "tingling".

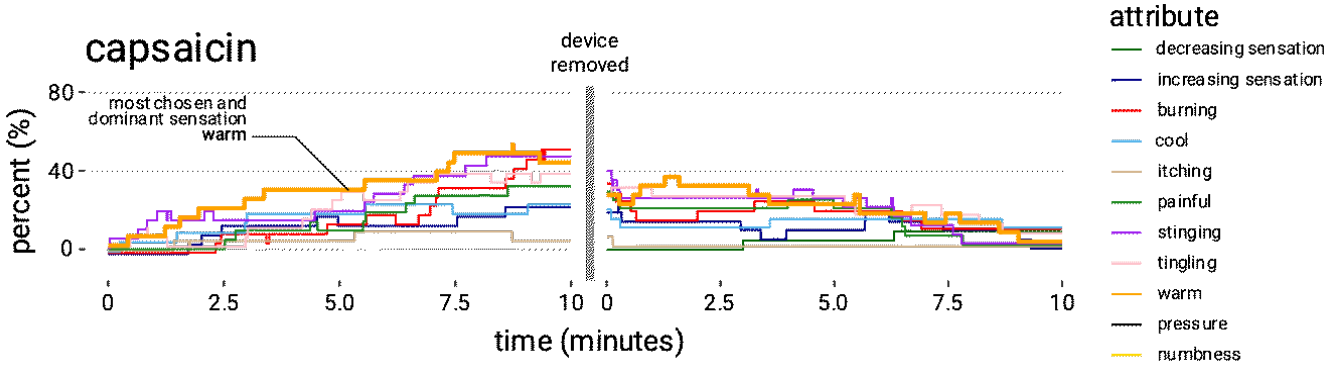

Figure 13: For capsaicin most felt sensations were "warm" and "burning".

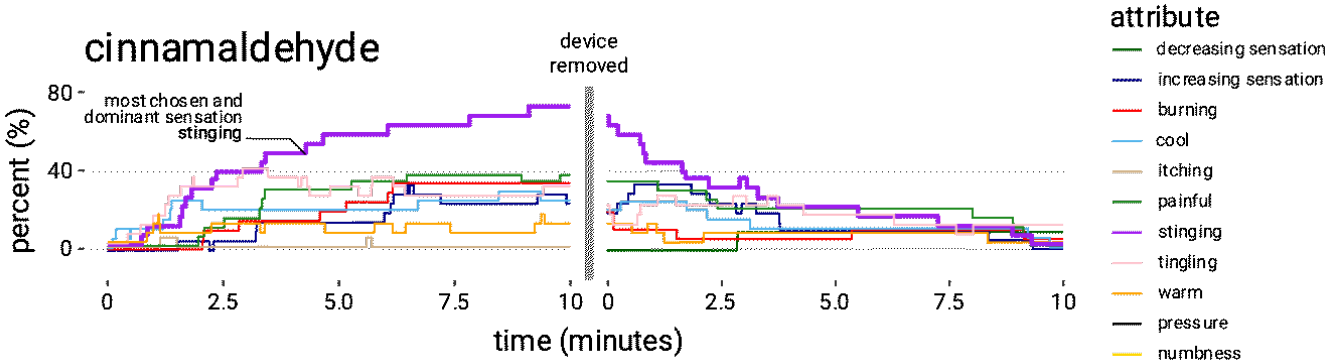

Figure 14: For cinnamaldehyde most felt sensations were "stinging" and "painful."

time and also reversed when the stimulus was removed. These observations, alongside the most dominant sensation being chose as "warm" point to capsaicin's ability to target the hot temperature receptors. Moreover, participants' comments echoed this, for example, "This one is super strong and long lasting. I'll check burning because it is much more intense than warm now" (P3) or "with device, it's burning, when it was off it's warm" (P1). This suggests that **capsaicin is a promising chemical haptic candidate for warm sensations.**

Cinnamaldehyde. In Figure 14, we depict the temporal profile of cinnamaldehyde. The sensations felt most often were "stinging", and secondly "painful" or "tingling". Notably, "stinging" was felt more often than any other sensation during stimulus, by all participants. Participants comments capture the clarity of this sensation "oh this is stinging" (P1) or "this one is really intense. It feels like I have a wound or something on my skin" (P2). This suggests that **cinnamaldehyde is a strong chemical haptics candidate for stinging sensations.**

