

# Modulating Olfactory Perception through Localized Nasal Thermal Stimulation

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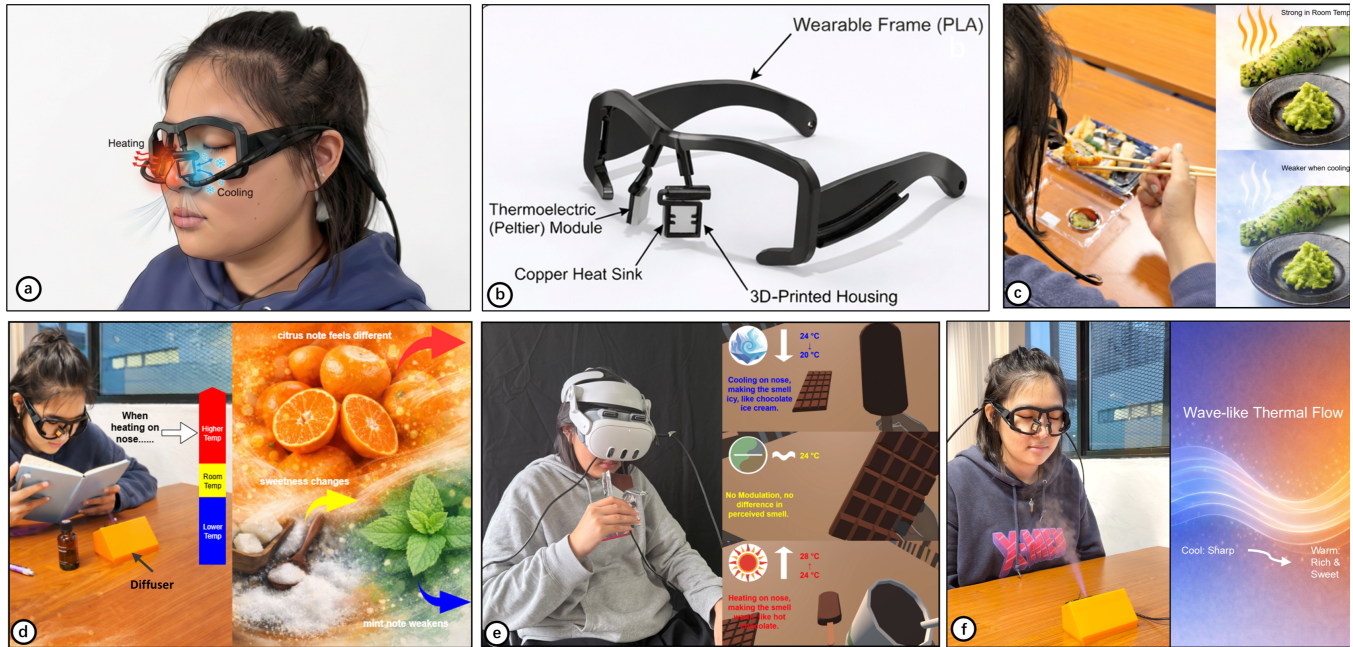
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**Figure 1:** We present a nose-mounted thermohaptic interface that modulates olfactory perception via localized heating and cooling on the nasal sidewalls. (a) Wearing configuration and (b) device structure. Example scenarios include (c) everyday food consumption, (d) ambient scent for attention/well-being, (e) VR food experiences: the same chocolate scent is perceived as ice cream under cooling and as hot chocolate under heating, and (f) olfactory evaluation tasks, demonstrating how nasal thermal modulation can subtly bias odor perception across diverse contexts.

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DIS '26, Singapore, Singapore

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ACM ISBN 979-8-4007-2563-0/2026/06

<https://doi.org/10.1145/3800645.3813007>

## Abstract

Smell and temperature are tightly intertwined in everyday experience, yet interactive systems often treat them as independent sensory channels. While thermohaptics and olfactory interfaces have been studied separately, it remains unclear how *localized nasal thermal stimulation* can modulate olfactory perception without changing chemical concentration. We introduce a nose-mounted thermohaptic interface that delivers precise, closed-loop heating and cooling stimuli to the nasal skin area (nasal sidewalls) to modulate olfactory perception. We evaluate our system in two user studies.

In the first psychophysical study, we estimate perceptual thresholds (just-noticeable differences, JNDs) for thermally induced changes in perceived odor intensity across three odors, revealing intensity biasing and asymmetric sensitivity between cooling and heating (mean JND: 4.33°C for cooling; 6.15°C for heating). In the second study, we profile odor quality in a structured multidimensional descriptor space, revealing odor-dependent, dimension-specific semantic shifts rather than uniform changes. Together, these findings suggest that nasal thermal modulation can serve as a rapid, reversible, and non-chemical approach for shaping olfactory experience, expanding the design space for perceptually driven olfactory interfaces in multisensory Human-Computer Interaction (HCI).

## CCS Concepts

• **Human-centered computing** → **Haptic devices**; *Empirical studies in interaction design*; Virtual reality; Interaction techniques.

## Keywords

Smell, Thermal feedback, Nose-worn device, Trigeminal sensation, Crossmodal perception

### ACM Reference Format:

Rui Zhang, Yitian Ding, Ningchang Xiong, and Shaoyu Cai. 2026. Modulating Olfactory Perception through Localized Nasal Thermal Stimulation. In *Designing Interactive Systems Conference (DIS '26)*, June 13–17, 2026, Singapore, Singapore. ACM, New York, NY, USA, 16 pages. <https://doi.org/10.1145/3800645.3813007>

## 1 Introduction

Smell is a fundamental component of human experience and everyday behavior, supporting food evaluation, hazard detection, and emotionally evocative memory [72]. In immersive media, prior multisensory research has further shown that incorporating olfaction can enhance presence, engagement, and affect in virtual and augmented reality (VR/AR) experiences [10, 25, 47, 60, 70, 86]. Yet most olfactory interfaces still emphasize delivery, controlling when and which odor is emitted—while intensity is typically adjusted indirectly via concentration, airflow, or exposure duration [86]. One of the limitations of these direct scent-delivery approaches lies in the physical behavior of odorants: once released, molecules linger, diffuse, and accumulate, making odors slow to dissipate and difficult to switch or clear. This latency produces “olfactory clutter”, where residual scents interfere with subsequent stimuli, posing a major challenge for dynamic, multi-scent interactions in VR/AR and other time-sensitive applications.

