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EXPANDING HUMAN AND COMPUTER SENSES THROUGH
PERCEPTUAL ENGINEERING

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To those who shaped my senses,
in life, in loss, and in learning.

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Abstract

This dissertation proposes *perceptual engineering* as a new solution to longstanding challenges in sensory interface design. Perceptual engineering is a computational approach that systematically modulates human sensory mechanisms (such as thermal receptors, trigeminal nerve endings, and taste buds) to alter perception in controlled and reproducible ways. As computing moves beyond screens and into the body, designers face persistent limitations in engaging the full range of human senses. Modalities like smell, taste, temperature, and subtle touch remain underexplored in interactive systems due to their high power requirements, difficulty of miniaturization, and lack of sensory specificity. Perceptual engineering addresses these issues by targeting the physiological roots of perception, offering precise, low-power methods to create embodied sensory experiences. As the first technical instantiation of this framework, I introduce *chemical interfaces*: a new class of wearable systems that produce targeted feedback by interacting directly with the body's chemical pathways. These systems exploit the potency and selectivity of safe chemical compounds to evoke haptic and thermal sensations as well as modulate gustatory sensations with minimal hardware. I demonstrate how chemical interfaces enable diverse applications: from delivering temperature illusions through trigeminal stimulation, to creating multi-sensation haptic feedback with a single actuator, to selectively suppressing or transforming specific tastes to promote healthier eating. Because they operate efficiently and can be miniaturized, chemical interfaces offer a practical path for integrating rich sensory modalities into everyday and immersive technologies. Building on this foundation, I extend perceptual engineering to include non-chemical forms of stimulation that share the same principles of direct, physiological modulation. For instance, I developed a stereo-smell interface that uses electrical stimulation of the nasal septum to generate lateralized

chemesthetic sensations (subset of smell sensations), allowing users to localize virtual odors. I also designed a system that applies thermal feedback to the nose during inhalation, creating the illusions of inhaling more or less air—without changing actual airflow. These systems support new applications ranging from gas localization for safety (e.g., detecting odorless carbon monoxide leaks) and smell-based navigation to anxiety regulation and improved mask comfort. Together, these contributions define perceptual engineering as a generalizable foundation for future sensory interfaces. Unlike traditional approaches that simulate perception through audiovisual substitution or mechanical actuation, perceptual engineering enables compact, energy-efficient systems that engage the sensory body directly. This work lays the groundwork for interfaces that not only render sensation but give users agency over it: systems that allow people to actively shape what they feel, taste, or smell in response to context, preference, or need. Ultimately, this dissertation advances a broader vision: a future in which modifying perception (whether to improve health, enhance comfort, or deepen immersion) is as seamless and accessible as adjusting a phone’s settings.

Introduction

I envision a future where users can customize their sensory experiences as easily as adjusting phone settings. This capability will empower users to modify their perceptions in profound ways not possible today—adjusting taste to encourage healthier eating, tweaking perceived temperature for comfort with minimal environmental impact, or even extending their sensory range to detect imperceptible noxious gases. However, despite the transformative potential of such advancements, today’s computer interfaces are unable to integrate these overlooked senses (temperature, touch, taste, and smell) owing to persistent technical challenges. These include power inefficiency, difficulties in miniaturization, and the inability to target specific sensory effects. Overcoming these barriers requires not only technical innovation but also a shift in how we conceptualize the computer interfaces that will interact with our senses.

I explore new ways to overcome these technical barriers. In my thesis, one approach I introduced is chemical interfaces, a new class of embedded, wearable systems that induce rich sensory feedback by chemically interacting with the body. For example, in Figure 1, a user modifies their sweetness perception using a phone app connected to a chemical interface worn as a necklace. This chemical interface directly intervenes with taste perception by delivering tiny, safe doses of compounds that temporarily reduce sweetness sensitivity. By altering the user’s perception, the device helps the user make healthier dietary choices.

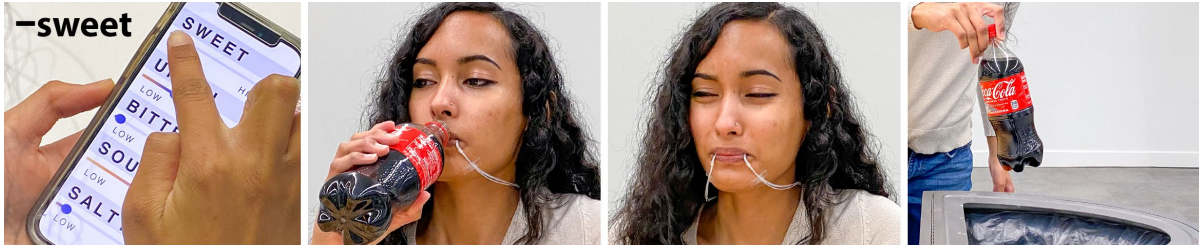


Figure 1: The user adjusts their taste perception via their phone, which signals a necklace-worn chemical interface. When drinking a soda, the interface reduces perceived sweetness, making the soda taste unappetizing and prompting a healthier choice. (From my UIST '23 paper.)

Unlike traditional methods like mechanical stimulation (e.g., adding seasoning) or sensory substitution (e.g., using sound to alter taste), chemical interfaces are power-efficient, versatile, and selective. They minimize power consumption, allow multiple sensations to be miniaturized within a single device, and directly modify sensory perception without indirect means. By integrating these interfaces with modern systems, we can unlock entirely new possibilities for interaction in health, training, and beyond, reshaping how we engage with both digital and physical environments.

Defining Perceptual Engineering

This dissertation introduces perceptual engineering as a new approach to interface design, one that directly modulates human sensory perception through precise stimulation of sensory pathways. Rather than relying on external metaphors (like audio-visual substitution) or solely on device affordances, perceptual engineering systematically intervenes in the physiological mechanisms that govern perception, using different stimulation modalities (e.g., chemical, electrical, or thermal stimulation) to alter what users feel, taste, or smell in predictable and reproducible ways. The aim is not simply to simulate reality, but to sculpt it: to render new sensations, illusions, or enhancements that serve functional purposes in health, interaction, and immersion.

Building on (yet diverging from) prior definitions

The term “perceptual engineering” has appeared in several prior contexts, but this dissertation departs from and extends those earlier conceptualizations.

In 2018, Sra coined *perceptual engineering* in her dissertation to describe immersive systems that subtly alter the user’s perception (often with the intention to fly under user awareness) by manipulating sensory input streams to influence balance, orientation, or attention [265]. These systems emphasize implicit bodily control, using techniques like galvanic vestibular stimulation to redirect users in VR or shift proprioception for redirected walking. In her framework, perceptual engineering aimed to replace explicit interfaces with embodied, involuntary guidance mechanisms that enhance presence, immersion, and trust in XR experiences.

While my approach shares a focus on intervening in perception, it diverges in both scope and mechanism. Whereas Sra’s work centers on manipulating cognitive-perceptual inferences (e.g., through vestibular manipulation or attentional shifts), my work intervenes at the sensory periphery, directly targeting the chemical, thermal, and somatosensory receptors that transduce environmental signals. The interface is not simply implicit; it is physiologically embedded. Moreover, my systems are not limited to XR contexts: they aim to extend to everyday interactions, dietary interventions, and environmental sensing.

LaValle et al. similarly propose *perception engineering* as a rigorous discipline that models how producers can create illusory perceptual experiences for receivers [144]. Rooted in control theory and dynamical systems, their formulation treats perception engineering as the design of perceptual illusions through environmental manipulation, emphasizing mathematical modeling of how agent-environment interactions give rise to internal perceptual states. Their work offers

valuable theoretical scaffolding, particularly in defining illusions as plausible yet false experiences arising from mismatches between internal models and environmental stimuli.

While I share their interest in perception as a system to be *shaped*, my work shifts the focus from external environmental control to internal perceptual modulation. Perceptual engineering in my framework is not solely about crafting illusions from external cues (e.g., visual manipulations) but about developing wearable systems that interact with biochemical and neural substrates of perception to actively reconfigure the sensory experience itself. Where LaValle et al. treat devices as agents manipulating environmental information to influence receivers, I treat devices as extensions of the body that reshape its own sensory channels.

Finally, Center et al. similarly advocate for engineering the perceptual experience itself (rather than the device) as the primary target of XR design [36]. They propose a perception engineering perspective that calls for bridging perceptual psychology, neuroscience, and dynamical systems modeling to construct richer illusions in XR. Their focus is largely visual and vestibular, grounded in predictive coding models of the brain.

Again, while aligned in spirit, my work departs in modality and material: by emphasizing chemical and other neural pathways, I extend perceptual engineering beyond vision and balance into less-explored but deeply intimate senses like taste and smell. These are not just media for illusions, but channels for direct perceptual transformation, modulating how sugar tastes, how breath feels, or how a gas is perceived.

Lastly, Warner defines perceptual engineering commercially as “designing experiences by shaping the human perception of reality through multisensory integration.” While this broad definition (grounded in visualization for information interface design) echoes my goals, it lacks specificity in implementation and does not foreground technical mechanisms for precision,

repeatability, or reproducibility. My contribution operationalizes perceptual engineering as a computational interface paradigm, grounded in experimental evaluations and physiological targeting.

Summary

Perceptual engineering, as proposed in this dissertation, expands prior definitions by:

- Targeting peripheral sensory transduction (e.g., chemical receptors, thermoreceptors) rather than only central processing or sensory fusion.
- Enabling selective, low-power, and embedded interfaces that work both for and outside of XR contexts.
- Establishing perceptual modulation not as illusion-making alone, but as a new form of personalized, physiological interaction.
- Unifying these approaches through a computational lens, mapping stimuli to percepts via controlled, replicable interface systems.

Through this lens, perceptual engineering becomes not only a concept, but a design practice and science: one that enables users to tailor their sensations, not just interpret them.

Contributions

This dissertation advances the field of human-computer interaction by introducing perceptual engineering—a new paradigm for designing interfaces that directly and selectively modulate human sensory perception through neural pathways, using a variety of stimuli (chemical, thermal, etc.). Unlike prior work that emphasizes perceptual illusions or implicit guidance through external cues, this work focuses on precise, computational interventions often at the sensory periphery,

enabling users to actively shape what they taste, smell, or feel. The key contributions of this dissertation are:

1. **The introduction of perceptual engineering** as a computational interface paradigm, which redefines how interactive systems can intervene in human perception. This paradigm emphasizes:
 - a. Direct interaction with the physiological mechanisms of sensory transduction, rather than high-level cognitive inferences or external illusion design.
 - b. Selectivity, variety, reproducibility, and low-power actuation to enable practical, wearable, and embedded sensory systems.
 - c. A shift from designing systems that simulate perception to systems that modulate it for interaction, comfort, health, and immersion.
2. **Chemical interfaces as the first instantiation of perceptual engineering**, enabling selective modulation of sensory experience through low-power, targeted stimulation:
 - a. A technique for evoking thermal illusions via TRP channel stimulation using compounds like menthol and capsaicin, achieving the sensation of temperature in VR without actual heating or cooling (*Trigeminal Temperature Illusions*).
 - b. A method for inducing a wide range of haptic sensations (like tingling or stinging) using topically applied compounds, enabling rich tactile feedback from a single actuator (*Chemical Haptics*).
 - c. A technique for taste retargeting that uses safe, ingestible modulators to temporarily suppress or transform individual basic tastes without interfering with the mechanics of eating (*Taste Retargeting*).

3. **Extension of perceptual engineering** to electrical and thermal stimulation, **demonstrating generalizability across sensory modalities:**
 - a. A stereo-smell interface that delivers lateralized chemesthetic cues via electrical stimulation of the nasal septum, enabling untrained users to localize “virtual odors” (*Stereo-Smell*).
 - b. A method for *breath perception modulation* using synchronized thermal stimulation to alter perceived airflow during inhalation, allowing users to feel as though they are breathing more *or* less air than they are (*Augmented Breathing*).
4. **The development of Smell & Paste**, a toolkit for low-fidelity olfactory prototyping that enables rapid, structured smell experience design. The toolkit lowers barriers to olfactory HCI by supporting non-technical users through an intuitive workflow, imagining how future designers might approach sketching such experiences.
5. **Comprehensive empirical evaluations and user studies** across all systems, validating the effectiveness and impact of perceptual engineering techniques. Studies range from parameter tuning experiments and perceptual matching tasks to interactive VR scenarios and sensory localization tests.

Through these contributions, this dissertation establishes perceptual engineering as a practical, extensible foundation for next-generation interfaces. By directly shaping perception through the body’s own sensory pathways, this work opens new possibilities for health interventions, immersive technologies, sensory augmentation, and everyday interactions that are more intimate, efficient, and responsive.

Trigeminal-based Temperature Illusions

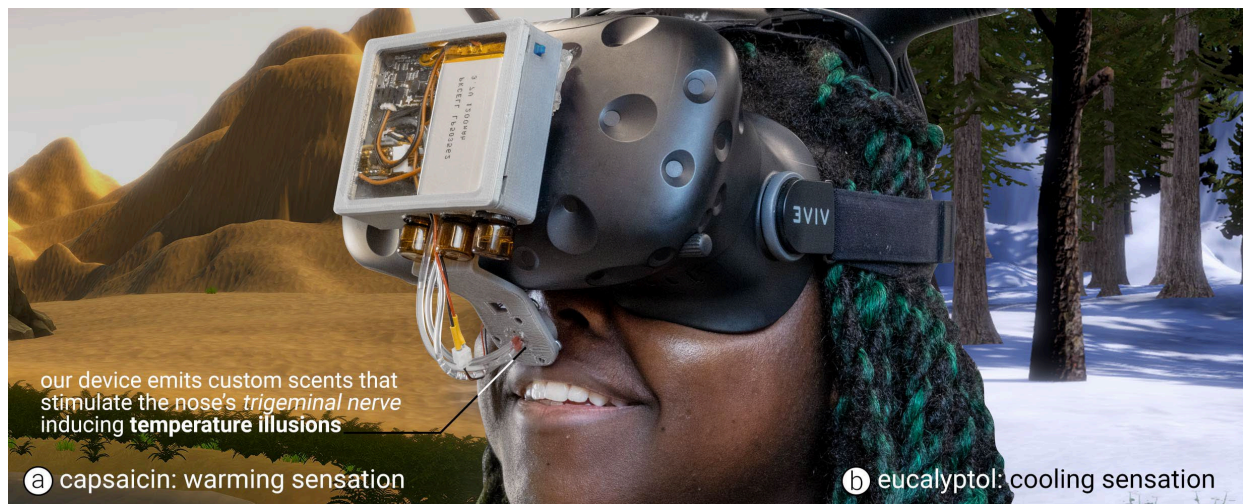


Figure 2: We engineered a thermal display that does not utilize heat or cold but instead creates an illusion of temperature by stimulating the *trigeminal* nerve in the user’s nose with different scents. This nerve is responsible for detecting temperature shifts but *also* reacts to chemicals such as 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.

Haptic feedback allows virtual reality experiences to match our sensorial expectations beyond just visual realism [15, 252]. Today, researchers focus on engineering wearable devices that deliver realistic haptic sensations, such as touch [15, 22], force feedback [81, 94]. More recently, researchers started also focusing on stimulating new senses, such as olfaction [86, 89, 308] and thermoception—the sense of changes in temperature [210]. 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 [320] or thermoelectric materials [212] (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 2, 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 [213, 221]), 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 3(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 3(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.

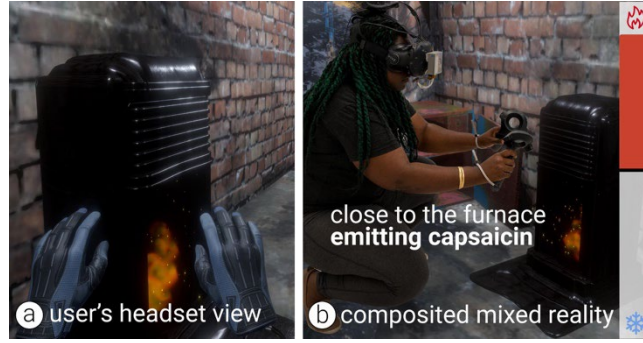


Figure 3: (a) User’s first person view of our “cabin in the woods” scene. (b) Composited mixed reality view, showing the user warmed by a furnace, our device atomizes a cayenne pepper tincture (capsaicin) to create a warming sensation.

As the cabin is ambiantly 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 4. 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.

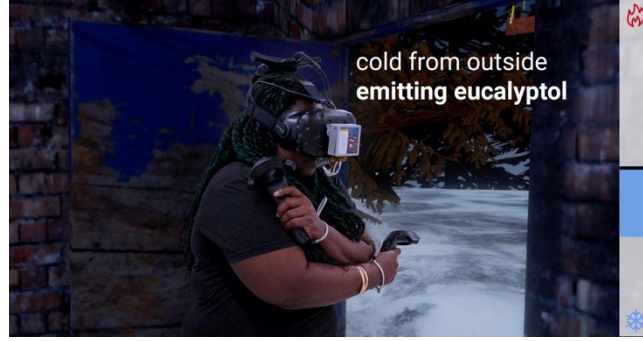


Figure 4: As the user stands at the doorstep of the cabin without heat and electricity, they feel the temperature drop as the mountain cold creeps in; here, our system atomizes eucalyptol, which stimulates the cold receptors of the trigeminal nerve.

As the user walks outside the temperature drops, which is depicted in Figure 5. Our device atomizes eucalyptol at shorter intervals of 6s, increasing the trigeminal stimulation of the cold receptors, which increases the cooling sensation.



Figure 5: 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 6. The user turns the backup generator on by pulling a lever, as depicted in Figure 6(a). When the generator starts, it exudes a little heat and some smoke, depicted in Figure 6(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* (CAS 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).

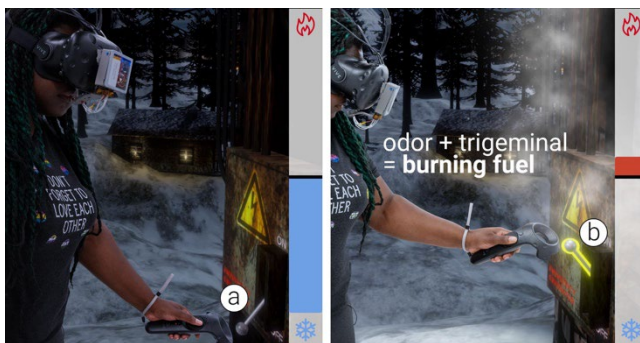


Figure 6: (a) Users turns on the backup generator; (b) The generator starts warming up and burning fuel; our device renders this by simultaneously mixing a fuel odor (olfactory stimulant) with the capsaicin (trigeminal stimulant).

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, Contributions, 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 [105], 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 [175]. 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 [314].

What is striking about these receptors is that they *also* respond to airborne particles [175]. In fact, it is their ability to sense both airborne particles and temperature shifts that explains why scents such as peppermint feel cold [173]. 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 [293]. Similarly, chili peppers feel hot when we eat them because their active ingredient, capsaicin, notably activates our TRPV1 receptor [314], 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 [23], neuroscience [102] and medicine [184]. 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 [57, 84, 107, 188, 212, 221]. The earlier forms of thermal feedback in VR were achieved via air conditioning units [306] or heat lamps [57, 98]. 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 [212]).

There are several examples of thermal stimulation using Peltiers. Vito et al. provide thermal navigation cues on a steering wheel [55]. *ThermalBracelet* [213] attached Peltiers to the user’s wrist to explore eyes-free feedback. *ThermoVR* [212] adds Peltiers to the VR headset, thus providing temperature sensations to the user’s face. *Season Traveler* [220] uses heating elements on the back of the user’s neck, as well as an olfactory display. *Affecting tumbler* [276] is an augmented beverage lid with Peltier elements that affect the perceived flavor. Lastly, *Thermotaxis* [199] 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) [84], gel packs [107], or resistive heating [128, 300]. 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 [57, 140, 216, 308] as well as notifications and communication [5, 162, 302, 305]. Olfactory displays deliver odors by: projecting vapors [183, 197, 220, 311]; heating fragrant solids [42, 58, 126]; evaporating a fragrant liquid [49, 141]; or, aerosolizing a fragrant liquid [4, 19, 88, 172, 186, 272]. The resulting gas is most commonly delivered near or in the nostrils, but can also be guided using fans, air vortex [311], bubbles [250], or ultrasound arrays [87].

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 implementation.

Hardware Design

Figure 7 shows our device. It measures 24 x 85 x 88 mm and weighs 119 g. At the core of our device is a combination of three piezoelectric diaphragm micropumps and a vibrating mesh atomizer.

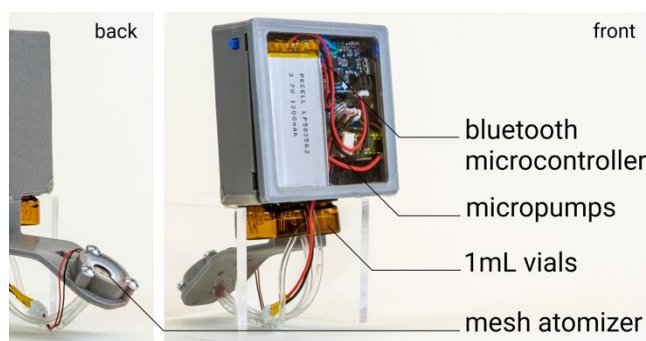


Figure 7: Front and back view of our device and its components.

Controlling atomization

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

We incorporate a vibrating mesh atomizer, which uses an annular piezo element to vibrate a perforated membrane in resonant bending mode [211, 289]. 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 μL) 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 0.127 mm. 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 16 mm of diameter. Other devices utilize one entire atomizer per channel [222], 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 [4, 5]. 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 [240], and Shoichi et

al. use four Peltier elements (KSMH029) each requiring up to 6.8W [196]. 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.

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 [267]. 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.

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 [46]. 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.

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 with less 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* [298] that had shown no trigeminal effect in studies with anosmics (individuals with no sense of smell, but intact chemesthesis) [60]. Our olfactory pink is composed of seven ingredients diluted in Everclear: 100% w/v 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.

Study 1: 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 as 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 [65], and then calibrated the other stimulants to be isointensense using the methods detailed in [65, 71].

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).

Error! Reference source not found. 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 [303] as well as reviewing relevant toxicology literature [44, 79, 110]. Our stimulants composition and preparation are depicted in Table 1.

Table 1: Composition and preparation of our stimulants.

Warming scents	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 15μm). 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.
Cooling scents	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 [71]), as L-menthol accounts for approximately 36.0-46.0% of peppermint essential oil's composition according to [284].

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.

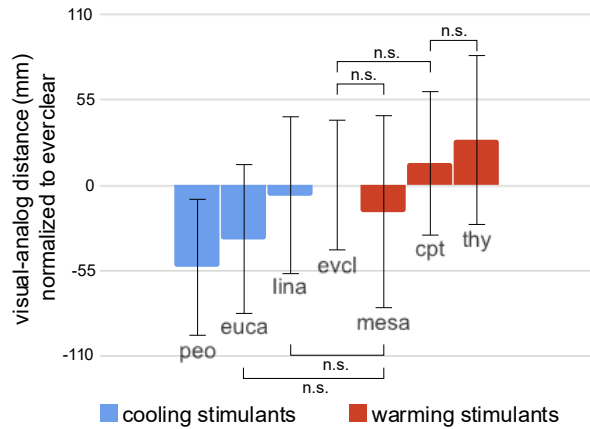


Figure 8: Perceived temperature of our six trigeminal scents (*peo* stands for peppermint essential oil; *euca* for eucalyptol; *lina* for linalool; *evcl* for Everclear; *mesa* for methyl salicylate; *cpt* for cayenne pepper tincture; and *thy* for thymol). All pairwise comparisons were significant 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 9 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.

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 [100], 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 [269], 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 the 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.

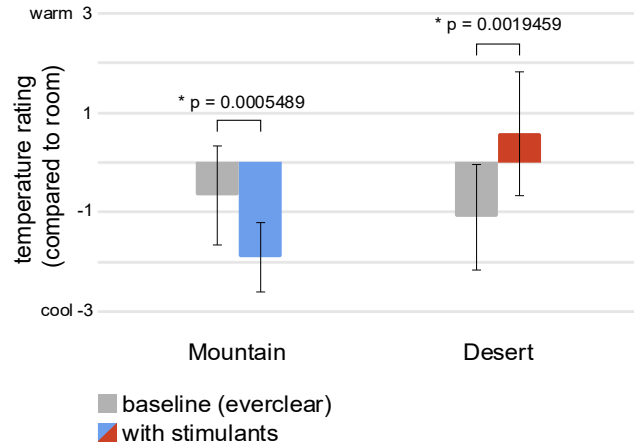


Figure 10: Rating of perceived thermal experiences across all participants. We found temperature sensations to be statistically more intense in with our trigeminal scents.

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 ($M=4.25$, $SD=1.14$).

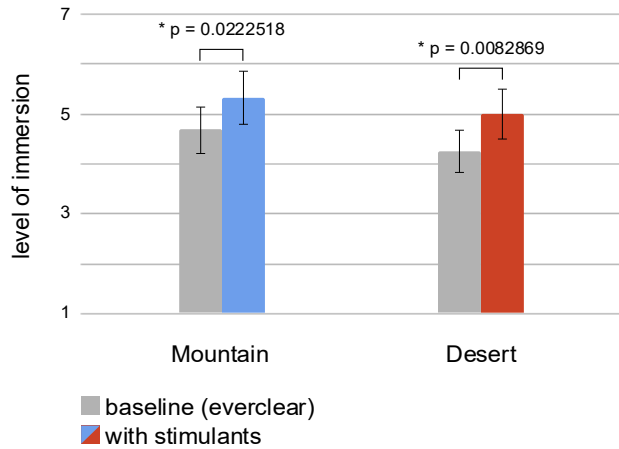


Figure 11: Rating of immersion across all participants. We found statistically stronger immersion with trigeminal scents.

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 [236]. The key factor here is the inter-stimulus interval, which determines whether capsaicin sensitizes or desensitizes [80, 218]. 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 [16, 148]. These novel ingredients, such as FEMA-4684, are expected to induce longer-lasting sensations. Similarly, *icilin* is odorless [296] and has been reported to be twice as cooling as menthol [70]. 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 [60].

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.

Chemical Haptics: Rendering Haptic Sensations via Topical Stimulants

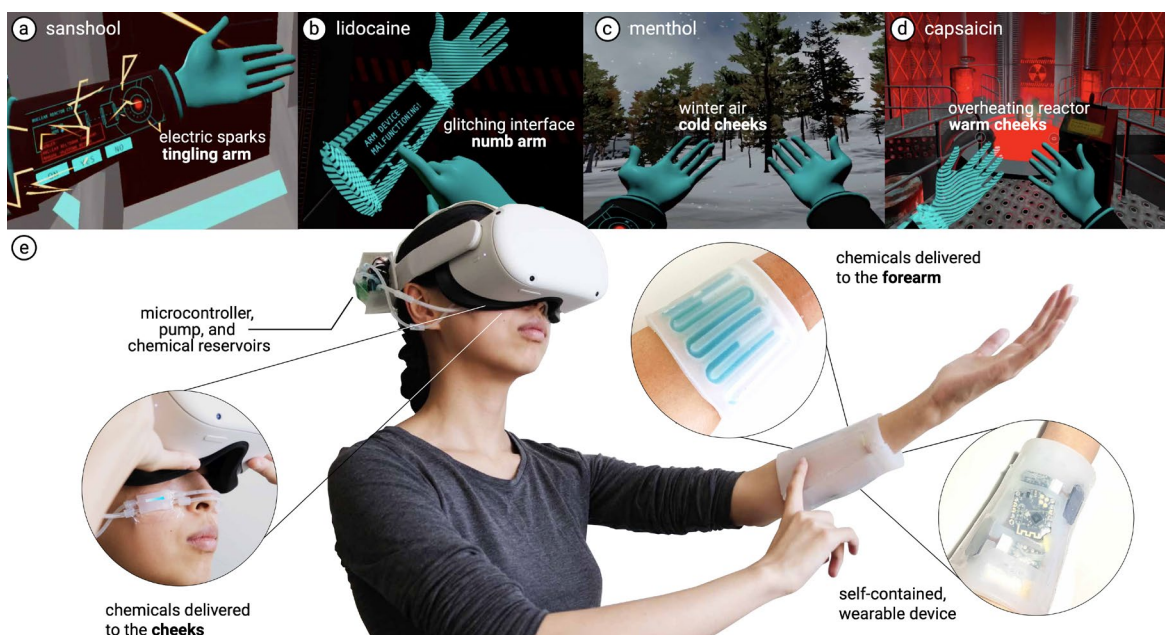


Figure 12: We propose a novel haptics approach, which we call *Chemical Haptics*, based on delivering topical stimulants to the user’s skin. Upon absorbing these stimulants, receptors in the user’s skin are chemically triggered, rendering distinct haptic sensations. To explore our approach in interactive 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.

In haptic interfaces, skin sensations like pressure, vibration, and temperature are typically created using mechanical devices, such as vibration motors in smartphones. However, generating a wide range of sensations often requires separate actuators for each effect, limiting compactness and versatility—particularly in mixed reality (AR/VR), where mobility is crucial.

To address this limitation, my colleague Jasmine Lu and I introduced **chemical haptics** in our ACM UIST 2022 paper [156]. This system expands my prior work with chemical stimulation for temperature to deliver a variety of skin sensations using safe amounts of compounds. For example,

sanshool creates a vibration-like effect, menthol produces cooling, capsaicin provides warmth, cinnamaldehyde induces stinging, and lidocaine causes numbing (see Figure 12 and Figure 13). By simply swapping chemicals, this approach reduces device size while increasing its expressivity, enabling unique sensations like the tingling of electric sparks or the sting of a wound.

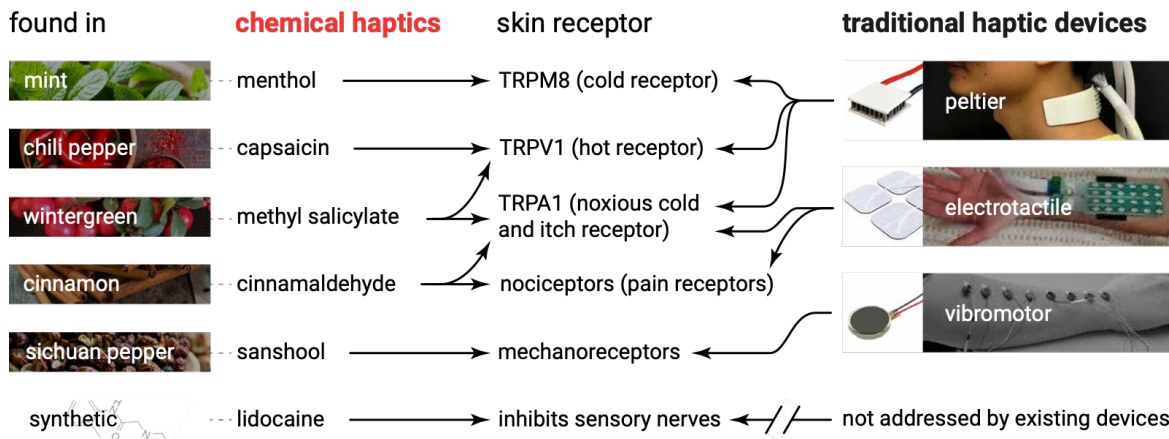


Figure 13: An overview of the six chemicals we explored in chemical haptics and the touch receptors they interact with. Also, a non-exhaustive depiction of some traditional haptics approaches for actuating these receptors.

Contribution: Our approach removes the need for bulky actuators while safely delivering sensations that are difficult to replicate mechanically, such as numbing or stinging. This work has since inspired further research in chemical haptics [82, 97, 112].