Methyl Salicylate. In Figure 15, we depict the temporal profile of methyl salicylate. The sensation felt most often was "cool", but "warm", and "tingling" were close seconds, as they were felt during the application period in almost equal amounts to cool by the end of

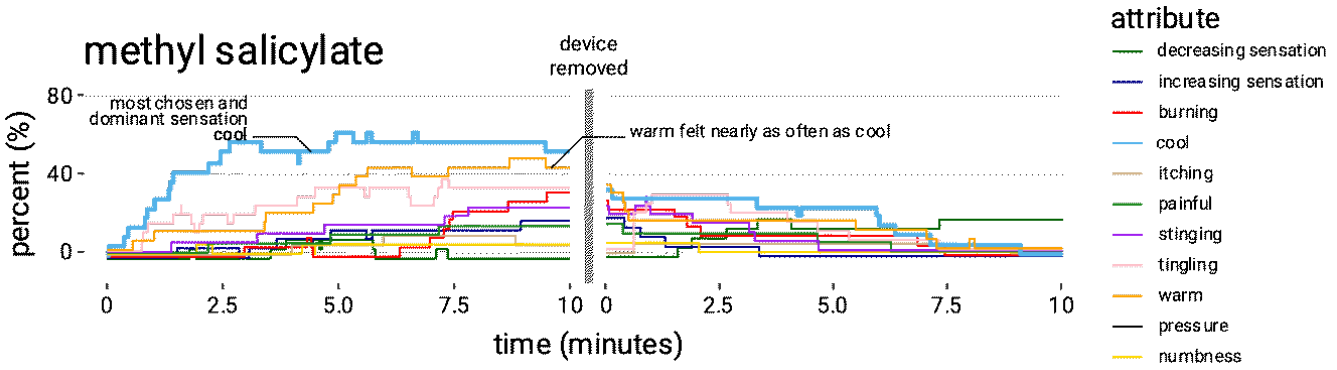

Figure 15: For methyl salicylate most felt sensations were "cool", "warm", "tingling".

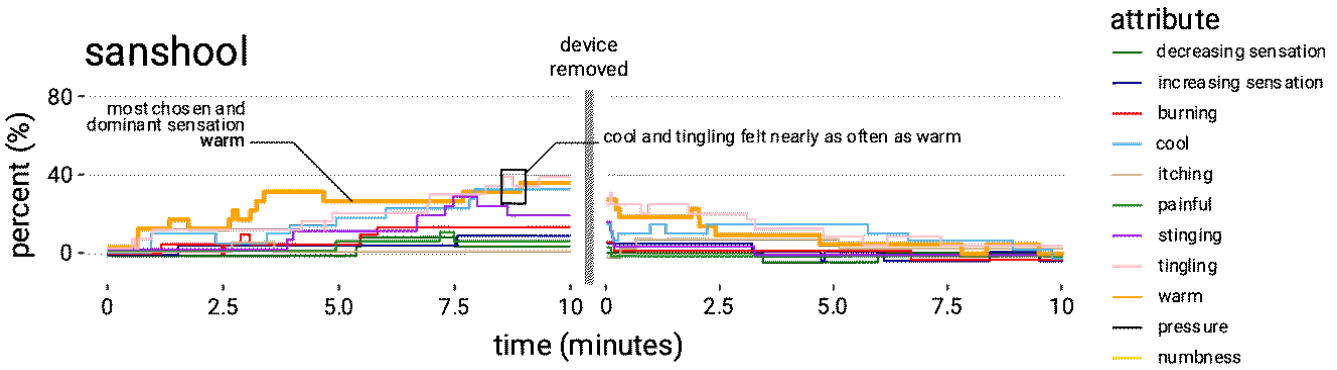

Figure 16: For sanshool most felt sensations were "warm", "tingling", and "cool".

trials. A reminder that we chose this chemical precisely since neuroscience work had demonstrated its ambiguous actuating of both the "hot and cold" receptors. Participants comments revealed this ambiguity, such as "it was cool, so that dominated (. . .) the initial intensity. But I felt the warm lasted longer, so that [is stronger] time wise" (P7) or "this is icy hot, I feel like it's cool then warm" (P3). This suggests that **methyl salicylate is not a straightforward candidate for chemical haptics, due to its ambiguous sensations**.