At the same time, olfaction is not experienced in isolation. Chemosensory perception is shaped by crossmodal interactions with other modalities, and designers can leverage such interactions to modulate experience without changing the chemical stimulus itself. For example, Narumi et al. demonstrated AR-based pseudo-gustation that alters flavor experience through visual manipulation rather than chemical change [58]. Beyond taste, perceptual and neuroscientific findings suggest that thermal cues can bias chemosensory experience, including perceived intensity, pleasantness, and discrimination [30, 31, 67]. In everyday contexts, warmth often amplifies food aroma, whereas cooling can strengthen impressions associated

with freshness, consistent with the nasal region’s thermal sensitivity and its coupling to perceived airflow and comfort [3, 81]. These observations motivate an alternative design direction: *modulating odor perception via localized nasal thermal stimulation*, rather than manipulating the odorant medium. Such modulation could be fast, reversible, and residue-free—properties that are well matched to rapid transitions and adaptive experiences.

Prior work provides early evidences that thermal cues near the nose could influence olfactory perception. Fujino et al. [17] showed that changing the temperature of air delivered to the nostrils alters odor sensation. Okamoto et al. [62] reported that the effect depends on factors such as odor type and the spatial configuration of stimulation, with larger perinasal heating areas producing greater perceptual changes in their setup. However, these studies do not yet establish quantitative mappings from localized nasal temperature changes to reliable perceptual outcomes (e.g., thresholds for intensity modulation) and how thermal stimulation reshapes perceptual odor qualities (i.e., how an odor’s attributes are redistributed within a multidimensional descriptive space). Without such grounding, it is difficult to treat temperature as a continuous and precise control signal in olfactory-based interactive system design.

In this paper, we ask: *How does localized nasal thermal stimulation quantitatively and qualitatively modulate olfactory perception?* We investigate how thermal stimulation near the nose biases perceived odor intensity and how it changes qualitative odor experience as reflected in semantic descriptors [9]. To this end, we introduce a lightweight, nose-mounted thermohaptic interface that delivers controllable heating and cooling synchronized with odor presentation. The device integrates two compact thermoelectric actuators (Peltier elements) into a nose clip mounted on eyeglass frames, positioned to contact the nasal sidewalls (Fig. 1a–b). A closed-loop controller rapidly drives local skin temperature to a target offset and maintains it, enabling repeatable and well-defined thermal stimuli.

We evaluate the approach through two user studies. First, a psychophysical experiment (N=12) estimates just-noticeable difference (JND) thresholds for thermally induced changes in perceived odor intensity across three odorants (Cherry Blossom, Sweet Orange, and Wasabi Oil). Results indicate asymmetric sensitivity: the mean JND is  $6.15 \pm 2.09$  °C for heating and  $4.33 \pm 2.04$  °C for cooling, where heating increases perceived intensity and cooling attenuates it. Second, we examine how nasal thermal modulation influences qualitative odor perception within an odor descriptive space [9]. We find that localized thermal stimulation selectively alters specific descriptor dimensions and yields odor-dependent and dimension-specific semantic shifts, suggesting opportunities for personalized olfactory experience design through thermal-olfactory crossmodal effects. Finally, we illustrate how thermal-based odor modulation can support diverse application scenarios design, including everyday food consumption (Fig. 1c), attentional and well-being scenarios with ambient scents (Fig. 1d), VR experiences with context adaptation (Fig. 1e), and olfactory evaluation tasks (Fig. 1f).

In summary, we contribute:

- A nose-mounted thermohaptic interface enabling precise, closed-loop heating and cooling for modulating olfactory perception.

- A psychophysical study (N=12) demonstrating that localized nasal thermal stimulation biases perceived odor intensity and establishing quantitative JND thresholds.
- An exploratory study of thermal–olfactory modulation within a structured descriptor space, revealing odor-dependent and dimension-specific semantic shifts that motivate personalized olfactory experience design.

## 2 Related Work

Our work draws on prior research in (1) odor perception and olfactory interfaces, (2) thermal feedback and thermohaptic interfaces, and (3) cross-modal thermal-odor perception. Together, these areas motivate localized nasal thermal stimulation as an alternative interaction mechanism for shaping olfactory experience without changing odorant chemistry.

### 2.1 Odor Perception and Olfactory Interfaces

Olfaction plays a distinctive role in human experience: it is closely linked to emotion and autobiographical memory and often functions as an ambient, affective cue rather than a high-bandwidth channel [68]. In HCI, this makes smell a compelling modality for multisensory experiences that aim to enhance immersion, presence, and affect, particularly in VR/AR [10, 86]. Accordingly, most olfactory systems focus on delivering the right scent at the right time, rather than encoding precise information.

A large body of work has explored how to generate and deliver odors with improved spatiotemporal control. Early projection-based approaches used localized puffs (e.g., vortex rings) to target users while mitigating room-scale contamination [56, 85]. More recent systems emphasize portability and integration with interactive contexts such as VR or consumption. Examples include head-mounted or VR-synchronized delivery [29], object-coupled scent emission for interaction [59], and retronasal augmentation during tasting [51]. Engineering work has also advanced airflow control, valve timing, and pump-driven delivery to reduce latency and residual odors [2, 23, 57, 80].

Across these systems, perceived odor intensity is typically adjusted indirectly through physical delivery parameters such as concentration, airflow rate, and exposure duration [86]. While effective for changing stimulus magnitude, this approach faces a persistent perceptual gap: intensity does not scale linearly with concentration [12] and is strongly affected by adaptation, context, and prior exposure [14, 24]. Moreover, large inter-individual variability in olfactory sensitivity and subjective ratings can make intensity control inconsistent across users [46, 66].

