

Trigeminal-based Temperature Illusions

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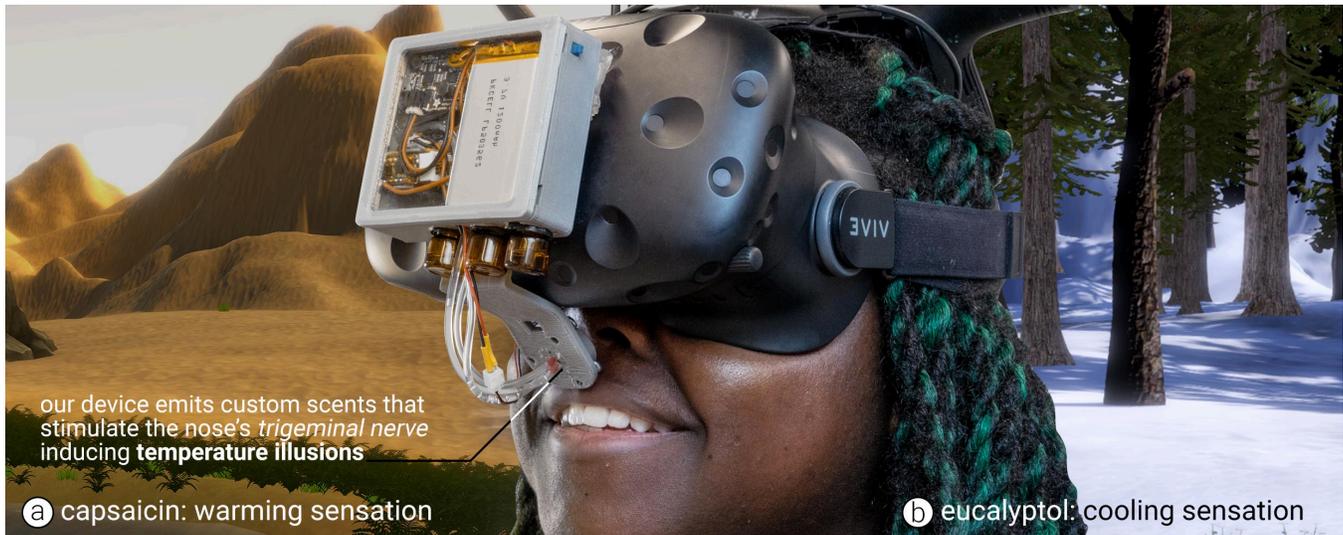


Figure 1: We engineered a thermal display that does not utilize heat or cold but instead creates an illusion of temperature by stimulating the *trigeminal* nerve in the user's nose with different scents. This nerve is responsible for detecting temperature shifts but *also* reacts to chemicals such as menthol or capsaicin, which is why breath mints feel cold and chilis feel hot. Here, how our device renders (a) the warmth of a desert by emitting a capsaicin-based scent and (b) the coolness of an icy mountain by emitting eucalyptol.

ABSTRACT

We explore a temperature illusion that uses low-powered electronics and enables the miniaturization of simple warm and cool sensations. Our illusion relies on the properties of certain scents, such as the coolness of mint or hotness of peppers. These odors trigger not only the olfactory bulb, but also the nose's *trigeminal nerve*, which has receptors that respond to both temperature and chemicals. To exploit this, we engineered a wearable device based on micropumps and an atomizer that emits up to three custom-made “thermal” scents directly to the user's nose. Breathing in these scents causes the user to feel warmer or cooler. We demonstrate how our device renders warmth and cooling sensations in virtual experiences. Participants rated VR experiences with our trigeminal stimulants as significantly warmer or cooler than the baseline conditions. Lastly, we believe this offers an alternative to thermal feedback devices, which unfortunately rely on power-hungry heat-lamps or Peltier-elements.

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CHI 2020, April 25–30, 2020, Honolulu, HI, USA.

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DOI: <https://doi.org/10.1145/3313831.3376806>

Author Keywords

VR; trigeminal; smell; thermal; illusion; haptics.

CSS Concepts

• **Human-centered computing~Human computer interaction (HCI);** *Haptic devices*; Virtual Reality.

INTRODUCTION

Haptic feedback allows virtual reality experiences to match our sensorial expectations beyond just visual realism [4, 64]. Today, researchers focus on engineering wearable devices that deliver realistic haptic sensations, such as touch [4, 7], force feedback [23, 29]. More recently, researchers started also focusing on stimulating new senses, such as olfaction [25, 28, 79] and thermoception—the sense of changes in temperature [52]. The latter has proven extremely hard to miniaturize into wearable devices because, in order to create the sensation of temperature, researchers rely on heat lamps [20] or thermoelectric materials [55] (e.g. Peltiers), which consume substantial power and require large batteries.

In this paper, we explore a temperature illusion that can be achieved with low powered electronics and enables the miniaturization of simple ambient warm or cool sensations. This illusion, depicted in Figure 1, is based on the properties of certain scents, such as mint, which not only stimulate our olfactory bulb (which feels the “smell” of mint) but also stimulates our *trigeminal* nerve-endings in the nasal cavity, which feel the “freshness” of mint. Our approach allows

users to feel ambient temperature changes, much like a Peltier element would achieve. However, unlike the traditional thermoelectric materials that consume a lot of power (e.g., 4-13W per Peltier [54, 58]), our approach uses low-power electronics (only uses 0.25W), and, thus, enables the miniaturization of simple warm or cool sensations.