Taste Retargeting via Chemical Taste Modulators

Taste is a critical aspect of our experiences, from rich sensory and hedonic experiences during eating, to guiding our dietary behaviors. Human taste perception roughly encompasses five basic tastes: sweet, sour, salty, bitter, and umami (savory). There has been a growing interest in interactive food experiences, especially generating virtual tastes but also *modifying real tastes* through sensory stimulation. Altering taste perception has primarily been achieved by conducting electricity through cutlery (“electrical taste” [193]), adjusting the strength of the taste via electrolytes [178], or adding seasonings to food [307]. Other approaches have explored modifying secondary aspects of the eating experience, such as applying weight on the tongue [91], sound [139], perceived texture [130], or scent [197].

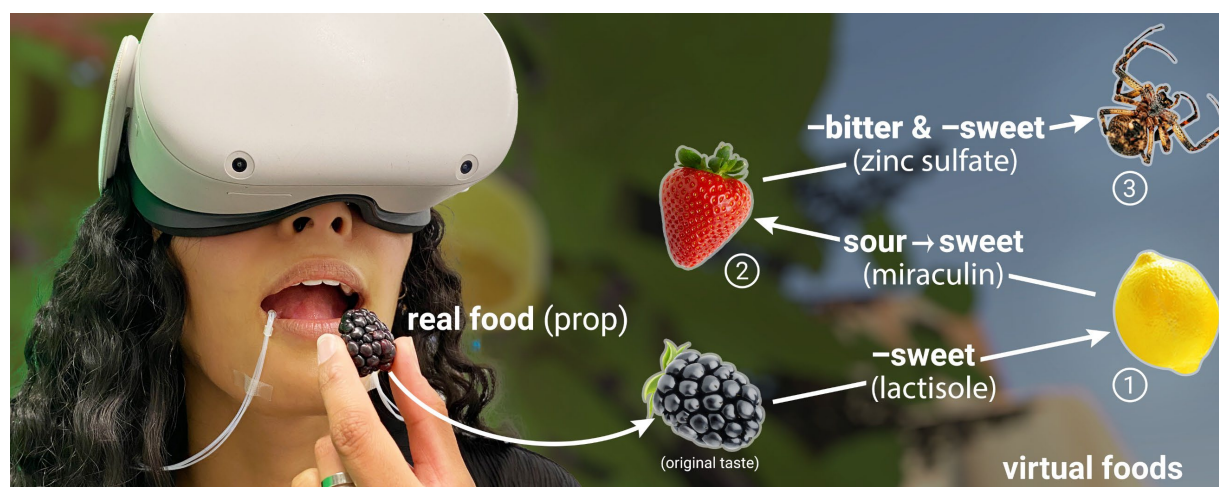


Figure 14: *Taste retargeting* selectively changes taste perception using *taste modulators*—chemicals that temporarily alter the response of taste receptors to foods and beverages. As our technique can deliver droplets of modulators *before* eating or drinking, it is the first interactive method to selectively alter the basic tastes of real foods *without* obstructing eating or impacting the food’s consistency. It can be used, for instance, to enable a single food prop to stand in for many virtual foods. This VR user always eats pickled blackberries but experiences more virtual tastes, such as (1) lemon by decreasing sweetness with *lactisole*, (2) strawberry by transforming sour to sweetness with *miraculin*, and (3) spider by suppressing bitter and sweet notes to highlight texture with *zinc sulfate*.

While these techniques are successful to some extent, they share fundamental limitations that prevent a broader application of interfaces that can alter taste: most existing taste interfaces can only elicit changes in taste perception *while the stimulation apparatus is in contact with the user's tongue* (e.g., cutlery with built-in electrodes). In fact, most prior techniques cannot alter basic tastes independently (e.g., the entire flavor profile is enhanced or suppressed), while many others can only alter the taste of simple liquid solutions (e.g., salty water or broths) but *not the taste of real foods*.

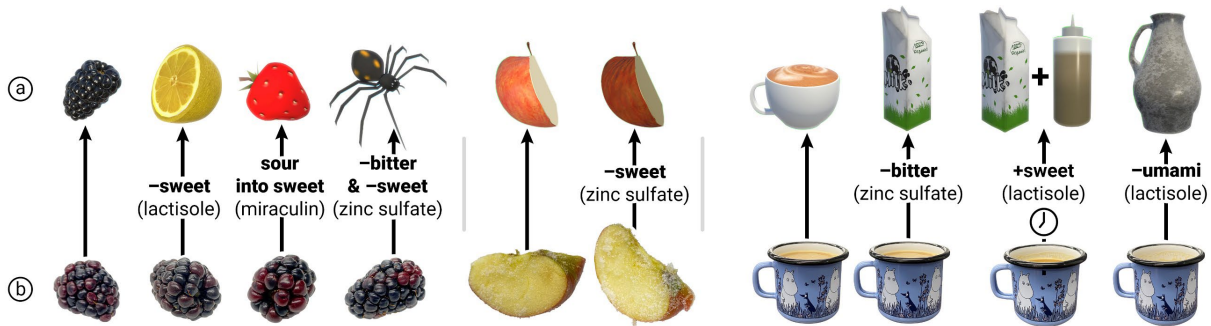


Figure 15: Timeline of (a) the virtual foods the user tastes and (b) the taste retargeted props they actually eat.

In this paper, we propose a new method for modifying taste perception of *real foods during eating*. This method, which we call *taste retargeting*, is based on delivering small drops of liquid taste modulators to the user's mouth before eating and drinking. Taste modulators are chemicals that alter the response of specific taste receptors to flavor stimuli. Modulators change the basic taste of the next bite or sip. For instance, one of the modulators we identified, *zinc sulfate*, can decrease the sweetness of a candy. Modulators achieve their taste effects by binding to taste receptor cells on the user's tongue and temporarily changing how this receptor responds to certain tastes on a molecular level [204]. With these effects, our technique produces selective changes to the user's perception of the five basic tastes. We leveraged insights from basic science to identify six accessible taste modulators: *amiloride* (salt suppression), *clofibric acid* (umami suppression),

gymnemic acid (sweet suppression), *lactisole* (umami & sweet suppression), *miraculin* (sour-to-sweet transformation), and *zinc sulfate* (sweet & bitter suppression).

Broadly, taste retargeting enables selective alteration of a real food’s flavor. While its applications are wide (from interactive dining experiences to dietary interventions) we believe it lends itself well as a way to improve the efficacy of food props in virtual experiences. Figure 14 illustrates how taste retargeting allows pickled blackberries to act as a realistic prop for multiple virtual foods: (1) lemon by decreasing the prop’s sweetness with *lactisole*, (2) strawberry by transforming sour to sweetness with *miraculin*, and (3) spider by further suppressing the prop’s bitter and sweet notes to highlight its texture with *zinc sulfate*. Note that this VR user is *always eating the same type of pickled blackberries*; yet, via the action of the modulators, their taste experience approximates these other virtual foods.

We validated our technique through two user studies. After identifying a set of six taste modulators, we investigated changes these evoked in basic taste perception. Our first study found that they could suppress salty, umami, sweet, or bitter sensations and transform sour into sweet. Using these findings, we then designed the virtual reality experience, depicted in Figure 14, to study the use of our technique in an interactive context. We found that taste retargeting reduced the flavor mismatch between a food prop and three other distinct virtual foods.

Finally, what sets taste retargeting apart from other techniques is that the modulators can be deployed *before* the user eats or drinks, leaving the user unobstructed while eating, chewing, and swallowing and eliminating the need for special eating devices, such as electrified cutlery.

Walkthrough: Altering Real Foods

To illustrate our novel technique with an example application, we designed a survival VR eating experience in which we retargeted three real foods (as props) to taste like virtual foods using three

modulators, depicted in Figure 15. For this, we engineered a wearable device (i.e., small battery and wireless). The device’s tubing attaches to the mouth’s corners to deliver modulators to the user, allowing it to change the taste of upcoming bites or sips from a food prop.

The experience includes three real foods as props: a bowl of pickled blackberries, apple slices sprinkled with sugar, and a latte. Our device is loaded with three of our modulators: lactisole, miraculin, and zinc sulfate. The user’s goal is to forage to replenish their health and stay hydrated. For clarity, we describe the experience from a third-person perspective.

The user starts the experience by finding berries in a bush, as seen in Figure 16. As they grab a virtual blackberry, they grasp a real, pickled blackberry. They then eat it, savoring the familiar taste of blackberries. Unfortunately, one berry does not replenish their health completely, so they keep foraging.

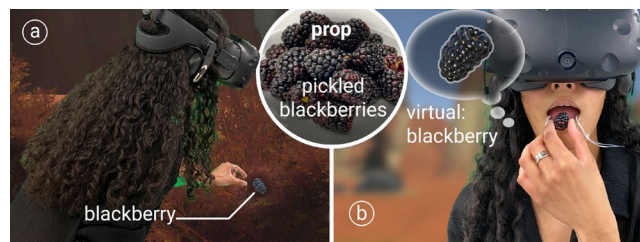


Figure 16: The user eats a blackberry (pickled blackberry prop).

While the user forages through trees (Figure 17), our device delivers *lactisole* droplets to suppress the prop’s sweetness and retarget it to the next virtual food: a lemon. They then spot a small lemon on a tree. Once they put it in their mouth and chew it, they recognize the sour flavor of the lemon. In reality, the user ate *another pickled blackberry*.

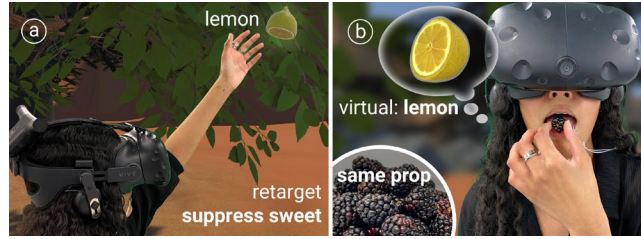


Figure 17: (a) The user grabs a lemon. (b) The same prop now tastes like a sour lemon after suppressing sweetness.

Our device then delivers *miraculin* to transform the next prop’s sourness into sweetness. As the user reaches out for a virtual strawberry they came across, they grab the same blackberry prop yet again. This time, it tastes sweeter, approximating the strawberry’s taste (Figure 18).

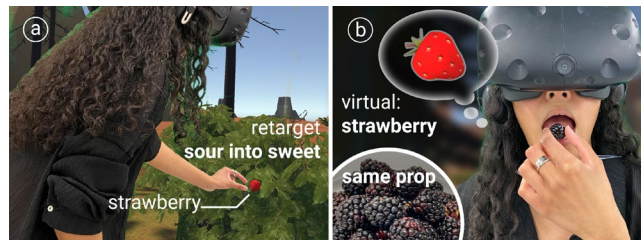


Figure 18: (a) The user picks a strawberry. (b) The same prop retargets by transforming the citric acid into sweetness.

Unfortunately, the user runs out of fruit to forage and must eat small spiders to heal. Our device drips *zinc sulfate* to suppress the upcoming prop’s remaining sweet or bitter notes, removing almost all taste to highlight the prop’s unique *texture* (the bumpiness of a blackberry). This transformation retargets the prop to match a plump spider, which the user finds and chews (Figure 19). With little taste remaining, the texture comes through bursting and gushing like a bug. This entire time, the user ate the *same* food prop four times yet experienced the tastes of *four* distinct foods.

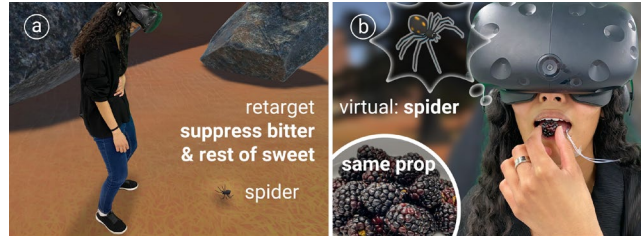


Figure 19: (a) They must eat a spider. (b) So, the prop retargets by suppressing bitterness and the rest of the sweetness.

Later, our user comes across an abandoned campsite in the sands (Figure 20). They search for food and find apple slices: our second *real food* prop. They eat a slice, tasting its sweetness from the granulated sugar coating.



Figure 20: (a) The user finds apple slices. (b) They eat the prop (sugar-coated apple) and taste the virtual sweet apple.

Suddenly, a powerful sandstorm kicks up (Figure 21), during which our device drips *zinc sulfate* to suppress the granulated sugar's sweetness. The user must then eat the remaining slice covered in sand. As they do, they notice the gritty texture of sand, which comes from the granulated sugar that no longer has a taste and is simply texture.



Figure 21: (a) A sandstorm kicks up and blows sand onto the second apple slice. (b) We suppress the prop's sweetness to render the sand grit using the (now) tasteless granulated sugar.

Next, we depict that some modulators, and even the delivery order of modulators, can produce even more complex effects. The user stumbles across and searches an abandoned cabin for hydration (Figure 22). They find an empty cup and grab it. In reality, they grabbed a cup with a latte: our third food prop. In the cabin, they find a coffee maker and press a button to prepare a small virtual latte to quench their thirst.

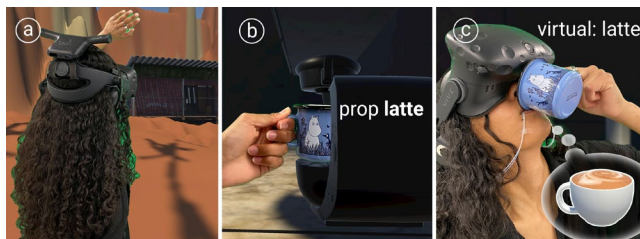


Figure 22: (a): The user sees a recently abandoned cabin. (b) They find an old, but working, latte machine and restore some of their hydration by (c) drinking a bit of latte (prop).

The user searches for more drinks while our device drips *zinc sulfate* to suppress bitterness. The user finds virtual milk, which they pour into their empty cup and drink. Without its bitterness, the prop latte’s milky (umami) taste is brought forward, retargeting the latte prop to a sip of milk. While the user searches the kitchen cabinets, our device delivers *lactisole* to create a taste “after-effect” specific to liquids known as *sweet water taste* [77]. This effect is well-known and elicited by water following the removal of lactisole from the receptors. The sweet water taste effect resembles “after-images,” patterns that become visible after looking away from an image being fixated on for too long [313]. We use this effect to retarget the user’s next sip. The user finds syrup and adds it to the remains of their milk. *Lactisole*’s sweet water taste effect adds sweetness, and the user now savors virtual sweetened milk (Figure 23).

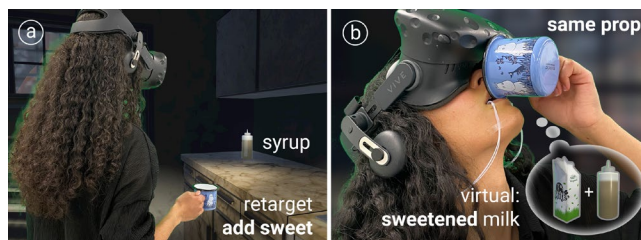


Figure 23: (a) The user sees a bottle of syrup. Our device retargets the prop to – initially – have sweetness, allowing the user to add syrup to their milk and (b) taste the sweetened milk.

However, much like after images fade away, so does the sweet water taste effect of *lactisole*. The user finds an old jug of water in a sink. By then, the modulator returns to its umami-suppressing behavior, and, with the latte’s bitter and umami notes now suppressed, it becomes nearly tasteless, approximating the taste of this stale water.

Moreover, the order of modulators can also produce different experiences. Figure 24 depicts alternative experiences depending on the interactive order of the modulators. If the user finds syrup instead of milk (after drinking the initial latte in the abandoned kitchen), our device will deliver *lactisole* instead of *zinc sulfate*. Due to *lactisole*’s sweet water taste effect, this order will sweeten the latte instead of the milk. Once this effect fades, the latte prop would lose its umami notes (*lactisole*) and taste closer to a virtual coffee. Finally, after *zinc sulfate* suppresses the prop’s bitterness, they would experience the same stale water taste as in the first version.

From these three props and three modulators (six physical ingredients total), we produce 12 virtual food items. Following, taste retargeting enables three real foods to stand in for 12 virtual tastes, a *four-fold* gain in distinct tastes.

Contrast to naïve solution

At this point, the reader might wonder why use modulators instead of simply adding additives with basic tastes (e.g., sugary water to enhance sweetness or an acidic powder to enhance sourness).

While this idea has some merit in theory, it exhibits fundamental issues that taste retargeting avoids.

First, this naïve solution can only *add* tastes to food without the ability to suppress or modify, which taste retargeting achieves. Second, sustaining this added taste requires frequently and repeatedly delivering a solution or powder, which might result in bursts of the added taste that will disrupt the experience. In contrast, taste retargeting produces a sustained, smooth change, as demonstrated in Study 1. Moreover, adding powders or liquids while chewing or drinking can unintentionally alter the foods texture or dilute its taste [90]. Taste retargeting avoids this since modulators are delivered in tiny amounts before eating or drinking.

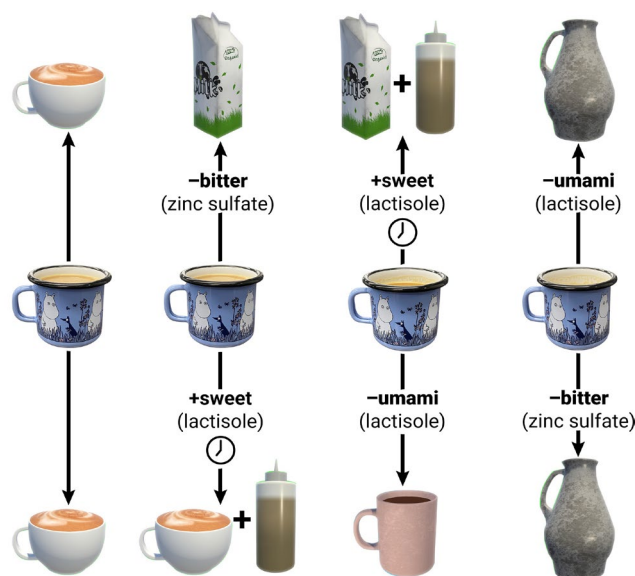


Figure 24: By swapping the order of two modulators (lactisole and zinc sulfate), the tastes of two additional virtual foods are available: sweetened latte and coffee (bottom row).

In sum, taste retargeting is a technique that addresses these issues and achieves selective taste modifications. Finally, our technique can be paired with prior techniques, such as adding inhaled odors, auditory feedback, or electrical stimulation.

Benefits, Contribution, and Limitations

Our key contribution is *taste retargeting*, a technique that can *selectively* modify basic tastes of *real* foods *during eating*.

Taste retargeting stands out from other techniques because modulators selectively affect taste receptors and can be deployed before eating. These unique features lead to several benefits. (1) The technique leaves the user unobstructed while eating, chewing, and swallowing, eliminating the need for special eating devices like electrified cutlery. (2) Taste retargeting works for any real food, not just electrolytic liquids, (3) without unintentionally changing the food’s texture or diluting its taste. Moreover, (4) our technique features temporary and robust alterations. When used for food props in VR, (5) taste retargeting reduces the flavor mismatch between a food prop and distinctly flavored virtual foods.

As the first exploration of a novel technique, its limitations are significant to discuss, revealing future research directions. (1) Taste retargeting is not currently suitable for short taste alterations. Our Study 1 results provide information on modulator offset times so that designers can design their experiences around this limitation. More research is needed to modify or dose the modulators to accelerate their offset time. (2) Some modulators may have their own taste (e.g., zinc sulfate). We provide potential methods to address this issue (see Study 2’s Discussion). (3) As with any technique based on chemicals, there might be cross-modulator interactions. Currently, only lactisole diminishes the strength of miraculin’s effect [138], and we did not notice additional cross-modulator interactions in our pilots and studies. (4) Additional effects require uncovering additional modulators. For instance, we chose our modulators because they are accessible and because most are food-safe, which leaned towards suppression and not enhancement. (5) Taste retargeting is a *taste* technique and does not solve the smell or texture incongruencies of food props

in VR. However, it is easily combinable with other techniques that alter texture or smell. Also, in the case of VR props, it is worth noting that taste retargeting requires some considerations with the prop since the technique only modulates *existing* flavors. The prop’s initial flavor must already contain facets matching each virtual food. However, this is as much a limitation as a tradeoff, as taste retargeting provides a key benefit in exchange: using readily available foods as props with little to no preparation.

Related Work

The work presented in this paper builds on the field of taste (gustatory) interfaces with an emphasis on *modifying* the taste of existing foods rather than producing artificial or virtual tastes. Additionally, we briefly review props for virtual reality because our application example relies on using real foods as props for VR.

Producing tastes

Literature on taste interfaces primarily concerns devices that produce or deliver a taste sensation on its own, typically in a virtual experience. In other words, the user is *not eating real food*. We provide an overview of these devices.

Chemical taste interfaces

A common design for interfaces that simulate a flavor involves chemical stimuli delivery. For instance, the *TasteScreen* drips flavoring agents onto a screen for the user to lick [171]. *TTTV* refines this concept by spraying taste solutions for each basic taste on a saran-covered screen [180]; the device sprays taste solutions on a 2D picture of the intended food item [179]—unfortunately, this is a one-off device that users cannot use in any other way (e.g., this would not work in VR, AR, etc.). Vi et al. engineered a game interface that delivers basic taste stimuli (e.g., sugary water)

to the user through a straw [290]. *LOLLio* is an interactive device with a lollipop that provides a passive sweet taste and that pumps citric acid into the mouth through the lollipop for sourness [189]. Even the method of chemical delivery alters taste perception, as shown in *TastyFloats*, which levitated small foods to the mouth [291]. Finally, the *Food Simulator* applies a force to the user's teeth while pumping basic taste solutions into the mouth to roughly simulate a food [106].

Thermal taste interfaces

Ranasinghe & Do [219] and Samshir et al. [238] developed thermal interfaces for sweet stimulation, leveraging how the TRPM5 sweet receptor responds to thermal stimulation. Both devices involved a Peltier element attached to a cooling system for which users must stick their tongues out to touch the Peltier.

Electrical taste interfaces

Electrical stimulation of the tongue is the most popular technique to induce taste sensations in HCI. Ranasinghe et al. [223] leverage direct electrical stimulation of the user's taste receptors to evoke perceived taste sensations in a virtual cocktail experience. Miyashita's *Norimaki Synthesizer* device [178] combines these approaches by differentially exposing the user's tongue to combinations of five tastes. The taste compounds are suspended in semi-permeable gels, for which electrical currents through each gel determine the intensity of the perceived taste.

While these interfaces aim to produce virtual tastes, our method *alters the existing taste of real* foods and beverages.

Modifying the taste of existing food

Researchers have explored how to *modify* the perceived tastes of real foods using different stimulation approaches.

Pseudo-taste interfaces

Considering that taste is also a multimodal experience, many have tackled altering taste by influencing *secondary* aspects of flavor perception such as sound, smell, temperature, or texture [261, 263]. Narumi et al. referred to the later as pseudo-gustatory or pseudo-taste displays [197]. For instance, researchers have experimented with audio to induce flavor changes. Some examples include, *Chewing jockey*, which augments the texture of food via auditory feedback [139], an auditory-augmented wine glass [177], or *Auditory Seasoning Filters*, which alters chewing sounds, influencing perceived flavor and crispiness of potato chips [129]. In a different vein, *MetaCookie* delivers inhaled smells to influence the taste of a basic cookie [197, 198]. *LeviSense* added smells and lighting to influence the taste of levitating food [292]. Similarly, *TransFork* diffuses odors while the user holds their eating utensil close to their mouth [151]. Unfortunately, these techniques focus on orthonasal (inhaled odors) delivery instead of retronasal (exhaled odors), of which the later contributes more to flavor perception through oral referral once food is in the mouth [20, 27, 260]. Finally, researchers have also experimented with tactile and thermal modifications. *Gravitamine Spice* alters the flavor of food by shifting the eating utensil’s center of gravity [91]. *Affecting tumbler* uses thermal feedback around the nostrils (when the beverage lid is held up for drinking) to modify perceived flavor [276].

Chemical taste interfaces

Three devices have focused on the modulation of flavor via seasoning, affecting both olfactory and gustatory elements. *Yaminabe YAMMY* modifies the flavor profile of a hot pot by dropping flavoring agents into the pot according to the emotional associations of a user’s email or photo [307]. *GustaCine* drops seasonings onto a bowl of popcorn based on the emotional content of a

movie [125]. These modifications to food items are irreversible: once a seasoning is added, it cannot be removed.

Miyashita expands this approach by combining it with his prior work, resulting in the *TTTV2* [181], which sprays basic taste solutions (“seasoning”) onto foods that serve as a substrate (e.g., tofu, rice, or sliced bread). While more controlled than prior seasoning-based approaches, current demonstration examples focus on using bland foods as bases (e.g., cold tofu sprayed to taste like mapo tofu), may be prone to non-uniform seasoning (e.g., only seasoning a particular patch and not the food item in general), can only add taste to the food item, and – like prior literature – modify the food’s flavor profile irreversibly.

Electrical taste interfaces

The predominant approach to alter real food tastes is electrical stimulation. For instance, Ranasinghe et al. developed electric cutlery that could slightly increase the sourness or saltiness of unsalted mashed potatoes and only slightly increase the sourness of unsalted miso soup [224]. While these are promising they also have three key limitations. (1) The foods or beverages altered are often simple in taste profile (mashed potatoes, biscuits, broth, sugary or salty water, etc.). Moreover, suppression techniques only work for electrolyte liquids, as suppression works through ionic migration [6, 7, 178]. This latter point essentially prevents suppression of real foods that are not soups or beverages. (2) Electrical stimulation is still typically deployed through *cutlery* [37, 193, 194], which means the experience stops once the utensil’s electrodes are no longer in contact with the tongue (e.g., during chewing and swallowing). In contrast, Aoyama et al. showed that electrical galvanic tongue stimulation (with electrodes at the chin and back of the neck) can induce, inhibit, or enhance the food’s taste intensity [6, 7]. Building off of this finding, Ueno et al. [287] demonstrated such stimulation can produce alterations to a beverage’s aftertaste in combination

with and beyond a utensil’s stimulation window. Unfortunately, this leads to the fourth limitation: both Aoyama et al. and Ueno et al. did not produce selective taste alterations. (4) Only the *overall* taste intensity could be impacted instead of individual basic tastes like bitter or sweet.

State-of-the-art summary

To this day, taste and flavor modification devices fail to selectively (e.g., at the individual, basic taste level) alter taste perception during eating and swallowing for any food and beverage item.

Redirection and props for virtual reality

Since we demonstrate our concept applied to retargeting the taste of real foods as food props in VR, we succinctly overview the fields of redirection and props for VR.

Redirecting techniques

At its core, *redirection* of human movement involves offsetting a user’s virtual body to produce a different virtual and real movement, helping overcome the limitations of limited tracking spaces or prop-based haptics. Examples include redirected walking [227], haptic and hand retargeting [10, 136, 217], etc. In our case, taste retargeting applies the same core concept of redirection but to flavor perception by altering the perceived taste of foods with modulators, circumventing the limitation of food props for virtual reality.

Props

Props are physical stand-ins for virtual objects typically employed to enhance realism [39, 270, 280]. Virtual eating experiences can also use *food props*: foods that serve as *edible stand-ins* for virtual foods. In its most straightforward application, a food prop can match the virtual counterpart (e.g., seeing and eating a lemon). For instance, *Aerobanquets RMX*, an interactive gastronomy experience, had diners wear VR headsets to eat real dishes recontextualized in a whimsical virtual

world [35]. However, preparing one prop per virtual food becomes cumbersome and laborious as the number of foods increases. A *useful prop* is one that can be reused for as *many* virtual items as possible. This is difficult for foods due to their distinctive flavors (e.g., lemon does not taste like a cucumber), the need for replenishment after every bite, and the abundance of cues (e.g., the smell, size, weight, and texture of a lemon is different from that of a cucumber). Weidner et al. explored this tension and demonstrated that one cannot simply transform a “neutral” (nearly tasteless and odorless) food into a more complex food (e.g., a banana) using visuals and smells alone [297]. Our technique advances food props by retargeting a food item’s taste into many.

Chemical Interfaces in Human-Computer Interaction

Smell and taste interfaces are often fundamentally *chemical interfaces* in that they stimulate these senses using chemical stimuli like fragrance oils, flavoring agents, or foods. Recent research in HCI has explored using chemicals to influence human perception by identifying sensory mechanisms that can be stimulated with carefully selected compounds. [24] demonstrated that an olfactory interface can be an alternative to Peltier elements by selecting odor molecules that chemically stimulate the same receptors that respond to temperature to produce a temperature illusion. *Chemical Haptics* extended this to identify chemical alternatives to vibromotors and electrotactile stimulation [157]. Research has continued to explore these effects in haptics [82, 112]. Taste retargeting sets itself apart by using chemicals to modulate receptors (and, thus, alter their response to other stimuli) instead of stimulating those receptors to produce a sensation.

Modulators Used for Taste Retargeting

We propose interactively delivering taste modulators to alter taste perception *while eating or drinking*. However, given the lack of prior work in using taste modulators for interactive

experiences, we had to identify and characterize a set of modulators that were accessible to realize our concept. Thus, we provide an overview of our modulators, including toxicological information. We specifically opted for easier access modulators (e.g., food safe, supplement, off-the-shelf, etc.), leading to modulators with suppressing or transforming effects. However, other modulators exist (e.g., demonstrated in mice or prescription medications) that might act as enhancers, which we discuss in *Future Work*.

Gymnemic acids: sweet suppressor

Gymnema acids allows us to achieve **sweet suppression**. This is a chemical isolated from the leaves of *Gymnema sylvestre*. This leaf powder is commonly available as a dietary supplement and thus food-safe; ours was purchased from *Best Naturals*. We use a concentration of 1.0% w/v based on Okamoto et al. [205].

Taste alteration mechanism: Of our chosen modulators, this may be the most well-known, second only to miraculin. This sweet suppression has been attributed to its triterpene glycosides [13, 275]. More recently, Sanematsu et al. found that these gymnemic acids bind to the human sweet taste receptor hT1R3 to produce its sweet-suppressing effect [239].

Clofibric acid: sweet and umami suppressor

Clofibric acid allows us to achieve simultaneous **sweet & umami suppression**. Clofibric acid (PubChem CID: 2797, Catalog #: 21608) was purchased from *Cayman Chemical Company* at its highest available purity ($\geq 98\%$). We use a dose of 51.45 mg, based on Kochem & Breslin [132], well below its acute oral toxicity (LD_{50}) of 897 mg/kg [324].

Taste alteration mechanism: Clofibric acid has been shown to be an antagonist for the sweet taste receptor (hT1R2-hT1R3), which also contributes to umami perception. In other words,

clofibrilic acid binds and inhibits this receptor's activity. This inhibition diminishes sweet and umami perception in humans [132, 133, 164].

Lactisole: sweet and umami suppressor

Lactisole (PubChem CID: 16231, Catalog #: 18657) was purchased from *Cayman Chemical Company* at its highest available purity ($\geq 98\%$). We use a dose of approximately 3.75 mg, based on Sclafani and Pérez [249]. This modulator is approved for use in foods at levels up to 150 ppm (approximately 150 mg) per food item [29]. Lactisole is a commonly used sweet modulator in industrial food processing [249]. The food industry typically uses lactisole to avoid perceiving an increase in sweetness when additional sugar is introduced for texture-purposes (e.g., softness).

Taste alteration mechanism: Lactisole achieves its sweet and umami suppression by blocking the activation of the hT1R2-hT1R3 receptor [132, 133].

Miraculin: sweet modulator

Miracle berry tablets are a commonly available food supplement derived from berries (*Synsepalum dulcificum*, known as “miracle fruit”). We source ours from the off-the-shelf product *mberry*. We use 200 mg of miracle berry dissolved in water. The key active ingredient, *miraculin*, produces the taste alteration. Miraculin is not associated with any safety concerns and does not represent a risk of allergy or toxicity to humans [277].

Taste alteration mechanism: Of our modulators, miraculin is the most recognizable as it is commercially advertised as a “party trick” [59]. Miraculin binds to human sweet taste receptor hT1R2-hT1R3. While miraculin acts as an inhibitor at neutral pH environments, it functions as a strong agonist in the presence of acidic pH environments [138]. In other words, miraculin causes acidic stimuli to activate a sweet taste receptor. This is why it is used as a “party trick” with acidic foods, such as making a lemon taste sweet. In addition, the perceived sourness of acidic stimuli is

diminished, with mostly the sweet signal reaching the primary taste area [309]. The exact mechanism of miraculin interaction with taste receptors remains unknown. However, miraculin interacts with lactisole, with psychophysical findings showing that lactisole diminishes the pH-dependent sweet response produced by miraculin [104, 138].