These limitations motivate interaction techniques that modulate olfactory experience without increasing chemical load. Accordingly, and in parallel to prior work on perceptual modulation in haptics [7], we explore a non-olfactory route for odor modulation that targets perception rather than the odorant medium. Prior studies indicate that thermal cues applied around the nasal region can alter odor perception without changing the underlying chemical stimulus [17, 62]. Building on this direction, we quantitatively examine localized, closed-loop nasal thermal stimulation as a controllable mechanism for modulating perceived odor intensity and reshaping qualitative odor experience.

### 2.2 Thermal Feedback and Thermohaptic Interfaces

Thermoception is the ability to perceive temperature changes through warm and cold receptors in the skin, largely mediated by transient receptor potential (TRP) channels [39]. Thermal cues are often treated as an experiential modality: because they are closely tied to comfort and affect, they are typically used to shape ambience, material plausibility, and emotional tone rather than to encode high-bandwidth information [13, 19, 44, 79, 84]. A key design constraint is temporal dynamics, where thermal feedback changes more slowly and produces longer after-effects than vibrotactile cues [32, 33, 35]. While this limits rapid event signaling, it aligns well with multisensory experiences and ambient modulation, where gradual and sustained changes are desirable [42, 65, 83].

Thermohaptic interfaces have been implemented via resistive heating, thermoelectric (Peltier) actuation, and airflow-based stimulation, among other approaches. Early work demonstrated handheld thermal cues using resistive elements [83], and later systems integrated thermal feedback into wearable and VR/AR contexts using thermoelectric devices or air or liquid flow to support localized, dynamic sensations [8, 21, 43, 45]. However, different thermal actuation approaches involve trade-offs in response speed, reversibility, localization, portability, and controllability. For example, radiative or infrared-based heating can be difficult to localize precisely and is sensitive to environmental conditions [28], while liquid/air-based systems often suffer from high thermal inertia and limited portability [8]. In practice, thermoelectric actuation is often favored when bidirectional control and closed-loop regulation are needed in compact form factors [18, 27, 87].

Beyond representing physical temperature or material properties, thermal feedback is often used as an experiential and affective design material. Thermal cues can increase realism and elicit more appropriate responses in virtual fire scenarios [69], and visual context (e.g., fire or water) can bias perceived warmth or coolness through multisensory integration [76]. Work on thermal illusions further shows that temperature perception is constructive and context-dependent, shaped by spatial layout, temporal dynamics, and cross-modal interactions [4, 22, 38, 64, 71, 82]. Together, these findings position thermal stimulation as a low-bandwidth yet high-context modality that can modulate interpretation and affect rather than encode discrete information.

This perspective is particularly relevant for olfactory interaction. The nasal region is thermally sensitive and tightly coupled to respiration and perceived airflow [3, 81], and localized nasal temperature changes can influence breathing comfort and airflow perception [3]. Building on this foundation, we treat the outside nasal skin as a promising site for controlled thermohaptic stimulation that may interact with chemosensory experience and trigeminal to modulate olfactory perception. We do not introduce a new thermal interface; instead, we leverage compact thermoelectric (Peltier-based) actuation with closed-loop control to deliver repeatable nasal thermal cues and study them as an interaction technique for olfactory interfaces.

### 2.3 Cross-Modal Thermal-Odor Perception

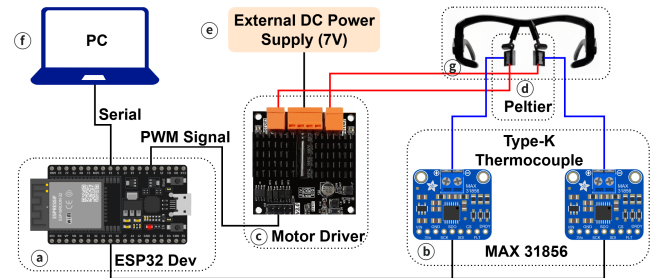
Cross-modal perception describes how signals from different sensory modalities interact to shape perceptual experience. Rather than operating as independent channels, sensory systems continuously influence one another, giving rise to integrated and context-dependent percepts. In chemosensation, a growing body of perceptual and neuroscientific research shows that thermal cues can influence the perception and interpretation of chemical stimuli, including taste, smell, and trigeminal sensations [3, 4, 30, 31, 67, 71, 81]. Notably, thermal feedback has also been shown to influence flavor perception in interactive contexts; for example, Suzuki et al. [75] demonstrated that thermal feedback applied to a drinking vessel can alter perceived flavor characteristics without changing the beverage itself, highlighting the broader potential of external thermal cues to shape chemosensory experience through crossmodal pathways. This positions temperature not merely as a concurrent sensation, but as a contextual cue that may modulate how odor intensity and quality are experienced.

The nasal region is a particularly relevant site for such thermal-olfactory coupling. Intranasal thermal sensation is closely related to airflow perception and trigeminal processing, both of which interact with olfactory experience. Weise et al. [81] reported that intranasal thermal sensitivity correlates with olfactory sensitivity and trigeminal-related measures, suggesting shared or interacting sensory substrates. Complementarily, Brooks et al. showed that trigeminal stimulation can induce robust thermal illusions [4] and that nasal temperature changes can alter perceived airflow and breathing effort [3]. Building on this broader coupling, prior work has provided initial evidence that temperature cues near the nose can influence odor perception without changing the odorant itself [17, 62], indicating a promising pathway for *thermal-olfactory crossmodal modulation* at the perceptual level.

However, existing studies on thermal-olfactory interaction have largely used static, non-interactive paradigms that compare a small set of discrete thermal conditions (e.g., [17, 62]). For example, Okamoto et al. [62] varied stimulation setups, facial locations, and stimulus areas, and compared odor impressions under limited temperature settings using subjective ratings. While these studies establish directional effects (e.g., warming vs. cooling) and demonstrate that odor impressions can shift, they provide limited insight into the *magnitude*, *perceptual resolution*, and *reliability* of thermal modulation. In particular, it remains unclear how much controlled thermal change is required to produce a reliable perceptual difference, and how incremental thermal variations map onto systematic changes in perceived odor quality.