WALKTHROUGH: A HOT/COLD VR EXPERIENCE

To help readers understand the applicability of our device, we demonstrate its usage in a virtual reality (VR) experience featuring several temperature changes. To explore this temperature illusion, we engineered a stand-alone device, shown in Figure 1, that attaches to the front of the VR headset. Our device delivers the trigeminal stimuli by pushing the scents using micropumps onto a vibrating mesh atomizer, which in turn emits the scents as a fine spray. The scents used in this experience were engineered to minimize their odor recognizability while maximizing their trigeminal “thermal” effect (refer to *Implementation* for details).

In our VR experience, the user finds themselves in a cabin in the woods, during the winter. Figure 2(a) depicts what the user experiences through the headset (1st person). However, for the sake of visual clarity we will depict a 3rd person composited image, shown in Figure 2(b), which allows us to highlight the different temperature effects that our system adds to this VR experience. Furthermore, on the right side of our illustrations we depict an indicator of whether our device renders a scent that induces a warming or cooling sensation.

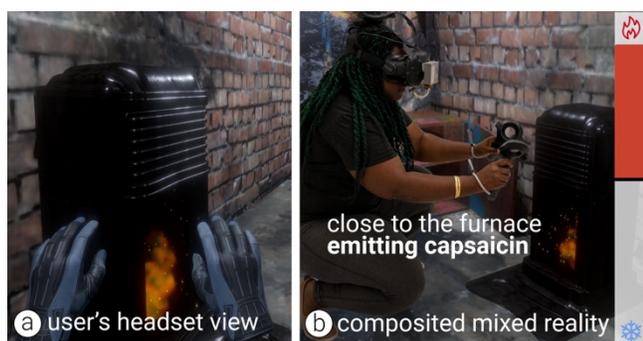


Figure 2: (a) User’s first person view of our “cabin in the woods” scene. (b) Composited mixed reality view, showing the user warmed by a furnace, our device atomizes a cayenne pepper tincture (capsaicin) to create a warming sensation.

As the cabin is ambiently heated by a furnace, our wearable device induces a warm sensation by stimulating the user’s trigeminal nerve via intermittent atomization of a cayenne pepper tincture solution (mostly based on capsaicin), every 6s. As the user is breathing in this trigeminally-rich scent, they feel warm. Suddenly, the winds outside in the mountain range blow the cabin door wide open, as depicted in Figure 3. The strong winds break the power lines outside, cutting off the cabin’s lights, and the wind puts out the furnace’s fire. This brings in an influx of cold from outside. Immediately, our device stops atomizing capsaicin and switches to atomizing eucalyptol intermittently, every 12s. This creates emulates the drop in the cabin’s temperature. To survive this cold, the user must restore electricity and heat to the cabin.



Figure 3: As the user stands at the doorstep of the cabin without heat and electricity, they feel the temperature drop as the mountain cold creeps in; here, our system atomizes eucalyptol, which stimulates the cold receptors of the trigeminal nerve.

As the user walks outside the temperature drops, which is depicted in Figure 4. Our device atomizes eucalyptol at shorter intervals of 6s, increasing the trigeminal stimulation of the cold receptors, which increases the cooling sensation.



Figure 4: As the user walks outside into the cold of the mountain, our device atomizes eucalyptol faster to induce a colder ambient temperature than at the doorstep.

Outside, the user finds out that the powerlines were cut by the storm but, luckily, they find a backup generator, depicted in Figure 5. The user turns the backup generator on by pulling a lever, as depicted in Figure 5(a). When the generator starts, it exudes a little heat and some smoke, depicted in Figure 5(b). As a response, our device atomizes two new scents, in addition to the 6s-interval eucalyptol used the cold ambient temperature: (1) it atomizes short bursts of CPT every 12s, which creates a slight warm sensation that renders heat from the backup generator; and, (2) it also atomizes *8-Mercapto-p-menthan-3-one* (CAS¹ 33281-91-3) for a few seconds as the generator starts up; this gives off a rubbery fuel-like odor. The latter demonstrates that our device can increase the realism of traditional smell displays by adding temperature sensations (e.g., not only it does smells like fuel, but it feels like the fuel is burning).

¹ CAS is a unique identifier of chemical substances; allowing researchers to quickly find these ingredients while replicating our work.

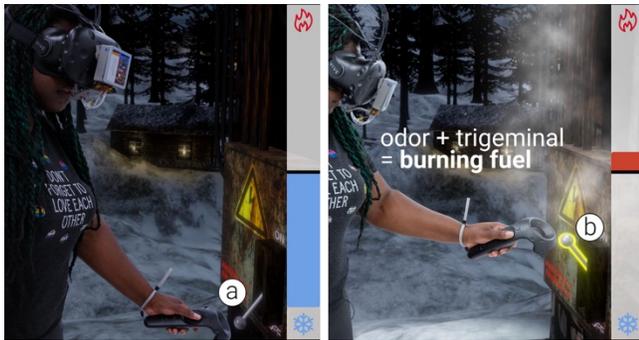


Figure 5: (a) Users turns on the backup generator; (b) The generator starts warming up and burning fuel; our device renders this by simultaneously mixing a fuel odor (olfactory stimulant) with the capsaicin (trigeminal stimulant).

Now the power is restored and the user walks away from the generator, therefore our device ceases to emit capsaicin. As the user re-enters the cabin and finds the furnace back on, our device slowly fades out the interval of eucalyptol and decreases the interval for capsaicin. Finally, creating the sensation of the room heating back up.

BENEFITS, CONTRIBUTION AND LIMITATIONS

Our key contribution is that we propose, explore, and engineer a device to create an illusion of temperature without actually requiring to cool/heat the room or the user.