Sanshool. In Figure 16, we depict the temporal profile of sanshool. The sensations felt most often were "warm","tingling", and "cool". Notably, "warm" was felt almost throughout the entire time participants felt sensation and "tingling" showed up consistently when the stimulant was removed. After removal of the stimulus, participants felt increasing levels of "tingling", possibly in contrast to when it was applied. While it was chosen as cold or warm at the end of the trial by many participants it was also often chosen as "tingling" during the time of the application. Moreover, participants' comments mentioned tingling more than warmth, for instance, "This one is super light, but I think I feel a slight tingle" (P2) or "This is both warm and tingling, but I think tingling is slightly stronger" (P3). **This suggests that sanshool is a potential chemical haptic candidate for tingling or warm sensations** (in our Study 2, we showed that visuals from VR can resolve this to "tingle").

Lidocaine. In Figure 17, we depict the temporal profile of lidocaine. The sensations felt most often were "cool", "tingling", and "decreasing sensation", which suggested some numbing was taking place. In fact, the recorded sensations were more varied than water, suggesting that participants perceived richer sensations than in the baseline. Participants comments suggested they felt numbing, such as "my skin feels like rubber" (P6), "I don't feel much, just a numbing, (. . .) hard to say [as in to put it in words]" (P7) or "I'm feeling less touch, [. . .] yes, yeah, I feel numb" (P7, another repetition). Yet, most participants were not able to relate a *decrease* in sensation to a numbing sensation. The challenge is that this sensation is not often occurring in everyday life, only occasionally when we receive analgesics. This result suggests that **lidocaine is a potential chemical haptic candidate for numbing sensations** but might require additional cues to inform participants of the sensation, because a diminished sensation is hard to "feel".

7.5 Discussion & narrowing the set of final chemical ingredients

This first study confirmed that our chemical stimulants display haptic sensations upon skin absorption. The strongest candidates were menthol (cool), capsaicin (warm) and cinnamaldehyde (stinging). These were so remarkably strong in their haptic sensations that they were felt in this distinct way by most participants even without any other stimulus (e.g., no visuals). Secondly, while more ambiguous, sanshool (tingling) and lidocaine (numbing) were promising in participants' comments, which often indicated that these worked

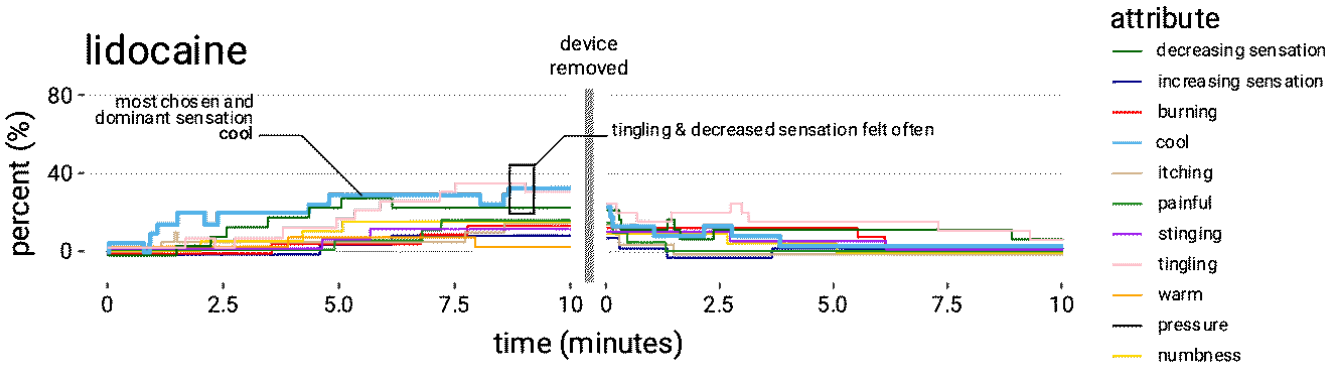

Figure 17: For lidocaine most felt sensations were "cool", "tingling", and "decreasing sensation".

as well. We decided to explore if the additional of visuals (from VR) would assist participants in clarifying the sensations induced by these chemicals—this comprises our set of five chemicals we use in the rest of the paper.