To enable controllable and repeatable modulation, beyond coarse condition-level comparisons, psychophysical methods [49] provide a principled framework for quantifying perceptual sensitivity and thresholds. Classic approaches include methods of constant stimuli, methods of limits, forced-choice paradigms, and adaptive procedures [49]. In particular, adaptive staircase procedures and JND estimation are well suited for capturing minimal perceptual changes (e.g., haptic perception) while accounting for adaptation and inter-individual variability [36]. Our work builds on classical psychophysical methods to quantify the sensitivity of cross-modal

thermal-olfactory modulation effects and to examine how localized thermal cues reshape odor perception within a qualitative descriptive space of odor experiences.



**Figure 2: System Diagram of the proposed Wearable, Nose-Mounted Thermohaptic Interface:** (a) ESP32 Dev Microcontroller, (b) dual MAX31856 thermocouple amplifiers with Type-K thermocouples, (c) DFR0601 DC motor driver, (d) OT025160 Peltier modules, (e) external DC power supply (7 V), (f) host PC, and (g) glasses-based wearable frame.

### 3 System Design and Implementation

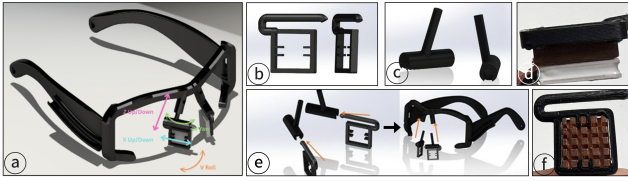
This section presents the design and implementation of our wearable, nose-mounted thermohaptic interface. The system consists of two core components: (1) a wearable glasses-based frame that provides mechanical support and stable thermal contact at the nose, and (2) a thermal feedback system that generates precise heating and cooling through closed-loop control. Fig. 2 illustrates the overall system architecture.

#### 3.1 Wearable Frame and Mechanical Design

The wearable adopts an eyeglass-style form factor (Fig. 2g) to distribute its load across the nasal sidewalls, ears, and cheekbones while avoiding interference with breathing and the visual field. The frame is fabricated from lightweight polylactic acid (PLA) using 3D printing, selected for its low mass, adequate stiffness, and rapid iteration during prototyping. The device measures  $145 \times 57 \times 150$  mm (frame width  $\times$  height  $\times$  depth) and weighs 46.1 g in total (frame: 26.1 g; Peltier modules, heat sinks, and electronics: 20.0 g), remaining comparable to typical sunglasses in both size and weight.

Fig. 3 summarizes the mechanical design. To accommodate diverse facial geometries and ensure stable thermal contact, the frame provides four adjustable degrees of freedom: vertical translation (13 mm range), horizontal translation (15 mm range), roll rotation ( $120^\circ$ ), and yaw rotation ( $360^\circ$ ). This adjustability enables consistent placement of the thermal modules relative to the nasal sidewalls across participants while maintaining an ergonomic fit.

The design was refined through four major iterations (P0-P3, Table 1) to improve comfort, stability, and contact consistency. The final prototype (P3) incorporates a dual-arm “hammer” mechanism with constrained degrees of freedom, which simplifies fitting, improves placement repeatability, and reduces positional drift during head movement. Pilot testing indicated mechanically stable wear performance during moderate head motions (nodding and shaking), and participants reported no discomfort during extended wear.



**Figure 3: Mechanical design of the glasses-based wearable frame. (a) Overview with annotated four-DoF adjustability of the thermohaptic module relative to the nose (X/Z up/down, V roll, and W yaw). (b) 3D-printed mounting housings. (c) Hinge joints for angular adjustment. (d) Assembled layered thermal contact module. (e) Exploded view of the frame and module assembly. (f) Integrated Peltier-heat-sink unit.**

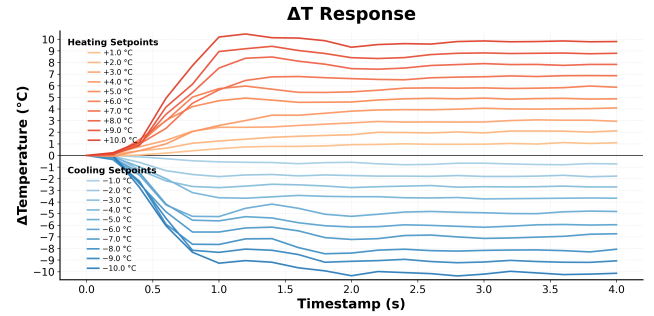
**Table 1: Design Iterations of the Wearable Frame**

Iterations	Key Design Changes	Observed Limitations	Outcomes
P0	Lower-cradle half-glasses with wire-suspended Peltier modules	Frame shift during motion and poor alignment repeatability	Stability improved through a rigid upper frame and holder
P1	Upper-cradle design with single yaw adjustment	Limited adaptability to variations in nose bridge geometry	Improved yaw alignment but limited adaptability remained
P2	Print-in-place ball joints with sport-temple curvature	Excessive degrees of freedom caused drift and re-zeroing difficulty	Constrained DOF enabled faster setup and improved repeatability
P3 (Final)	Dual-arm “hammer” mechanism with copper heatsinks	Cheek or nasal interference observed in early geometries	Improved comfort and consistent thermal contact

### 3.2 Thermal Feedback System

Thermal stimulation is delivered by two thermoelectric (Peltier) modules (OT025160, TECooler<sup>1</sup>; Fig. 2d) mounted symmetrically on the nasal sidewalls. Each module ( $12.5 \times 12.5 \times 2.75$  mm, 5 g) provides  $Q_{c,max} \approx 10$  W under near-zero temperature differential and  $\Delta T_{max} \approx 70^\circ\text{C}$  under no-load conditions, operating within 3.0 A and 7 V. Each module is paired with a compact copper heat sink ( $13 \times 12 \times 5$  mm, 5 g) to improve heat dissipation, temperature uniformity, and settling speed. The modules, heat sinks, and sensors are integrated in 3D-printed friction-fit housings that ensure stable