Our approach has the following four benefits: (1) it is the first interactive device dedicated to the underutilized trigeminal nerve; (2) it provides an alternative hardware means for temperature sensations, which might result in new types of devices in the future (similar to how several technologies emulate touch sensations: vibrotactile, electrotactile, etc.); (3) it requires substantially less power than traditional approaches (such as Peltier modules, air conditioning, or heat lamps), in fact, it requires 20x less power than a TEFC1-03112 Peltier module; lastly, (4) it enables existing olfactory interfaces, such as [33], to easily upgrade to olfactory *and* temperature by simply incorporating the trigeminal stimulants from our paper.

Our approach is limited in that: (1) currently, the range of our illusion are limited, i.e., it can simulate a “warm firepit” but not a “hot coal ember”; (2) like any wearable chemical olfactory display, our device relies on reservoirs that must be refilled, though one reservoir lasts for approximately 2 hours; (3) our trigeminal scent changes act primarily on the trigeminal nerve at the nasal pathway, and therefore are not distributed over the user’s entire skin; and, lastly (4) the temperature sensation is tied to the user’s breathing. Furthermore, as a first work venturing in stimulating the trigeminal nerve, there are still many unexplored avenues. However, we do believe this offers a solid first step in alternative modalities for temperature.

RELATED WORK

The work presented in this paper builds primarily on the field of haptics, in particular on thermal and olfactory displays. Also, to familiarize the reader with the underutilized trigeminal nerve, we present an overview of its mechanisms.

Trigeminal system & nasal pungency

The trigeminal nerve (cranial nerve V) is a somatosensory nerve primarily known for sensing mechanical and thermal stimulation, i.e., it senses changes in pressure, vibration or temperature [44]. Of the receptors of the trigeminal nerve, we focus on the family of transient receptor potential (TRP) ion channels that are activated by specific temperatures (thermoTRP channels). These channels comprise the molecular mechanisms of thermosensitivity [81].

What is striking about these receptors is that they *also* respond to airborne particles [44]. In fact, it is their ability to sense both airborne particles and temperature shifts that explains why scents such as peppermint feel cold [43]. It is not the olfactory quality of peppermint that feels cold, but instead a *trigeminal-effect* of menthol, the principal active ingredient stimulating the TRPM8 receptors—these receptors respond to both temperatures under 25°C and chemical compounds such as menthol [71]. Similarly, chili peppers feel hot when we eat them because their active ingredient, capsaicin, notably activates our TRPV1 receptor [81], which conversely responds to temperatures above 42°C. Our approach hinges precisely on this perceptual duality to simulate temperatures.

While no interactive device has been designed to interface with the trigeminal nerve, its effects are widely studied in psychophysics [8], neuroscience [32] and medicine [46]. Also the effects of the trigeminal nerve is readily recognizable in everyday life, such as in situations involving spicy foods, minty flavors, breathing cold air, and so forth; these effects are all attributed to the trigeminal nerve [1].

Thermal feedback

To maximize VR realism, researchers have been adding more haptic sensations. Recently, attention has been given to rendering a realistic depiction of a virtual environment’s temperature [14, 24, 34, 48, 55, 58]. The earlier forms of thermal feedback in VR were achieved via air conditioning units [78] or heat lamps [14, 30]. Unfortunately, due to their size and power requirements, these cannot be mounted to a moving user, which limits their use in VR/AR.

As a response to this disadvantage, researchers turned to thermoelectric elements, also known as Peltier elements. These devices create a temperature difference across two joined conductors in the presence of an electric current. Peltier elements quickly became the most adopted thermal actuator in VR due to their compact size (e.g., *ThermoVR* uses modules of 4 Peltier elements, each 8mm x 8mm [55]).

There are several examples of thermal stimulation using Peltiers. Vito et al. provide thermal navigation cues on a steering wheel [13]. *ThermalBracelet* [54] attached Peltiers to the user’s wrist to explore eyes-free feedback. *ThermoVR* [55] adds Peltiers to the VR headset, thus providing temperature sensations to the user’s face. *Season Traveler* [59] uses heating elements on the back of the user’s neck, as well as an olfactory display. *Affecting tumbler* [68] is an augmented beverage lid with Peltier elements that affect

the perceived flavor. Lastly, *Thermotaxis* [50] uses Peltier elements on the user's ears to render temperature changes.

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], gel packs [34], or resistive heating [37, 74]. Much like all the remainder, these cannot be easily miniaturized and/or require a lot of power.

Olfactory displays

Since our device utilizes the same hardware backbone as typical olfactory displays, we also review the technologies used to project scents. Typically, olfactory displays are used for the sake of immersion [14, 38, 56, 79] as well as notifications and communication [2, 41, 75, 77]. Olfactory displays deliver odors by: projecting vapors [45, 51, 59, 80]; heating fragrant solids [9, 15, 36]; evaporating a fragrant liquid [12, 39]; or, aerosolizing a fragrant liquid [3, 6, 27, 42, 47, 67]. The resulting gas is most commonly delivered near or in the nostrils, but can also be guided using fans, air vortex [80], bubbles [63], or ultrasound arrays [26].

Unlike previous research focused on scents that stimulate the olfactory bulb (smell), our wearable projects custom scents specifically targeting the *trigeminal* nerve (temperature).

IMPLEMENTATION

To help readers replicate our design, we now provide the necessary technical details. Furthermore, to accelerate replication, we provide all the source code, firmware, and schematics of our implementation².

Hardware Design

Figure 6 shows our device. It measures 24mm x 85mm x 88mm and weighs 119g. At the core of our device is a combination of three piezoelectric diaphragm micropumps and a vibrating mesh atomizer.