8 DEMONSTRATING FIVE CHEMICAL HAPTIC SENSATIONS IN VIRTUAL REALITY

Now, equipped with the set of chemical contenders for haptic sensations from our first study we designed five VR experiences, i.e., one VR experience per chemical. We present the design of these VR experiences in detail, while in our second user study, we validate that our chemical haptics adds immersion to each of these VR experiences.

Electrical tingling with sanshool: lighting up the room with tesla coils. The user shoots electrical rays from a "portable tesla coil" on their arm as shown in Figure 18. Using these rays, they light up lamps on the ceiling. When the ray shoots from their arm, they feel as a *tingling* sensation, which our device renders by using sanshool.

Stinging of a wound with cinnamaldehyde: finding the antidote to the poison. A flask of poison falls and drips poison onto the user's arm, depicted in Figure 19 (a). Thus, a wound develops, and our chemical haptics device delivers cinnamaldehyde to the arm. This causes a strong *stinging* sensation. The user tries to find the antidote amidst several flasks. When they finally find the antidote that cures the poison from affecting their arm, our device stops cycling cinnamaldehyde over their skin and the sensation fades away, as the antidote starts working.

Warming the face with capsaicin: exploring the nuclear reactor overheating. In this VR experience users roam around a nuclear reactor core, which is slowly heating due to a malfunction. While the reactor heats up, users see and hear more steam coming out of the core. Additionally, they feel this steam is *hot* as our device passes a solution of 0.025% capsaicin in their cheeks; this scene is directly inspired from our walkthrough (Figure 5).

Cooling the face with menthol: catching snowflakes in winter. In this VR experience, the users find themselves in a cold forest, in the middle of a light snow fall, which is similar to the scene depicted in Figure 3. Users can roam around the forest and collect

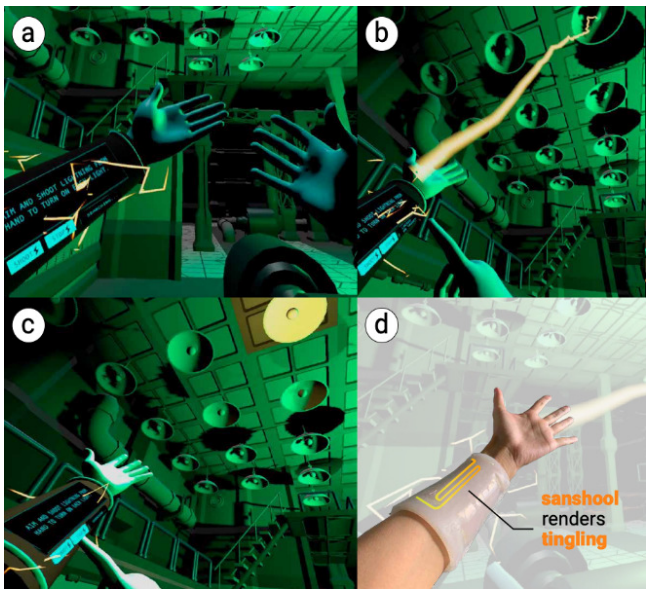

Figure 18: (a, b, c) Users shoot electrical rays from their arm. They use this power to turn on all the lamps in a dark warehouse. (d) The electrical sparks visuals are paired with sanshool stimulating the arm, which renders a tingling sensation.

points by catching falling snowflakes before they reach the ground; however, the longer the user stays out in the cold, the stronger the cold sensation will be, which is delivered by our chemical haptics device by cycling a 10% menthol solution across the user's cheeks.

Numbing tactile sensations with lidocaine: defending from the lasers. In this VR experience, users must defend themselves from incoming lasers from a rotating cannon by setting up force fields around them, which they achieve via buttons on their arm interface. However, when hit by a laser the arm interface starts to visually malfunction and becomes transparent with its buttons disabled, and our chemical haptic device starts cycling lidocaine. This reduces haptic sensations on that arm. Then, the user needs to regenerate a new arm interface but this time on their dominant arm.