<sup>1</sup>Datasheet available at [http://www.tecooler.com/en/products/datasheet/tec/TECooler\\_Technology\\_Datasheets\\_OT025160\(12.5,12.5\)\\_NO175190\\_English.pdf](http://www.tecooler.com/en/products/datasheet/tec/TECooler_Technology_Datasheets_OT025160(12.5,12.5)_NO175190_English.pdf)



**Figure 4: Temperature tracking ( $\Delta T$ ) characterization for heating and cooling stimuli under different setpoints during (0–4 s).**

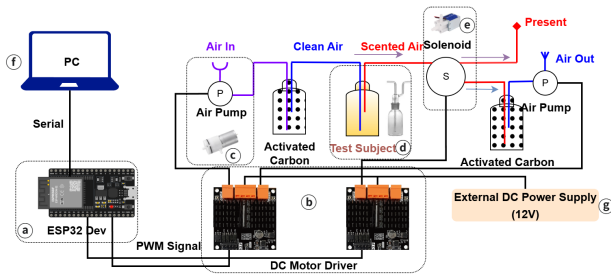
contact while enabling rapid assembly and replacement. Two K-type thermocouples are placed between the modules and the nasal skin to directly measure delivered temperature, improving effective heat transfer and control accuracy.

Closed-loop control is implemented on an ESP32 Dev microcontroller (Fig. 2a), which logs data to a host PC (Fig. 2f). The Peltiers are driven by a dual-channel H-bridge (DFR0601; Fig. 2c) to support bidirectional current for heating/cooling, with thermocouple signals conditioned via MAX31856 amplifiers (Fig. 2b). Temperature is regulated using a PID controller that tracks a specified set-point, updating the PWM drive in real time; gains were empirically tuned to balance rise time, overshoot, and steady-state error under realistic loads. The system is powered by a tabletop DC supply (7 V, 6 A, Fig. 2e).

### 3.3 Temperature Tracking Performance

To characterize system performance, we evaluated temperature regulation accuracy, stability, and response dynamics across heating and cooling setpoints spanning  $\pm 1.0$  to  $\pm 10.0^\circ\text{C}$ . We report root mean square error (RMSE) and mean absolute error (MAE), separately for a rapid-transition *FAST* phase (0–2 s) and a steady-control *STABLE* phase (2–4 s), defined relative to stimulus onset. Fig. 4 illustrates the  $\Delta T$  trajectories for all conditions for a representative participant with the device worn on the nasal skin at  $32.0^\circ\text{C}$ : The responses show a rapid initial change followed by convergence to the target, with larger setpoints producing greater transient deviations during *FAST*.

During *STABLE*, regulation accuracy remained high across all setpoints. For heating, RMSE was characterized by  $M \pm SD = 0.135 \pm 0.071^\circ\text{C}$ ; for cooling, by  $M \pm SD = 0.190 \pm 0.097^\circ\text{C}$ . MAE was characterized by  $M \pm SD = 0.132 \pm 0.067^\circ\text{C}$  for heating and  $M \pm SD = 0.180 \pm 0.086^\circ\text{C}$  for cooling, indicating reliable steady-state maintenance even at large offsets. As expected, across setpoints, errors were higher during *FAST* due to the emphasis on rapid transitions: RMSE increased with target magnitude, with  $M \pm SD = 0.976 \pm 0.805^\circ\text{C}$  for heating and  $M \pm SD = 1.214 \pm 0.717^\circ\text{C}$  for cooling; MAE followed a similar trend, with  $M \pm SD = 1.943 \pm 1.009^\circ\text{C}$  for heating and  $M \pm SD = 1.726 \pm 0.956^\circ\text{C}$  for cooling.



**Figure 5: System diagram of the odor delivery system: (a) ESP32 Dev Microcontroller, (b) DFR0601 DC motor drivers, (c) air pumps, (d) washing bottles, (e) solenoid valve, (f) host PC, and (g) an external DC power supply (12 V).**

Overall, the device supports rapid temperature shifts while maintaining  $\sim 0.3^\circ\text{C}$  steady-state accuracy. Fig. 4 reports system characterization obtained while worn by a single participant, but temperature dynamics at the nasal surface may vary across users due to differences in skin blood flow, skin moisture, and tissue thickness [11, 52]. However, our closed-loop PID controller continuously regulates temperature using real-time thermocouple feedback at the skin–module interface, which helps compensate for user-specific physiological variability during operation.

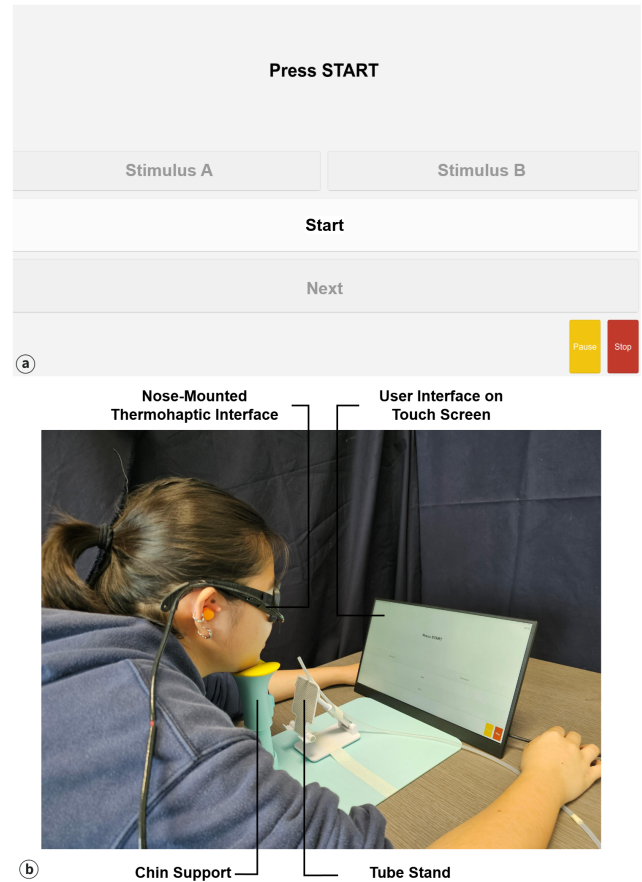
#### 4 Study 1: Thermal–Olfactory JND Measurement

We first conducted a psychophysical study to characterize how localized nasal thermal stimulation affects perceived odor intensity, and to quantify users’ perceptual sensitivity to such odor modulation.