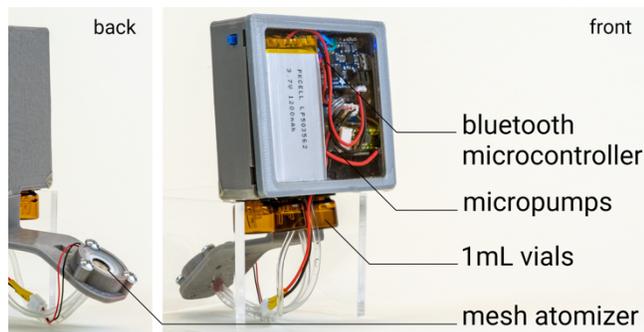


Figure 6: Front and back view of our device and its components.

Controlling atomization

One of the key technical challenges in engineering olfactory displays is achieving a fine control over the atomization.

² <https://lab.plopes.org/projects/trigeminal>

We incorporate a vibrating mesh atomizer, which uses an annular piezo element to vibrate a perforated membrane in resonant bending mode [53, 70]. The mesh itself has conical perforations at the center (aperture), which generates a micro-pumping action pushing the liquid in contact with the underside of the aperture and creating an aerosol.

We designed our device to deliver small drops (of 1 μ L) to the back of the atomizer's aperture, which in turn nebulizes the liquid. To ensure these small drops, we limit the output of the micropump using a capillary tube with an inner diameter of 0.127mm. To push the drops to the atomizer, we activate our micro-pump using small bursts of 70ms.

Reducing cross-contamination, while enabling mixing

To keep device size to a minimum, we designed it around one single transducer because these are large components at 16mm of diameter. Other devices utilize one entire atomizer per channel [60], which results in larger hardware footprints. When using a single atomizer for multiple channels of liquid, it becomes paramount to reduce cross-contamination, i.e., ensure that only the selected channels are atomized. Most devices using a vibrating mesh use a cotton wick to draw the liquid up to the transducer via capillary forces [2, 3]. However, this results in cross-contamination as the wick mixes all liquids. Our tubes extend independently from each pump to the atomizer, and each has its own capillary tube. As such, in our design, mixing of the liquids only occurs at the atomizer level. Additionally, by pumping out very small droplets, we can effectively avoid cross-contamination because these small droplets are quickly atomized and do not linger in the transducer. Furthermore, our capillary tubes are so narrow that the surface tension of the inner liquid will not allow any of the other samples to flow backwards.

Battery life & sample life

Our complete prototype uses only 0.25W of power, which is 20 times less than generating actual temperature changes with typical Peltier elements, as these use at least 5W (e.g., the TEFC1-03112). For direct comparison with prior work, *Ambiotherm* uses two Peltier elements requiring up to 13W, Hutchison et al. use four of the aforementioned TEFC1-03112 [62], and Shoichi et al. use four Peltier elements (KSMH029) each requiring up to 6.8W [49]. Thus, generally speaking, our approach is around 20-52 times more efficient.

However, unlike Peltiers, heat lamps, or air conditioning units, our device has limited operation due to the need for refilling reservoirs. A test revealed that three 1mL vials can induce a sustained temperature change for 5.84 hours. The device itself can run for nearly 18 hours, using a 3.7V, 1200mAh Li-Po battery. To achieve sustained temperature our prototype does not require continuous delivery, as once exposed to a trigeminal scent (e.g., warming), users feel warm for a few seconds (this time depends on scent used, see *Discussion*). We optimized sample life at an inter-stimulus interval of 6 seconds followed by 1 second of atomization.

Operating latency

The total latency of our device is around 200ms, i.e., from a keyboard trigger in the Unity3D to an actual mist starting to

be atomized. This overall latency includes: Unity latency, the Bluetooth channel latency, microcontroller latency, physical action of micropump, liquid flowing to the atomizer.

ENGINEERING OUR TRIGEMINAL STIMULANTS

As this is a first work venturing in stimulating the trigeminal nerve, we detail three methods that we created to prepare trigeminal stimulants. Each of these methods equips future researchers using our device with different approaches depending on their desired goals. In this section, we take as examples the six candidate trigeminal scents (all obtained from safe and off-the-shelf ingredients) that we evaluated in a later study: capsaicin, methyl salicylate, thymol, linalool, eucalyptol and menthol.

1. Odorless trigeminal stimulants

The ideal trigeminal stimulants should be odorless, i.e., they cannot be identified by smell but only by their temperature. While odorless trigeminal stimulants are not abundant in off-the-shelf and safe ingredients, we were able to find one: capsaicin—the active component of hot peppers. Capsaicin is an odorless warming trigeminal stimulant that requires no modifications when used in small doses [65]. Note that hot peppers do have an associated faint smell which is not capsaicin itself but the other spices. Capsaicin can be diluted in odorless vehicles, for example ethanol, dimethyl sulfoxide, or hypotonic saline, or even added to existing fragrances dispensed by olfactory displays.

2. Diluting the stimulus

Most common trigeminal stimulants also stimulate the olfactory bulb when in high concentrations. Though not a perfect solution, one can iteratively adjust the concentration of a trigeminal stimulant to reduce its olfactory stimulation. However, dilution will not preserve trigeminal stimulation while only lowering olfactory stimulation. In fact, olfactory thresholds are much lower than trigeminal thresholds [11]. In all of our trigeminal scents, except capsaicin, we used serial dilution to minimize their odor. This involves a stepwise dilution of a substance in another solution to reduce its concentration in a logarithmic fashion. The main disadvantage of dilutions is that it will soften the trigeminal impact of the scent.