Zinc sulfate: sweet & bitter suppressor

Zinc sulfate (PubChem CID: 24424) is a chemical commonly available in food supplements and has the U.S. Food and Drug Administration's "Generally Regarded as Safe" status for food and beverages. We source it from an off-the-shelf product by *Triquetra Health*. We use a dose of 4 mg derived from pilots. Zinc sulfate's acute oral toxicity (LD₅₀) is 1,538 mg/kg.

Taste alteration mechanism: Zinc sulfate is a sweet inhibitor [121, 122] and selective bitter inhibitor [123]. The exact mechanisms by which zinc ions affect sweet and bitter taste are still unknown, but Keast et al. suggests that they bind to taste receptors, altering their binding properties [121].

Amiloride: salty suppressor

Amiloride (PubChem CID: 16231, Catalog #: 14409) was purchased from *Cayman Chemical Company* at its highest available purity ($\geq 98\%$). We use a dose of 1.722 mg, based on Schiffman et al.'s [245]. This modulator's acute oral toxicity (LD₅₀) of this modulator is 300 mg/kg [322].

Taste alteration mechanism: Amiloride has been used as a specific inhibitor of sodium transport (reducing saltiness). The psychophysical findings that amiloride reduces the intensity of taste perception of sodium and lithium salts is consistent with its action in which the fluxes of sodium and lithium are molecularly blocked [245].

Hardware Implementation

To help the readers replicate our design, we provide the necessary technical details below. We additionally provide all source code, firmware, and hardware for our implementation online.¹ Figure 25 shows our complete and self-contained 3-channel prototype, including its battery, liquid-safe pumps, and reservoirs.

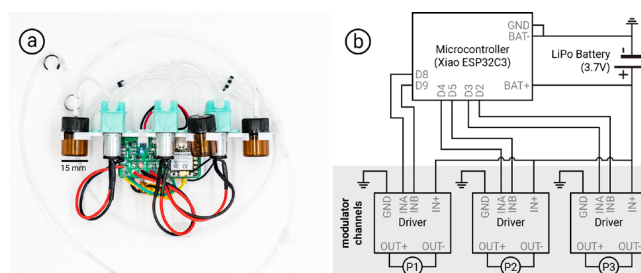


Figure 25: (a) Our device is comprised of a printed circuit board, pumps, vials, tubing, and cuffs. (b) High-level schematic.

Our device uses a Seeeduno Xiao ESP32C3 for its compact size and integrated Bluetooth Low Energy (BLE) radio. We use the BLE to communicate with external devices, such as a computer, a VR headset (e.g., Oculus Quest), or even a mobile phone. To deliver the taste modulators, we used three mini peristaltic pumps (Takasago Fluidic Systems, RP-Q) connected to thin silicone tubing (ID = 1 mm; OD = 2 mm) via barbed connectors. Each tube is then connected to thinner PTFE tubing (ID = 0.6 mm, OD = 1 mm) leading to the mouth. We use silicone adhesive to connect silicone to PTFE. All three tubes are then attached to 20-gauge (0.8 mm thick, 8 mm loop diameter) lip cuffs to hook at the mouth corners, which ensures the tubes stay in place. Both the hooks and final PTFE tubing are kept very thin to minimize their interference during talking, drinking, and

¹ <https://github.com/humancomputerintegration/taste-retargeting>

eating. The peristaltic pumps' mechanical compression of the tubing serves a secondary function: maintaining pressure so that users cannot suck the modulator solution ahead of time.

This hardware is one of many ways to achieve taste retargeting. For example, modulators could be sprayed onto foods from a wrist-worn device or could be dynamically coated onto cutlery. However, we found our device to currently be the most compact and unobtrusive option.

Study 1: Measuring the effect of modulators

Our first study sought to extend results from prior taste modulator literature. Most literature on taste modulators originates from their applications in industrial foods and medicine, such as helping with taste disorders caused by radiotherapy. As a result, prior studies focused on understanding which basic taste a particular chemical alters and to what degree. Following, our study aimed to measure the *strength and duration* of a modulator's effect on a relevant basic taste within a 6-minute window. This study was approved and determined to be exempt by our Institutional Review Board (IRB22-0260).

Participants

We recruited eight participants (average age 26.38, SD = 2.72) from our local institution. Six participants identified as men, one as a woman, and one as non-binary. We did not recruit participants with allergies or sensitivities to any ingredients used in the study. Participants were untrained and only screened for a basic understanding of taste-related descriptors (sweet, sour, bitter, salty, umami). We compensated participants with 25 USD for their time.

Modulators and taste solutions

We used the taste modulators detailed in Section 4: amiloride (0.1148 mg/mL), clofibric acid (3.43 mg/mL aka saturation), gymnema powder (1.0% w/v), lactisole (0.25 mg/mL), miraculin (13.33

mg/mL), and zinc sulfate (0.266 mg/mL). We then used medium-intensity solutions of basic taste stimuli (*tastants*) prepared according to Hoehl et al. [92]: 8.00 g/L sodium chloride for salty, 48.00 g/L sucrose for sweet, 1.08 g/L caffeine for bitter, 2.40 g/L citric acid for sour, and 4.00 g/L monosodium glutamate for umami. All solutions used room-temperature filtered tap water as a solvent. Modulators' effects were measured on taste(s) they effected in prior literature. Following this, we tested nine modulator-tastant pairs: amiloride on salty, clofibric acid on umami, gymnema powder on sweet, lactisole on sweet, lactisole on umami, miraculin on sour, zinc sulfate on sweet, and zinc sulfate on bitter.

Procedure

Participants performed a multi-sip, multi-attribute time-intensity test for each modulator-taste pairing, as depicted in Figure 26. In other words, each participant drank a tastant at the start, then the modulator, then the tastant six more times (multi-sip) and evaluated its taste each time (multi-attribute time-intensity). The examiner pre-poured all solutions (same volume at 3 mL) and told participants that every tastant could be different or identical to avoid any expectation bias. Participants drank a cup each minute and were asked to maintain a consistent sip size. For the modulator, participants were asked to swish the solution in their mouth for 5 seconds before swallowing to ensure proper coverage of the oral cavity. After each drink, they then rated the solution's taste intensity across five attributes (salty, sweet, sour, bitter, and umami) using a Likert scale ranging from 0 (not at all) to 10 (the most).

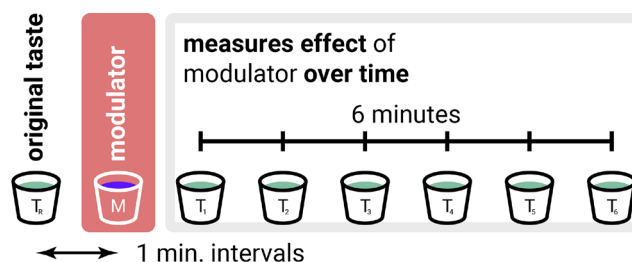


Figure 26: Study protocol to measure the effect of a modulator on a target basic taste over time.

We asked participants to refrain from eating and drinking for at least 30 minutes before a trial. Trials were randomized in order, and participants had to wait at least 45 minutes between trials to avoid any unintended effects across trials. For this reason, we did not conduct repetitions, as the study would be extremely long for participants.

Results

As reference ratings for the tastants vary across untrained individuals, we used the relative change (difference between a time point T and the reference T_R) to determine the modulator's impact on taste perception. We summarize the results for each modulator below and illustrate their impact in Figure 27.

Gymnemic acids (gymnema powder). The gymnema powder solution suppressed sweetness the most effectively, with a maximum relative change in the sweetness of -2.5 . The powder's suppression effect slowly recovers with a positive trend toward the original taste.

Clofibric acid. Clofibric acid suppressed umami. On average, the relative change in umami is -1.75 , with an overall downward trend. Due to the umami compound (monosodium glutamate), participants also rated a decrease in perceived saltiness with a maximal relative change of -1 around the 250-second mark. Finally, clofibric acid might induce a sweet sensation on average $+1$.

Lactisole. Surprisingly, lactisole did not appear to strongly affect the sweet solution despite prior literature demonstrating an effect (see *Discussion*). In contrast, lactisole successfully

suppressed the umami of an umami solution. Lactisole-induced umami suppression steadily strengthens over time, with a maximal relative change in umami intensity of -2.5 but no trend back towards neutral within this timeframe. Lactisole also produced a sweet sensation ($+1.4$) that faded after 200 seconds. A similar phenomenon occurred for umami during the sweet solution.

Miraculin. Miraculin transformed sourness into sweetness. However, this relationship is not one-to-one. While the relative change in sweet intensity stays largely at $+2.6$, the relative change in sour intensity decreased over time and plateaus around -1.7 between 150 and 250 seconds.

Zinc sulfate. Zinc sulfate suppressed the sweetness of a sweet solution, with a maximal relative change in intensity of -2.2 . However, unlike the gymnema powder, the sweet suppression effect lasted longer, with no positive trend back towards the original taste (neutral) in this timeframe. Zinc sulfate also suppressed the bitterness of a bitter solution, with a maximal relative change in intensity of -2.5 . As with its effect on sweetness, the bitter suppression effect lasted long, starting off smaller (-1.8) and plateauing (-2.5) without a positive trend back to neutral within this timeframe.

Amiloride. Amiloride suppressed saltiness, though some participants also rated this as a decrease in perceived umami despite the salty solution only containing sodium. If both the relative changes in saltiness and umami are summed, amiloride's maximal relative change in saltiness was -2.0 . Suppression is strongest around 100 and 300 seconds after modulator delivery, and the effects trended back to the original taste soon after.

Discussion

Our study results mostly align with prior literature for each modulator and the basic taste tested. We additionally discuss a few results from the study in further detail.

Zinc sulfate reducing sourness. While some participants mistook bitterness for sourness, sour-bitter confusion is well-documented [206, 230]. When we account for this confusion, this “sour” decrease pointed to the further efficacy of zinc sulfate at suppressing bitterness over time.

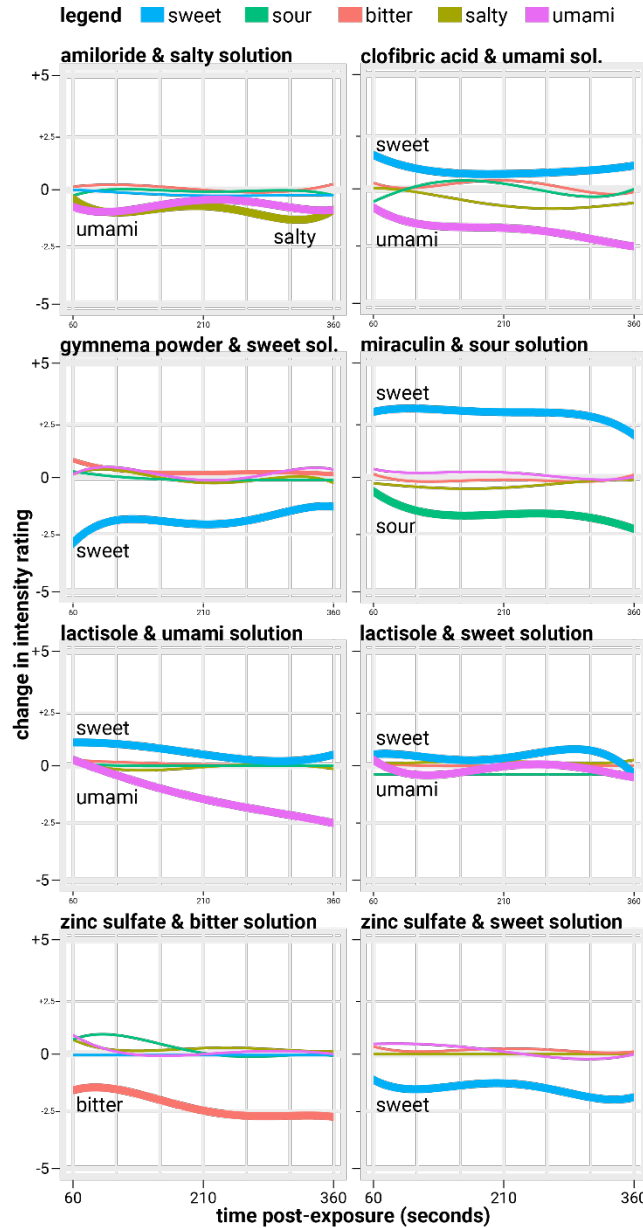


Figure 27. Plots of the relative change in intensity of basic tastes measured under the effect of each modulator. For clarity, we bolded the polynomial fits for basic tastes that are relevant to the modulator and taste solution of each plot.

Zinc sulfate’s change in mouthfeel. Participants sometimes reported a brief (within the first 10-20 seconds) change in mouthfeel with zinc sulfate. This aligns with prior literature suggesting that zinc may bind to the salivary protein responsible for oral lubrication, reducing salivation [122].

Lactisole and sweet water effect. While our results on the effect of lactisole on a sweet solution may seem mild, they point towards a secondary effect that lactisole has on liquids like water—the sweet water effect. As seen by the bump in the perceived sweetness for an umami solution, exposure to lactisole causes a “sweet water taste”, in which water tastes sweet for some time after exposure (does not apply to solids) [2]. Most likely, the lactisole *suppresses* sweetness, but the sweet water taste initially counteracts this effect. For this reason, we do not completely rule out lactisole’s well-known sweet suppression but embrace the sweet water taste effect as another opportunity for taste retargeting.

Taste modulation onset. Given our study protocol, we did not characterize each modulator’s effect during the first 59 seconds post-exposure. However, prior literature for each modulator establishes that their effect is (1) noticeable and (2) comes into effect shortly after or immediately upon exposure. Rated as “immediate effect” are lactisole [249], zinc sulfate [121], miraculin [34], and gymnema sylvestre tea [295]. While clofibric acid’s effect was measured 75 seconds post-exposure [132], our pilots suggested clofibric acid’s effect on umami occurred almost immediately after exposure. Likewise, while recent literature on amiloride suppression of saltiness was unclear on how quickly (<60 seconds) the effect started [245], our pilots suggested the change was noticeable around 30 seconds after exposure.

Study 2: Use in a VR interactive application

Our first study confirmed the effects of six modulators from literature and provided insights into their strength and duration. In our second study, we investigate taste retargeting used in an

interactive application. Here, we apply taste retargeting to help address an ongoing limitation in VR eating experiences: the sensory mismatch between a food prop and its virtual counterparts. This limitation presents a complex challenge in which our technique could offer considerable benefits. We hypothesized that the addition of taste modulators would **(H1) reduce the sensory mismatch** between a prop and each of its virtual counterparts and **(H2) make the taste of virtual foods more distinguishable**. This study was approved and determined to be exempt by our Institutional Review Board (IRB22-0260).

Participants

We recruited 11 participants aged 22-60 years old ($M = 29$, $SD = 12.3$) from our local institution. Five participants identified as women and six as men. None of the participants took part in Study 1. We screened out participants with known allergies or sensitivities to foods or prone to motion sickness. Participants were compensated with 25 USD.

Tasks

For this study, we adapted one portion of the VR experience describe in our *Walkthrough*. Similar to the study design in [24], we designed the VR scene so that participants took at least 40 seconds to find new food items. This gap ensured that our device had time to drip the modulators. Any virtual foods that users could interact with appeared at the closest suitable location (but out of view) only after delivery was complete.

Participants entered a deserted forest and were tasked with foraging food to survive. As they teleported through the forest, they could find a blackberry, then a lemon, a strawberry, and – now that no other food was available – a dead spider. For these transformations, we delivered lactisole (blackberry to lemon), miraculin (blackberry to strawberry), and finally, zinc sulfate (strawberry to spider). Before they could eat any virtual item, participants had to “wash” any virtual food they

found in a virtual pot of water. Only then could the participant use their hand to grab the virtual food from the pot, which aligned with a physical prop in the room. Following, the participant always grabbed the same pickled blackberry prop from a physical bowl. We did this to reduce the visual mismatch from tracking the real food item.

Apparatus

Participants wore a Wireless HTC VIVE with built-in headphones. The tracking area was 5×5 meters. We added a tracked table (using a VIVE tracker) to mark the prop bowl.

Participants wore an early prototype delivery system in a backpack, with the same tubing outlets comfortably hooked at the mouth corners. Through pilots, we calibrated the delivery system to go unnoticed by two authors. Our device delivered solutions at a drip of 0.05 mL per 6 seconds to reduce perceiving the modulator solution's taste and delivery. For reference, humans swallow 0.46 ± 0.31 mL of saliva every 60.8 ± 39.0 seconds [235].

Conditions

Participants experienced the VR task once for each condition in random order: **with taste retargeting** and **without** (baseline). In the baseline, participants received filtered water instead of taste modulator solutions. It is important to note that our participants were not informed in which condition they were in (baseline acted as a sort of placebo). Comparing these two conditions would then let us robustly identify the taste modulators' impact on virtual tastes.

Moreover, we did not include an electrical stimulation condition or other taste displays, as current techniques cannot produce the taste alterations described in this task.

Procedure

We took into consideration the experimental protocol discussion from *DeepTaste*. In it, Nakano et al. reported that some participants said they would have experienced something closer to the virtual food had they not seen the original prop [195]. Following, we hid all food props from the participants' view whenever they were not in VR to avoid reducing the strength of manipulation in both conditions.

After a participant had finished the VR experience in one condition, we provided a screenshot of each virtual food and asked the participant to rate how much each flavor matched the virtual food (*flavor match*) on a 7-point Likert in which 1 stood for “not at all” and 7 for “perfectly.” Next, we provided participants with a visual analog scale used to collect how different each food tasted compared to each other. The VAS was a horizontal 1630-pixel length scale (presented on a 35.56 cm laptop screen) with no anchors. We instructed participants to place four markers (one for each virtual food) on the VAS, i.e., clustering them closer if they were similar in flavor and spacing them further if different. We refer to the average of the three smallest inter-food distances on the VAS as the *average inter-flavor distance*. Participants could also provide open-ended feedback, which we transcribed. Once a participant completed both conditions, we asked them to pick which condition they preferred and asked for feedback on their experience.

Quantitative Results

We conducted a two-way ANOVA. Figure 28 depicts our main findings. We found a statistically significant effect of the food item [$F(3,75) = 27.08, p < 0.001$] and condition [$F(1,75) = 19.95, p < 0.001$] on the flavor matching score. A Tukey post-hoc test revealed that taste retargeting resulted in higher matching on average than in the baseline condition.

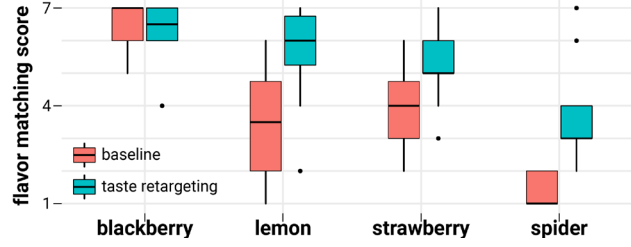


Figure 28: Flavor matching scores between conditions.

For visual clarity, we report the statistical differences from post-hoc pair-wise comparisons that used Benjamini-Hochberg-corrected t-tests in Table 2.

Preference. Of the eleven participants, ten preferred the experience with taste retargeting and one preferred without.

		baseline				taste retarget		
		blackberry	lemon	strawberry	spider	blackberry	lemon	strawberry
baseline	lemon	**						
	strawberry	**	n.s.					
	spider	****	**	**				
	blackberry	n.s.	*	**	****			
taste retarget	lemon	n.s.	*	*	***	n.s.		
	strawberry	*	n.s.	*	****	*	n.s.	
	spider	**	n.s.	n.s.	**	**	n.s.	n.s.
	blackberry							

Table 2: Summary of post-hoc pair-wise comparisons.

Distinct flavors. For the average inter-flavor distance, we normalized the distance by the scale’s length (results in the range 0 to 0.33, where 0.33 is the maximal spacing between all four items). A Shapiro-Wilk test showed that the average inter-flavor distance did not show evidence of non-normality [$W = 0.938$, $p > 0.05$]. Following, we decided to use a one-way ANOVA. We found a statistically significant effect of condition on the average inter-flavor distance [$F(1,16) = 9.0701$, $p < 0.01$]. As seen in Figure 29, the taste retargeting condition increased the perceived difference in flavor between all food items ($M = 0.25$, $SD = 0.057$) compared to the baseline condition ($M = 0.15$, $SD = 0.083$). As such, we found that taste retargeting nearly doubled the perceived difference in flavor between these virtual foods.

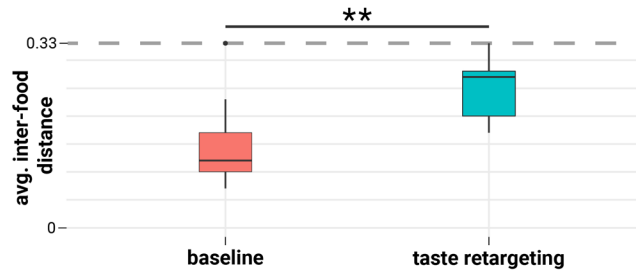


Figure 29. The average inter-flavor distance between all four food items for baseline and taste retargeting. The maximum possible result would be a spacing of 0.33 between four foods.

Tactile stimulation. Although we did not design the study to assess tactile effects, only 2 of 11 participants mentioned noticing the delivery’s tactile stimulation.

Interference. All participants ate the food props without reporting any discomfort or interference from the delivery system’s hooks.

Qualitative Results

We collected and transcribed 60 minutes of comments. We analyzed transcripts and identified three major topics (*flavor matching*, *distinct flavors*, and *incongruencies*) and two minor topics (*prop’s identity* and *limitations*).

Flavor matching

Most participants commented that taste retargeting led to better flavor matching to the intended virtual taste. For instance, after both conditions, P2 believed the taste retargeting condition was better than the baseline and added that the change in taste surmounted the little discrepancies left. “When I taste the lemon, I can feel that it’s more sour, [...] I have illusion that makes me think, ‘it’s lemon’” (P2). Likewise, P9 reported that the sourness of the lemon came out very noticeably with lactisole’s sweet suppression and that, for the miraculin transformation, the virtual strawberry was “very strawberry-like as if it were a sweet strawberry.” Many participants commented on the retargeted spider (P1-7, P9-11). To illustrate this: P9, who debated rating it a six or seven, voiced,

“a seven would be disingenuous because [they] never had a spider before, but it was the energy for what a spider *would* taste like.” P1 had a visceral reaction to the spider in the taste retargeting condition only, screaming loudly and rating it as six in flavor matching. They later stated that the baseline “was okay, but the [taste retargeting] time... perfect spider taste: it blocked everything else and had just a little bitter [...] now I can brag about, you know, eating a spider.”

Distinct flavors

Five participants (P6, P4, P5, P9, P10) stated that the flavors were clearly distinct with taste retargeting, e.g., “they’re definitely much more spread out” (P10). P9 stated, “[there] was more variance across the board in what [they were] tasting [...] felt like a more interesting and fun experience to just have the tastes be more varied: more sour sour, more sweet sweets, etc.”

Incongruencies

While taste retargeting improved the flavor matching and distinct taste of the virtual foods, three participants noted incongruencies with smell (P10) and texture (P7, P8). P10 stated that the lemon’s citrus taste was clearly present during taste retargeting, but there was also “a hint of some floral note [prop taste]” that would not typically be in a lemon. P7 noted that the blackberry’s texture was still noticeable despite the flavors matching more in the taste retargeting condition. Instead, P8 recognized the texture of the blackberry when grabbing berries. Surprisingly, given the differences between the virtual foods and prop, no further incongruencies were reported.

Prop’s identity

While most participants were unsure if the prop was a blackberry (with some asking to have it revealed after the study), they often did not discuss the prop itself. As mentioned above, P7 and P8 were outliers that recognized the prop as a blackberry from grasp or texture. In fact, P6 initially

thought they knew the prop's real identity but started questioning themselves as the modulators kicked in, "When I ate the blackberry, it felt like a perfect match, but later, [I was] less and less convinced it was a blackberry."

Limitations

Participants only stated two limitations with our chosen modulators. First, P2 reported that a very slight sweetness appeared *before* the strawberry, likely due to the miraculin taking effect on some leftover prop residue from the previous bites. Second, zinc sulfate's taste was noticeable to three participants (P4, P5, P8) during delivery, but all three stated it dissipated quickly and before they ate the food.

Discussion

Overall, the quantitative and qualitative results from Study 2 confirm both of our initial hypotheses. First, the addition of taste modulators reduced the sensory mismatch between the blackberry prop and each of its virtual counterparts (H1), as seen in Figure 28. Moreover, even if the flavor increased but did not match perfectly, taste retargeting made the taste of virtual foods more distinct (H2), as seen in Figure 29. These results are especially exciting because the complexity of retargeting a prop increases as the prop undergoes additional transformations. Moreover, as previously mentioned, taste retargeting modulates *existing* flavors. Thus, the prop's initial flavor profile must contain facets matching *each* virtual food. This consideration is not so much a limitation as a tradeoff, as taste retargeting provides a benefit in exchange: using readily available foods as props with little to no preparation. Finally, future research might address zinc sulfate's taste (noted by three participants) with techniques like mixture suppression (e.g., adding a sweetener to diminish the initial slight bitter taste of zinc sulfate).

Further applications

Our exploration of taste retargeting to reduce flavor mismatching between a food prop and virtual foods represents only one of its possible applications. Alongside opportunities for taste retargeting to potentially support future immersive experiences (e.g., online co-creation of foods or reliving food memories [48]), we highlight four potential scenarios where one might expect our technique to find further applications.

Interactive dining experiences

Chefs (and researchers) have long sought to surprise and entertain diners through all their senses, leading to new culinary approaches, like molecular gastronomy [264], digital gastronomy [317], and interactive dining experiences [35]. While certain taste modulators are not new to haute cuisine (e.g., miraculin), their interactive delivery and the opportunities for taste retargeting *are*. Taste retargeting could contribute to interactive dining experiences. For instance, Figure 30 depicts a multi-course dinner with an element of surprise: the diners use their smartphone to randomly pick a taste alteration via taste retargeting, yielding different experiences for each person.



Figure 30: (a) Diners are served a course. (b) They use their smartphone to randomize a taste alteration and (c) eat their dish. (d) Each person thus experiences a different flavor.

Speeding up recipe development

Developing new food products involves *recipe development*, a process like prototyping in design. Taste retargeting could make recipe development faster and easier, as Figure 31 illustrates. Recipe developers could produce a single test and retarget it to different taste profiles. By previewing several flavor possibilities from a single test, developers could save time and effort, speeding up the recipe development process like rapid prototyping for design.

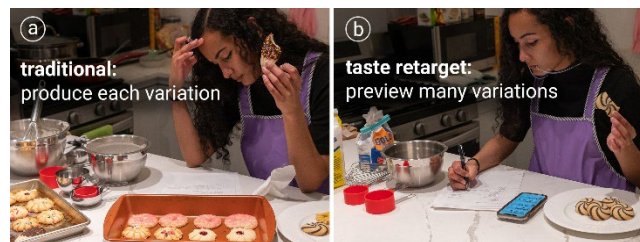


Figure 31: (a) Traditional development requires producing each recipe variation. (b) Taste retargeting could offer previews of flavor variations using a single iteration.

Embodied understanding of foods

We imagine leveraging taste retargeting so that a user can use *their tongue* to interactively understand the impact of basic tastes (or even compounds) on the flavor of *any* food, *anywhere*. For example, as illustrated in Figure 32, a user wants to understand how the 110 mg of sodium and 20 g of sugar – declared on their cookies’ nutritional label – contribute to the sensory experience. They use their phone to scan the beverage’s barcode, which accesses a database of nutritional label contents and provides the quantities to our device. By suppressing the sweetness, umami, or saltiness of their beverage interactively, the user can directly experience and understand how these quantities impact the flavor, rather than reading abstract numbers. This interaction could also lead to more playful experiences with everyday foods or better nutritional education. We were inspired by Schroeder & Flannery-Schroeder’s class exercise using gymnema tea to experience the contributions of basic tastes to flavor [248].



Figure 32: (a,b) A user scans their bag of cookies' barcode and (c) explores how saltiness or sweetness contribute to the flavor. They suppress the sweetness completely and (d) *taste* how the 20 g of sugar impacts the cookie.

Dietary interventions

Taste retargeting may also be a promising tool for dietary interventions, as sensory properties (taste, smell, sound) strongly influence food choice and intake [69]. As shown in Figure 33, our device could decrease the sweetness or saltiness of unhealthy foods to help users reduce their intake of added sugars or ultra-processed foods. Already, Turner et al. demonstrated that gymnema sylvestre can reduce the desire for high-sugar sweet foods [286]. Conversely, taste retargeting could enhance the taste of healthier, yet less palatable, foods. For example, suppressing the bitterness of vegetables to make them more appealing to individuals who struggle to consume them regularly.



Figure 33: (a) Our device responds to the user drinking a sugary carbonated beverage by suppressing its sweetness. (b) The user no longer enjoys it and (c) casts the beverage aside.

Future work

We believe this technique represents a novel step towards the selective taste alteration of real foods. Now that we know that taste perception can interactively be altered with modulators, future research may investigate the technique’s finer details.

Combining with existing techniques

As tasting represents a multimodal sensory experience, taste retargeting may benefit from combinations with existing techniques to complement with other aspects of flavor like sound, smell, temperature, or texture. For example, Weidner et al.’s results around visual and olfactory modifications [297] or Kleinberger et al.’s *Auditory Seasoning Filters* [129] could pair with taste retargeting to further reduce flavor mismatching between a food prop and virtual foods. Finally, taste sensors, like the TS-5000Z [179], might be able to further measure the effects of modulators on basic taste solutions.

More delivery mechanisms

While our implementation focused on thin tubes delivering modulators to the corners of the mouth, this is just one of the many ways to achieve taste retargeting. Future work could investigate spraying modulators directly on the food (e.g., combining with *TTTV2* [181] or spraying from a wrist-worn device), dynamically coating cutlery, or even integrating the modulators into an intro-oral device (e.g., a retainer).

More taste modulators

Given that this paper represents a first step towards using modulators for interactive taste retargeting, we opted for modulators that were readily accessible to most HCI researchers. While most of these modulators function as suppressors, there are more experimental compounds to

explore in the future that act as *enhancers*. In literature, *bortezomib* enhances sourness for mice, and in IRB-approved pilots, we noticed that trace amounts of bortezomib could drastically enhance the sourness of foods [204]—to further explore these, we recommend Deepankumar et al.’s review for details on such compounds [53]. Future research can also explore the identification of bitter enhancers, which were otherwise never a research goal in industry or academia. Alternatively, collaborations with clinics could investigate repurposing existing drugs that cause distortions in taste perception [61, 246], including characterizing their alteration and determining whether non-prescription levels of these compounds can produce selective taste alterations.

Conclusions

In this paper, we proposed *taste retargeting*, a novel technique for the selective alteration of taste perception using chemical modulators. While previous research has explored modifying taste through electrical stimulation, these approaches are limited in altering flavor and are often only effective when in contact with the user’s tongue. In contrast, taste retargeting delivers chemical modulators to the mouth *before* eating, temporarily suppressing or altering basic tastes without obstructing the ability to eat, chew, and swallow.

Our first study identified six accessible taste modulators that could suppress salty, umami, sweet, or bitter sensations and even transform sour into sweet. Building on these findings, we designed a virtual reality experience to demonstrate the effectiveness of taste retargeting in an interactive VR context, retargeting three real food props to 12 distinctly flavored virtual foods. Our second study validated the technique and reduced the flavor mismatch between a food prop and four distinct virtual foods.