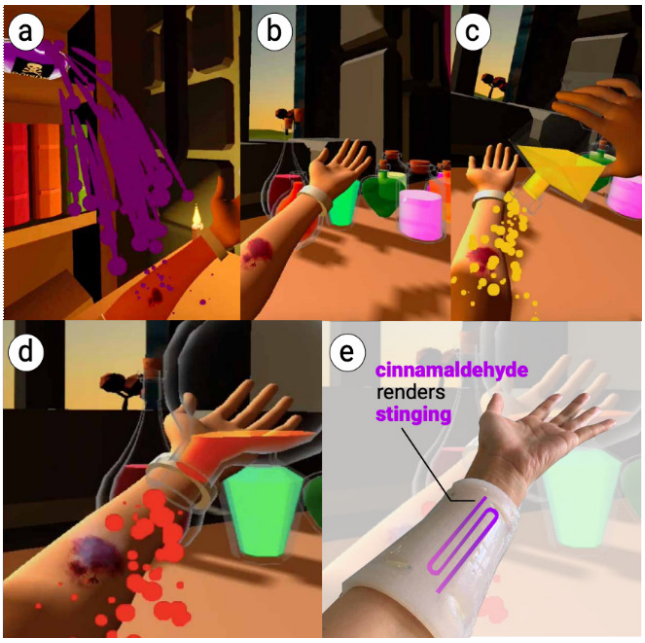

Figure 19: (a) In VR, users find themselves around flasks. A bottle of poison topples and sprays their arm, inducing a wound. (b) The user must find the antidote that will cure the wound. (c, d) However, most potions make the wound worse. (e) The sensation of a stinging wound is rendered via the application of cinnamaldehyde to the arm.

To achieve this, they need to tap several times on their malfunctioning arm interface, which displays a "regenerate on other arm" button. This design allowed us to have users touch both arms, enabling them to feel the difference in tactile sensations. As revealed by our first study, participants found it hard to understand the sensations from lidocaine because they are not arising but decreasing, a rare event in everyday life. As such, we hoped that this interaction design, which offers a stronger visual explanation, might provide lidocaine some opportunities for haptic effects (we validated this in our second study and found that lidocaine did add immersion to this scene).

9 USER STUDY: CHEMICAL HAPTICS IN USE FOR VR

We conducted a user study to verify our hypothesis: our stimulants will enable more immersive experiences in VR. During this study, participants explored five distinct VR scenes with either five different stimulants or no stimulants as a baseline. Out of concern of COVID-19, study participants were mailed a study kit and the study was conducted remotely over Zoom. These stimulants were dispensed using a desktop version of our device, i.e., same silicone channels on the arm and cheeks but the pumps were laying on the participants' desks for simplicity (prevented participants from tinkering with Bluetooth, LiPo batteries and fitting the electronics). The study was approved by our Institutional Review Board (IRB20-0290).

9.1 Procedure

Participants tried all five VR experiences (from previous section, each using one single chemical) with our device and without, in a counterbalanced order. Moreover, since the results of our first study suggested that water did not elicit distinct haptic sensations compared to our set of chemical haptics, we opted to not include water as a baseline in this study; this also allowed us to minimize each participants' study time and the overall complexity of the study setup. The VR scenes were adjusted to ensure that the participants experienced them for a minimum of three minutes, providing a comparable experience across participants. After each trial, we asked participants to assess how immersive the scenes were using a 7-point Likert scale and at the end of all trials we asked them which condition they preferred for each scene.

9.2 Participants

We recruited four participants (two self-identifying as female, two as male, 30.5 ±5.5 years old). All participants had tried VR, but none tried it in conjunction with haptics on skin. No participant reported any allergies or sensitivity to the ingredients in our chemicals. With consent of the participants, we videotaped their VR experience (by remotely controlling their Oculus Quest). Participants were compensated for their time with 50 USD.

9.3 Results

Figure 21 depicts our main findings. We refrain from statistical analysis due to the low sample size, but we are confident these results