3. Obfuscation via olfactory pink noise

Obfuscation is a last-resort method we offer for the extreme case in which designers might want to maintain maximum trigeminal effect of a scent yet render its odor unidentifiable. To achieve this, designers command our device to emit an “olfactory pink noise” anytime that the trigeminal scent is emitted. The effect is that, much the same way that auditory pink noise prevents hearing other frequencies, olfactory pink noise will obfuscate the smell of the trigeminal scent but will not decrease its trigeminal effect. This olfactory pink is useful, for instance, in obfuscating the strong smell of mint, which we also found to be the most powerful cooling trigeminal scent in our later study. The main disadvantage of obfuscation is also its advantage: it creates an olfactory environment where nothing is identifiable. This is limiting in that it prevents designers from using it in scenarios where olfactory realism is important, such as in some VR scenes.

Engineering an olfactory pink without trigeminal stimulation

When creating our olfactory pink noise, we ensured two key aspects: (1) maximum olfactory intensities in a wide range, with (2) minimum trigeminal effects. The latter was critical because otherwise, the olfactory pink noise would induce trigeminal effects that could confound its purpose. Thus, we selected seven compounds selected from Weiss et al.’s *olfactory whites* [73] that had shown no trigeminal effect in studies with anosmics (individuals with no sense of smell, but intact chemesthesis) [16]. Our olfactory pink is composed of seven ingredients diluted in Everclear: 100% w/v³ vanillin (CAS 121-33-5); 0.1% v/v amyl acetate (CAS 628-63-7); 50% v/v geraniol (CAS 106-24-1); 50% v/v phenyl ethyl alcohol (CAS 60-12-8); 10% w/v coumarin (CAS 91-64-5); 0.5% w/v indole (CAS 120-72-9); and, 5% v/v limonene (CAS 5989-27-5). Lastly, while we empirically verified with olfactory experts that this obfuscation is very powerful (e.g., it renders menthol unidentifiable), it is a last-resort solution we provide for extreme cases and we do not use it in our VR applications for realism’s sake.

USER STUDY 1: THE BEST TRIGEMINAL SCENTS

In our first study, we aimed at identifying the most effective trigeminal stimulants to achieve simple hot and cold sensations. We focused on six off-the-shelf stimulants that can be easily obtained by other researchers to increase the replicability and applicability of our findings.

Our hypothesis was that different trigeminal stimulants would exhibit different levels of cooling and warming sensations, which can be perceived by comparison against each other. Our study was approved by our Institutional Review Board (IRB19- 0907).

Stimulant Preparation

First, we determined concentrations of the stimuli with equal intensity, also known as *isointensity*. We started by utilizing the concentrations for eucalyptol and menthol suggested by [17], and then calibrated the other stimulants to be isointense using the methods detailed in [17, 19].

Stimulants

We used the following stimulants (all solutions used Everclear as a solvent as it is available off-the-shelf and mostly odorless): cayenne pepper tincture (a capsaicin-based solution), methyl salicylate, thymol, eucalyptol, linalool, and peppermint essential oil (a menthol-based solution). Figure 7 depicts each stimulants’ composition, preparation and denotes which trigeminal (TRP) receptors it targets.

For each chosen stimulant, we checked its safety-dosage by comparing to the concentrations used in over-the-counter products on DrugBank [76] as well as reviewing relevant toxicology literature [10, 21, 35]. Our stimulants composition and preparation are depicted in Figure 7.

³ Units % v/v and % w/v are concentration ratios. % v/v is a ratio of two volumes when combining liquids (e.g., 50% v/v eucalyptol in Everclear is 50mL of eucalyptol in every 100mL of solution). % w/v is a weight (g) to volume ratio (ml).

1. Capsaicin-based (cayenne pepper tincture). Triggers the TRPV1 receptor.

Composition: 10% v/v cayenne pepper tincture.

Preparation of tincture: We let 2g of cayenne pepper soak in 30mL of Everclear for 20 min, while on the magnetic stirrer. We let the mixture sediment for 30 mins. Then, we collected the resulting tincture by filtering out any sediment with a fine filter (10 to 15 μ m).

2. Methyl salicylate. Triggers the TRPV1 and TRPA1 receptors.

Composition: 100% v/v methyl salicylate solution (CAS 119-36-8) in Everclear.

3. Thymol. Triggers the TRPV3 and TRPA1.

Composition: 0.05% w/v thymol solution (CAS 89-83-8) in Everclear.

1. Eucalyptol. Triggers the TRPM8 receptor.

Composition: 60% v/v eucalyptol solution (CAS 470-82-6) in Everclear.

2. Linalool. Triggers the TRPM8 and TRPA1.

Composition: 80% v/v linalool solution (CAS 78-70-6) in Everclear.

3. Menthol-based (peppermint essential oil). Triggers the TRPM8 receptor.

Composition: 20.05% v/v peppermint essential oil solution in Everclear. The concentration of the peppermint essential oil was determined to reflect an approximate concentration of 17.85% w/v L-menthol (as in [19]), as L-menthol accounts for approximately 36.0-46.0% of peppermint essential oil's composition according to [69].

Figure 7: Composition and preparation of our stimulants.

Lastly, to understand whether Everclear itself has a strong trigeminal effect that could bias the perception of our six scents, we added three solvents to the study's stimulants: Everclear (75.5% ethanol); dimethyl sulfoxide (DMSO, CAS 67-68-5); and, saline (0.65% v/v sodium chloride).

Task and Procedure

For each trial, participants were presented a random pair of stimuli (warm, cool, or baseline) with a brief pause in between (10s). Stimulants were presented in a randomized in order, but counter balanced for within-trial order across trials (42 trials). After each trial, participants were asked to rate both stimuli on a visual-analog scale with only annotations on the extremes, denoting *cool* and *warm*.