##### 4.1 Apparatus and Stimuli

During the study, participants wore the nose-mounted thermohaptic interface described in Section 3, which delivers rapid, bidirectional temperature modulation using compact thermoelectric (TEC) modules. Temperature was regulated by a closed-loop PID controller with real-time feedback from K-type thermocouples positioned adjacent to the nasal skin. Thermal stimuli were defined relative to each participant’s physiological baseline skin temperature, measured and averaged during a 30 s resting period preceding each trial. During stimulation, the target temperature offset was continuously tracked using real-time thermocouple readings at the skin–module interface, allowing the PID controller to adjust output online according to the participant’s on-body thermal state. Each stimulus followed a fixed temporal profile comprising a rapid transition phase and a subsequent stable phase, during which the odor was delivered to ensure sufficient sampling time [63]. All temperature outputs were constrained to a safe range ( $20\text{--}43^\circ\text{C}$ ) to minimize discomfort or irritation.

Odors were delivered using an airflow-based olfactory display (Fig. 5). Filtered air was bubbled through liquid odor reservoirs (washing bottles; Fig. 5d) and routed to the participant’s nose via silicone tubing. Delivery timing and airflow were controlled using DC pumps (Fig. 5c) and a solenoid valve (Fig. 5e), coordinated



**Figure 6: (a) Touchscreen graphical user interface for experiment control and trial progression. (b) Experimental setup with a participant wearing the nose-mounted thermohaptic interface; a chin rest and tubing stand stabilize head position and airflow tubing during trials.**

by a microcontroller (ESP32 Dev; Fig. 5a) and monitored via a host PC (Fig. 5f). Pumps and valves were driven by dual motor drivers (DFR0601; Fig. 5b). The system operated at 12 V with a peak current of approximately 3 A, powered by a tabletop DC supply (Fig. 5g). Valve-to-outlet latency was consistently below 0.5 s, enabling reliable synchronization with the thermal *STABLE* phase. To reduce residual odors and cross-contamination, both intake and exhaust air passed through activated-carbon filters, and tubing was replaced when switching odorants.

A touchscreen-based graphical user interface (GUI) was used to present on-screen instructions and to support experiment operation. Fig. 6a illustrates the user interface. Fig. 6b illustrates the experimental setup. Participants were seated comfortably in a height-adjustable chair with their head supported by a chin rest, ensuring consistent alignment between the thermal interface and the odor delivery outlet across trials, with a constant room temperature of  $24.5 \pm 0.2^\circ\text{C}$ . Earplugs were provided to reduce noise.

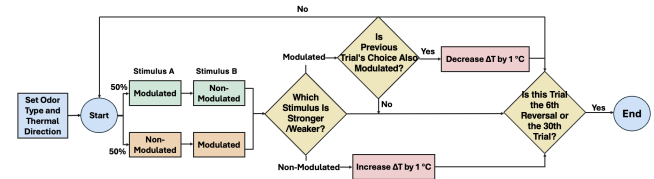
We selected three odorants: Cherry Blossom, Wasabi Oil, and Sweet Orange, to span distinct semantic and sensory profiles. All

odorants were presented at a fixed concentration throughout the study (50% essential oil diluted with 50% dipropylene glycol; 50 mL total volume per odorant). Based on the odor descriptor framework [9], Cherry Blossom is primarily associated with Dimension W1 (Fragrant/Floral/Perfumery), Wasabi Oil with Dimension W9 (Sulfurous/Gas/Pungent), and Sweet Orange with Dimension W10 (Citrus, Lemon, Fresh). The set includes two generally pleasant odors (Cherry Blossom and Sweet Orange) and one relatively pungent, trigeminally stimulating odor (Wasabi Oil), enabling comparisons across different chemosensory profiles under identical delivery and thermal stimulation conditions.

## 4.2 Study Design

We adopted a within-subject psychophysical design to estimate just-noticeable difference (JND) thresholds for changes in perceived odor intensity induced by nasal thermal modulation. The independent variable was the temperature difference between a thermally modulated stimulus and a baseline reference stimulus. A two-interval forced-choice (2IFC) paradigm [20] was employed. The experiment followed a fully within-subject design with two thermal directions (heating and cooling) and three odorants, yielding a total of six experimental conditions. Each participant completed all conditions. Fig. 7 illustrates the experimental flow of each experimental condition. For each experimental condition, the measurement consisted of a sequence of trials, and each trial was composed of two sequentially presented stimulus intervals. One interval presented a reference stimulus delivered at the participant’s baseline nasal skin temperature, while the other interval presented a test stimulus delivered with a temperature difference of  $\pm\Delta T$  relative to baseline. The test stimulus was either warmer or cooler than the reference by  $\Delta T$ . The two stimulus intervals were presented in a random order within each trial. The first presented interval was labeled as *Stimulus A*, and the second as *Stimulus B*. Participants were required to indicate which interval was perceived as stronger in odor intensity (for heating conditions) or weaker in odor intensity (for cooling conditions). According to the 2IFC paradigm, participants were required to choose one interval over the other, without the option to report the two stimuli as equal.