Taste retargeting represents a significant step towards exploring taste modulation in interactive contexts with real foods. We believe this work points to an emerging direction in HCI, in which

chemicals provide unique methods of interfacing with the human body to unlock new interactive possibilities. We are excited to see how other researchers in HCI, nutritional & food sciences, and health will build upon and extend our findings. Future research may explore new taste modulators, smaller delivery systems, or even combinations of our technique with existing methods to refine the fidelity and applications of taste retargeting.

Stereo-Smell via Electrical Trigeminal Stimulation

The sense of smell is what allows us to understand a wide range of everyday experiences, from pleasurable ones (such as enjoying good food) to detecting potential hazards (e.g., smell of rotten food, microbial threats, and non-microbial threats such as from hazardous gases) [268].

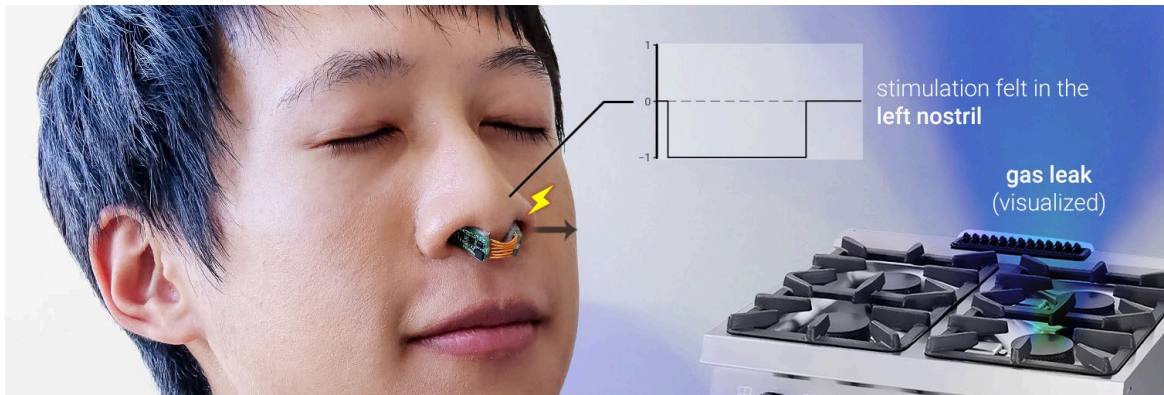


Figure 34: We propose a novel type of olfactory device that renders readings from external odor/gas sensors into trigeminal sensations by means of electrical stimulation. By stimulating the trigeminal nerve, it allows for smell augmentations or substitutions without the need for implanting electrodes in the olfactory bulb. To realize this, we engineered a self-contained device that users wear across the nasal septum, it communicates with external gas sensors using Bluetooth. In this example, it enables a user to perceive the gas's direction (i.e., to their left or right) by varying the pulse-width and current polarity of the electrical impulses. The result is that this user can quickly locate their gas leak using our device as a *stereo-smell augmentation*.

Traditionally, olfactory interfaces physically push odor molecules into the user's nose. This methodology is limiting: it requires olfactory interfaces to be built from bulky actuators (tubes, pumps, and transducers) that redirect smell from containers to the user's nose. While this works in scenarios where one can hide a large device (e.g., smells as notifications while driving [11]) these actuators are impractical for ubiquitous everyday use because their form-factor is dictated by the size of reservoirs and actuators. One of the most promising ways to break from size-limitations is to shift from analog (i.e., pushing odor molecules to the nose) to digital (i.e., stimulating the olfactory bulb to generate the odor perception) actuation. This approach has gained some attention

in the HCI community [262]. While this approach digital actuation is certainly promising, it involves risky insertion procedures with little success at reproducing smells.

Instead, we approach digital actuation from a new angle by searching for a less-invasive location to apply electrical nose stimulation, one that still works without the need for invasive and risky electrodes attached to the olfactory bulb.

The principle behind our approach is the fact that while, previously, the sense of smell was attributed to the function of the olfactory bulb alone, this notion has been revised once the contributions of the trigeminal nerve to smelling were understood. In fact, the trigeminal nerve, which has nerve-endings lodged in the nasal cavity, works in tandem with the olfactory bulb to detect the warmth, freshness, astringency, etc. of incoming odors (e.g., the freshness of mint) [23]. In other words, we do not perceive the “freshness of mint” in isolation from the “odor of mint” because the experiences of the trigeminal nerve and the olfactory bulb are often *fused* together into what we experience as a “smell.” In fact, some of our examples for the role of smell included situations in which the trigeminal sensations are key, for instance, in detecting potential hazards via the smell of noxious gases [268].

Building on this perceptual fusion between the sensations of the trigeminal nerve and olfactory bulb, we propose a novel type of olfactory substitution device that renders readings from odor or gas sensors as trigeminal sensations by means of electrically stimulating their trigeminal nerve. Our device is a new alternative to olfactory devices that stimulate the olfactory bulb via electrodes deep in the nose [299], which unfortunately require trained personnel. Our device sits across the user’s nasal septum, where it can *already* access the trigeminal nerve, unlike other devices that require the insertion of electrodes up the nasal cavity. While our device does not create an entire

“digital smell,” because it does not extend to the olfactory bulb, it does create sensations typically associated with smelling: *trigeminal sensations*.

Our device measures 10x23 mm and communicates with external sensors via Bluetooth, allowing it to fit entirely inside the user’s nose (including battery, sensors, wireless, stimulator, electrodes) like a nose-ring across the septum. While our device is self-contained, it is only capable of electrical trigeminal stimulation and requires a connection to external odor sensors (via Bluetooth) to obtain odor or gas readings. It stimulates the trigeminal nerve using an electric, biphasic waveform (using a positive and negative current) with computer-controlled pulse-width, depicted in Figure 34. This electrical waveform design is key to how our device allows users to feel via trigeminal cues: not only the intensity of the odor but also its direction, i.e., *stereo-smell*.

Walkthrough: A user smelling the direction of a gas leak

Figure 35 shows an example of a user, who while making toast for breakfast uses our device to find a gas leak. In this case, our device augments their perception, making a gas that humans cannot detect, *methane*, interpretable via the trigeminal sensation. To sense this gas, our device is connected (via Bluetooth) to a combustible gas sensor (see Implementation for details). In everyday life, gas leaks are recognizable because gas providers inject an additional odor molecule called *mercaptan*, which smells of “rotten eggs”, to alert consumers to the presence of a leak. Unfortunately, mercaptan often fails to alert users due to: temporary loss of smell (e.g., as a cause of other illnesses, such as COVID-19); smell impairments (such as anosmia, loss of sense of smell, or hyposmia, reduced sense of smell); or simply due to the unfortunately common odor masking (i.e., other smells that are stronger and mask the mercaptan) [226].



Figure 35: (a) Our user burnt their toast while making breakfast, which unfortunately emits a strong odor that masks the actual danger, a gas leak in their stove. (b) As the user inhales, our device renders the smell of methane by stimulating the user’s trigeminal nerve electrically and to the left—indicating the location of the methane gas leak, which is tracked via an external odor sensor that relays these readings to our sensor via Bluetooth. (c) This allowed the user to find the leak.

To this user these limitations are not a problem, since our device allows this user to perceive the gas leak (the methane sensed by the external combustible gas sensor) by feeling *a tingling sensation inside their nose* which is *synchronized* with their breathing-in, depicted in Figure 35 (b). This sensation is a trigeminal cue, like the sensation when smelling white vinegar.

To render this trigeminal sensation: (1) our device detects inhalation by measuring the flare of the user’s nostril with a photoreflector (i.e., as the user breathes in, their nostrils enlarge); (2) then, as the user inhales, our device stimulates their trigeminal nerve with an electrical impulse which renders both the intensity of the gas, and its direction (i.e., to the left or right of the external odor sensor). The latter is particularly useful to locate odors in space and allows this user to experience *stereo-smell for methane*. As such, as depicted in Figure 35 (c), they find that it is their stove, which is to their left, that is leaking the gas and it is not the burnt toast smell to their right. As we will detail in our implementation and study, we induce this stereo-smell sensation by varying the electrical characteristics of the stimulation waveform (pulse-width and polarity).

Related Work

The work presented in this paper builds primarily on the fields of electrophysiology, olfactory interfaces, and sensory substitution. Also, to familiarize the reader with the underutilized trigeminal nerve, we present an overview of its functions.

Sensory substitution

Sensory substitution involves a translation of information from one sensory modality to another. Sensory substitutions for vision are most common and translate images into other modalities, usually as assistive devices for visually impaired individuals. For instance: *SmartTouch* is a system that uses electrotactile stimulation on the skin to render an image [117]; and, the *tongue display unit* is a tactile-vision sensory substitution system which translates an image from a camera into electrotactile stimulation on the tongue [11]. Other popular sensory substitutions involve image-to-sound, such as Meijer et al.’s device [174].

Olfactory sensory substitution

While sensory substitution for vision has been extensively researched, little research has investigated the translation of olfactory cues into other sensory modalities. Two key contributions in olfactory substitution have investigated the translation of non-olfactible gaseous compounds (e.g., combustible gases, such as methane) into detectable stimuli for humans. The *Olfactory Assist Mask* is a wearable that converts metal-oxide gas sensor responses to combustible gases that cannot be smelled into actual smells, such as the fragrance of apple [169]. Choi et al. engineered a wearable augmentation that converts detected combustible gases into vibrotactile stimulation on the forearm [41]. Unfortunately, as far as we know, no other existing works explore the substitution of olfactory cues to other sensory modalities.

Trigeminal system

The trigeminal nerve (cranial nerve V) is a somatosensory nerve primarily known for sensing mechanical and thermal stimulation, sensing changes in pressure, vibration, or temperature [175]. A lesser known property of the trigeminal nerve is that its receptors (the transient receptor potential ion channels) *also* respond to airborne particles [175]. It is their ability to detect both airborne particles and temperature shifts that explains why scents such as peppermint feel cool [173]. The effects of the trigeminal experiences are readily recognizable in everyday life, e.g., eating or smelling spicy food, pungent flavors, and breathing cold air [1]. What is remarkable is that *humans rarely experience pure olfactory or pure trigeminal sensations in isolation*—in other words, these senses are uniquely intertwined.

Trigeminal-Olfactory fusion

Though the trigeminal and olfactory bulb have different structures and functions, most smells simultaneously activate *both* systems, each contributing to the overall perception of smell (e.g., freshness of menthol being inseparable from its minty odor). There are few chemicals that selectively stimulate only one of the two: *carbon dioxide* only stimulates the trigeminal nerve and *vanillin* only stimulates the olfactory bulb. Several electrophysiological and imaging studies have demonstrated that the perception of trigeminal and olfactory systems is intertwined and that these systems influence one another [23, 99, 158, 159]. For further detailed information, Brand et al. present a thorough review of literature on the interactions between the olfactory bulb and the trigeminal nerve [23:200].

Trigeminal interfaces

Our device is inspired by four recent interactive systems that stimulate the trigeminal nerve. The first two interfaces leverage the interactions between the thermal-side of the trigeminal nerve and olfactory bulb to modulate the perception of an odor: Fujino et al. change the temperature of the air to modulate the perceived odor [76]; and, similarly, *affecting tumbler* is a cup lid that thermally stimulates the skin around the nose during drinking to modulate the perceived flavor [276]. The other two interfaces leverage the chemical side of the trigeminal nerve, creating a temperature sensation. In *Season Traveller*, Ranasinghe et al. utilize peppermint essential oil (which contains menthol) to stimulate a cooling sensation for their VR winter environments alongside thermoelectric materials [220]. Similarly, Brooks et al.’s wearable device induces temperature illusions, both hot and cold, by delivering aerosolized trigeminal stimulants to the user’s nose [24].

Unlike these devices, our approach is the first wearable device to *electrically* stimulate the trigeminal nerve endings in the nose. This has several advantages when it comes to sensory substitution: (1) it is a much smaller device (no need for liquids, reservoirs, pumps, large batteries, etc.); and (2) stimulation patterns can be controlled at the microsecond level, which is difficult to achieve using liquids or gases.

Intranasal electrical stimulation of olfactory bulb and trigeminal nerve

Previous neuroscience and physiology research have investigated the perceived sensations of electrical stimulation of the nasal mucosa and olfactory epithelium.

Researchers have been exploring reproducing smell via electrical stimulation of the olfactory bulb. Such stimulation requires a trained experimenter to insert a long prong up the user’s nostril to touch the olfactory bulb (brain region at eye-level) with an electrode, holding the electrode-prong in place to maintain constant contact with the olfactory bulb. Unfortunately, most

researchers either fail to produce such smell percepts via electrical stimulation of the olfactory bulb [93, 271, 299] or fail to produce consistent sensations among participants [40, 93]. Nonetheless, they all succeeded to produce several unintended *trigeminal* percepts, such as warm, tingling, painful, etc.

In contrast, less research has been devoted to electrical stimulation of intranasal trigeminal nerve-endings. Most notable is Iannili et al.’s studies that confirmed that electrical stimulation consistently elicited trigeminal sensations, rather than olfactory ones [101]. The sensitivity threshold for the trigeminal nerve was determined to be at 0.6 mA and upper-threshold stimuli to be 1.8 mA for electrical stimulation [101].

Stereo olfaction and odor lateralization

Humans can track an odor and follow its route by searching and comparing different locations in an odor field, i.e., by sampling different locations one builds a mental map of odor intensities. However, this process is not what we typically would call “stereo-smell” as the user needs to move to sample the space. Surprisingly, there is recent evidence that humans do exhibit stereo-smell even when standing still, however these sensations are pre- or non-conscious and cannot be verbalized [304]. When non-trigeminal smells arrive at the olfactory bulb via different nostrils, they moderately bias humans’ perceived direction of self-motion towards the nostril with a higher concentration of the smell, but when asked users cannot verbalize which nostril smells stronger [304]—this is called *stereo-olfaction* (as in olfactory bulb).

On the flipside, the trigeminal nerve is capable not only of recognizing the concentration of trigeminal-odors in the different nostrils, but its user is capable of verbalizing it, i.e., we can consciously tell in which nostril we smell more of a particular trigeminal odor [50, 131, 247]—this is called *trigeminal lateralization*.

In contrast, pure odorants such as *vanillin* (the core ingredient in the smell of vanilla) cannot be consciously used for spatial navigation, but trigeminally irritants such as *menthol* (minty fresh compound) yield lateralization rates of more than 96% [131].

As discussed, the trigeminal system responds to mechanical, chemical, and electrical stimulation [101]. When electrically stimulating the olfactory epithelium (which includes trigeminal innervation [244]) in one nostril, participants reported localizing the stimulation to the stimulated side [66, 85, 93, 101, 103], suggesting one may also accurately lateralize electrical stimulations detected by the trigeminal system. We take advantage of these neuroscientific observations to propose using the electrical-sensitivity of the trigeminal nerve for stereo-smell.

Framing our approach: lateralization via electrical stimulation of the intranasal trigeminal nerve

This lateralization, which is a unique feature of the trigeminal nerve, is what our device leverages to allow users to experience a kind of “stereo-smell”; one that is not driven by the olfactory bulb but instead by the electrical stimulation of the trigeminal nerve. To leverage this lateralization, we designed our novel device to be *inside* the nose and stimulate the nasal septum, where the trigeminal nerve can be easily found [74]. While theoretically one might be able to access the trigeminal nerve by electrically stimulating different areas of the nose, we found that not only the septum was more easily accessible, but other areas of the nose did not work in our initial experimental pilots.

Furthermore, it is worth emphasizing that we found that while our approach shares some similarities with electrotactile skin stimulation (e.g., [116, 118, 282]), our approach is in fact *specific* to the trigeminal nerve inside the nose. While the area where we attach the electrodes is also skin (hence the apparent similarity to electrotactile), yet, as we will demonstrate in our studies,

electrical stimulation of the septum creates lateralizable sensations. Feeling the direction of the current is something that we found to be unique to the nose's trigeminal nerve; in fact, to support this assertion, we placed our device across the finger pad, but we failed to elicit any lateralization in the finger pad's skin.

Benefits, Contributions, and Limitations

Our key contribution is the first wearable device that fits in the user's nose to electrically stimulate their trigeminal sense. Our device enables users to feel, via trigeminal cues, not only the intensity of an odor but also its direction (i.e., to their left or right).

Our approach has four key benefits: (1) as we observed in our second study, users are able to make use of our device to locate smells **without any training**; (2) this new modality (electrical trigeminal stimulation) can also be employed as an assistive device for smell-impaired individuals, because it electrical stimulating the trigeminal nerve, which remains functional in most anosmics, instead of the olfactory bulb; (3) it is an safe alternative to electrically stimulating the olfactory bulb with electrodes inside the user's nose, which require surgical and invasive procedures; and, (4) it is the first wireless and self-contained interactive device that can be worn nasally, providing an alternative means for trigeminal stimulation without the use of chemical reservoirs, utilized in prior research [24, 220].

However, our approach is not without its limitations. (1) We purposely explored electrical stimulation of the trigeminal nerve rather than the olfactory bulb for accessibility reasons. This means that our device is limited to the creation of trigeminal sensations—as such our stereo-smell is trigeminally induced: in other words, this is not a traditional olfactory device (one with chemical-based odors). (2) While our device is entirely self-contained (including battery, sensors, wireless,

stimulator, electrodes), it is only capable of trigeminal stimulation and depends upon a connection to external odor sensors (via Bluetooth) to obtain odor readings.

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.

Figure 36 shows our complete and self-contained prototype, including its battery. It measures 10x23x5 mm in one nostril, 10x23x7 mm in the other, and weighs 3.4 g.

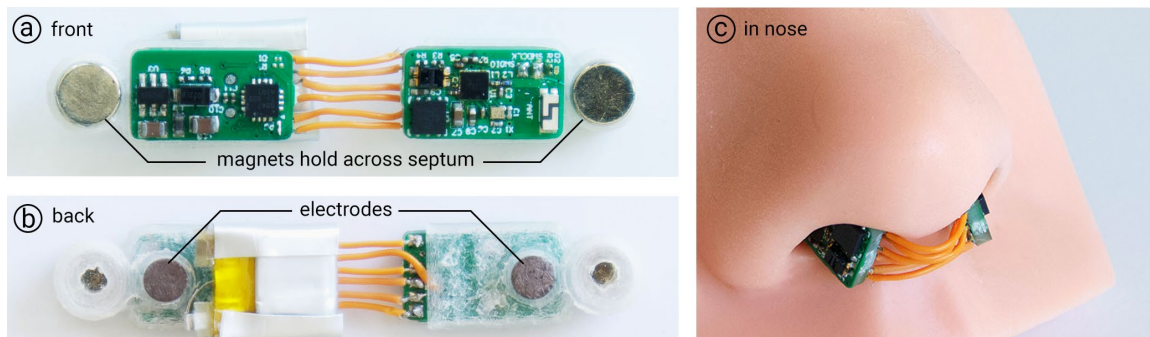


Figure 36: (a, b) Our device is comprised of two printed circuit boards (PCB), one in each nostril. (c) Small magnets on each side allow the device to hold securely to the user's nose by means of magnetism.

To implement our device, we utilized an nRF52811 (Nordic Semiconductors) as the system's microcontroller, because of its small size as well as integrated ARM Cortex M4 and Bluetooth Low Energy (BLE) radio. We leverage the BLE to communicate with external devices, such as gas sensors or even mobile phones.

² <https://lab.plopes.org/#stereo-trigeminal>

Design of our intranasal stimulator (output)

To create an electrical stimulation of the user's trigeminal nerve, we designed our own stimulator based on the results from our Studies 1 and 2; its circuit design is depicted in Figure 37 (a). We did so because no existing stimulator would fit in the user's nose. Additionally, the septum is an ideal stimulation location as trigeminal stimulation is perceived as stronger in the front of the nasal cavity [74]. To create the stimulation waveform depicted in Figure 37 (b), we utilize a DRV8847 (Texas Instrument), a dual h-bridge capable of outputting up to 18 Vpp in a 3x3 mm footprint. The voltage supply for the stimulation is generated from a MT3608 (Aerosemi Technology) boost-converter with adjustable voltage output, which we set at 18V. The parameters of the generated waveform (such as pulse-width or current polarity) are generated by the microcontroller by controlling the h-bridge's enable and direction.

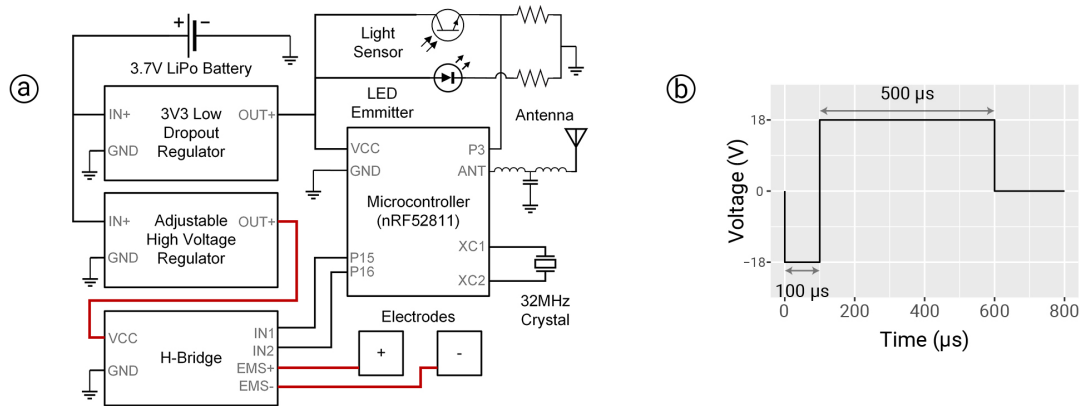


Figure 37: (a) High-level schematic for our device's hardware and (b) a stimulation that creates trigeminal sensation to the left nostril (i.e., a lateralized sensation to the left; more details of how we found these waveforms in our first user study).

Lastly, to deliver the electrical impulses from our stimulator to the user's trigeminal nerve, we utilize two silver/silver chloride (Ag-AgCl) disc electrodes, which protrude on the back side of each PCB. Thus, these act as points of contact with the nasal septum for stimulation. Ag-AgCl

electrodes were chosen because they do not corrode over time, as it is common with copper or other types of electrodes.

Design of our intranasal nostril movement sensor (input)

To allow users to feel the trigeminal sensations in a realistic manner, we coupled the stimulation to the user's breath-in phase. To track the breathing patterns, we added a SG-105F reflective-type infrared photo interrupter (Kodenshi Corp) on the PCB, angled directly outwards to one of the user's nostrils, as depicted in Figure 38. We sample this sensor at over 100 Hz (at a 12-bit resolution) to measure the distance between nostril and PCB as the user's nose flares during the breathing cycle; it is known that nostrils enlarge as we breath in [134]. Furthermore, users can turn on/off the stimulation by quickly inhaling three times; moreover, we acknowledge there are other methods to handle nose gestures as input [147].

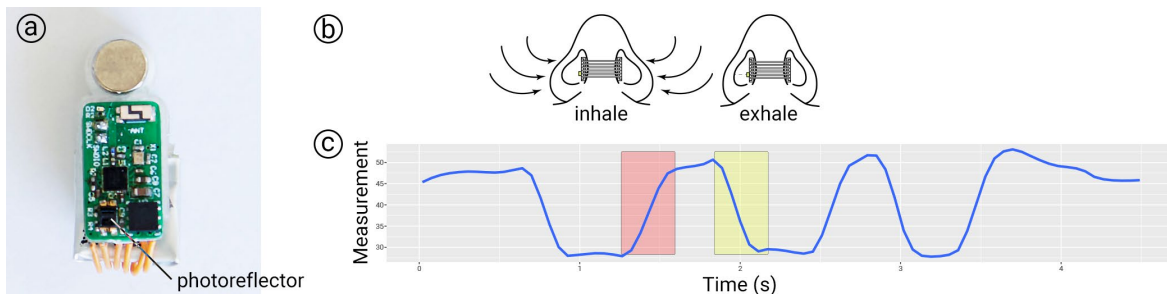


Figure 38: (a) To stimulate the during inhalation, we use a photo-interrupter. (b) The sensor measures how nostril flares during inhalation. (c) In turn, this flare creates an increase in the distance between the photo-interrupter and the nostril.

Securing our device inside the user's nose

To ensure the device makes good contact with the user's septum without the need for implantation (e.g., such as an actual nose ring) we use two magnets, one on each side of the PCB. The magnets hold the device in place by attracting each other, even across the nasal septum. The use of magnets

also allows a user to snap the device on or off their nasal septum, without any overly complicated insertion procedure.

Battery Life

We power our device using a 10 mAh lithium polymer battery (PGEB201212, General Electronics Battery Co.). It draws an average 0.2 mAh while connected wirelessly to an external odor sensor using BLE. To this, it adds an additional current draw of 0.05-1 mAh during electrical stimulation. Thus, at an average of 12-20 stimulations per minute (human's average respiratory rate [231]), our device runs for around one hour using a single battery. Note that a second one can be added to the other PCB to double the battery life.

Pairing our device with an existing stereo gas sensing device

While we chose to focus our contribution on the stimulation side of our device, which is entirely novel, the sensing side is important to close the loop between odor-sensing and stimulation. There is a wide range of approaches that previous engineers and researchers have devised to sense the intensity of a gas, such as methane, in the air. The most popular approach is to use metal oxide sensors (often also referred to as combustible gas detector) to determine the location of a gas source [31, 233, 241, 278]. Additionally, researchers have employed gas sensors in wearables, such as wristbands, for personal air quality monitoring [160, 166, 215].

As such, to complement our device and to demonstrate it in a closed-loop fashion, we replicated the sensor design of Kohnotoh and Ishida's *ASNose* [137], using two 3.0 V pumps (SC3101PW) and two metal-oxide sensors (MiCS-5524); this configuration is referred to as an "active stereo nose" as it detects the gas's direction (i.e., to the left or to the right) by comparing intensity of the readings on both sensors. We sample the metal-oxide sensors systems using a

RedBear DUO BLE microprocessor. The gas' direction and intensity are sent directly from the sensor-device to our intra-nasal device with Bluetooth.

Study 1: Intensity & direction using electrical trigeminal stimulation

Our first study aims to understand the relationship between the stimulation parameters and the perceived direction and intensity. We hypothesize that different stimulation patterns result in different trigeminal sensations. Our study was approved by our Institutional Review Board (IRB20-0308). User Study 1 and 2 were completed before our device implementation, as we used these studies to inform the stimulator's design.

Apparatus

A simplified version of our wearable device was used. Participants wore a 3D-printed nose clip with Ag-AgCl electrodes (same as used in our final device), but this time connected to a Hasomed RehaMove 3, a medically compliant functional electric stimulator. We used this stimulator as it allowed us to vary all possible waveform parameters prior to designing our own device based on the study findings. Once we found the relevant waveform parameters from this study, we started the design of our own stimulator to support those waveforms.

Prior to the start of the study, we asked participants to insert the nose clip into their nose such that the bridge was flush against the bottom of the nose and the pressure felt even across the septum.

Stimulus Design

Since our study was the first to explore the sensations that arise from electrical stimulation across the septum, we aimed to vary as many waveform parameters as possible to maximize our insights into this novel modality. Following, we varied the three parameters of a typical squared stimulation

waveform: (1) pulse width, (2) polarity, and (3) phase order. We fixed the frequency of stimulation at 62 Hz and the intensity of each pulse was at 1 mA, within the range of noticeable yet pain-free electrical stimulation as shown in [101].

Pulse width: We utilized pulse widths of 100 μ s, 250 μ s, and 500 μ s for each pulse phase. All 0mA phases were reduced to a pulse width of 0 μ s to avoid redundancy.

Waveform polarity: We designed our study around the two traditional types of electrical stimulation waveforms, which are depicted in Figure 39: (a) monophasic (only one polarity, as in DC currents); or, (b) biphasic (i.e., current switches direction, as in AC currents).

Phase order: Additionally, the phase order was variable, e.g. positive first or negative first, which is depicted in Figure 39 (a) and Figure 39 (b) respectively.

Thus, all combinations of the parameters above result in a total of 25 different waveforms (the total was in fact 75, but to avoid redundant stimulations, we removed all waveforms that starts with a pulse of 0 mA intensity).

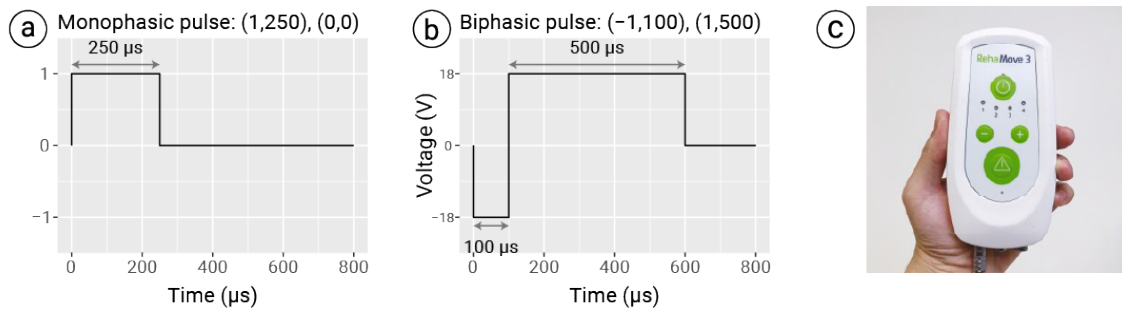


Figure 39: Two example pulses, of which (a) is monophasic and (b) is biphasic. (c) The Rehamove signal generator, which we used in our studies.

Trial design and procedure

Each participant performed a total of 75 trials: 25 possible waveforms x 3 repetitions. Waveforms were presented in a randomized order across participants.

Per each trial, participants felt one brief electrical trigeminal stimulation (out of the possible 25), delivered to across their nasal septum. Each stimulation contained a sequence of 20 impulses, lasting a total of 322 ms. After each trial, participants rated the stimulation **intensity** (1=“did not feel”; 7=“most intense”) and **direction** (-3=left; +3=right) using 7-point Likert scales.

Participants

We recruited 10 participants from our local institution (4 women, 5 men, and 1 non-binary person) aged 20-25 years old ($M=22.7$, $SD=1.9$). Participants received 25 USD compensation for their time. Participants were given the Nasal Obstruction Symptom Evaluation (NOSE) 5-point Likert Scale [269] at the start. With it we confirmed that no participant had nasal congestions or stuffiness ($M=0.5$, $SD=0.53$), blockages or obstruction ($M=0.2$, $SD=0.42$), trouble breathing through nose ($M=0.5$, $SD=0.53$), trouble sleeping ($M=0.5$, $SD=0.53$), or difficulty breathing through their nose during exercise or exertion ($M=0.1$, $SD=0.32$).

Metrics for analyzing electrical waveforms

Towards our results, we describe the aggregated electrical properties of our waveforms using two existing metrics, which are exemplified in Figure 40: the total electrical charge, which represents the sum of all charges over time regardless of sign; and the net electrical charge, which represents the charge imbalance.

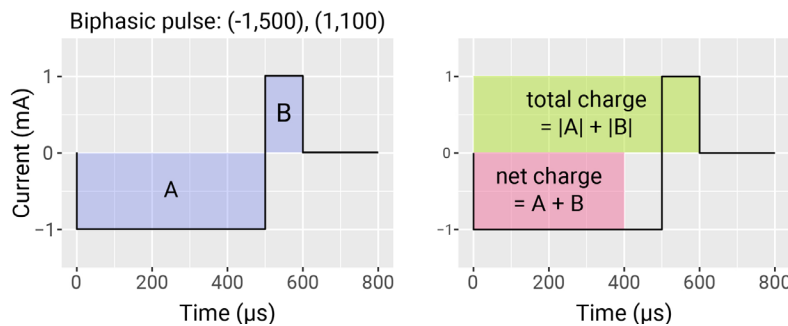


Figure 40: Metrics used to analyze the electrical waveforms are *total charge* (yellow) and *net charge* (red).

Results

We conducted a one-way MANOVA and used Bonferroni-corrected t-tests. Figure 41 depicts ratings for (a) lateralization and (b) intensity for all 25 pulse candidates.