Upon concluding all the trials, participants were then presented two consecutive solvent stimuli (Everclear, DMSO, or saline) in random order, counter-balanced for the within-trial order (six trials). After each trial, participants were again asked to rate both stimuli on the same scale.

Ultimately, participants completed 48 comparison trials each, for a total of 480 trials across all participants.

Apparatus

A simplified version of our wearable device was used. This device utilized allowed participants to press a button to control when to start the atomization. The device was placed on a stand, under participant's nose. Lastly, to ensure that all trials had precisely the same volume, all stimuli were pipetted at a volume of 1 μ L onto the surface of the atomizer. Our experiment was conducted in a ventilated laboratory, with one perforated duct ventilation (500CFM) and two fume hoods. The ambient temperature was kept at 24°C.

Participants

10 participants (3 self-identifying as female, 7 as male) were recruited from our local institution and received a 10 USD compensation. No participant reported any allergies.

Results

Our main finding was the perceived temperature of each of the simulants, depicted in Figure 8. We conducted a one-way within-subjects ANOVA and then used Bonferroni-corrected t-tests.

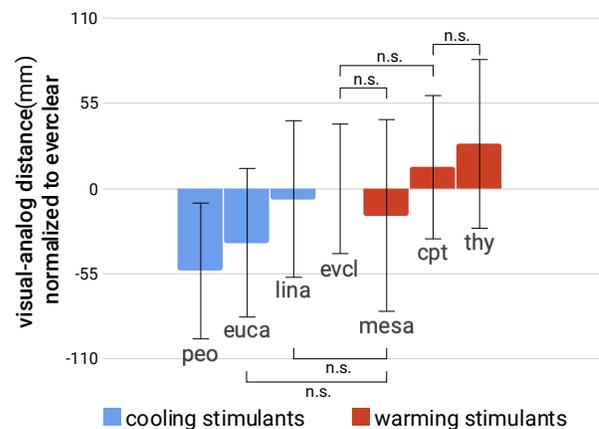


Figure 8: Perceived temperature of our six trigeminal scents (peo stands for peppermint essential oil; euca for eucalyptol; lina for linalool; evcl for Everclear; mesa for methyl salicylate; cpt for cayenne pepper tincture; and thy for thymol). All pairwise comparisons were significant unless indicated.

We found a significant effect of trigeminal stimulants on the reported temperature [$F(2,826)=37.01$, $p<0.001$]. Out of six candidate scents, we found that two stimulants were perceived as warm (thymol and capsaicin), while the remainder four were perceived as cooling; all of these comparisons, except five, were statistically significant ($p<0.05$) using an ANOVA for multiple comparisons.

Firstly, we found that peppermint ($M=-53.01$, $SD=43.86$) and thymol ($M=29.11$, $SD=54.48$) were rated as the most temperature inducing scents. These were followed by eucalyptol ($M=-34.77$, $SD=48.01$) and the capsaicin ($M=13.99$, $SD=46.30$). Lastly, participants rated methyl salicylate ($M=-17.17$, $SD=61.95$) and linalool ($M=-6.49$,

SD =50.61) as weaker cooling stimulants and we did not see a statistical difference between both.

Despite participants rating all solvents around neutral, we found a significant effect of solvents on reported temperature [$F(2,105)=5.65$, $p=0.0046$]. DMSO was perceived towards the warming side ($M=9.75$; $SD=46.77$), hypotonic saline towards the cooling side ($M=-21.16$; $SD=30.56$), and Everclear around neutral ($M=2.00$; $SD=40.55$). No statistical significance was found between DMSO and EVCL. On the other hand, hypotonic saline was statistically significant in its difference with DMSO ($p=0.000$) and Everclear ($p=0.007$).

Discussion

The study confirmed our hypothesis that certain scents induce simple hot/cold sensations; this forms the basis of our temperature illusion. Of all our initial expectations, depicted in Figure 8 via its color coding, only methyl salicylate fell short, as it instead induced cooling sensations for most participants. In fact, linalool and methyl salicylate activate both a warm TRPV receptor and the cold TRPA1 receptors, it is difficult to predict what perceptual properties either have. We would advise against using these for temperature illusions. The unpredictability of this combination was emphasized in comments from participants (P4, P5, P8) who experienced “simultaneously cold and burning” sensations. When compared to cooling scents, warm scents appeared weaker in intensity. This warrants further investigation in engineering stronger warming scents, though it will likely require ingredients that are not store bought.

From participants’ comments, both thymol and peppermint were easily identifiable. In contrast, participants could not identify eucalyptol or capsaicin. When describing qualities of the trigeminal experience, P3 remarked that “cold ones seemed almost to clog [my] nose like cold air; hot ones open [my] nose like hot air”. Similarly, P7 and P3 described the eucalyptol as breathing in “fresh air” and “cold air”.

Regarding our solvent of choice, the perceived temperature of Everclear was around neutral but distinct from hypotonic saline. We still deemed Everclear as our best solvent because most ingredients are not soluble in water or hypotonic saline.

USER STUDY 2: RENDERING VIRTUAL TEMPERATURE

We conducted a second user study in to verify our key idea: our stimulants can induce simple hot/cold sensations in VR. During this study, participants explored two distinct VR scenes while breathing in our trigeminal hot scent, cold scent, or a no-stimulant (baseline). Our study was approved by our Institutional Review Board (IRB19-0281).