A one-up/two-down staircase procedure [36] was adopted for each experimental condition to determine the value of  $\Delta T$  corresponding to the JND threshold, which tracks a performance level of 70.7% correct responses. In this staircase procedure, two consecutive correct responses resulted in a decrease of  $\Delta T$ , whereas a single incorrect response resulted in an increase of  $\Delta T$ . For heating conditions, the initial value of the test stimulus was set to  $+6^\circ\text{C}$  relative to baseline, with an upper bound of  $+10^\circ\text{C}$ . For cooling conditions, the initial value was set to  $-4^\circ\text{C}$ , with a lower bound of  $-10^\circ\text{C}$ . These initial values were determined based on pilot testing to ensure that the starting stimuli were perceptually distinguishable and allowed stable convergence of the staircase. The initial step size  $\Delta T$  was set to  $1^\circ\text{C}$ . A change in the direction of temperature adjustment from increasing to decreasing, or vice versa, was recorded as one reversal. After the first reversal, the staircase continued until six complete reversals were reached or until a maximum of 30 trials had been completed, whichever occurred first. The JND threshold for each condition was estimated as the average value of  $\Delta T$  over



**Figure 7: The Study 1 trial flow. Each followed a familiarization phase and a staircase-based 2IFC procedure with synchronized thermal stimulation and odor delivery.**

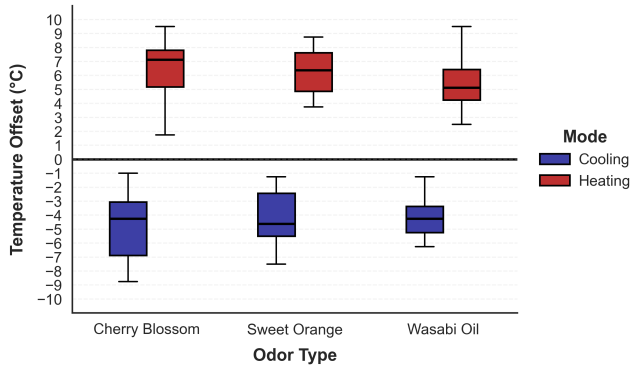
the final four reversals. If fewer than four reversals were obtained, all available reversals were included in the average. In addition to accuracy-based staircase responses, response times and response revisions were recorded as supplementary behavioral measures. Odor materials, concentrations, and airflow parameters were held constant across all thermal conditions and trials as controlled variables. The order of thermal directions (heating and cooling) was counterbalanced across participants. Within each thermal direction, the order of odor presentation was randomized.

## 4.3 Procedure

Upon arrival, participants were briefed on the study procedure and safety precautions, after which written informed consent was obtained. They then completed a short demographic questionnaire and a nasal health assessment [73]. The experimenter subsequently introduced the touchscreen interface and the overall timing structure of the task. A brief familiarization phase preceded the formal measurements to ensure participants understood the task and were comfortable with the stimulus sequence. During familiarization, participants experienced baseline odor presentations without thermal stimulation to establish a perceptual reference; no responses were recorded.

The formal experiment comprised staircase-based measurements. At the start of each trial, participants initiated the sequence by pressing a *Start* button on the touchscreen. A 3 s countdown followed, after which the first interval (*Stimulus A*) was presented. Each interval consisted of a rapid thermal transition (2 s) followed by a stable phase (2 s) during which the odor was delivered. After *Stimulus A*, a mandatory 15 s inter-stimulus rest period was enforced before presenting the second interval (*Stimulus B*) with the same temporal profile. Participants then reported their judgment by selecting the corresponding option on the touchscreen and confirming their choice. This confirmation step enabled the system to log response time as well as any revisions made before submission. Participants were instructed to breathe normally and avoid intentional sniffing outside stimulus periods.

To mitigate fatigue and olfactory adaptation, participants were given a mandatory rest period of at least 1 min between successive trials, with an additional longer break of approximately 3 min between every two experimental conditions. Each participant completed all conditions in a single session, lasting approximately 4 h in total including breaks. After the session, participants took part in a brief exit interview to provide subjective feedback on task understanding and their perceptual experience of nasal thermal modulation.



**Figure 8: JND thresholds from Study 1 for Cherry Blossom, Wasabi Oil, and Sweet Orange under heating and cooling conditions.**

#### 4.4 Participants

We recruited 12 healthy adult participants (six males, six females; age  $M=25.17$ ,  $SD=4.51$ ) from a local university. All participants reported normal olfactory function and no history of nasal surgery, chronic respiratory illness, or fragrance allergy. Nasal health assessment results indicated low levels of nasal congestion and airflow obstruction across participants. The study was approved by the institutional ethics review board.

#### 4.5 Results

In total, we collected 6 conditions  $\times$  12 participants = 72 JND threshold estimates. All participants completed the study within 30 trials, and six reversals were obtained in every condition. JND thresholds were computed for each participant across six conditions (three odor types  $\times$  two thermal directions) by averaging the last four reversals, and results are illustrated in Fig. 8. The results showed that heating made perceived odor intensity stronger while cooling made it weaker.

**4.5.1 Perceptual Thresholds.** Descriptive JND thresholds for each odor and thermal direction are summarized below. For Cherry Blossom, the mean JND was  $4.77 \pm 2.55$  °C for cooling and  $6.60 \pm 2.32$  °C for heating. For Sweet Orange, the mean JND was  $4.06 \pm 1.96$  °C for cooling and  $6.31 \pm 1.70$  °C for heating. For Wasabi Oil, the mean JND was  $4.15 \pm 1.62$  °C for cooling and  $5.54 \pm 2.22$  °C for heating. Collapsing across odorants, the overall mean JND was  $4.33 \pm 2.04$  °C for cooling and  $6.15 \pm 2.09$  °C for heating.