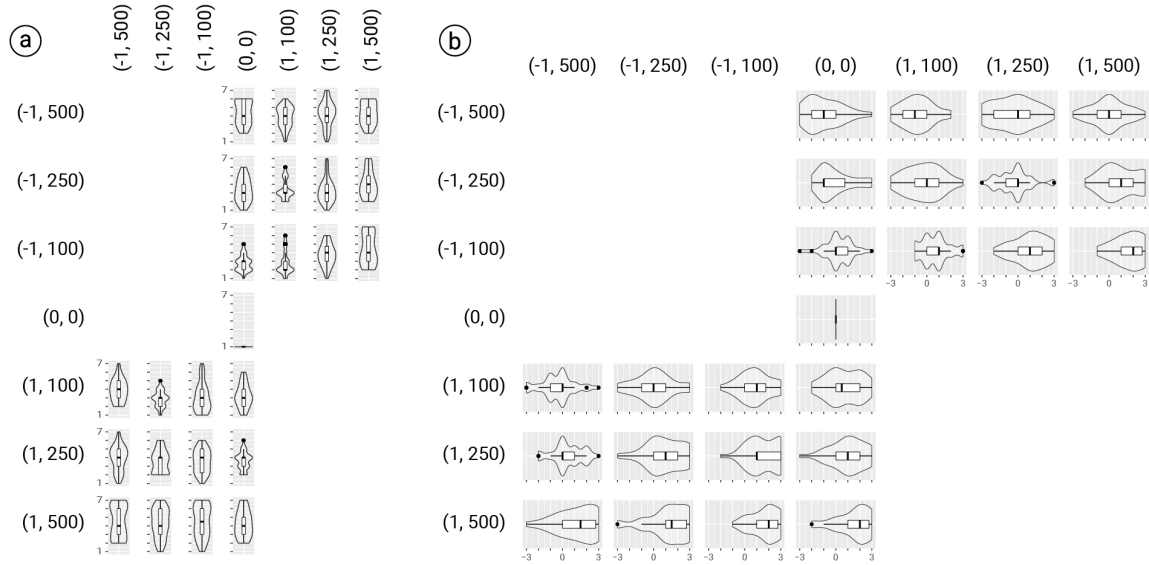


Figure 41: Participants reported the (a) intensity and (b) lateralization of all 25 pulse candidates. The left-most column and top-most row represent the pulse's first and second phases, respectively.

First, we examined the perception of the **intensity** of the stimulation for the different waveforms. We found a statistically significant effect of total electrical charge on reported intensity [$F(7,719)=10.5$, $p=1.2e-12$]. Of the eight total electrical charges, all were statistically significant, except for 250 mAs and 500 mAs. This suggests that, as total charge increases, we tend to observe an increase in perceived intensity, as depicted in Figure 42.

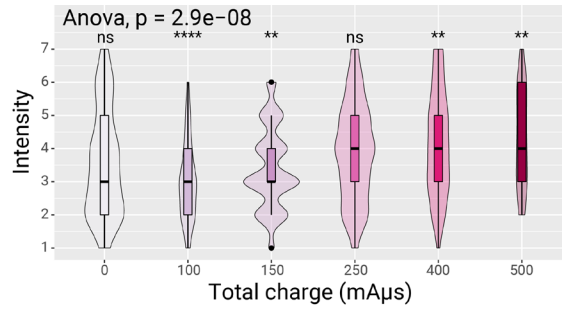


Figure 42: Perceived intensity ratings for the different waveforms according to their total charge.

Secondly, we examine the perception of **direction** (also known as trigeminal lateralization). We found a statistically significant effect of net electric charge on reported lateralization [$F(10,719)=16.8$, $p<2.2e-16$], as shown in Figure 43 (a). Of the 11 possible net charge values, all were statistically significant, except for -100 mA μ s, 0 mA μ s, and 100 mA μ s; suggesting that net charge influences perceived lateralization.

Additionally, we found that the phase order (whether the pulse began with a negative or positive stimulation) also had a significant effect on perceived lateralization [$F(1,719)=41.3$, $p=2.3e-10$]. As depicted in Figure 43 (b), pulses beginning with a positive phase were typically perceived as right-sided stimulus.

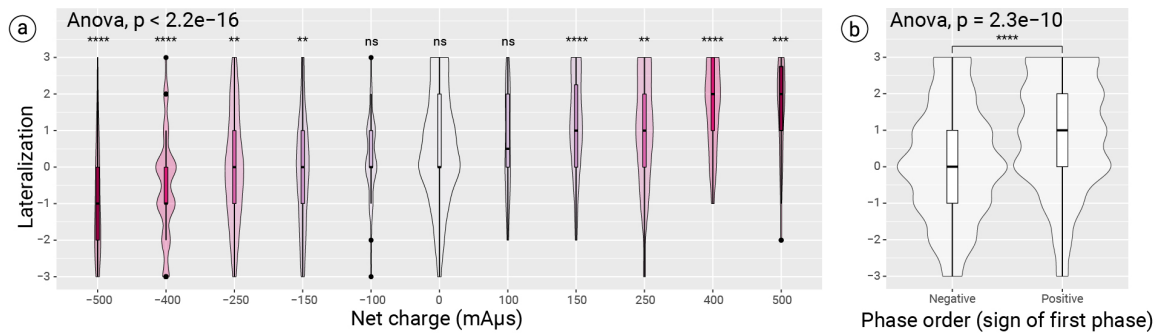


Figure 43: (a) Perceived lateralization (direction) of the different waveforms based on their net electric charge. (b) Pulse candidates were categorized as either starting with a negative or positive current; (0,0)-pulses are excluded. Participants ultimately rated pulses starting with a positive phase as more to the right.

Resulting waveforms that achieve multiple intensities and directions

To make use of our findings we chose nine pulses that allow us to render three intensity levels (low, middle, high) and three directions (left, center, right), which are depicted in Figure 44.

The final set of waveforms is: at a **low intensity** $(-1, 250)$, $(1, 250)$ for **left**; $(-1, 100)$, $(0, 0)$ for **center**; and $(-1, 100)$, $(1, 100)$ for **right**; at a **medium intensity** $(-1, 250)$, $(0, 0)$ for **left**; $(1, 100)$, $(-1, 250)$ for **center**; and $(-1, 100)$, $(1, 250)$ for **right**; lastly, at a **high intensity** $(-1, 500)$, $(0, 0)$ for **left**; $(-1, 500)$, $(1, 500)$ for **center**; and $(1, 500)$, $(-1, 100)$ for **right**. Next, we will put these waveforms to an actual test in our User Study 2.

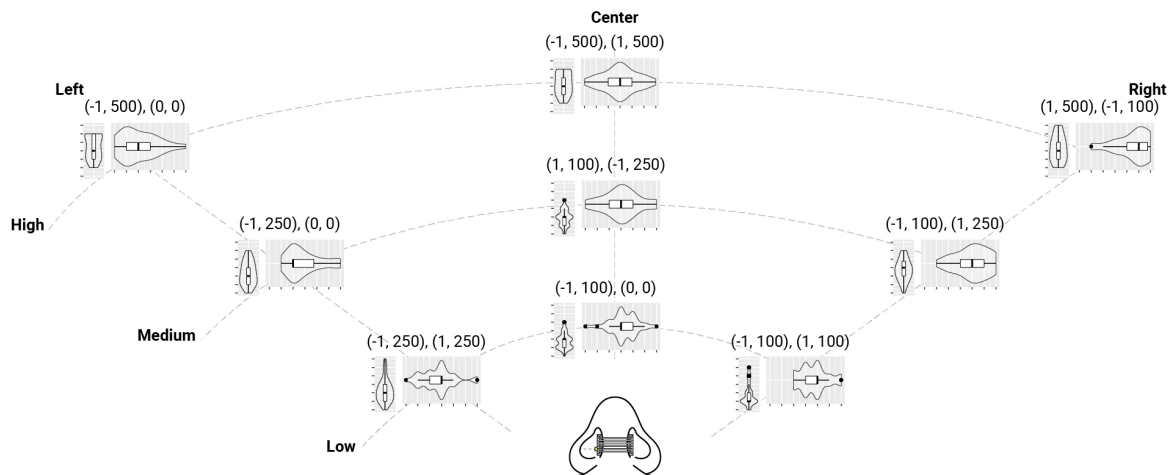


Figure 44: Our suggested pulses are divided into three directions and three intensities to render both changes in source location and proximity. Each pulse shows its reported intensity (vertical plot) and reported lateralization (horizontal plot).

Qualitative Feedback

All participants commented being interested in and entertained by the sensation; no pain was reported by any participant. P6 reported a watery nasal drip and had to blow their nose. This was consistent with the type of dripping that occurs when eating trigeminal stimulants in food, such as in spicy food [225]. The drip ended as soon as the study was completed, and no other participants reported similar experiences.

Study 2: Finding an odor using our (electrical) stereo-smell

In our first study, we found the waveform parameters that allow us to render the intensity and direction of an odor via electrical trigeminal stimulation. As such, in our second study, we aimed to determine whether participants new to this modality, could make use of these trigeminal cues to locate an odor source. As such, our study's objective was explorative: we were not aiming to show which condition improved gas source localization, but instead were interested in seeing whether localization using electrical trigeminal stimulation had similarities to how we ordinarily navigate gas sources.

Apparatus

Participants explored a simplified, virtual reproduction of the testing space using a Wireless HTC Vive, headphones, and the same stimulator and nose clip from our previous study. The tracking area was approximately 5 x 5 meters, and this study was conducted in the same location as our previous study. The virtual space and VR headset served as a "blindfold" so that the participant was unable to see where the odor source was placed but would be alerted by the headset to walls as they approached them. Our experiment was conducted in a ventilated laboratory, with one perforated duct ventilation (500 CFM) and two fume hoods. The ambient temperature was kept at 24°C.

A fan was placed at a 45-degree angle, approximately 2.5 meters away from the participant at one of 3 pre-selected locations. Using an anemometer, the fan's wind speed was 2.7 m/s at 5 cm away from the fan and 0 m/s after 50 cm. From pilot studies, participants were not able to feel the tactile stimulation of the fan, and as the fan produced no measurable wind space after 50 cm,

unintentional tactile stimulation from the fan was ruled out as a confounding factor in navigating the odor field.

Conditions

Participants were presented with two possible conditions: navigating a *real* or *virtual* odor field.

Real odor field

In the real odor field condition, a small cup filled with a 50% v/v peppermint essential oil in ethanol solution is placed behind the fan to inject a steady stream of mint/menthol throughout the task. The participant was asked to localize the source with their sense of smell, while wearing the nose clip but not receiving any stimulation. Note that adding a real odor field condition setup was not unique to our study design, as this setup is often used in gas source localization studies, which typically involve gas searching robots [30].

Virtual odor field

The participant was asked to localize the virtual odor source using the trigeminal stimulation. In this *virtual odor field* condition, as there was no odor. Instead, we simulated a turbulent virtual odor field in a simulated laboratory space matching ours as closely as possible. We did this to exclude any potential confounds from tracking odor sources using external sensors, all of which have tracking errors that are not what we are interested in measuring. On the contrary, simply guiding participants via perfect left/right cues to the source is unrealistic as odors move fluidly and turbulently through air, and as we smell around in the real world we also deal with these turbulences. As such, a simulated odor field *with turbulences* proved the best setting to gather a realistic understanding of our device. Adding these turbulences allowed us to make the conditions more comparable. The inclusion of a simulated odor field condition is also not unique to our study

design, previous olfactory work has leveraged CFD for modeling virtual conditions: "[CFD] enables us to have the dynamic odor concentration distribution even if we have complicated obstacles in the virtual environment" [192].

To simulate the virtual odor field, we used ANSYS, a computational fluid dynamics (CFD) software, to mimic as many parameters as possible from a real odor field: (1) we added turbulent air sources from the fan, HVAC, and participant movements in the space; (2) we added the odor's dynamic viscosity, which was estimated by that of liquid ethanol at 24°C and 1 bar, approximately 1.1 cP. The simulation's timestep results (around 41M air flow intensity samples from ANSYS) were then exported, segmented using a simple Bounding Volumes Hierarchy algorithm, and imported into Unity3D. From Unity3D, a script simulates the detection of the odor, comparing the odors concentration captured in two Unity3D colliders, one for each nostril. To emulate the tidal breathing, each collider is approximately 0.25 L in volume. We then separately sum the concentrations of any odor samples within the colliders for each nostril to get estimated inhaled odor concentrations. The estimated intensity of the odors uses the following equation based on Murphy's results for varying menthol concentrations [190],

$$i = 2.5 \times \left(\frac{c}{1.7}\right)^{0.617}$$

where i is the estimated intensity and c is the total inhaled menthol concentration. Additionally, we cut off any concentrations below 1.4e-3 ppm to reflect human odor detection threshold of menthol [47].

Finally, we map the estimated intensity to three intensity levels for stimulation obtained in our User Study 1 (see Figure 44). Estimated intensities under 3 were mapped to the low intensity stimulations. Estimated intensities between 3 and 6 were mapped to medium intensity. Finally, estimated intensities above 6 were mapped to high intensity. The Unity3D script then stimulates

the participant's nose 24 times per minute with a short trigeminal cue. Our CFD simulation and study scripts are provided to assist with replication of our study¹

Task and Procedure

Participants performed a total of four trials: 2 conditions x 2 repetitions; the order of trials was randomized.

Per trial, participants were asked to navigate the room and identify where the odor source (either real or virtual) was by declaring when they finished and standing at the estimated location. The examiner then measured the distance between the user and the target. Participants were given 5 minutes to complete the task, and—at the end of the allocated time—were given a few seconds to make a forced choice.

Most importantly, we designed this procedure to have **no training**. We never shown the stimulation to the participants beforehand nor there were any “habituation trials” or explanations. We just let them locate the odor.

Deodorization

After each trial, the participant was asked to take a 12-minute break outside of the testing room. During this time, the examiner deodorized the space. For odor control with ozone oxidation, we used a portable ozone generator that outputs 50 mg/h. To comply with OSHA exposure limits in a workspace (0.2 ppm for no more than 2 hours exposure [142]), we only emit 10 mg of ozone for the entirety of a study with one participant (not counting the ventilation). Following, the ozone generator is placed at the gas source location and turned on for only 6 minutes (5 mg of ozone) after real odor field condition trials.

Participants

We recruited four participants from our institution (two self-identified as women and two as men) aged 20-40 years old ($M=30.3$, $SD=6.55$). Participants were given an intake form at the start of the study. Of the four participants, three participants reported using VR before and one reported experiencing VR with smell before. Participants were given the Nasal Obstruction Symptom Evaluation (NOSE) 5-point Likert Scale [269] at the start. With it we confirmed that no participant had nasal congestions or stuffiness ($M=0.5$, $SD=0.58$), blockages or obstruction ($M=0.25$, $SD=0.5$), trouble breathing through nose ($M=0.5$, $SD=0.58$), trouble sleeping ($M=0.75$, $SD=0.96$), or difficulty breathing through their nose during exercise or exertion ($M=0$, $SD=0$). Additionally, we asked that participants estimate how well they detect odors in their daily lives: of the 4 participants, 2 reported normal smell function, 1 reported higher sensitivity, and 1 reported not detecting odors frequently. Finally, we asked participants to rate how often they experienced a runny nose after eating spicy food on a 5-point Likert Scale, which they reported experiencing every so often ($M=2.25$, $SD=1.26$).

Results

Considering the small sample size ($N=4$), we opted to discuss the measured data without invoking statistical tests. Our results are depicted in in Figure 45. We observed that even without any training or calibration phase participants in the virtual condition halved their average distance (m) to the target ($M=0.631$, $SD=0.337$) compared to the real condition ($M=1.20$, $SD=0.585$).

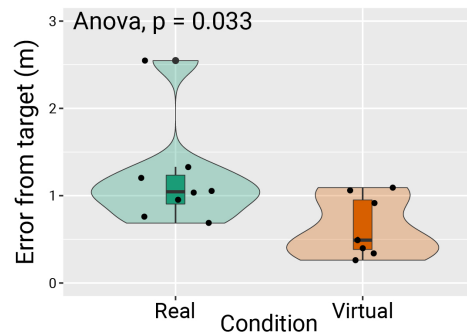


Figure 45: On average, participants were closer to the odor source in the virtual condition than in the real. Note that there was **no training** phase whatsoever in our study and these participants had no experience with our electrical trigeminal stimulation.

Qualitative Feedback

Of the four participants, only one reported experiencing some nasal drip after one virtual odor trial. Participants reported that the electrical stimulation was clear and easy to use. P1 and P2 shared that their confidence locating the virtual odor field was much higher than when locating real odors. Similarly, P3 describes the electrical stimulation as “strong, loud and clear,” and P1 refers to the experience as “clear zaps”. Most participants reported that the electrical stimulation felt like a new sensation (P1, P3). Participants were able to distinguish levels of intensity and direction at different rates: P3 specifically mentioned the directional sensation and P2 reported distinguishing two intensities as well as two “nostril type stimuli”; P2 shared that they wished the stimulation were more constant, which is why our final device is tied with the user’s breathing cycle. Finally, most participants reported interest or excitement about the sensation (P1, P2, P4), though P2 shared that the stimulation in fact made them want to avoid the smell instead of pursuing it but did find the experience fun.

Discussion

As we observed in our second study, users are able to make use of our device to locate smells without any training, we expect this to be the case as these sensations are similar to those elicited by the trigeminal nerve upon chemical or thermal stimulation (e.g., eating spicy food or inhaling cold air), which previous research has shown to be easily lateralizable. Additionally, we believe this contributes to the potential success of the system's olfactory substitution, as users would not need a long learning phase to use the directional sensation's information. This is in stark contrast to other types of sensory substitutions – such as that of the tongue display unit [11]– which require careful training to make sense of the new mapping.

As P1 reported, the sensation is unique and does not feel like smell (echoing results from prior papers such as [299]). This may be due to the waveforms not being designed to elicit more subtle stimulation (as 1 mA is already perceived quite intensely [101]), no variation *during* a stimulation itself, and because the RehaMove 3 does not provide stimulation in phase with inhalation nor varies stimulation based on the participant's sniff strength (e.g., P2 desiring a “more constant” stimulation).

P3's comment regarding “two nostril type stimuli” may stem from the limitation in our first user study. Although we characterize relationships for intensity and lateralization with total and net charge, stimulations have perceivably different trigeminal *qualities* (e.g., prickling, warm, tickling, pressure, etc.). Following, despite the virtual odor field getting rendered for intensity and lateralization, the virtual odor's quality may be non-uniform as the participant navigates the plume.

Most participant's confidence in the stimulation may come from the fact that they are experiencing verbalizable stereo-smell via electrical stimulation or may be due to clear differences

between intensity levels and lateralization directions (as compared to smaller variations with the real odor).

Potential benefits as an assistive device

Smell is often leveraged in the detection of hazardous situations, such as expired food or chemical risks. Unfortunately, an individual with anosmia (loss of olfactory function) cannot detect gas, smoke, or fire through their sense of smell [18, 201]. In Keller and Malaspina's reports, 72% of their subjects reported fearing exposure to dangers due to their olfactory dysfunction [124]. The main concern was the inability to detect a fire, volatile compounds, or a gas leak. (The latter stems from people with anosmia not being able to smell the compound—methyl mercaptan—added to odorize natural gas, which is normally odorless.) Bonfils et al. reported similar results from incidents with their survey population [21]. 63% regularly burned their food, 47% had incidents where they did not detect a gas leak, and 26% had not detected active fires. These consequences ripple across many aspects of a person's lives such as active avoidance of housing with natural gas, food poisoning, prolonged exposure to hazardous volatile chemicals, reduced quality of life from lack of flavor, and more.

In contrast to their olfactory dysfunction, people with anosmia often retain trigeminal function, though it may be dampened in sensitivity [72, 73]. Our device may serve as an assistive technology for people with anosmia, as it can enable them to sense gases in the air. The specificity of the gaseous response is directly tied to the sensor, and the commercially cheap option (metal oxide sensors) often detect smoke and natural gas at incredibly low concentrations. If using a stereo sensing system, people with anosmia may use our device to also lateralize the direction of the gas and navigate towards the odor source to hopefully prevent potential harm from exposure. Though our device may serve as a technical foundation to achieve trigeminal-based stereo-smell, additional

research on the design space of trigeminal stimulation and co-design with people with anosmia is necessary to further validate our system as an assistive tool.

Conclusions

In this paper, we proposed, explored, and engineered a novel type of olfactory device that creates a stereo-smell experience, i.e., directional information about the location of an odor, by rendering the readings of external odor sensors as trigeminal sensations using electrical stimulation of the user’s nasal septum. Our device outputs by stimulating the user’s trigeminal nerve using electrical impulses with variable pulse-widths; and it inputs by sensing the user’s inhalations using a photoreflector.

In our first user study, we found the key electrical waveform parameters that enable users to feel an odor’s intensity (absolute electric charge) and direction (phase order and net charge). In our second study, we demonstrated that participants could immediately make use of these stimulations to find a target (a virtual odor) without any previous training with it.

We believe this opens exciting new interactive uses. Most importantly, we believe this device is useful for users with loss of smell (anosmia) because our technique relies on electrical stimulation of the trigeminal nerve, and not on stimulation of the olfactory bulb; as such it is expected to work for most people with anosmia.

Moreover, while we think of our device as a sensory substitution device to create a proxy of smell sensations, other researchers might be inspired to use it for more general interactive uses, for example to build new types of haptic interfaces. For instance, feeling navigation cues, such as walking directions as though one were “smelling their way home.” Finally, we expect researchers to explore combinations of our device with chemical stimulation of the olfactory bulb.

Augmented Breathing via Thermal Feedback in the Nose

Breathing stands out as a unique autonomic function because it is primarily controlled by the brain [256, 257], resulting in a significant impact on human experiences, particularly our comfort and emotional state [95, 214]. Additionally, as it is commonly practiced in everyday life, voluntary deep breathing affects the autonomic nervous system, modulating comfort and stress levels [111]. As such, it is unsurprising that breath-responsive interactive systems and experiences are increasingly popular in human-computer interaction. For instance, a number of games have integrated breath as one of their input modalities [167, 258, 266, 281, 316]. Further, implementing breath as an input has been a common feature in biofeedback systems to support calming interventions, such as promoting stress relief through visual or auditory feedback [154, 182, 185, 285].

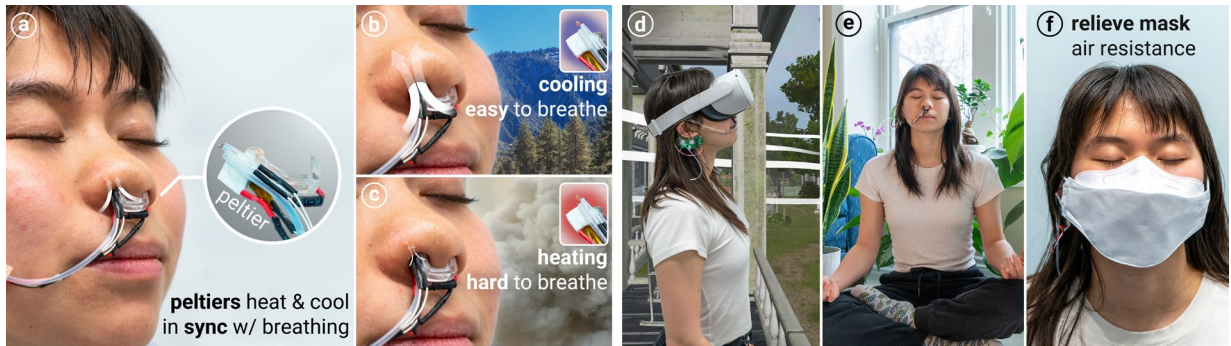


Figure 46: (a) We propose a novel nasal interface that *augments* the perception of breathing via thermal feedback in the nose. By cooling or heating the nasal cavity in sync with inhalations, our device can make the user feel as if they are (b) breathing easier (i.e., inhaling more air) by cooling the inside of the nose or (c) having a harder time breathing (i.e., stuffy room or blocked nose) by heating. Based on study participants’ analogies, we demonstrate our method with several applications: (d) a VR game that simulates experiences like breathing dust or fresh air in the outdoors; (e) a meditation app that draws the user’s attention to their breathing; and (f) an application that relieves mask-wearers from the perceived air resistance while breathing through the mask filter.

While leveraging the user’s breathing as an *input* channel has been explored and can be implemented via a wide range of solutions (e.g., hot-wire [312] or -film [113] sensing,

microphones [316], force sensors on the chest [266]), the reverse is not the same—output devices that can *alter* the user’s *breathing* are very limited.

Output devices for breathing remain non-trivial since, to alter one’s breathing, the user’s airflow needs to be altered. In fact, interactive devices that can achieve this are extremely rare. One such example is *AirRes Mask*, a mask-based device that uses a servo motor to block the entrance of a tube the user breathes through, thereby physically restricting airflow to enhance virtual reality immersion [279]. This unique example highlights the challenges in engineering a suitable method for altering breath, as to manipulate inhaled airflow, one requires motors, tubes, pumps, and more, making these devices cumbersome and non-practical, which might explain why so few such devices have been proposed.

In this paper, we take a different approach to altering the user’s airflow, one that does not require large tubes, pumps, and other mechanical actuators—we alter the user’s perceived airflow by cooling down or heating up their nose using Peltier devices, as shown in Figure 2. Our illusion builds on the physiology of breathing: we perceive our breath predominantly through the cooling of our nasal cavities during inhalation. Our user study confirmed that this type of in-nose temperature stimulation significantly influenced breathing perception in *both* directions: making it feel harder or easier to breathe.

To enable this novel sensation in interactive applications, we engineered a compact device worn across the septum featuring Peltiers and air pressure sensors. Finally, we illustrate the potential of augmented breathing for a range of contexts, from virtual reality to everyday interactions.

Related Work

The work presented in this paper builds on the literature on breath-responsive systems and the physiology of breathing.

Breath as an input modality

The proliferation of breath as an input modality in human-computer interaction (HCI) springs from the abundance of methods available to sense respiratory activity, ranging from hot-wire sensing [113, 312], microphone-based systems [316], force sensors mounted on the chest [266], and emerging approaches like acoustic signal reflections [273]. This plethora of sensing techniques catalyzed a surge in research on integrating breath control into interactive systems.

Examples of breath as input include mapping breathing to navigation in VR [52] or the movements of an amusement ride [167]. Subsequent works incorporated breathing actions, like exhaling with different strengths, to heighten immersion in VR [33, 38, 266, 294]. *Masque* played altered breathing sounds—fast and loud versus light and slow—in synchronization with the user’s breath to influence their sense of attraction [154]. Additionally, given the intimate connection of breath with stress relief and relaxation, many systems exist for guided breathing or biofeedback [28, 208, 259].

In comparison, we focus on breath as output—i.e., the interactive device alters the user’s perceived breathing. This is conceptually and technically important for “closing the loop” for breathing as an interactive modality.

Rendering breath to the user via haptics

Several haptic technologies in the form of interactive objects [9, 64, 120, 127, 274] or wearables [56, 62, 75, 115, 153, 187] render breathing in a way that is perceivable—yet external: they do not

use haptics to alter breathing; they just *represent* it using haptics. These systems focus on creating *awareness* of breathing rather than altering its perception.

Altering breathing as an output modality

Unlike research geared towards breathing as input or representing breathing via haptics, there is little research focused on *directly* altering the perception of one's breath. Two systems explored mechanically compressing one's chest to guide breathing [68] and to enhance social connections [187]. Unfortunately, Foo et al.'s participants found that mechanically restricting one's abdominal (lung) expansion can also cause some discomfort [68].

Even more closely aligned with our work is *AirRes Mask* [279], which mechanically restricts breathing by blocking airflow through a gas mask. This allows users to experience progressively harder breathing as the system reduces the air tube's opening diameter, thus constricting airflow. Compared to prior approaches, our approach stands out since (1) it does not require a large facial coverage (i.e., not a mask form factor as in [279]); (2) non-mechanical actuators are smaller and quieter (e.g., compared to servos [279] or pumps); (3) importantly, it can make users feel it is *both* harder or easier to breathe (which no prior work has achieved); finally, (4) its effect is *perceptual*—there is no risk of mechanical actuators preventing the user from breathing.

Our approach to realizing *augmented breath*

Altering the perception of breathing directly presents a formidable challenge. As described, the only current method to modify breathing requires cumbersome mechanical devices, like motors and tubes, to physically constrict the user's breathing [279]. This approach not only requires mechanical parts but also limits practical applications and introduces safety concerns—it prevents real airflow.

In the study of the nose, nasal patency—the sense of how open or congested one’s nose feels—is considered a key aspect of breathing perception. Interestingly, subjective sensations of nasal patency or airflow do not always align with the objective measurements of nasal obstruction [114, 165]. Medical research has revealed that the nasal vestibule (septum) is a critical area for sensing airflow [152], with temperature fluctuations being more pronounced in regions of turbulent airflow, like the mucosa of the turbinates [310]. This cooling of the nose’s surfaces, rather than the mere temperature or volume of the inhaled air, triggers the trigeminal sensation influencing the perception of nasal airflow [315]. Medical studies have confirmed that the sensation of airflow is heightened during deep breaths, correlated with larger mucosal temperature changes [12, 301]. Thus, the subjective experience of nasal patency and airflow is closely tied to the changes in intranasal temperature [251].

Building on these physiological insights, we propose and validate a novel approach to realize *augmented* breathing by altering the perception of nasal patency and airflow, allowing users to experience sensations of inhaling more or less air. Our approach utilizes *targeted cooling and heating* in the nose in sync with inhalation, capitalizing on the principle that the perception of breath is primarily influenced by the cooling effect on the nasal mucosa.

It is important to note that we found, in early pilot experiments, that synchronizing the heating/cooling with the inhalation is key to feeling that this effect is about airflow instead of just feeling that one’s nose is hot or cold (merely a thermal effect, not our goal). As seen in our study, this synchronized temperature stimulation successfully altered participants’ perception of their breathing, with ~90% of their remarks focused on perceived airflow or patency.

As a result, our approach offers a compact way to augment breathing that can *both* decrease and increase perceived nasal patency and airflow without requiring physical obstruction.

Walkthrough: Altering perceived breathing

To illustrate our technique with an application, we designed a virtual reality (VR) experience in which the user navigates through various environments where their sense of breathing is altered. The experience uses our wireless wearable device equipped with Peltier elements and airflow sensors, enabling real-time adjustments to the temperature inside the user’s nose, which we found to alter their breathing perception. The design of this application draws upon insights from our user study, specifically leveraging direct quotes and real-world analogies that participants used to describe augmented breathing. These highlight how participants perceived changes in ease of breathing, such as feeling like breathing “more air” or inhaling “through a narrow straw”. These augmentations are purely perceptual: the device does not physically restrict airflow. Users maintain constant access to air, experiencing only a *sensation* of altered nasal airflow.

Figure 47 depicts our VR user trying to escape a room where they were being held. As they walk through this old house in search of the door’s key, their movements kick dust into the air. In sync with their breathing, our device heats the inside of their nose, creating a brief sense of breathing less due to the dusty and “*stuffy room*” (quote from Study, by P1).

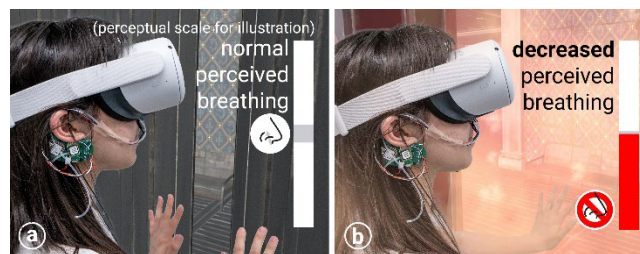


Figure 47. (a) The user opens a room and (b) kicks up dust. Scale depicts perceived nasal airflow for illustration purposes only.

As depicted in Figure 48, upon finding the key and opening this room’s door, the user inadvertently triggers the alarm, releasing smoke—in sync with inhaling, our device increases the nose’s temperature to emphasize the feeling of “*smog in the air*” (direct quote from Study, by P8).