Hypotheses

Our main hypothesis was that our trigeminal cold and hot stimulants would be perceived respectively as cooler and warmer than the no-trigeminal condition, in which we atomized Everclear. Because our trigeminal stimulants are diluted in Everclear, any perceived temperature difference between the trigeminal and baseline would be a result of the effect the trigeminal ingredients. Secondly, we hypothesized

that these hot and cold sensations would increase one’s sense of immersion.

Interface conditions

We presented three scents. As the goal of this study is to evaluate immersion, we opted for stimulants that are harder to identify by means of their odor but were still effective in our previous study: (1) **cooling**: our eucalyptol scent, (2) **warming**: our capsaicin scent; and (3) **baseline**: Everclear. The order of conditions was randomized across all subjects.

Apparatus

Participants explored the VR scenes using a Wireless HTC Vive and headphones. Our prototype was attached to the headset. The tracking area was 5 x 5 meters. This study was conducted in the same location as our previous experiment.

Task

For each task, participants were asked to explore a VR scene. Our scenes were either a patch of grass in a **desert** oasis or a flower patch on an **icy mountain**, as depicted in Figure 9. The instructions were to *find a flower of a unique color*.



Figure 9: Study VR scenes: (a) desert and (b) icy mountain.

Our VR scenes were designed to ensure that the participants experienced them for a minimum of two minutes, to have a comparable experience across participants. Thus, the flower only appeared after two minutes. To ensure that the flower did not appear unrealistically in the user’s view, we analyzed the user’s viewport in real-time and displayed the flower in a random location behind the user. No participant reported that the flowers appeared in an unrealistic manner.

After each trial, we asked participants to judge the perceived temperature using the ASHRAE scale [31], which is a bipolar 7-point Likert scale, specifically designed to measure temperature; it ranges from -3 (cool) to 3 (warm).

Participants

We recruited 12 participants (5 self-identifying as female, 7 as male, 25 ± 5 years old). 10 participants had tried VR, but only two tried it in conjunction with smell at art exhibitions. No participant reported any allergies or sensitivity to the ingredients in our trigeminal stimulants. Two trials were repeated due to depleted battery in the VIVE headset.

Participants were given an intake form at the start of the study. Using the 5-point Likert questions from the NOSE questionnaire [66], we confirmed that no participant reported nasal congestions ($M=0.55$, $SD=0.52$), nasal obstructions ($M=0.18$, $SD=0.40$), or difficulty breathing ($M=0$, $SD=0$).

Participants reported low spice sensitivity ($M=1.45$, $SD=0.82$), regular consumption of spicy foods ($M=2.54$, $SD=0.82$), and rare use of products with substances like menthol ($M=0.64$, $SD=1.03$). With consent of the participants, we videotaped their trials. Participants were compensated for their time with 20 USD.

Results

We conducted a one-way within-subjects ANOVA and used Bonferroni-corrected t-tests.

Figure 10 depicts our main findings. We found a statistically significant effect of trigeminal stimulants on perceived temperature [$F(3,44)=46.57$, $p=0.0046$]. Using a paired t-test, we found a statistically significant difference between our cooling scent and the baseline ($p<0.001$). Similarly, we found a statistical difference between our warming scent and the baseline ($p<0.002$). In the mountain scene, participants perceived a cooling temperature with the eucalyptol scent ($M=-1.92$, $SD=0.67$) when compared to the baseline ($M=-0.67$, $SD=0.98$). In contrast, participants perceived a warming temperature in desert with the capsaicin scent ($M=0.60$, $SD=1.32$), while the baseline was perceived as cold ($M=-1.08$, $SD=1.084$). This validates our first hypothesis.

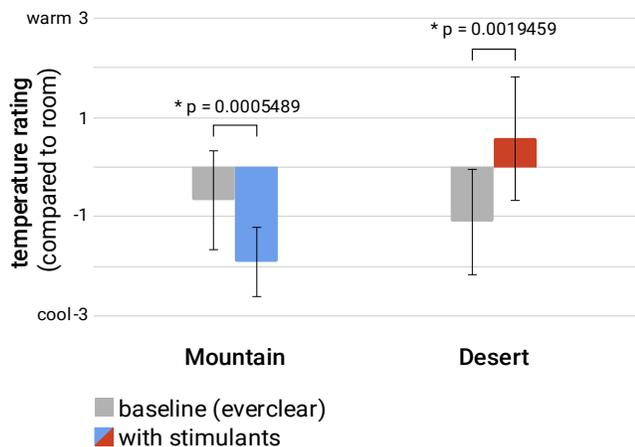


Figure 10: Rating of perceived thermal experiences across all participants. We found temperature sensations to be statistically more intense in with our trigeminal scents.

Figure 11 depicts our findings regarding induced immersion. The effect of trigeminal stimulants on immersion was significant [$F(3,44)=17.41$, $p<0.001$]. We found out a statistically significant difference between the immersion induced by our cooling scent and the baseline ($p<0.022$); and, a statistically significant difference between the immersion induced by our warming scent ($p<0.008$). Participants rated the mountain environment with the eucalyptol scent ($M=5.33$, $SD=0.98$) as more immersive than the baseline condition ($M=4.67$, $SD=1.15$). Similarly, participants felt the desert environment with the capsaicin scent ($M=5.0$, $SD=1.13$) as more immersive than the baseline condition ($M=4.25$, $SD=1.14$).