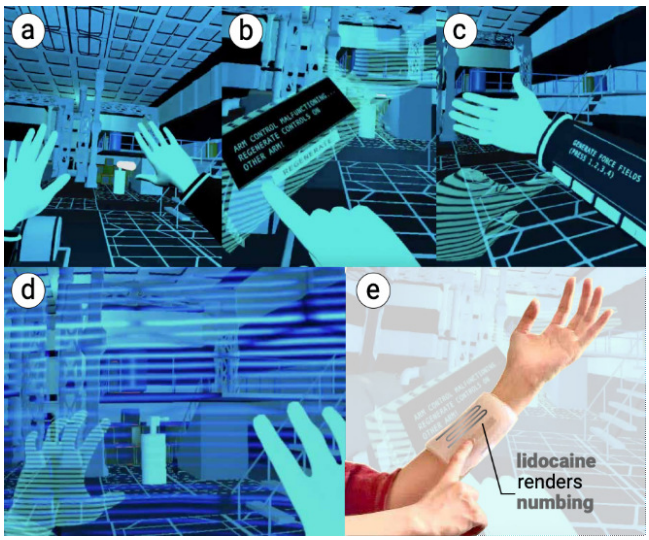

Figure 20: (a) In VR, users find themselves needing to defend themselves against a laser cannon. (b) They try to use their arm interface to generate the force fields, but it malfunctions, rendering their left arm holographic and glitching. (c, d) Instead, users must regenerate the controls to their right arm to create the force fields to protect themselves. (e) Lidocaine stimulating the arm is used to render numbing for the holographic and glitching left arm.

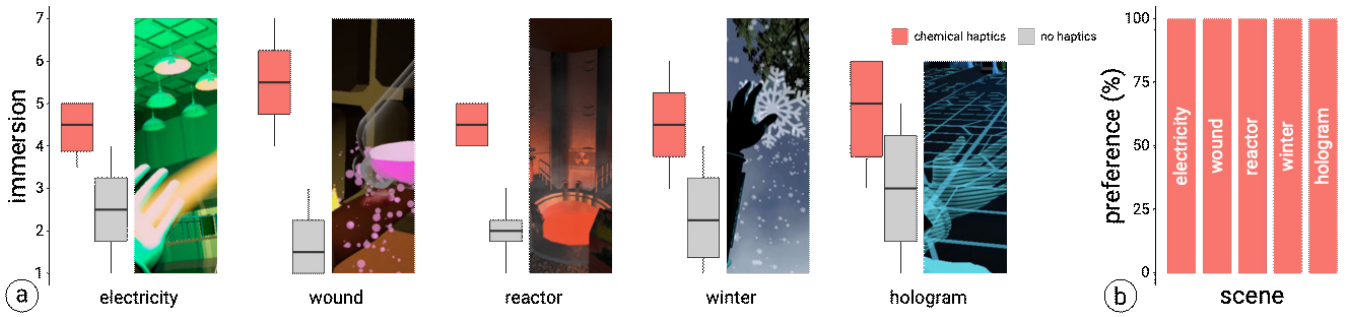

Figure 21: The results from Study 2: (a) immersion (1-7) per each interactive VR experience, and (b) interface preference.

indicate how our device added immersion to these VR experiences. First, we observed an average immersion rating, across all trials (all VR experiences), of M=4.8 (SD=1.094) for chemical haptics, and of M=2.3 (SD=1.238) for the baseline.

Immersion per-chemical. We analyze each VR application independently, which allows us to see how each individual chemical improved immersion when compared to the baseline. First, in the "electrical sparks" VR scene, participants rated their immersion as M=4.4 (SD=0.8) with sanshool, and M=2.5 (SD=1.3) with the baseline; suggesting that it added immersion. Second, in the "wound" VR scene, participants rated their immersion as M=5.5 (SD=1.3) with cinnamaldehyde, and as M=1.8 (SD=1.0) with the baseline; suggesting that it added immersion. Third, in the "reactor" VR scene, participants rated their immersion as M=4.5 (SD=0.6) with capsaicin, and as M= 2.0 (SD=0.8) with the baseline; suggesting that it added immersion. Fourth, in the "winter" VR scene, participants rated their immersion as M=4.5 (SD=1.3) with menthol, and as M= 2.4 (SD=1.4) with the baseline; suggesting that it added immersion. Last, in the "hologram" VR scene, participants rated their immersion as M= 4.8 (SD=1.5) with lidocaine, and as M=3.0 (SD=1.8) with the baseline; suggesting that it added immersion. Again, the immersion of all experiences improved with our device. This last result validated that numbing via chemical haptics adds immersion.

Interface preference. Moreover, Figure 21 (b) depicts participants' preferences of condition. All participants chose chemical haptics for all scenes. While there is certainly a potential confound for a novelty effect, almost all participants did comment on negative aspects of the complexity of setup or setup time but added at the end that "this adds a whole new dimension to it" (P1 and similarly P3).