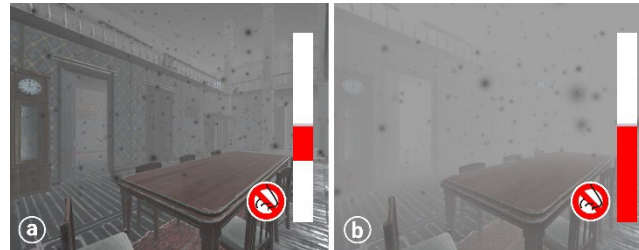


Figure 48. (a) Smoke starts to fill the house with black specks and smog until (b) it feels as if it becomes harder to breathe.

Reacting to the smog, shown in Figure 49, the user finds a gas mask and equips it. Immediately, our device starts to cool off their next inhalations, creating a feeling of “*more air entering my nostrils*” (direct quote from Study, by P6).



Figure 49. (a) User finds a mask, and (b) equips it, which causes our device to increase their feeling of perceived nasal airflow.

However, as the virtual mask’s filter deteriorates, the perceived breathing becomes harder, which can be felt as “*a lot more effort to move air into my lungs*” (direct quote from Study, by P4). As shown in Figure 50, to render this sensation, our device progressively increases the temperature during each inhalation (i.e., fading from cold to hot). As the user finds a new mask and equips it, our device responds by cooling their inhalations and allowing the user to feel like breathing “*more air*” (direct quote from Study, by P3).



Figure 50. (a) As the mask’s filter deteriorates, our device renders a difficulty in inhaling air. (b) With a replacement, our device resets the perceived nasal airflow sensation.

Finally, the user opens the door of the gas-filled room and escapes. As they open the doors (Figure 51), our device pushes through its maximum cooling effect to emphasize the transition from claustrophobic to the relief of “*breathing in an open space*” (direct quote from Study, by P2).

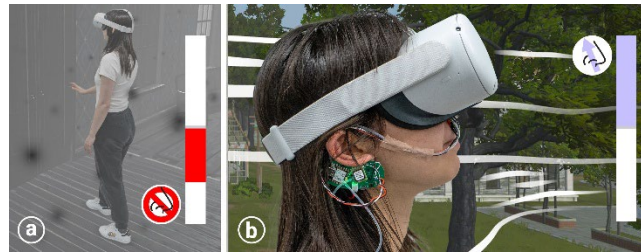


Figure 51. (a) The user opens the final door, leading to an (b) open space where they feel as if they breathe more easily.

Implementation

To help readers replicate our design, we provide technical details and an open-source repository.

Figure 52 shows our device worn on the nose and around the user’s ear.

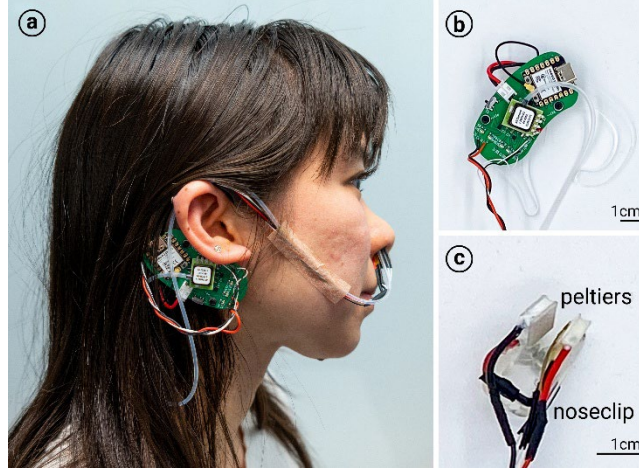


Figure 52. (a) A user wearing our device around the ear and in the nose, comprised of its (b) control unit and (c) nose clip.

Circuit design

Our circuit, depicted in Figure 53, is engineered around an ESP32C3 with Bluetooth Low Energy. To change the nose's temperature, we attached two 8×8 mm Peltiers (*Custom Thermoelectric*, 00711-5L31-03CA-S) paired with thin $10 \text{ k}\Omega$ thermistors (*TME*, B3950) for temperature monitoring. We also added a $10 \text{ k}\Omega$ thermistor and a small silicone tube (1 mm ID, 2 mm OD) in one nostril to record the baseline temperature during inhalation, providing a reference point for temperature adjustments. This silicone tube connects to a differential air pressure sensor (*Amphenol All Sensors*, 1 INCH-D1-4V-MINI) to monitor respiration. Finally, we concentrate most of the components behind the ear (microcontroller, battery, etc.). The in-nose components weigh only 7 g, while the components positioned behind the ear weigh 26 g. This separation balances functionality with wearability.

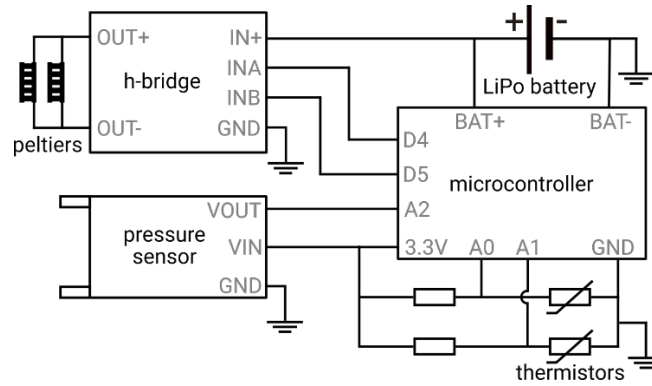


Figure 53. High-level schematic of our device's circuitry.

Control loop

To regulate the temperature of the Peltiers, we tuned a PID controller, which activates if the temperature is more than 0.25°C from the set point. The activation of the Peltiers is synchronized with the user's inhalation, capitalizing on the exhalation phase as a natural cooling period that allows the Peltiers to return to the user's baseline body temperature, thus conserving power without the need for active cooling.

Inhalation detection

To achieve accurate inhalation detection, our system includes a calibration process. Initially, users hold their breath for two seconds to establish a baseline for the differential air pressure (difference between the pressure measured in the nostril and pressure measured in the room) while not breathing, representing the static noise level of air pressure. The device then records the mean and standard deviation of this baseline pressure. An inhalation is detected when the differential air pressure falls two standard deviations below this mean. Likewise, an exhalation is identified when it rises two standard deviations above.

Latency

To assess system latency, specifically the delay between the temperature peak induced by our device and the peak of inhalation, we analyzed recorded data from all participants. This dataset comprised 3247 breaths, each with temperature stimulation. We found an average latency of 0.21 ± 0.67 seconds between the onset of the temperature peak (when the Peltier reaches its extreme temperature) and the peak of inhalation (the point of maximum inhalation). Considering that the average inhalation duration was 1.81 ± 0.49 seconds, a latency of 0.21 seconds is reasonable for our interactive system. Notably, the temperature peak occurred within the inhalation phase for 91.32% of the breaths, confirming effective synchronization with the breathing cycle.

Power consumption

Our prototype draws a *maximum* of 6 W during inhalation. Under a continuous change of perceived airflow only during inhalation, it lasts ~22 minutes with a small 300 mAh Li-Po battery. The device can operate longer with larger batteries, but we note that 22 minutes of perceived airflow change is relatively long, considering participants in our studies detected a change in perceived airflow within their first inhalation with our system active.

Benefits, Contribution, and Limitations

Our key contribution is a novel method to augment a user's breathing, creating the sensation of inhaling more or less air than normal. Moreover, we contribute a device that can realize our approach, which we validated in a user study.

Our approach has four key benefits: (1) our method is the first, to the best of our knowledge, that can *both* decrease and increase perceived airflow (breathing); (2) our device can achieve these sensations without the need for physical obstructions to the user's actual breathing. Unlike

previous interactive devices (e.g., [279]) that mechanically restrict the user’s breathing to create a feeling of difficulty, our approach has a *perceptual* effect—as such, our device has fewer associated risks than existing approaches that require opening/closing the user’s airways; (3) our device can achieve these sensations with small temperature changes as demonstrated in our study, enabling our device to operate on a small battery; finally, (4) our approach is a conceptual and technical step toward “closing-the-loop” for breathing as an interactive modality—while breath as input is fairly popular, breath as an output modality is heavily underexplored.

As the first exploration of this novel idea, it is not without limitations, which reveal future research directions: (1) the limits of our approach to breath augmentation are constrained by the Peltier elements’ ability to rapidly achieve the desired temperature during the user’s inhalation, namely its speed and power consumption; (2) as with any perceptual illusion, individual physiological differences could affect its efficacy—our study validated its efficacy with people without nasal cavity abnormalities, yet it is not certain if this extends to individuals that had nose surgery, and so forth; (3) our device occupies a portion of the nostril openings, which slightly reduces the baseline nasal patency while wearing the system; finally, (4) while effective, our method only augments *nasal* breathing, not mouth breathing.

Study: Altering perceived airflow via intranasal temperature

Our study sought to characterize the relationship between in-nose thermal stimulation and perceived nasal airflow. We designed a psychophysical study with three tasks: (1) measuring the just-noticeable difference (JND), when participants noticed a change in perceived airflow; (2) measuring the range of comfortable airflow sensations; and (3) understanding the sensations qualitatively.

We hypothesized that cooling/heating the nasal cavity in sync with inhalation would produce a noticeable change in nasal airflow. This study was approved by our Institutional Review Board (IRB24-0416).

Apparatus

Participants wore our complete setup (including its Peltiers, air pressure sensor, and temperature sensors) as a nose clip with the control unit resting on a table. For maximum sensing and stimulation quality, we added a second air pressure sensor and two thermistors to the other nostril to control the Peltier temperatures independently.

Calibration

We included an automated calibration at the start of the study to calibrate the system for maximal inhalation sensitivity. This asked participants to hold one breath to record average ambient pressure. Then, we set the inhalation threshold to two standard deviations below the average ambient pressure.

Procedure

We conducted our study in a lab environment with a consistent temperature of 24.78 ± 0.12 °C and no measurable airflow near participants (measured with an anemometer). Participants wore noise-canceling headphones with white noise. Our device was tested in its two functionalities: cooling and heating, in sync with participants' inhalation. The order of the two functionalities was counterbalanced.

Task 1: Measuring the Just-Noticeable Difference

The first task measured the Just-Noticeable Difference (JND) in perceived nasal airflow due to temperature changes. This task used a standard psychophysical staircase method. Participants were

asked to evaluate if a set of five breaths felt easier to breathe than another set of breaths (forced choice).

In one of the two sets of breaths participants compared per trial, our device either cooled or heated their nasal septum in sync with inhalation. In the other set of breaths, our device was off. Participants were unaware that two conditions existed—providing a suitable baseline for the study. The set ordering was random. If a participant’s answer was “yes”, the temperature was adjusted by 0.5 °C increments or decrements based on the tested functionality (cooling or heating)—and the temperature adjustment was reversed for the “no” answer. We selected 0.5 °C given that our PID can maintain a target temperature within a 0.25 °C error margin.

The staircase concluded after reaching four reversals or completing 20 trials. The staircases began at a temperature offset determined from a pilot study: +2 °C for heating and −5 °C for cooling. Finally, after each trial, participants were also invited to voice any sensations that were elicited.

Task 2: Range of sensation characterization

In our second task, we characterized the range of perceived nasal airflow. Starting with the JND determined from *Task 1* as *level 1*, participants compared their ease of breathing between the current level and a comparative level. If participants did not notice a difference between the two levels, the second level was incremented by 0.5°C (increasing for heating, decreasing for cooling). If participants indicated that they noticed a difference between levels, the comparative level was then established as a new distinguishable level. The process repeated for 20 trials or until the participant indicated discomfort or pain. Finally, after each trial, participants were also invited to voice any sensations that were elicited.

Task 3: Qualitative exit interview

After completing both tasks, participants engaged in a brief interview. They were asked to describe their experiences during the study and then to compare them to any sensations encountered in real-world situations. Then, participants could provide open feedback about the study experience.

Participants

We recruited ten participants with an average age of 26.5 years old ($SD = 2.72$) from our local institution. Four participants identified as men, four as women, and two as non-binary. We did not recruit participants with a deviated septum or a known history of nasal surgery. At the start, participants were given the Nasal Obstruction Symptom Evaluation (NOSE) 5-point Likert Scale [269]. With it, we confirmed that most participants did not have, during the last month, nasal congestion ($M = 0.8$, $SD = 0.79$), blockages ($M = 0.6$, $SD = 0.84$), trouble breathing ($M = 0.4$, $SD = 0.52$), trouble sleeping ($M = 1.2$, $SD = 1.14$), or difficulty breathing during exercise ($M = 0.1$, $SD = 0.32$). However, two participants disclosed having congestion at the start of the study: P6 reported congestion, and P9 shared that they sometimes experience light congestion. Both stated that they easily perceive differences in their day-to-day ease of breathing (perceived nasal airflow and patency). Participants were compensated with \$10 USD for their time.

Quantitative Results: JND & perceived levels

In this section, we present the quantitative findings from our study, namely the JND and the number of perceived levels.

Task 1 Results: Just noticeable difference (JND)

We summarize our results in **Error! Reference source not found..** We found that cooling the septum by an average of -3.9 ± 1.4 °C led to a perceivable increase in perceived nasal airflow

(Weber's fraction of 12.11%) while heating it by 1.5 ± 0.6 °C caused a perceivable decrease (Weber's fraction of 4.71%).

Task 2 Results: Number of perceived airflow levels

Participants identified an average of 6 different levels of airflow change, with an ability to discern approximately 7 ± 5 levels for increased perceived nasal airflow (cooling effect) and 6 ± 4 levels for decreased (heating). To perceive a new level of sensation, an average temperature change of 1.0 ± 0.4 °C was necessary for increased perceived nasal airflow (cooling) and 1.4 ± 0.9 °C for decreased perceived nasal airflow (heating). The range of sensations explored by participants ranged from -10.5 ± 3.9 °C to 10.6 ± 1.6 °C offsets from their baseline cavity temperature.

Qualitative Results: What does it feel like?

In this section, we present the qualitative findings from our study, which come from two moments when participants commented: (1) in *Tasks 1 (JND) & 2* after any trial where they felt a difference, and (2) during the exit interview.

Comments were transcribed and analyzed by one author. Each comment was classified as any combination of the following categories: **tactile** (skin sensations like tingling or pain), **temperature**, and **airflow** (any aspects of breathing like patency, airflow, congestion, difficulty or ease in breathing, etc.). Figure 54 depicts a concrete example of how the participants' comments were annotated.

“The second set, the air coming
in felt ***much cooler*** and ***just easier to breathe*** in general.”
(temperature) (airflow)

Figure 54. Example response from P6 with annotations.

This qualitative data complements the understanding of our perceptual illusion, providing descriptive insights into how these changes were interpreted.

Does it feel like airflow or temperature?

Our analysis revealed that from the 389 descriptors from transcribed comments, an overwhelming majority (89.2%) pertained to airflow, underscoring this as the prominent aspect of the perceived experience (e.g., P4 saying their nose felt “much more open” or P2’s “I could just breathe easier because it was fresher air, versus being stuffy”—to illustrate such comments). In contrast, temperature descriptors accounted for 7.46% of the comments. Notably, among these temperature-related comments, approximately half (46.7%) were concurrently associated with airflow (for example, P6 explaining, it’s like a “windy day and [you] have a deep breath and you have the cold air rushing into your nostrils”—to illustrate). Finally, only 3.34% accounted for comments classified as tactile (e.g., P4’s “second set felt easier, but the septum felt a little bit tingly this time”—to illustrate).

In other words, participants associated the sensations predominantly with changes in perceived airflow and not temperature or tactile sensations.

Unprompted analogies

Some participants already employed (unprompted) analogies to describe changes in the sensation during *Tasks 1 & 2*. These analogies not only reflect real-world sensations but specifically real-world *breathing* sensations, without any additional context, pointing to their strength.

For ***increased airflow***, all ten participants provided unprompted analogies for this airflow sensation. Five participants used analogies relating to the openness of their nose (i.e., nasal patency), such as: “breathing through both nostrils instead of just one” (P2); “clear passage of air through my nostrils” (P6); “decongestion” (P10); or lack of resistance” (P5). Four participants used specific airflow analogies: “there was wind in my nose [...] it was coming through faster” (P9); “more air entering my nostrils” (P6); “more airflow” (P3); “like inhaling more air” (P1). Four

participants used air quality analogies such as crisp (P2), clean (P4), fresh (P2, P5), and “good quality” (P8) air. Three participants also likened the increased ease-of-breathing to environmental conditions, such as: “sharp, like breathing in winter” (P9)—though P9 specified that they meant only the sharpness not the cold aspect of winter air in their exit interview—or “windy day and [you] have a deep breath and you have the cold air rushing into your nostrils” (P7).

For *decreased airflow*, seven of ten participants likened it to congestion, clogging, restricted, or high-effort breathing with analogies such as “breathing through narrow straws [...] or a “pinched nose” (P4); “like something was blocking the airflow” (P8); “like [the] breathing equivalent of a weighted blanket” (P9); “scuba diving type breathing” (P8); or even that they “could no longer breathe” (P5). Four participants used air quality analogies: “like smoky [...] breaths felt heavier coming—like the air got thicker” (P9); “felt very, very heavy” (P8); and even like a “smoggy city” (P8). Three participants mentioned air resistance analogies: “[like] wearing a mask” (P8); “a lot more effort to move the air into my lungs” (P4); and “difficulty passing air” (P2).

Task 3 results: prompted analogies to real-world experiences

In addition to the unprompted analogies that some participants used to describe sensations in *Tasks 1 & 2*, during the exit interview, participants were specifically prompted to provide real-world analogies to their experiences. Again, these analogies not only reflect real-world sensations but specifically real-world *breathing* sensations, without any additional context, pointing to their strength. These prompted analogies also provided further explanation for how the sensations were described, as participants could provide more information for disambiguation (e.g., P9 disclosing that breathing winter air referred to its sharpness in breath and *not* the air’s temperature). Of all

prompted analogies, all focused primarily on airflow. We report the specific aspects of breathing altered below.

For *increased airflow*, five of ten participants compared it to moments in life where wind or good air impacted their breathing: “feels like when I do outside and it’s windy: [...] like I am breathing in more” (P7); “like stuff was more crisp. Like normal versus really good air [...] the air just felt crisp – not cold” (P2); “like when you’re in the wind” (P9); “less thick – the air passing through faster” (P9); “felt like going from an airplane with bad air quality and going outside to a city that has nicer air quality—like I can actually breathe” (P8). Five participants likened the increased inhalation to moments where they were decongested: “much more open” (P4); “using stickers to open your nostrils, but this one is much stronger” (P3); “like inhaling mint [...] when you have a cold. I definitely feel I am breathing more air and fresher air” (P5), which P1 echoed as “like if I were to open a window in a stuffy room, [...] the air I was breathing was fresher”. P6, who had some congestion, reported that “there [were] some instances where [my] congestion just went away pretty immediately”. Three participants mentioned that the device helped them breathe: “it felt like something was helping me breathe” (P9); “best breathing I’ve experience in a while – calming” (P2); and “really comfortable, like long breathing [...] it kind of helped me calm down” (P5).

For the *decreased airflow*, participants likened the sensation to moments with high-effort breathing: “running or scuba diving, it feels like you are using your lungs more or takes more effort” (P8); “harder to move the air in and out” (P4); “when you’re walking up a good amount of stairs, now it’s a little harder to breathe” (P2); “as if I was under a blanket” like a “stuffy room” (P1); “it just feels like I cannot breathe in enough air” (P5); or, “it’s like being closed in a hot room or smoke [...] I had to work a little harder to get [the air] through” (P9). Four participants likened

sensations to real-life moments with nasal blockage: “felt even more congested” and “only felt this when I am really sick” (P6); “when you get a cold, and you try to sleep and you cannot fall asleep, because your nose is clogged” or even “accidentally breathing in water [while swimming]” (P5); “stuffy nose [or] pinching the nose” (P4). Finally, two participants mentioned the decreased airflow reminded them of their breathing during asthma (P4) or anxiety attacks (P5).

Discussion

While our study was chiefly aimed at quantitatively characterizing our method’s effect, it also captured a remarkably wide range of expressive details from participants. This richness in feedback underscores the depth of personal interaction with the breathing experience and provides a holistic understanding of *what* the effect feels like.

Device comfort

All participants reported becoming accustomed to the nose clip within the first minute of use. Participants wore the most implemented version of our device for our psychophysical study (sensors for each nostril). Some of their feedback suggested that further reducing the device’s weight would improve comfort. Based on their input, we simplified the standalone device by decreasing the number of tubes and sensors to improve comfort.

Perceived our effect as a change in breathing

Participants primarily framed their experiences in terms of changes in breathing dynamics, such as airflow, blockage, and ease of breathing, rather than temperature sensation. This supports our hypothesis that thermal feedback in the nasal cavity alters one’s perception of one’s own breathing. These changes were perceived as if their breathing has changed (e.g., “feels like I cannot breathe hard enough”) or that they are even being helped to breathe (P9). Moreover, we remind readers

that these descriptions and analogies occurred *without any additional context* (e.g., no VR, no visuals, no sound, nothing else). This perception, emerging consistently across responses, validates the notion that thermal feedback can be a powerful modulator of breathing sensation, and our quantitative findings suggest that it only requires a small difference in temperature to produce a noticeable change.

Their analogies also provided further explanation for how the sensations were described, as participants could provide more information (e.g., P9 disclosing that breathing winter air referred to its sharpness in breath and *not* the air's temperature). While there was variation in analogies (i.e., describing changes in airflow, patency, or even effort), participants' descriptions converged on *changes in breathing* that were most akin to *changes in perceived nasal airflow*.

Secondary effects of augmented breathing

The feedback from some participants, especially P1, P2, and P5, also highlighted that the increase in perceived nasal airflow also had a calming or relaxing effect. Conversely, decreased perceived nasal airflow was reported to induce feelings of anxiety or asthma for two participants. These findings suggest that augmented breathing could also influence both physical states and emotional well-being. This is not surprising given breathing's well-established link to emotion [8, 54, 95], such as controlled breathing enhancing relaxation [25] and reducing pain [119].

Participant-suggested applications

While *Task 3* was about analogies, two participants also voiced applications for which they would be excited to use the system. P5 felt that the increased perceived nasal airflow “would be really good to help me go to sleep. I imagine if my breath was like that while I was sleeping, I would imagine I would have a better quality of sleep”. P8 wanted to use the device to help alleviate the

perceived air resistance when wearing a mask is “blocking your airflow, but if you put this device to open it up—it’ll feel comfortable”—which we implemented and described in the next section.

Further Applications

Alongside opportunities for augmented breathing to support future VR experiences, like in our *Walkthrough*, we highlight three potential scenarios where one might find our technique to have further applications. All these additional applications run on an Android mobile phone and communicate to our device using BLE. We implemented these applications in *Java*, using *Processing* and *Android Studio*.

Relieving the perceived air resistance of masks

The widespread adoption of face masks has been a crucial measure in curbing the transmission of respiratory illnesses, including common colds or COVID-19. However, the success of masking interventions significantly hinges on user compliance. As Koh et al. showed, mask discomfort is the primary source of noncompliance in mask-wearing [135], with a strong correlation between increased air resistance—making breathing *feel* more laborious [209]. Inspired by P8’s suggestion that our system could help, we envisioned an application in which our system relieves the perceived increased air resistance. As seen in Figure 55, the user can switch our device’s “mask mode” on to counteract the perceived decrease in airflow.

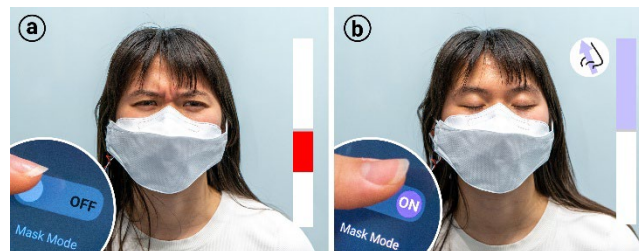


Figure 55. (a) This user finds it hard to breathe with a respirator mask. (b) They use an app to switch on “mask mode”, which increases their perceived nasal airflow.

Meditation and relaxation

Most relaxation & meditation applications require users to actively follow audiovisual guides to reach a specific breathing pattern to achieve stress relief. Here, our approach provides a new output channel for these kinds of applications—by *directly* influencing the aspect that they are focusing on, i.e., their breathing.

This was inspired by comments from participants suggesting our system helped them feel calmer or more relaxed. To this end, we developed a meditation application that makes use of our device to alter the user’s perceived airflow in a rhythmic pattern. As depicted in Figure 56, the meditation app increases the perceived airflow of every second breath, making it feel deeper and more pronounced.

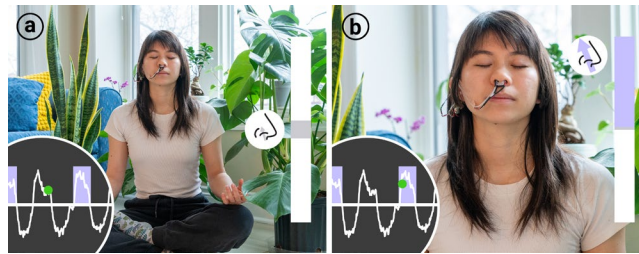


Figure 56. (a) Paired with our meditation app, our device makes every other breath feel deeper. (b) The user relaxes and meditates while experiencing augmented breathing.

Promoting nasal breathing when helpful

Our system may even offer a novel approach to encourage nasal breathing when helpful, e.g., during physical exercise, leveraging its known benefits for breathing efficiency [51]. Figure 57 envisions this as the example of an application we implemented where our device progressively cools down the user’s nose to promote nasal breathing during exercise.

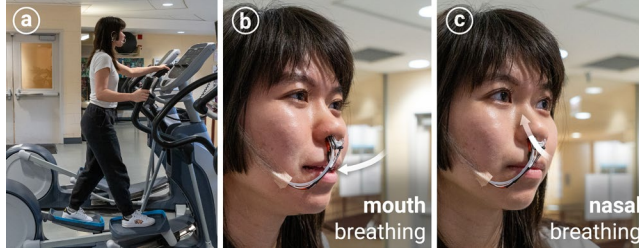


Figure 57. (a) A user does cardio while wearing our device. (b) Normally, they inconsistently breathe through the nose and, instead, breathe through the mouth, but (c) at times, our device encourages nasal breathing by increasing the perceived airflow when they inhale nasally.

Diving simulator

In addition to applications that increase perceived airflow, we developed an application that leverages the utility of decreased perceived airflow. Inspired by feedback from participant P8, who likened the sensation to the difficulty of breathing while diving, we created a VR diving simulator where our device replicates the “difficulty to breathe” via a scuba air tank and its mask (Figure 14). This simulator allows users to safely acclimate to the sensation of difficult breathing before engaging in actual diving activities.



Figure 58: Our device replicates the “difficulty to breathe” via a scuba air tank for a diving simulator.

Conclusions

We introduced a technique for altering the perception of breathing through thermal feedback, using Peltiers to alter the user’s sensation of nasal airflow. Unlike existing systems that rely on mechanical parts to restrict breathing, our perceptual approach modulates airflow *perception* and

not the actual volume of air that users are inhaling—making it safer than previous devices. Moreover, it is the first approach that enables *both* decreased *and* increased perceived airflow. Our study unveiled that our effect can be achieved with small Peltiers and minimal temperature adjustments. This opens potential practical implications for our findings, providing a working method to enrich interactive experiences like virtual reality and apply augmented breathing to everyday contexts.

We envision our work as a foundation for future investigations on how thermal feedback can be harnessed to augment breath perception. Future research may explore altering not only the perception of our inhalation but also our exhalation, developing power-saving strategies, exploring new actuators (e.g., flexible Peltiers [146]), or even investigating its potential impact for therapeutic purposes.

Smell & Paste: Low-Fidelity Prototyping for Olfactory Experiences

Low-fidelity prototyping approaches, such as paper and video prototyping, are foundational to Human-Computer Interaction. Many practitioners, researchers, and students are taught to use these essential techniques because they allow for quick *iteration cycles* and use *non-technical (low-tech) media* when designing screen-based user interfaces. However, experience designers have recently moved beyond the screen [203], noticing the opportunities afforded by many new modalities, including olfaction [202]. Odors play critical roles in our lives: from the pleasures of food and its influence on our metabolism [229] to detecting potential hazards [268] to an essential role in memories and emotions [109, 237].



Figure 59: Prototyping with Smell & Paste (lo-fi) vs. current practices (hi-fi). Smell & Paste enables rapid, low-fidelity prototyping of smell experiences using off-the-shelf materials. A designer (a) tests an odor sequence for a VR experience. To revise it, they (b) open the cassette, (c) cut and paste scratch-and-sniff stickers onto the tape, and (d) re-test the sequence within minutes as the driver advances and the cassette comb releases the smells. In contrast, current practice requires high-fidelity development: designers (1) handle fragrance chemicals, (2) build and program a delivery system, and (3) can only test after extensive setup, making each iteration slow and labor-intensive.

Moreover, all societies have their own cultures and practices around smell, charged with cultural values that also shape how they interact with the world [43]. For example, in the past, Northern Māori villages were noted for the pungent notes of fermenting corn (kānga pirau) emanating from steeping pits [45] (a dish that can be smelled several houses away even today [321]), while Roman Catholic masses marked symbolic transitions with the smell of burning balsam [96]. HCI researchers have been leveraging these opportunities in interactive experiences, such as to increase virtual presence [14], provide notifications [162], promote wellbeing [3], enhance safety [169], and support funeral rites [288], just to cite a few.

However, while lo-fi techniques support visual UIs, the same does not hold for experiences leveraging smell. Even with advancements in scent technologies, olfactory experiences remain rare. We posit that designers need *both* hi-fi hardware for final development *and* low-fidelity prototyping techniques to make olfactory experience design *quick, low-cost, and approachable* to those of diverse backgrounds/regions (including those without technical experience).

Following this, we asked, do olfactory experience designers draft lo-fi prototypes? In short, *they do not*. In our first study, we interviewed experts that previously authored smell experiences for the public (games, interactive exhibits, etc.). We found most *jumped* from concept to hi-fi version, *taking months before they integrated or tested actual smells*. These difficulties stem from lacking structures or toolkits to prototype with low-fidelity odor materials. In turn, experts take an idea and must often compose or buy fragrances, build, and program a dispensing system, and test ergonomics before they can test design choices or ideas. Each step ultimately requires significant time, cost, and expertise.

To tackle this, we designed a low-tech, low-fidelity toolkit that makes prototyping olfactory experiences quick, cheap, and easily approachable. As seen in **Error! Reference source not**

found., our toolkit comprises (b) a 3D-printed (or cardboard) cassette with which users draft odor sequences and transitions by adding scratch-and-sniff stickers. These low-cost stickers have a coating of microencapsulated fragrances, which lets one store and later release smells by scratching their surface. The toolkit enables drafting experiences by (c) simply cutting and pasting stickers onto paper tapes, loading them into a cassette, and (d) hand-operating the cassette. This editing workflow draws inspiration from film, tape, and reel editing techniques. The kit exhibits all the fundamental elements of paper prototyping: it (1) leverages commonly available materials (printer paper and scratch-and-sniff stickers), (2) does not use hardware or software, (3) is cheap to make, and (4) has low operational costs. Our toolkit frees users from electronics, liquids, or programming during early prototyping phases. Most importantly, the kit is approachable to people of any technical ability to draft expressive olfactory experiences.

We evaluated our device through two additional user studies. In the second study, our toolkit supported novices to experiment with the full breadth of key olfactory design features, drafting sequences that leverage smell’s chemical, emotional, spatial, and temporal features [161]. The kit also paired well with established prototyping strategies (paper, video, Wizard of Oz) and let participants even compose custom smells. In the third study, two experts incorporated the toolkit into their professional practices. One expert demonstrated its use in a small storytelling workshop with two young children. Both experts especially highlighted Smell & Paste’s technical and tangible affordances, and both were interested in incorporating the toolkit into their future professional work. Ultimately, our toolkit let the participants *iterate over and draft lo-fi smell prototypes*, allowing them to focus on design. We found that novices and experts alike appropriated and extended the toolkit, making it highly personalized.