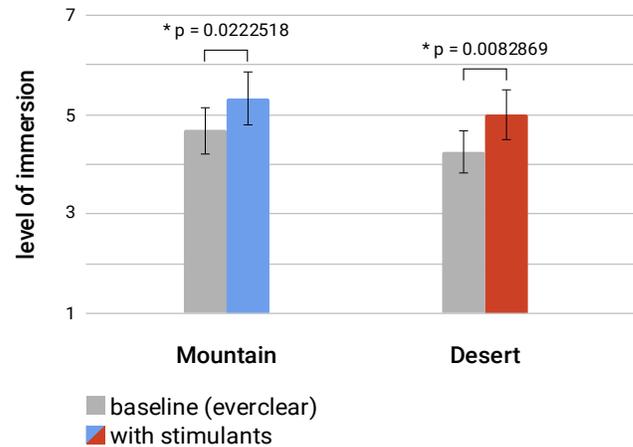


Figure 11: Rating of immersion across all participants. We found statistically stronger immersion with trigeminal scents.

Qualitative feedback

When asked whether they preferred such thermal experiences with or without the trigeminal stimulants, 8 of the 12 participants preferred with stimulants. P6 preferred without stimulants but clarified that it was because the experience was “too intense”.

Several participants remarked that our cooling trigeminal scent increased their sense of immersion in the environment and felt as though the “air breathed in was cold”. P3 additionally remarked that the cooling sensation “spread to her chest (...) as if there was air conditioning” and that they “paid more attention to environment details such as snow patches and the desert sun”. Outside of P3’s remark, trigeminal stimulation was perceived as mostly localized to the nose or face.

As seen in the previous study, the warming sensations were less pronounced. This manifested also in less comments regarding the desert experience. However, P3 mentioned that with the warming scent the desert made them “feel thirsty”.

Lastly, no participant in this study identified the capsaicin scent by its odor. Only one participant (out of 12) identified eucalyptol by its odor.

DISCUSSION

We now condense our guidelines, limitations and suggestions for engineering new trigeminal scents.

Summary of guidelines for designers

We suggest that designers use thymol or capsaicin for warm sensations and peppermint essential oil or eucalyptol for cooling. That said, the stronger warm and cooling scents that we engineered here have a caveat: they are easily identified by their odor traces. For this reason, we advise they are used in congruency with the virtual environment they are depicting, e.g., a VR scene in hot day at the park might fit well with the smell and heat sensation of thymol (as it will remind users of thyme plants); conversely, a hot desert without any vegetation would not be fitting to thymol. As a solution to this problem, we encourage designers to use capsaicin for warming (has no smell) or diluted eucalyptol for cooling (less recognizable than peppermint).

Limitations of Everclear as solvent

The utilization of ethanol (the main ingredient in Everclear) as a solvent poses minor limitations because it lightly triggers the TRPV1 receptor; also shown in our study. Future researchers may consider substituting ethanol for DMSO or propylene glycol for ingredients that are solvable in it.

Potential desensitization effect

Repeated stimulation of the trigeminal nerve may have time-dependent effects. Prior work on habituation focused mostly on oral desensitization from repeated exposure [61]. The key factor here is the inter-stimulus interval, which determines whether capsaicin sensitizes or desensitizes [22, 57]. Intervals under approximately 3 minutes cause sensitization while intervals above that can cause desensitization.

Future trigeminal scents

We believe our research is only opening the door to the underutilized trigeminal nerve. Many more ingredients might be worth investigating; for instance, the Wilkinson-Sword cooling ingredients [5, 40]. These novel ingredients, such as FEMA-4684, are expected to induce longer-lasting sensations. Similarly, *icilin* is odorless [72] and has been reported to be twice as cooling as menthol [18]. In contrast, warming scents have not been as abundantly researched.

FURTHER APPLICATIONS

While we explored using hot/cold trigeminal stimulants at the example of inducing temperature sensations in virtual reality, we believe this is just the tip of the iceberg to a range of applications. Furthermore, our hardware is simple in that the atomizer can be mounted to a variety of situations by simply extending its tubing.

Untethered thermal experiences

Thermal research has been mostly conducted in lab environments with the devices tethered to power outlets. While our device is limited in many ways, it can still enable a new range of experiments that take thermal sensations to mobile contexts, such as Augmented Reality (AR/MR).

Accessibility: experiences for anosmics

Our trigeminal-based thermal illusions, unlike most olfactory experiences, can be experienced by anosmic (smell impaired) individuals. While this requires further validation, there are many studies in psychophysics illustrating that anosmics can perceive many trigeminally-rich odors [16].

CONCLUSIONS

In this paper, we proposed, explored, and engineered a device that creates an illusion of temperature without actually requiring to cool/heat the room or the user. Our illusion is based on the properties of certain scents, such as mint, which not only stimulate our olfactory bulb (which feels the “smell” of mint) but also our *trigeminal* nerve-endings in the nasal cavity, which feel the “freshness” of mint. Furthermore, we contributed with the design and implementation of a self-contained wearable device that emits scents using an ultrasonic transducer and micropumps.

In our first user study, we found out that our trigeminal scents induce simple warming/cooling sensations. We extracted guidelines for their application and condensed insights on

preparation methods for creating new scents. Then, in our second study, we demonstrated how our device enables participants to feel temperature changes in virtual environments, such as experiencing a desert or an icy mountain.

Lastly, our device achieves this temperature illusion with low powered electronics, enabling the miniaturization of simple temperature sensations. We see this as the first alternative to the traditional thermoelectric materials (e.g., Peltier elements) that consume a lot of power in order to generate temperature changes.

FUTURE WORK

We believe this paper represents a first step towards empowering a broader set of HCI researchers to explore the role of the trigeminal nerve. Now that we know that the trigeminal nerve can be interfaced to create temperature sensations, future research might want to investigate finer details of these illusions: the speed of change from one temperature to another, the number of different temperature levels, and compare these with other existing approaches.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. (DGE-1746045). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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