Comments from participants. Participants comments provide a glimpse of their lived experienced with chemical haptics. In the "wound" VR experience, participants acknowledged stinging, for instance, "slight pain. . . and now it's stinging. It comes in waves" (P1), "the chemical one, [. . .] even though it was painful it was really immersive. It was really cool [not in temperature sense]" (P2), or "literally looked exactly how it felt" (P4) or "oh it stings a bit like the wound, wow... it does feel like a wound" (P3). In the "electrical sparks" VR experience, participants acknowledged some form of tingling, for instance, P2 stated "Felt [...] pulsing kind of like in sync with the light flickering [. . .] and tingling too a little bit" or P3 stated "it pulsates [. . .] that feels like electrical tingle". In the "reactor" VR scene participants acknowledged sensations related to heat, for instance, "warm, stinging, burning. . . It was cooler. . . not in the sense of temperature but because it introduced a sense of urgency to the scene" (P2), "[felt like a] spice burn" (P1) or "the sensations [from chemicals] made me feel more like I was there with the steam" (P4). In the "winter" VR scene, participants reported feeling their arm as cold, for instance, "chilling" (P1) or "I can feel it's cold" (P3). Finally, the "hologram" scene evoked more numbing sensations than our previous study, where lidocaine was applied in isolation from any explanation or visuals. We observed comments such as "oh this is much better [than the baseline, which was the previous trial], the weird [hologram] hand also feels weird, [. . .] it is feeling strange, I can't put a name on it, weird, like the [hologram] hand" (P3), or "I don't feel my arm much" (P4).

10 RECOMMENDATIONS FOR DESIGNING WITH CHEMICAL HAPTICS

We now condense our recommendations, which we gathered from our two user studies as well as our many pilot experiments and design sessions using chemical haptics.

1. When to use chemical haptics: We believe chemical haptics is best suited for slow changing haptic events (e.g., how the sting of a wound evolves over the first few minutes or rising heat) rather than rapidly changing discrete haptic events. While some chemicals are relatively faster than others, e.g., menthol, cinnamaldehyde or capsaicin all act withing the first 30s of application, these are still relatively slow events when considering fast-paced interactive applications. As such, for these types of applications, such as videogames, we recommend using mostly these three sensations, which can be achieved quicker, but still for slowly evolving haptic events (e.g., ambient temperatures, slowly evolving body conditions, such as the wound, tingling, and so forth). Prospective designers can find inspiration in our VR experiences for how to use each of these chemicals even in a game-like fast paced environment. Lastly, for slowly evolving applications (e.g., a guided meditation app that uses chemical haptics to lead users into slowly focusing their awareness on different body parts) our approach is properly paced.

2. Where to use chemical haptics: We recommend that designers, wishing to explore chemical haptics, adjust the

concentrations of their chosen chemicals for the body location. This is important because epidermal thickness varies across different parts of our skin, for instance: the thickness of cheek skin is around 38.8 micrometers while forearm is 60.9 micrometers [63]. As such, thin skin regions, such as the cheeks, afford quick absorption, which also provides opportunities for faster effects than that of thicker skin regions, such as the arm or legs.

3. Which chemicals to use: In choosing a set of chemicals for a particular haptic design, we recommend that designers first prioritize chemicals by their dominant sensation, and only subsequently, by their haptic complexity (variety of multiple sensations). The results of our Study 1 can supply guidelines to choosing chemicals based on their dominant sensation. As demonstrated by our Study 2, when chosen by their dominant sensation, cinnamaldehyde (stinging), sanshool (tingling), menthol (cooling) and capsaicin (warming) are clear choices. This study also illustrates one way that lidocaine can be used, but it requires an additional "explanation" to work, as this is not a readily recognizable sensation that occurs often in daily life (we describe how to design for numbing below).

4. How to ensure safety: We recommend that safety precautions should be taken at all times when handling or using these chemicals. At high dosages, some chemicals might cause skin irritation and might exhibit variable effects across individuals [22, 29]. Additionally, epidermal thickness and other skin characteristics can vary across people [20, 57]. We minimized these risks by choosing ingredients from off-the-shelf products (safe at their dosage). In our studies, we also made sure that participants did not have any skin allergies or sensitive skin before using our devices.