We believe our prototyping toolkit will enable new work across HCI, design, and education. To accelerate the lo-fi prototyping of smell experiences, we not only provide our device as open-source but complement it with a dataset of 800 scratch-and-sniff stickers (some as cheap as 0.035 USD per cm²) that can be purchased online.

Smell & Paste is *not* an end product but a *process* to enable designers to *rapidly validate and test design decisions* early in prototyping, and could be combined or help users transition to high-fidelity smell toolkits [143, 149, 163].

Walkthrough: Prototyping with Smell & Paste

We present an example walkthrough in which a designer uses Smell & Paste prototyping to draft smell interactions for an existing virtual reality (VR) experience. As seen in Figure 60, the experience is a simple game in which the player must find food and shelter in a forest. They stumble across fragrant ingredients to cook with, such as a suspicious mushroom. The player then finds their way to a cabin by following a smokey scent that grows stronger as they approach. Once inside, they find a boiling stew to which they can add foraged ingredients, changing its smell. If they add the mushroom, the stew’s smell turns foul to warn that it is poisonous.

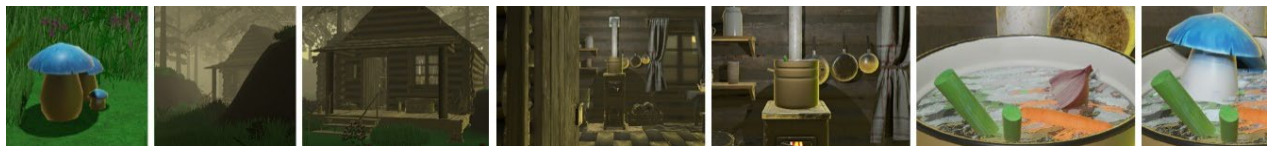


Figure 60: Key moments of this VR experience, for which our designer intends to *prototype its olfactory* experience.

First, our designer iterates over the moment the player steps from the forest into the cabin—their objective is to immerse the player in the rich smell emanating from the kitchen. They test this scene on themselves and, with every run, tweak the smell sequence. Figure 61 shows the key to prototyping with Smell & Paste: (a) the designer tries the VR scene while holding and manually

advancing the cassette to release odors; (b) dissatisfied with the current smells, they modify the sequence by adding a sticker to the exposed tape; and now (c) rewind the tape to (d) try the olfactory transition once more. This olfactory prototyping is approachable and takes the designer *a few minutes*.

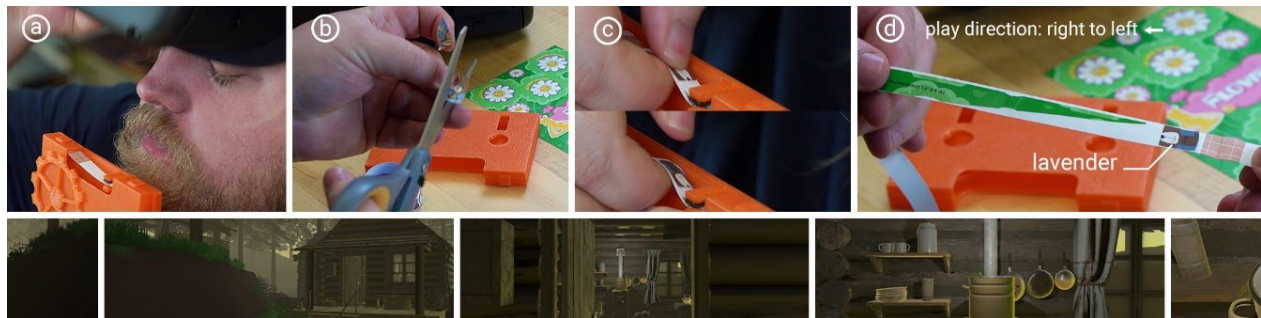


Figure 61: (a) The designer tests a fade-in of a chili scent while entering the cabin and modifies the sequence. They rewind and (b) cut a square of lavender to (c) add to the start, emphasizing the soup’s fragrant herbs. (d) Sequence presented outside of the cassette.

Since our technique uses low-tech materials (paper and stickers) and is approachable, the designer rapidly drafts variations of the interactions, see Figure 62. Each variation tests their ideas for the forest scents, the transition from woods to cabin, and the aromatic notes released when entering the kitchen. These three variations took *3-4 minutes*.

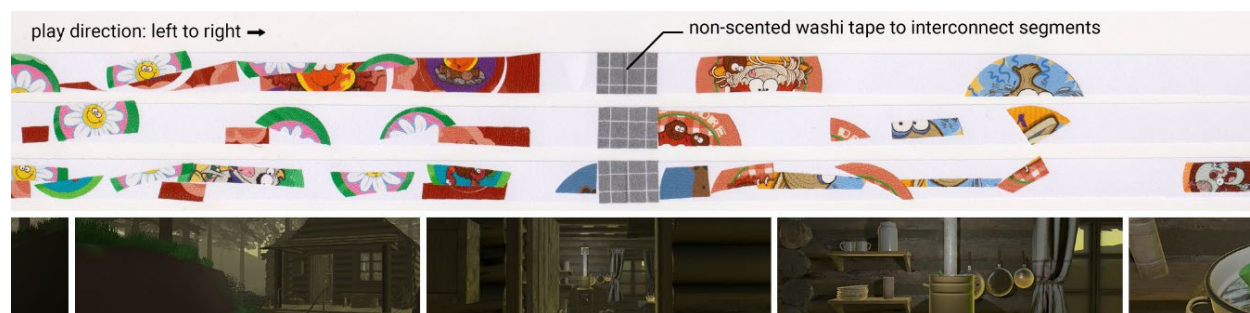


Figure 62: Our designer made three different sequences to test how to transition between the forest and cabin kitchen.

The designer repeats this process for the cooking interaction to experiment with how the foraged ingredients change the stew’s scent. The designer wants to warn the player when the stew

becomes poisonous, so they try adding a sharp, pungent aroma (Figure 63). Smell & Paste lets them draft and test many combinations to identify which works best.

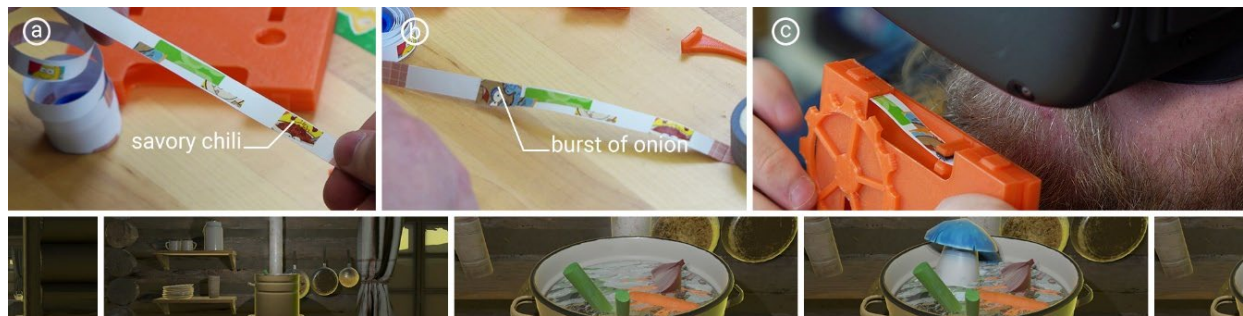


Figure 63: (a) An odor sequence for the kitchen stew interaction initially uses a transition from savory chili to a meat medley with hints of onion. (b) The designer decides to warn their user of the poisonous mushroom by increasing the onion odor's intensity. (c) The designer then tests the modified sequence while immersed in the scene.

In contrast to Smell & Paste's rapid prototyping, most olfactory experience designers take hours to months to produce one draft of a similar olfactory experience, as informed by our Study 1 and prior work [143, 149]. Figure 64 illustrates the standard steps when prototyping an experience using electronics. This process often requires formulating or finding fragrances compatible with the delivery mechanism and then making or programming electronic dispensers, which are less approachable in early phases. These limitations can hinder the designer's creativity too early in the process [78].



Figure 64: Illustration of typical key steps involved in hardware-based olfactory prototyping.

While our walkthrough depicts Smell & Paste used to draft smells for an existing experience, our prototyping toolkit is suited for many stages of the design process. Designers can pair Smell & Paste with established techniques like paper prototyping, video prototyping, and Wizard-of-Oz

sessions (as observed from participants in our Study 2), or even combining our lo-fi smell toolkit with hi-fi smell toolkits (e.g., Lai and Cao's kit [143] or O&O [149]).

Related Work

Our work builds on low-fidelity and low-technology prototyping, especially paper-prototyping. As our toolkit leverages scratch-and-sniff stickers, we cover microencapsulation to familiarize the reader with this little-discussed format in HCI.

Low-fidelity and high-fidelity prototyping

Low-fidelity prototypes act as *stand-ins* for an interactive application: these are meant to be produced *rapidly* and *early in the design process*. They allow designers to validate and test design decisions as well as test how users might respond to the envisioned final UI design or experience [242]. In HCI literature, lo-fi prototype implementations are often implemented for visual or auditory mediums, such as via a series of static UI layouts that represent scenarios and choices in an application or even acted through the Wizard-of-Oz session [170]. The most popular and rapid lo-fi prototypes are typically paper prototypes, usually hand-drawn sketches of a user interface or experience. As the user then interacts with the prototype, a human facilitator guides the experience by modeling the prototype responses such as changes in the layout [228]. This methodology is widespread in HCI and taught in virtually all introductory HCI or design courses.

Lo-fi prototypes introduce a wide range of advantages [234]. They require little development cost (e.g., pen and paper), which enables designers to evaluate multiple design concepts. The prototypes can help address issues in the layout or experience and are useful artifacts for communicating the concept to others. Unfortunately, they also have disadvantages as they represent rough approximations of the eventual design or experience. For example, they need a

facilitator, have limited utility after requirements are established, and have issues with navigation or flow in an interface or experience.

Inspired by traditional paper prototypes, our toolkit can be facilitated but it can alternatively be experienced by a user independently. The latter resembles the *experience prototyping* attitude, which focuses on the experiential aspect of prototyping [26]. In other words, where traditional ways of prototyping often focus on a passive audience witnessing a demo or someone else's experience, the experience prototyping attitude focuses on methods that allow an active audience to “experience it themselves” via low-fidelity prototypes.

In contrast to lo-fi prototypes, hi-fi prototypes are more functional and interactive versions of a design that can be experienced by the user alone. These prototypes often have the look and feel of the final version. However, hi-fi prototyping has its disadvantages too, namely: these are more expensive to develop, require a lot of time to create (at times weeks or even months), and are inefficient for proof-of-concept designs.

Olfactory interfaces

HCI researchers and artists have long explored ways to incorporate our senses into digital experiences, including olfaction [86, 89, 186, 308]. Olfactory interfaces typically deliver smells by diffusing vapors [220, 311], heating solids [58, 126] or liquids [49, 141] to produce vapors, or aerosolizing [4, 24] fragrant liquids. The resulting vapor or aerosol is commonly delivered near the nostrils or guided by fans, air vortices [311], bubbles [250], or ultrasound arrays [87]. HCI researchers have largely explored olfaction for immersion [141, 216] and communication [162, 302]. While researchers are refining delivery technologies, little attention has focused on how designers prototype olfactory experiences.

High-fidelity toolkits for olfactory experiences

While toolkits with fragrances—such as the *Smell Memory Kit* [150]—exist to evoke and share autobiographical stories using smells as probes, little work has investigated lo-fi or low-tech toolkits for *prototyping olfactory experiences*.

In fact, the existing toolkits explicitly designed for olfactory experiences are on the high-fidelity and high-tech end of the spectrum. For instance, Lai and Cao created an electronic-based toolkit to facilitate high-fidelity prototypes of olfactory interactions as part of their TEI 2019 studio [143]. The kit includes electronically controlled smell diffusers with a control module connected to an Arduino microcontroller and a set of liquid containers. This type of smell hardware can only emit smells from very low viscosity fragrances and needs circuit modifications to allow more than four smells at a time. To prototype with this toolkit, a designer fills the containers with fragrances to be aerosolized via a transducer and a wick. Designers then combine the kit with sensors, props, and everyday items to produce their experience. Similarly, *O&O* [149] is a DIY toolkit for high-tech prototyping of olfactory interfaces that provides odor-delivery modules using a combination of electronics (fans, transducers, etc.), cardboard, and plastics or waterproofing materials. While both kits are useful, the components are high-tech (based on transducers and electronics often found in final devices [4, 24]) and, consequently, *require* engineering and programming knowledge as well as fragrance handling. These researchers acknowledged this limitation in the workshops (and workflows) they conducted using their toolkits. (1) In Lai and Cao’s TEI studio, participants did not present scent-enabled prototypes, but presented lo-fi visual prototypes (“image collages, videos, skits”). (2) In O&O’s first workshop, participants reported relying on team members with engineering/software experience to prototype, and the one team without such expertise received guidance from the organizers [149]. Additionally, some participants reported that the prototyping

phase was insufficient to complete a hi-fi prototype; thus, in their follow-up workshop, each individual participant received programming and hardware mentors to complete a single hi-fi prototype over the course of 5 days.

In contrast to hardware solutions, *OWidgets* is a software solution that provides a GUI for olfactory design [163], but is not designed to support lo-fi prototyping. The software coordinates scheduling and delivery across arbitrary olfactory interfaces (high-tech), which can also be used for high-fidelity prototyping, but has yet to be tested with designers.

To summarize in Table 3, we contrast existing toolkits and the key attributes expected of a lo-fi toolkit: i.e., low-cost, approachable to users without hardware or software expertise, supporting many odors, fast to use, and easy to appropriate or remix. As shown in Table 3, because prior work focused exclusively on hi-tech prototyping or final products, there is no work that has investigated lo-fi prototyping of olfactory experiences.

low-fidelity attributes							
fidelity	toolkit	low-cost	no hardware	no software	many odors	fast	remix
High	OWidgets [163]	~	N/A ^(a)	✓	✗ ^(b)	✓	✗ ^(c)
	Lai & Cao's kit [143]	~	✗	✗	✓	✗	✓
	O&O [149]	~	✗	✗	✓	✗	✓
Low	Smell & Paste	✓	✓	✓	✓	✓	✓

table footnotes: (a) software only, but still requires access to and some knowledge of smell delivery hardware.
(b) odors extendable but requires database (valence, arousal, associations); initial database has 9 odors; number of odors dependent on hardware.
(c) modification and remixing require an understanding of programming.
Blue tildes (~) are used when the kit's cost is unclear, as it depends on the price of electronics, Arduinos, transducers, insulation, etc.

Table 3: Contrast between high-fidelity toolkits and our low-fidelity toolkit.

Scratch-and-sniff stickers (microencapsulated fragrances)

“Scratch-and-sniff” media is paper, or plastic, covered in fragrances sealed in microscopic capsules. Pressure from scratching the surface breaks these small capsules and releases the odor. The earliest uses of microencapsulated fragrances included perfume advertisements in magazines [318], and later postage stamps with odors congruent to their illustrations [63, 243]. Moreover,

another application lies in the food industry as scratch-and-sniff finishes allow consumers to preview a product's smell before purchase (e.g., jam packaging with scratch-and-sniff [108]).

Many took note of scratch-and-sniff stickers' ability to produce olfactory experiences for printed media and leveraged them to create more engaging and accessible products. For instance, scented books and stickers were proposed as methods to engage blind and visually impaired children (or parents) in readings [17, 83, 283].

While scratch-and-sniff was only paired with static print media in its earliest decades, the 80s explored its use in film, notably through John Waters' iconic *Polyester* [319]. These explorations continue to the present date, with games [155, 176] and contemporary movies at premier festivals leveraging the format (e.g., *The Beach Bum* at SXSW 2019 [323]).

The only proposed use of scratch-and-sniff in a device appeared in 2001 as a patent that described the concept of an electrically actuated odor bank, which would move to the target odor and heat it to release the microencapsulated scent [191]. To our knowledge, this proposed device was never produced or studied.

Benefits, Contribution, and limitations

Our key contribution is a toolkit that enables low-fidelity, low-tech prototyping of olfactory experiences informed by expert interviews and user studies.

The Smell & Paste toolkit has the following benefits. **(1) The toolkit enables very fast drafting of an odor sequence.** In turn, designers can iterate on an interaction or experience to test ideas much faster and earlier than with high-fidelity or high-tech approaches. Like any lo-fi and low-tech prototyping method, Smell & Paste is only a stand-in for an experience *meant to validate and test design decisions early on*. **(2) The toolkit's materials keep iteration costs low** when compared to iterating via fragrances and delivery hardware. Like paper prototypes, Smell & Paste

prototypes use readily available paper and scratch-and-sniff stickers, which can be acquired and operated for lower cost than delivering fragrances with pumps, atomizers, etc. Due to this, there is also a low cost to creating, remixing, or discarding drafts. Additionally, the cost of our cassettes can be lowered by using cardboard and paper towel tubes. Finally, the cost of our approach depends on the cost and accessibility of scratch-and-sniff stickers themselves, which might vary over time or by region. **(3) The cassette form factor overcomes the limitations of the low-fidelity odor product and is intuitive to use.** As seen in Study 1, designers are excited about using low-fidelity materials like scratch-and-sniff stickers but do not have the infrastructure to address their limitations (e.g., need for manual scratching, insufficient surface area for long sequences, unclear how to produce fades). Unlike books or cards, our cassette design allows for an arbitrarily long sequence stored in a small space. Studies 2 and 3 demonstrated that the design is also robust for odor delivery. Our cassette also leaves the eyes unobstructed (unlike scented books). **(4) Designers can combine our toolkit with existing prototyping techniques.** As seen in Study 2, Smell & Paste is flexible enough to allow participants to combine their prototypes with video prototypes of interactive experiences, paper prototypes of UI designs, or even Wizard-of-Oz prototypes. **(5) Smell & Paste is simple and expressive.** Designers only need to cut & paste stickers and advance or rewind the tape to draft odor sequences rapidly. By building off these simple actions, a designer can fade and crossfade a variety of scents or even compose new fragrances.

Our approach is not without its limitations. **(1) Our toolkit inherits navigational, flow, and facilitation limitations typical to lo-fi prototyping techniques.** Designers must find ways to map branching experiences onto a linear form factor, which is typical of these techniques [234]. Additionally, designers know the pace to advance their cassette but must provide facilitation for others (e.g., metronome for pacing), which is also common to lo-fi prototyping techniques (see

Section 4.1). Finally, **(2) while our toolkit enables lo-fi prototyping, more research will need to follow to measure how it impacts translating low to high-fidelity prototypes.** Unlike other modalities, olfaction can vary based on the delivery method, and, as is for all prototyping methods, *materialities* (the material artefacts used during prototyping) may influence the design process [168]. So, while Smell & Paste may be helpful for low-fidelity prototyping, future work needs to investigate how it translates to high-fidelity and final experiences that do not use low-fidelity materials like scratch-and-sniff. Still, our toolkit provides the groundwork to explore this question.

Study 1: Are there low-fidelity olfactory prototyping methods?

Our first study sought to understand the prototyping processes of artists and researchers working with smell, particularly what challenges they faced. We conducted semi-structured interviews (via Zoom) with experts, each lasting approximately one and a half hours. This study was approved by our Institutional Review Board (IRB20-2071).

Participants

Eight participants were directly recruited for their olfactory experience expertise covering a range of interactive applications (narrative, games, art, research) for all ages (children to adults), see Table 4. Four identified as women and four as men. All participants reported having produced several olfactory experiences for the public: four participants were game designers, three worked with film or performance, and one was an artist & researcher focused on olfactory experiences. We compensated each expert with a 25 USD gift card for their time.

Table 4: Experts on interactive olfactory experiences interviewed for Study 1. These experts covered a range of backgrounds and media for all ages (from children to adults) and audience scales (individual to theater experiences).

Expert	Background	Relevant projects or experience
E1	Filmmaker, olfactory artist	Olfactory experience designer for film screenings with scent, scented workshops and activities with children and people with disabilities, etc.

Expert	Background	Relevant projects or experience
E2	Artist, exhibit and experience developer, playworker	Olfactory experience designer for film screenings with scent, olfactory experiences for children, smell experiences for neighborhood communities.
E3	Film programmer	Olfactory experience designer for film screenings with scent.
E4	Game designer, researcher	Academic researcher on scent in games, olfactory game designer.
E5	Game designer, programmer	Lead designer for commercially distributed video game with scratch-and-sniff card (over 750,000 copies sold).
E6	Game designer, programmer	Lead designer for commercially distributed text-adventure with scratch-and-sniff card (over 130,000 copies sold).
E7	Game designer, researcher	Interactive art installations and games exhibited internationally, sensory design & teaching.
E8	Artist, HCI researcher	Interactive olfactory installations, research on olfactory HCI.

Procedure

We started our semi-structured interviews by gathering professional experience around scent, using their prior work as a probe. This structure follows the critical incident technique [67], in that we gave a clear statement to participants of what is being investigated. We discussed what influenced their prototyping, project iterations, and challenges.

Qualitative data analysis steps were then followed to identify major themes from an a-priori list of categories. We used Burnard’s stage by stage method [32] as follows: (1) close reading of the transcripts; (2) open coding of the responses; (3-4) developing broader categories based on the open coding; and (5) reducing the interviews to words and phrases.

Results

We summarize and report the three most relevant major categories.

1. Most experts skip lo-fi prototyping. Six of eight experts (E1, E2, E3, E4, E7, E8) did not introduce smells in their early design process. They typically delayed integrating actual smells until they finished producing the underlying hardware. When reflecting on their hardware choices, experts that developed custom hardware for their experiences (E4, E7, E8) mentioned spending most of their time on this portion of their projects, *to the detriment of the experience design* (E8).

As E8 explained, they were “not [...] able to focus exclusively on the olfactory experience design due to the time spent on developing hardware and learning electrical engineering.” Experts often emphasized the overhead associated with acquiring domain expertise and tacit knowledge *early in* their work. Experts stated difficulties or time spent learning how to (1) program or engineer (E4, E7, E8); (2) produce their own fragrances (E2, E3, E7); (3) use existing delivery technologies (E2, E4, E7, E8); and (4) determine best practices for safety (E7).

2. Reusing low-tech & low-fidelity smell products to make a final experience. Five experts explored less conventional methods of odor delivery (E1, E2, E3, E6, E7). For example, E2 designed an interactive art installation in which visitors could spray post-it notes with ready-made fragrances and attach them to a zoetrope, which combined the ease of assembling a sequence with the zoetrope’s ability to animate the sequence by spinning. E1 similarly recounted using spices from a store in unlabeled jars to make a small story with a friend’s child, as they prefer thinking about “the sequence of odors than to get caught up in [smell] delivery.” Others used low-tech and low-fidelity products like scent-imbued fabrics, commercial food products and items (e.g., soaps), and even scratch-and-sniff stickers. Commercial foods and items left experts with little control over the odors and their intensity. All options required manual cueing. Conversely, when asked about their experience with scratch-and-sniff stickers, the consensus was that it was easy to use and offered a variety of available odors. E3 mentioned scratch-and-sniff saved production (instead of foods and fabrics) and that stickers addressed “issues of cross-contamination” and “offered a variety of new odors” (E3, E5, E6).

3. Early tests. Only E5 and E6 introduced odors early in the development of a major project. They iterated on their interactive games’ scents by changing the layout with scratch-and-sniff

sample cards. They both remarked that testing their games' smells with scratch-and-sniff was "straightforward" and did not require domain expertise (it is just paper).

Discussion

Most experts went from concept to directly spending their time building and iterating over complex high-fidelity or high-tech versions of their experiences. While high-tech solutions provided the benefit of control, experts did not draft and test their olfactory design choices early on.

This issue arises because there is no structured toolkit or method to help experts draft lo-fi prototypes. However, the exploration of low-tech, low-fidelity products to quickly create final experiences provided insights. We identified scratch-and-sniff stickers as the ideal candidate for enabling olfactory prototyping. Unlike foods or beverages, they do not spoil, are consistent over time, and can be stably stored. Unlike ready-made fragrances, even children can handle them safely. Unlike imbued fabrics, they do not cross-contaminate easily. Scratch-and-sniff stickers are cheap, widely varied in smell, easy to access, compact, and easy to handle. However, scratch-and-sniff cards require cueing for manual operation (e.g., number flashing in a corner) and – as a form factor – cannot handle long or complex odor sequences. For example, how does one draft a crossfade between two smells on a scratch-and-sniff card? Our toolkit design needed to improve upon the card form factor for scratch-and-sniff stickers.

Second, olfactory experiences can be thought of and deconstructed into component odor sequences (E1). Following this, our toolkit must provide the flexibility to produce many individual odor sequences and allow designers to compare sequences easily. These findings provided design considerations and inspirations for Smell & Paste.

Smell & Paste Toolkit Implementation

With these findings, we implemented the Smell & Paste toolkit around a 3D-printed cassette (no electronics). This design builds upon the scratch-and-sniff card form factor. With Smell & Paste, designers draft odor sequences by adding stickers along the cassette's paper tape and can animate the sequence, allowing complex effects like crossfades. The cassette form factor also supports arbitrarily long odor sequences as it is compact (rolled up), like a *Compact Cassette* for music. As demonstrated in Study 3, our toolkit reliably delivers odors. Figure 65 presents the key components of Smell & Paste. We open-sourced all assembly and design files for replication, modification, and dissemination. We also provide a hyper-low-cost version that uses commonly available corrugated cardboard and paper towel tubes (craft tubes).

Toolkit components

Smell & Paste components were optimized to be printed with small, entry-level FDM printers. We designed the 3D models to require almost no support materials or overhangs. Alternatively, we implemented a hyper-low-cost version of the cassette with corrugated cardboard and craft tubes. We made our designs parametric to support size modifications. For example, users can change the tape width, and the 3D or cardboard cutting files will adjust accordingly.

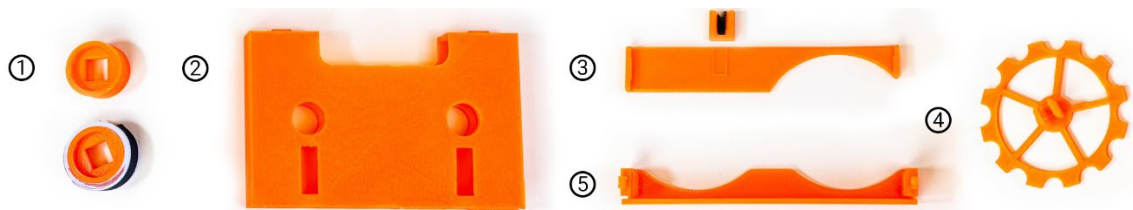


Figure 65: The kit is made from: (1) tape, (2) cassette, (3) scratch plate with comb, (4) driver, and (5) cassette connector.

1. Paper tape. We use inkjet or copy paper for the tape material as it is commonly available and flexible. Most scratch-and-sniff stickers adhere to it well since the paper is uncoated (or they

can be glued on easily). To produce a paper tape, a user must tape together paper cut to the intended tape width. We recommend washi tape to connect paper strips (for its flexibility and thinness) and a stickier tape (e.g., gaffe tape) to connect the paper tape to two spools. The user then authors sequences by pasting stickers and can play a sequence by placing the tape (with spools) in a cassette.

2. Cassette. To assemble a cassette, the user prints and assembles the top, bottom, idle rollers, and hinges. The cassette's two slits let the user monitor the tape's progress. The idle rollers align the tape with the comb and decrease tape friction. After inserting a tape, the user closes the cassette and attaches the scratch plate.

3. Comb and scratch plate. The scratch plate is a modular attachment that clips onto the cassette and aligns the comb with the tape at the cassette's opening. The comb slots around a loaded tape and scratches its stickers. We designed the comb to print separately from the plate so future designers could make new designs and integrate them quickly into the kit. We initially made the comb entirely 3D-printed; however, three out of five participants from Study 2 mentioned the 3D-printed teeth would sometimes jam the tape. In turn, we redesigned the comb to use Velcro-like hook and loop fasteners, and Study 3 showed this new version worked reliably. We additionally ran a small pilot that further demonstrated this final comb's reliability. Over the course of scratching a five-smell sequence 105 times, the tape never got jammed and two participants had a detection rate of $100 \pm 0\%$ and identification rate of $85 \pm 14\%$ (getting better over time instead of worse) for the smells.

4. Driver. We designed a simple driver to mechanically advance the tape: a gear with a solid cantilever inserted through one cassette hole. The cantilever slides into one of the cassette holes

and clicks in place, securing the driver to the spool. The user then rotates the driver to advance the tape.

5. Cassette connector. We designed an optional component that allows users to *stack* multiple cassettes, as in Figure 66. This component attaches to a cassette’s bottom and exposes two cantilevers that can couple with another connector. Both the scratch plate and connector have clearance for the driver of another cassette. Connecting two cassettes can help a designer – for example – evaluate the legibility of odor interactions (sequences) happening at the same time.

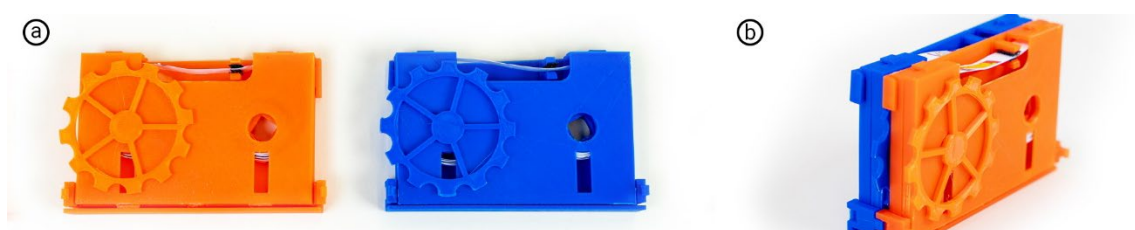


Figure 66: (a) Two cassettes side-by-side and (b) two cassettes stacked together using the connectors (for multi-track mode).

Editing techniques

While we purposefully designed our low-fidelity toolkit for *simplicity*, its simplicity does not hinder its expressivity. As we now present, Smell & Paste provides simple modes of operation that, when combined, allow users to test complex odor sequences quickly. For example, users can try switching odors, fading in or out, mixing aromas in parallel, or even transferring entire chunks of a sequence from one tape to another. These editing techniques build upon existing film, tape, and reel-based editing techniques (e.g., for film or audio) [145, 255], which are widely used and versatile.

1. Cut and paste. Our toolkit’s underlying technique is cutting and pasting. Users select scratch-and-sniff stickers and cut these to fit the paper tape. By pasting several odors, they can

prototype a sequence in less than a minute (Figure 67) and even control the odor's intensity by changing its surface area on the tape.



Figure 67: Designers cut and paste scratch-and-sniff stickers to form an odor sequence. Here, it would play root beer then smoothie.

2. Fade. Users can produce fade-ins and fade-outs by controlling the sticker's surface area *over time*. Figure 68 depicts two simple methods. In the first method (a), the user cuts the sticker so that it tapers or enlarges as the tape advances. Alternatively, the user can *pulsate an odor* (b) by cutting an odor into pieces and spreading the fragrance over time, which allows for more control over fading duration. Both techniques translate to *crossfades* (e.g., fade between smells).



Figure 68: (a) Fade in of smoothie scent by cutting sticker into a long triangle. (b) Fade out of root beer scent by pulsing stickers. Both techniques can be extended to crossfades.

3. Multi-track. To mix odors, users can cut thin slices of stickers and lay them side-by-side on the same tape or use connectors to smell two tapes simultaneously (Figure 69). The latter is helpful when testing scent combinations non-destructively, iterating over previously authored sequences, etc. However, while smelling two tracks is manageable, anything beyond would require the user to sweep their nose across all tapes.



Figure 69: Playing two smells simultaneously: (a) cutting scratch-and-sniff stickers into thinner tracks and superimposing them, or (b) using the included connector to play two independent cassettes simultaneously.

4. Splice. Finally, a user can cut the paper tape to join two different areas together or introduce a new sequence. Users then use washi tape to reconnect the areas into a single tape. As shown in Figure 70, this technique enables quick reuse of previously drafted sections or could even be used to crossfade entire sequences.