5. Haptics are contextual: We recommend that after choosing a set of chemicals, haptic designers revisit this choice based on their actual applications. As demonstrated by the comments we recorded from participants in our Study 2, the visual suggestions provided by the VR experiences collapsed the variability of the chemical sensations that were recorded in isolation (from Study 1). For instance, while sanshool felt warm for some participants when applied in isolation, it was perceived as tingling by the VR participants when visually observing the electrical sparks on their VR arm. This is similar to how if a VR wall displays electrical sparks, even a vibration actuator (which does not stimulate one's skin with electricity) might still feel realistic to many users [46]; in other words, haptics is contextual and chemical haptic designers should take advantage of this to resolve any ambiguities.

6. Designing for reduced haptics (numbing): There is very little literature in HCI that tackles designing for reduced sensations, especially those as strong as the numbing effect our lidocaine can achieve on skin. The key challenge in designing for lidocaine is that this sensation is not often occurring in everyday life, only occasionally when we go to the dentist/doctors and receive analgesics or when our arm "falls asleep" (the latter is slightly different from the feeling of lidocaine as it also tickles). As such, we provide some guidance for prospective designers using lidocaine to achieve the numbing effect. The main insights are three-fold, (1) the situation must involve touching the stimulated area, potentially multiple times as one single event might not resolve the oddness of the sensation; (2) add a simple "explanation" that users can build their mental model on to understand the effect (e.g., in our VR scene the arm interface displayed a "arm malfunctioning" and appeared as transparent, visually suggesting reduced touch); and (3) allow users to compare the intensity of the sensation to a non-stimulated skin area—this allows users to finally understand that the intensity of touches in the two areas are *very* different, thus, allowing them to infer their skin is numb; these three key insights are how we made the lidocaine haptic effect from "nothing" (Study 1 results) to "I don't feel my arm much" (Study 2 results). We recommend prospective designers to also take advantage of these three techniques as well when designing for numbing.

11 CONCLUSIONS

We proposed, explored, and engineered a new class of haptic devices that provide haptic sensations by delivering liquid-stimulants to the user's skin, which we called *chemical haptics*. Our approach leverages the ability of a user's skin to be chemically triggered to render haptic sensations such as tingling, numbing, warming, cooling, and stinging. We identified five promising chemical stimulants for use in our approach and engineered two wearable haptic devices that pump these liquid stimulants through channels open to the skin. Our devices demonstrate that chemical haptics can be achieved through wearable, self-contained devices and stimulate various locations of skin.

In our first user study, we characterized the temporal profiles of sensations elicited by six potential chemicals. Using these insights, we designed five interactive VR experiences utilizing chemical haptics, one for each of our chosen chemical ingredients. Our experiences centered around the haptic sensations of tingling (sanshool), numbing (lidocaine), stinging (cinnamaldehyde), warming (capsaicin), and cooling (menthol). In our second user study, we validated that chemical haptics adds immersion to these five VR experiences. Last, as the first work exploring the use of chemical haptics on the skin, we condense recommendations to designers for how they may employ our approach for their own interactive experiences.

We believe our novel approach is unique to our community in three ways: (1) generally speaking, it pushes the boundaries of haptics by emphasizing the role of sensations beyond just vibration and pressure; (2) it offers a new pathway, via the skin's chemical receptors, for achieving multiple haptic sensations using a single actuator, which would otherwise require combining multiple actuators (e.g., Peltier, vibration motors, electro-tactile stimulation); and, finally, (3) it explores the use of a numbing agent, which was not possible via existing haptic actuators. While our device is the first to deliver a numbing haptic ingredient, the participants' comments in our user studies included a mix of references to actual "numbing" but also other ambiguous descriptions. Ultimately, we believe that more research is still required to improve the quality of numbing sensations; still, we hope this investigation inspires more research into "numbing" haptics.

Finally, we believe our work represents a first step towards empowering a larger set of HCI researchers to explore chemically actuated haptic sensations on the skin. Now that we know that the skin can be interfaced with liquid stimulants to create unique haptic sensations, future research might want to investigate finer details of these haptic sensations: transitions from one sensation to another, new sensations by mixing compounds, direct comparison

of these with other traditional approaches, and of course, using custom-engineered chemicals.

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