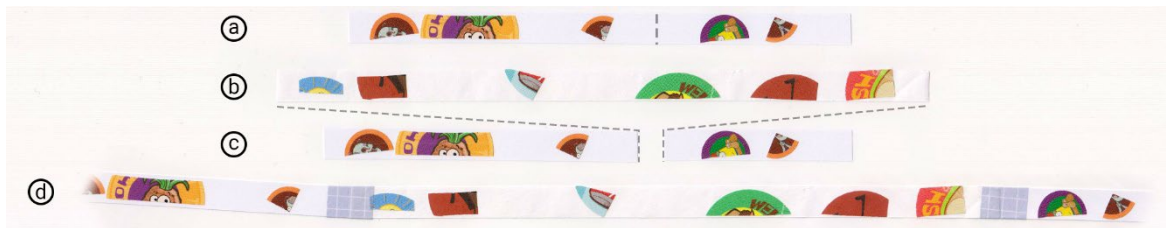


Figure 70: (a) A user will insert a recent odor sequence into (b) another previously prototyped sequence (c). They cut the base sequence (c) and then use washi tape to insert (also known as splice) the old sequence into the new one (d).

Dataset of commercial scratch-and-sniff stickers

For our toolkit to be practical, users must acquire scratch-and-sniff stickers. Commercial scratch-and-sniff stickers for children are incredibly accessible and cheap, including good and bad scents. We created a dataset of 800 scratch-and-sniff stickers from 22 brands to facilitate sticker selection. We manually extracted each sticker's scent, dimensions, and price per cm^2 . The dataset includes 538 unique scents, depicting a wide variety at costs as low as 0.00035 USD per cm^2 .

Study 2: Exploring Smell & Paste with Novices

While novices can use paper prototyping to design and explore their first screen-based interfaces in minutes (as used in virtually all Introductory HCI classes worldwide), the same is not possible for novices who want to explore olfactory UIs. We realized that Smell & Paste's low-fidelity materials might be approachable to novices with introductory skills.

In turn, we designed our second study to explore Smell & Paste with a group of novices, recruited from an HCI class. We were interested in whether our kit (1) supported novices to quickly

explore olfactory design [161, 202] and (2) what techniques emerged when using the kit. This study was approved by our Institutional Review Board (IRB20-2071).

Participants

We deployed our study as an optional assignment in a university-level HCI course. Participating in the study was entirely optional for the course. We recruited seven students (three women and four men), aged 20 to 26. While five had no experience in design or engineering, two had engineering degrees. None had any prior experience conceiving olfactory applications or experiences. Participants were compensated 50 USD for their participation.

Procedure

Participants received a toolkit with two cassettes and 41 different scratch-and-sniff odors. We also provided a short video tutorial. As the study occurred during social distancing measures, participants received their toolkits by mail.

We assigned design prompts to allow a refined analysis of the design and prototyping experience [207, 232, 253, 254]. See Table 5. The prompts reflected a small variety of previous olfactory applications from HCI (notifications [162] and games [200]) and product design [325]. As participants had no experience conceiving olfactory applications, providing prompts let them focus on the olfactory interaction design. In turn, this focus allowed us to observe their techniques with our kit and whether the toolkit supported rapid exploration of olfactory design [161]. We randomly assigned prompts to all participants (P1-5), while, given the engineering backgrounds of P6 & P7, we assigned them a prompt to test the kit's flexibility for add-ons. Upon finishing, participants submitted at least three process photos and a video of their prototype(s) that explained their work. Participants could also provide written feedback on our toolkit.

Table 5: Participants, their design prompt, and prototyped experience summary from Study 2. As participants had no experience conceiving olfactory applications, we provided these prompts to inspire participants and encourage using smells.

Participant	Prompt	Description	Resulting prototypes from participant
P1	1	Design an olfactory notification system.	Pomodoro-timer with olfactory notifications conveying timer state and urgency.
P2	2	Design smell interactions for a game.	Interactive odor cues for <i>Mario Kart & Pokémon Go</i> , as well as olfactory versions of popular board games, a smell escape room puzzle, a smell maze.
P3	2	Design smell interactions for a game.	Olfactory <i>Pictionary</i> .
P4	3	Design olfactory experiences for a user interacting with two makeup products.	Face mist that conveys its fragrance and functionality (spray) before use.
P5	3	Design olfactory experiences for a user interacting with two makeup products.	Eye shadow palette with scents matching shades. Lipstick, whose odor presents its shade and changes if it's fresh or expired.
P6 (engineer)	4	Engineer an add-on for the toolkit's cassette.	Add-on to automatically advance and rewind the cassette.
P7 (engineer)	4	Engineer an add-on for the toolkit's cassette.	Adapter to turn cassettes into an automated olfactory interface for VR headsets.

Results

We clustered our findings into nine categories based on the video, photo, and open feedback analysis. Smell & Paste enabled participants to rapidly draft lo-fi prototypes of their olfactory experiences (see Figure 71). Participants enjoyed prototyping their experiences with Smell & Paste. P1 stated that it was a “great experience” and “incredibly useful to have a physical form as a starting point for brainstorming and prototyping.” P2 and P3 appreciated the variety and realism of the scratch-and-sniff smells and stated that “it was very fun using this smell kit” (P2).



Figure 71: Participants made lo-fi prototypes by taking their design ideas and repeatedly (1) drafting with stickers, (2) loading tapes into cassettes, and (3) testing their ideas with their nose. Photos by and reproduced with the permission of participants.

1. Smell & Paste allowed novices to draft lo-fi prototypes exploring all key olfactory design features. Each participant (P1-5) explored chemical, emotional, spatial, and temporal design features in detail. P4 and P5 conveyed information through established scent-associations to provide information about the visual, spatial, and temporal qualities of their makeup products and iterated on these aspects. We now present focused examples from P1 and P2 to further exemplify the design ideas participants were able to quickly draft and evaluate with Smell & Paste.

P1 began prototyping their “Olfactory Pomodoro timer” by testing whether “certain aromas may perceptually and materially improve concentration, task lag time” (P1). They iterated over two key aspects: the chemical and emotional features of selected odors and their semantic meanings. They tested if scents felt like (1) “boost one’s state” and (2) “motivate to work”. For the start-time interaction, they compared and experimented with lemon to reduce stress or peppermint to increase concentration, settling for the latter after trying both options in the prototypes (“my experience with peppermint smell was poignant stimulation”). For their break-time notification, they compared lavender for its “known relaxation properties” and menthol as a simpler stimulator (a component of peppermint), settling for menthol. Then, P1 also experimented with “more pungent”

and “strong smells to encourage users to resume timer and work intervals” that conveyed a semantic sense of urgency. They selected and compared star anise, cinnamon, hay, manure, wet dirt, and campfire from the kit. P1 then arranged and composed scent notifications according to pungency and semantic meaning to convey urgency: hay for five idle minutes (slightly unpleasant), a manure and wet dirt combo for ten idle minutes (“funky”), and burning campfire for fifteen idle minutes (strong, pungent, and semantically urgent).

For P2, who delivered several lo-fi prototypes, we focus on their most advanced one: odor interactions for *Mario Kart*. P2 compared and combined scents for different effects after drafting and iterating on individual sequences. For the squid ink penalty (screen blocked by ink), P2 experimented with translating its visual mechanism to scent by using strange combinations with abrupt transitions to confuse and distract the player. They tried many combinations of smells and eventually settled on three “stranger” composite odors “so that scent changes *are* distracting” (emphasis by P2): smell one with bubblegum, rose, and manure; smell two with tomato, cotton candy, and campfire; and smell three with cake, new car, and corn. In contrast, P2 designed the invincibility power-up to “do gradual scent transitions [with] familiar scents [...] so that the scent changes are not distracting,” selecting “pleasant scents” like strawberry, chocolate, and lilac. The cassette allowed P2 to iterate and refine the sequence transitions): “scents for invincibility are tessellated for smoother scent transitions”; “scents for squid ink have gaps (...) for abrupt transitions”; and “speed boost has one segment for a briefer scent experience” whereas “invincibility and squid ink each have three segments, since these are meant to be experienced for a longer time.” P2 additionally drafted scent interactions that conveyed spatial information (competitors approaching), semantic information (fish for incoming tortoise shell), and more.

2. Participants rapidly drafted and iterated on many lo-fi prototypes. Not only did all participants complete their prototypes within the assignment timeframe, but they produced iterations. Alongside *Mario Kart* interactions, P2 initially rapidly prototyped olfactory interactions for a battery of other games: *Hide and Seek* (imagining scents for each player that would get stronger when approaching); an interactive maze in which two cassettes encode the solution (left vs. right turns); an envisioned expansion to *Pokémon Go* (including scents for spatial information and monster states); and more. Participants also reported completing many iterations of odor sequences and composed smells (P2, P4, P5).

3. Smell & Paste paired well with established lo-fi prototyping strategies. Participants combined Smell & Paste with other prototyping strategies. **(1) Paper prototype:** P1, P3, and P4 used our toolkit with the more traditional paper prototyping, especially for interactive applications well suited for this method, such as P1's screen-based UI for a Pomodoro timer complemented with olfactory notifications. **(2) Wizard-of-Oz:** P2 used our toolkit in combination with Wizard-of-Oz, in which they "played the scent tapes" while a friend played the actual game of *Mario Kart*. This combination let P2 quickly prototype by querying the user on how the smell interactions contribute to the experience. P3 similarly leveraged this combination to test their olfactory game with a roommate. P5 did this when possible, such as advancing or rewinding the tape while opening their lipstick. **(3) Video prototype:** P2 also employed our toolkit with prerecorded videos of *Mario Kart* runs, allowing them to iterate quickly over a sequence until it felt right.

4. Participants iterated on sticker size to control and test odor intensity. Participants tested and controlled an odor's intensity over time by cutting the sticker into smaller or larger areas. As shown in Figure 72, P2 prototyped interactions to convey approaching vehicles (fading natural gas) and collisions (burst of wet dirt). By changing a sticker's thickness for intensity and length

for the duration, P2 experimented with transitions, such as homing in on noticeable switches between disparate scents for squid ink to fade-ins to convey approaching competitors.

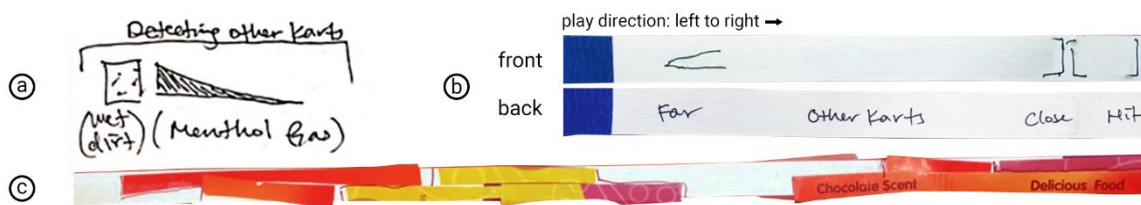


Figure 72: Participants cut stickers to control their intensity. P2 used two methods: (a, b) long triangles for fades followed by a burst (clear stickers) and (c) transitions by staircases between odors. Photos by and reproduced with P2's permission.

P4 used scent intensity the most in their face mist interaction prototypes. They prototyped how to encode the product's delivery mechanism (spray) before use through scent, settling on a prototype that delivered a sudden strong watermelon scent that quickly fades when the user opens the face mist's cap. They used a second cassette to precisely control the watermelon scent's intensity (more surface area to work with) and add short bursts of vanilla.

5. Stickers can be combined to compose a new scent. Participants prototyped not only sequences but also *new scents* by recombining scratch-and-sniff stickers. For example, P4 tried to compose a powdery smell. They first investigated what fragrance notes produced powdery perfumes, identifying rose, vanilla, cake, and lavender. They then tested and combined those odors at various intensities to create a new identifiable scent. P2 also used a similar technique for their more complex odor-releasing *Mario Kart* game events. P4 took this a step further and prototyped conveying the makeup's state (closed, opened, in-use) by subtly changing the component odors' intensities, see Figure 73. P3's entire prototype relied on scent composition, as players craft new scents and sequences to convey a prompt to others.

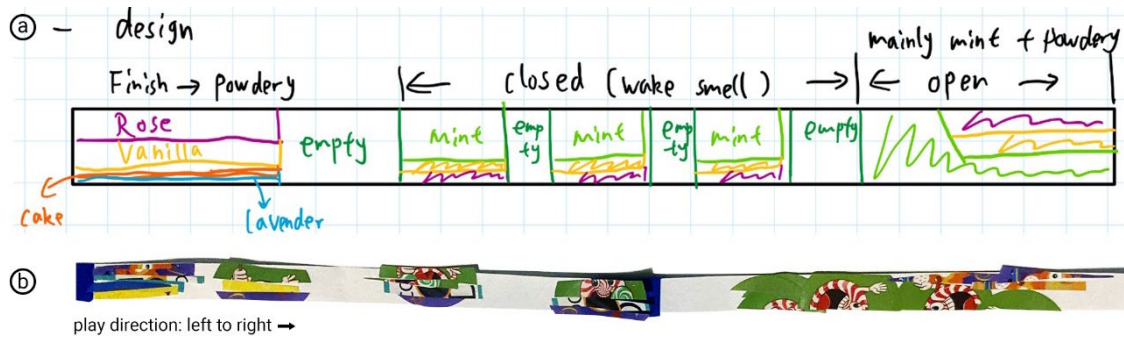


Figure 73: An example of how participants prototyped not only an interactive odor release but also mixed new fragrances (P4).

6. Participants developed strategies to map branching experiences onto the tape. We observed different approaches to mapping branching experiences onto the cassette's linear structure. P5 used advancing and rewinding the cassette to encode and prototype branching states, with the area at the opening representing the branching point.

For instance, P5 translated the eye shadow palette's physical layout by splitting it at the central eye shadow and letting the user move the tape either left for the shades to the left or right for the matching shades. This participant reapplied the technique to prototype their lipstick interaction in which its odor changes to convey whether it is fresh or expired, as shown in Figure 74. If the lipstick is fresh, the user rewinds to receive a lemon odor (refreshing) followed by cherry (smell-color association). If the lipstick is expired, the user advances the tape and gets a corn odor.



Figure 74: P5 used advancing and rewinding to prototype an interaction that branched based on whether an envisioned interactive lipstick was fresh or expired. Photos by and reproduced with P5's permission.

For their Pomodoro-timer, P1 prototyped odor sequences for each machine state in separate areas. P1 used advancing and rewinding to different regions to then test certain decisions. In

contrast, P2 leveraged two *connected cassettes* to prototype an olfactory experience accompanying *Mario Kart*), see Figure 75. P2 used two tapes for two types of scent interactions: one for spatial interactions (i.e., a kart approaching and colliding) and another for power-ups (player state). Using two cassettes allowed them to quickly test how the experience would smell when interactions of two types occurred concurrently and then adjust the odors to make them mutually intelligible.



Figure 75: (a, b) P2 separated scent-triggering events across two stacked cassettes. (c) P2 also embedded notes directly on the tape to keep track of prototyped interactions, such as “close” and “hit”. Photos by and reproduced with P2’s permission.

7. Participants took notes directly on the tape. For example, P2 prototyped their interactions in separate areas of the tapes with no specific order, so they wrote each sequence’s name on the tape, as seen in Figure 75 (b).

8. Participants redrafted sequences instead of splicing. Participants found it quicker and more convenient to redraft sequences in blank areas than to splice sequences. This approach enabled them to compare variations.

9. Smell & Paste is modifiable. The two participants with an engineering background (P6-7) found the toolkit customizable. P6 altered the cassette to advance automatically, as seen in Figure 76 (a), adding a motor inside the cassette. P7 prototyped an add-on that adapted their cassette into a VR-ready digital olfactory display, as seen in Figure 76 (b).

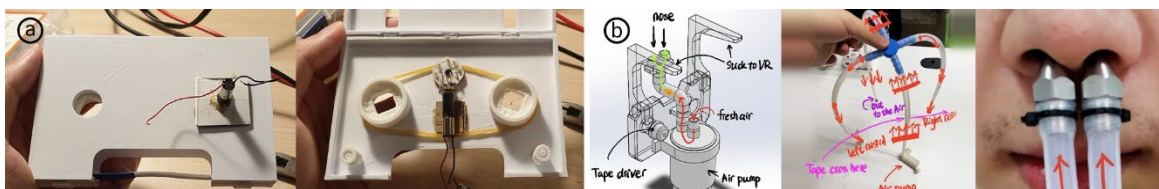


Figure 76: (a) Two iterations of P6's add-on that automatically advanced their cassette. (b) Progress images from P7's adapter to turn cassettes into automatic olfactory interfaces for VR headsets. Photos by P6 and P7 and reproduced with participants' permission.

Suggested improvements. While participants found the kit useful for lo-fi prototyping (P1-5), participants also provided suggestions for improvement. Three participants (P2, P4, P5) noted that the 3D-printed comb teeth occasionally jammed if several scratch-and-sniff stickers overlapped. P5 wished synchronizing movements between cassette advancing or rewinding and interacting with another object were easier. P4 suggested adding tactile markers to the tape to allow users to gauge where they are on the tape without looking down.

Fixes. We resolved jamming issues by redesigning the comb to use hook-and-loop fasteners (Velcro) as teeth instead. These fasteners are stiff enough to scratch the stickers' surface and flexible enough to let arbitrarily thick tapes pass.

Study 3: Toolkit in Experts' Activities

Finally, we engaged with olfactory experts to understand their impression of the kit and determine its potential when integrated into their practices. This study was approved by our Institutional Review Board (IRB20-2071).

Participants

We recruited experts E1 and E3 from Study 1 for their extensive experience designing olfactory experience for diverse audiences (children, people with disabilities, etc.) and because they had reported having enough time to evaluate the kit in their professional practices. Both received a 50

USD gift card for their time. As we were interested in the kit's applicability in expert work, we did not provide prompts. Instead, we asked the experts to experiment with the kit in their olfactory practice for two weeks. Participants then provided documentation (photos and videos) and feedback via Zoom. As the study occurred during social distancing measures, participants received their toolkits by mail.

E1 decided to use the toolkits in a workshop with kids. This participant requested four full toolkits. E1 prototyped a workshop for children (aged 7 and 9.) E1 designed a curriculum with the kits in which children compose scent tracks to train each other's noses and then produce interactive smell stories for their parents. Both children were authorized to participate in the workshop by their parents. Their parents provided permission to reproduce and use documentation. E1 was able to conduct the workshop as their country allowed small gatherings during quarantine.

E3 decided to test the toolkit to prototype olfactory movie experiences. This participant requested a single kit. Over the two weeks, E3 experimented with their kit to uncover its potential use in their olfactory film practice. For this, they recruited their spouse as a participant to iterate over odor sequences.

Results

Even though the two activities were very different, their results provided common ground. Following this, we decided to cluster the separate findings into three combined themes based on the video, photo, and feedback analysis.

1. Experts would use Smell & Paste in their work. E1 stated that they would use the toolkit again. Likewise, E3 began imagining possible ways to extend the toolkit, namely motorizing the cassette to play in sync with a game.

2. Smell & Paste provides technical and tangible affordances. E3 found that the cassette and comb worked successfully, similarly echoed by E1's successful workshop with children. E3 stated odors "only lingered for a short period after passing the comb" and that "odors directly under the nose were stronger than accumulated odors from the spooled tape" (E1 mentioned this too). For subtle smells, E3 recommended spacing out stickers by approximately 4-6 cm to produce bursts that faded quickly, stating "more complex odors needed additional space". E1 and E3 highlighted Smell & Paste's ability to rapidly draft sequences: "this [toolkit] is really useful [...] because it gives you a sequence" (E3).

E1 and E3 also praised the cassette's design, requiring little to no explanations. E1 did not show the children our tutorials and reported "they had no problem using" it, stating "the mechanical design is straightforward and communicates its functionality." Moreover, both agreed that toolkit assembly was easy: E1 said it was "incredibly simple" and they did so without watching the tutorial.

3. The cassette form factor provided surprise. E3 mentioned they entered the study believing the cassettes "could be really fun as a toy" while being skeptical of the benefits over a typical scratch-and-sniff card, which they had previously worked with and designed. However, upon using the toolkit, they "immediately realized a big advantage: the cassette can hide the stickers' visuals." Moreover, E3 raised one more added benefit compared to traditional scratch-and-sniff cards: "even with a scratch-and-sniff card that doesn't indicate the smell, one can sniff around at the card ahead of time and have an idea of what's to come, and who could resist that. But [...] hidden inside the cassette, there's no way to know what scent is coming next." Furthermore, E1 mentioned using this "surprise effect" to let the children train each other's noses, as depicted in Figure 77 (a).



Figure 77: (a) The kids taking turns testing each other's ability to identify the odors on a tape. (b) Their mom smelling the interactive olfactory story they drafted. Photos by E1 and reproduced with participant and parents' permission.

The children created their own odor sequences, which they presented to each other as a smell identification game. They then independently explored which odors worked well and could be integrated into their interactive stories. In just one afternoon, both children drafted and iterated over interactive olfactory stories, sharing their experiences with their mom at the end of the workshop as seen in Figure 77 (b).

Suggested improvements and considerations. Experts noted that the driver's cantilevers could snap if carelessly inserted or removed (E3). E1 reflected on their experience using our toolkit with the children's workshop, noting that selecting odors took more time than necessary. We provided 41 different scratch-and-sniff odors with our toolkit, which E1 found overwhelmingly vast for children to explore in a limited time. Finally, E1 suggested that a thicker and bigger version of a tape (closer to a VHS size) might help those with less dexterity (including children).

We found E1's thickness suggestion important and easily actionable. We made our files parametric, allowing designers to choose their desired tape width and cassette dimensions. All parts will then adjust accordingly. Additionally, E1 and E3's experience with the cassettes proves that they work reliably and do not jam with the new combs.

Recommendations for Using or Deploying Smell & Paste

Based on insights gained from Studies 2 and 3, we now synthesize eight recommendations for prospective designers interested in using Smell & Paste to prototype olfactory experiences or disseminating the toolkit for their studies:

1. Use Smell & Paste to draft and evaluate design choices quickly and frequently. Smell & Paste works well to lo-fi prototype long or short interactive sequences and quickly compare isolated interactions. For example, a designer can fine-tune which smells are released when the player receives a power-up in *Mario Kart*. To make the most of Smell & Paste, we recommend using the toolkit early and frequently in the design phase.

2. Smell & Paste is easy to use for experts and novices. As evidenced by Study 2 and E1's workshop with two children in Study 3, Smell & Paste's form factor is intuitive. Since Smell & Paste uses scratch-and-sniff stickers instead of liquid fragrances, there is also little need to train designers on *how to smell and handle fragrances* before developing an interactive olfactory experience. Moreover, Smell & Paste may not even need a video tutorial (E1). This ease-of-use contrasts with other kits requiring multipage brochures or manuals [149, 150] and instructions [143]. Additionally, unlike handling fragrances, which require safety practices, commercial scratch-and-sniff stickers are safety compliant for even children. Experts and novices can handle them with no worries.

3. Smell & Paste produces lo-fi olfactory prototypes that can be stored and shared. While the kit supports radical and destructive drafting (e.g., tossing entire sections), the resulting lo-fi prototypes are long-lasting and keep smelling even after many scratches. For example, Study 1's E3 mentioned their 1981 scratch-and-sniff cards still smell, and sequences we produced for pilots smell even two years later. Additionally, both participants in Study 2 and 3 were excited about

sharing their prototypes with friends and family. The Study 3 experts also highlighted Smell & Paste prototypes' ability to be shipped without restrictions or special handling. Several mentioned experiencing issues transporting materials for interactive exhibits due to restrictions on fragrances. This problem often prevented them from mailing or bringing early prototypes to museums or theaters.

4. Document directly on the paper tape. Designers can annotate tapes by writing on them, e.g., notes for timing cues, labels for a particular interaction, etc. We recommend this practice to keep track of and draft sequences so that designers can return to their lo-fi prototypes later with context (just like in programming).

5. Scratch-and-sniff stickers provide a great variety of smells but pre-select them for a quick start with children. While adults had no problem smelling and choosing from an extensive library of smells (41 provided in kits), this variety overwhelmed children and had them spend too much time sniffing scents before prototyping. Per E1's suggestion, we recommend designers pre-select relevant odors when working with children.

6. Modify the kit as desired. We encourage prospective users to adapt the kit to their needs. First, the mechanical design of Smell & Paste is parametric. Per E1's expertise with children and disabled people, we recommend printing a version of the cassette with wider tape to let those with less dexterity handle it better. Second, pairing the cassette with braille labels may allow blind and visually impaired designers to use the kit. Finally, designers can extend the cassette with electronics for new applications, such as automated playback. For example, we produced a hyper-low-cost version of our cassette from commonly available corrugated cardboard; Figure 78 shows one made from an Amazon package.

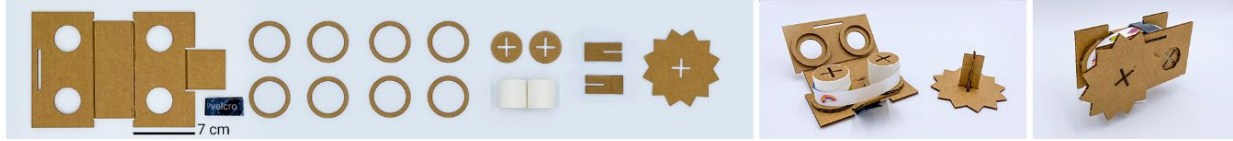


Figure 78: Our variation on the cassette made entirely of commonly available corrugated cardboard, one cardboard craft tube cut in two, paper, and a strip of Velcro. This variation can be cut by hand using an X-Acto knife and assembled with everyday glue.

7. Combine or transition to hi-fi smell toolkits. Smell & Paste – and lo-fi methods in general – mark the start of prototyping an interactive experience, not its end. We encourage prospective designers to transition from their lo-fi prototypes, created using Smell & Paste, to hi-fi toolkits or even combine Smell & Paste with hi-fi techniques. We present examples with existing kits. *(1) Combine with physical hi-fi olfactory toolkits:* In Lai and Cao’s toolkit workshop [143], participants used visual sketches as early prototypes prior to engaging with the hi-fi toolkit. By combining a lo-fi toolkit, such as Smell & Paste, participants can couple their lo-fi sketches with lo-fi smell prototypes, allowing them to transition more smoothly to the higher-fidelity hardware. Similarly, combining Smell & Paste in the O&O workflow might provide designers an opportunity to test and iterate on ideas in the early design phases (e.g., in the “Prototype” and “Test” steps of the manual [149]) before committing days to a hi-fi O&O prototype. Additionally, O&O’s design manual could be paired with Smell & Paste to provide a structured thought process for designing for the smell in all prototyping stages. *(2) Combine with software hi-fi olfactory toolkits:* Smell & Paste’s linear structure may translate well to OWidgets’ similar linear timeline editor [163], and – vice versa – a prospective designer might test an OWidgets sequence without hardware to dispense smells.

Conclusions

This paper proposed Smell & Paste, the first prototyping toolkit for olfactory design that enables a structured workflow for lo-fi olfactory prototyping. Our findings suggest that Smell & Paste enables rapid and cheap prototyping of smell experiences, is approachable to people of any technical background, and is extensible. From the studies, we improved the toolkit's design and extracted recommendations for prospective designers interested in using Smell & Paste.

We believe our toolkit might accelerate and make olfactory prototyping more approachable across various fields, including HCI, design, and education. As part of these efforts, we provide our toolkit as open-source with a dataset of 800 commercial scratch-and-sniff stickers. Alongside our expert interview insights and toolkit, we believe these efforts form the groundwork to investigate future research questions, such as how olfactory experience designers could transition from low-fidelity and high-fidelity prototypes to final experiences. Exploring this area is imperative to support the development of new, rich olfactory experiences.

Conclusion

This dissertation introduced perceptual engineering as a new paradigm in human-computer interaction: one that aims to systematically and precisely alter human sensory experiences through novel interface technologies. At its core, perceptual engineering reframes the design of interfaces to directly engage the physiological mechanisms underlying perception, enabling new forms of interaction that go beyond the limits of mechanical or audiovisual feedback.

The first instantiation of this approach took the form of chemical interfaces, which modulate sensory perception via controlled chemical stimulation. These interfaces are power-efficient, selective, and miniaturizable, making them ideal for wearable or embedded applications. I demonstrated this through a series of projects:

- Trigeminal-based temperature illusions showed that small amounts of trigeminal stimulants like menthol or capsaicin can create compelling sensations of warmth and coolness without changing actual temperature, enabling efficient and immersive thermal feedback in VR and everyday settings.
- Chemical haptics expanded the sensory repertoire by using topical compounds to render tactile sensations such as tingling, stinging, or numbing, without the need for multiple mechanical actuators.
- Taste retargeting leveraged taste modulators to selectively suppress or transform individual basic tastes, enabling seamless modification of flavor perception while eating real food.

This opens new pathways for nutritional interventions and adaptive dietary support.

Building on these chemical approaches, I extended perceptual engineering to electrical and thermal stimulation. For instance, stereo-smell used electrical stimulation of the nasal septum to generate directional smell-like sensations, enabling spatial olfactory feedback even for individuals

with anosmia. Similarly, augmented breathing demonstrated how synchronizing nasal thermal feedback with inhalation could alter perceived airflow, with implications for anxiety relief and mask compliance.

Across these projects, I contributed new hardware designs, stimulation protocols, and evaluation methods that collectively push forward the possibilities for sensory computing. This work also foregrounds the importance of real-time delivery control and user safety when manipulating perception, and it offers a compelling case for multisensory interfaces that are energy-efficient, expressive, and accessible.

Together, these contributions lay the groundwork for a future where users can shape their sensory experiences intentionally, adjusting what they taste, feel, or breathe for health, comfort, and enriched interaction with both digital and physical environments.

Future Directions

While this dissertation establishes the foundations of perceptual engineering, several exciting directions remain open for future research.

Operating Systems for the Senses

To scale perceptual engineering, there is a need for perceptually-aware computational frameworks that manage multiple sensory outputs. A sensory “operating system” could coordinate the timing, dosage, and sequencing of stimuli (chemical, electrical, or thermal) based on perceptual dynamics. Such a system would enable fine-grained control over complex, multi-modal experiences (e.g., simulating a windy mountain with synchronized cooling, airflow illusions, and directional olfactory cues).

Machine Learning for Sensory Modeling

The high dimensionality and non-linearity of sensory data, especially in chemosensory interactions, call for advanced modeling. Machine learning models (such as autoencoders or SVMs) can help decode sensory responses from electrophysiological data or predict the perceptual effect of stimulation parameters. This approach is essential not only for personalization but also for inverse design: generating stimulation patterns that reliably produce target sensations.

Applications in Health and Accessibility

Many of the interfaces developed here have promising applications in health contexts. Taste retargeting may support individuals with dietary restrictions or disordered eating. Electrical stereo-smell offers a novel sensory substitution method for people with anosmia. Breathing-based illusions could aid anxiety management or respiratory therapies. Future collaborations with clinicians and patient advocacy groups will be key to translating these systems into real-world use.

Environmental Sensing and Responsiveness

Interfaces that engage smell, irritation, and airflow also have untapped potential in environmental sensing. Future work may explore systems that use olfactory or trigeminal feedback to communicate air quality, pollution, or the presence of airborne pathogens. By augmenting perception in situ, these systems could support more intuitive, embodied responses to environmental risks.

Tools for Designers and Developers

Finally, future research should also support the growing community of designers exploring olfactory and chemesthetic experiences. Building on tools like *Smell & Paste*, new toolkits and

datasets could help standardize workflows, bridge low- and high-fidelity prototyping, and support cross-modal experience design in XR, games, and education.

Through perceptual engineering, we move toward a future where computing is not only visual or tactile, but sensory in the fullest sense, where users can sculpt what they taste, feel, and breathe to improve comfort, health, and immersion. This work lays a foundation for interfaces that engage the body directly and meaningfully, empowering people to reshape how they perceive and interact with the world.

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