We analyzed JNDs using a two-way repeated-measures ANOVA with thermal direction (heating vs. cooling) and odor type (Cherry Blossom, Sweet Orange, Wasabi Oil) as within-subject factors. Results showed a significant main effect of thermal direction ( $F(1, 11) = 12.99$ ,  $p = 0.0041$ ,  $\eta_p^2 = 0.541$ ), indicating different perceptual thresholds for heating and cooling. Specifically, cooling required a smaller temperature offset to produce a discriminable change in perceived odor intensity ( $4.33 \pm 2.04$  °C) than heating ( $6.15 \pm 2.09$  °C), suggesting higher sensitivity to cooling-induced modulation.

In contrast, we found no significant main effect of odor type ( $F(2, 22) = 1.68$ ,  $p = 0.209$ ,  $\eta_p^2 = 0.133$ ) and no thermal direction

$\times$  odor type interaction ( $F(2, 22) = 0.72$ ,  $p = 0.498$ ,  $\eta_p^2 = 0.061$ ). Pairwise comparisons between odorants were non-significant after multiple-comparison correction. Together, these results suggest that the direction-dependent asymmetry (cooling vs. heating) is consistent across the tested odorants, spanning both relatively mild (Cherry Blossom, Sweet Orange) and pungent, trigeminally stimulating odors (Wasabi Oil).

**4.5.2 Subjective Feedback and Analysis.** Overall, participants consistently reported perceivable changes in odor intensity under both cooling and heating conditions. Notably, eleven out of twelve participants described cooling effects as more immediate and salient, whereas nine out of twelve characterized heating-related changes as more gradual. As P4 noted, “When cooling was applied, the odor seemed sharper and more noticeable immediately. With heating, the change felt more gradual and subtle.” Several participants further emphasized heightened sensitivity to cooling during the thermal change (P9: “The cooling effect hits immediately, making the smell pop, whereas the heating effect feels like it builds up slower.”). This perceived immediacy was broadly consistent with behavioral data: mean response times were shorter for cooling trials ( $M \pm SD = 2444.35 \pm 985.81$  ms) than for heating trials ( $M \pm SD = 2783.22 \pm 849.75$  ms). Response times were also modulated by odor familiarity, with familiar odors eliciting faster responses ( $M \pm SD = 2328.40 \pm 900.62$  ms), compared to slower responses for less familiar odors ( $M \pm SD = 3041.85 \pm 810.98$  ms); revision rates likewise remained lower for familiar odors (12%) than for less familiar odors (20%).

Despite clear differences in baseline odor character, participants reported that the qualitative pattern of nasal thermal modulation felt broadly consistent across odorants. As P6 remarked, “Cherry Blossom and Sweet Orange smelled very different, but the way cooling or heating changed intensity felt similar.” Wasabi Oil was frequently described as sharper or more pungent, yet participants still reported being able to detect thermal amplification or attenuation. Finally, all participants reported high comfort with the nose-mounted interface, with only brief initial awareness and no discomfort affecting task performance.

In summary, the results of Study 1 demonstrate that both nasal heating and cooling stimulation can modulate perceived odor intensity. Specifically, cooling attenuated perceived odor strength, whereas heating enhanced it. Further analysis revealed that the thermal modulation mode had a significant effect on odor intensity sensitivity, while odor identity played a secondary role within the tested concentration range. Together, these results confirm the feasibility of using localized nasal thermal stimulation as a quantitative and controllable means of modulating olfactory intensity perception under controlled conditions.

## 5 Study 2: Effects of Nasal Thermal Modulation on Odor Quality Perception

Building on Study 1, we established that participants could detect odor intensity changes induced by nasal thermal modulation. Study 2, therefore, examined how thermal modulation reshapes the qualitative structure of odor perception, particularly when specific odorants are paired with moderate and threshold thermal stimuli.

Following Castro et al. [9], we conceptualize odor quality as a position within a structured, multidimensional descriptor space, in which verbal descriptors cluster into categorical dimensions. Using this framework, we investigate whether localized nasal thermal stimulation is associated with changes in the distribution of perceived odor qualities within this space, thereby influencing how an odor is described and interpreted.

## 5.1 Apparatus and Stimuli

The apparatus and experimental setup were identical to those used in Study 1. Participants wore the same nose-mounted thermohaptic interface, and temperature modulation followed the same temporal structure with closed-loop control based on real-time thermocouple feedback at the skin-module interface. Odor presentation was delivered using the same airflow-based olfactory system as in Study 1. We used the same three odorants (Cherry Blossom, Wasabi Oil, and Sweet Orange) with the same concentration as in Study 1 (50% essential oil diluted with 50% dipropylene glycol; 50 mL total volume per odorant).

A touchscreen-based GUI was used to present instructions and collect participant responses. Fig. 9a illustrates the user interface. Fig. 9b illustrates the experimental setup. Participants were seated comfortably with chin support to maintain consistent alignment between the nasal region and the odor outlet, with a constant room temperature of  $24.5 \pm 0.2^\circ\text{C}$ . Earplugs were provided to reduce noise.

## 5.2 Study Design

We employed a within-subject perceptual rating design to examine how nasal thermal modulation alters odor quality. After each trial, participants rated perceived odor qualities on a 7-point Likert scale (1 = not at all, 7 = extremely). Odor quality was assessed using ten perceptual dimensions (W1–W10) derived from a categorical odor descriptor space obtained via non-negative matrix factorization [9]. The dimensions were: W1 (Fragrant/Floral/Perfumery), W2 (Woody/Resinous/Earthy), W3 (Fruity, Non-Citrus/Sweet/Light), W4 (Sickening/Putrid/Rancid), W5 (Chemical/Medicinal/Solvent), W6 (Minty/Cooling/Eucalyptus), W7 (Sweet/Vanilla/Caramel), W8 (Nutty/Roasted/Popcorn), W9 (Sulfurous/Gas/Pungent), and W10 (Citrus/Lemon/Fresh). For clarity, we refer to each dimension by its index (W1–W10), accompanied by representative high-loading descriptors in parentheses.

We tested five thermal stimulation levels:  $\Delta T = 0^\circ\text{C}$  (baseline),  $\pm 2^\circ\text{C}$ , and odor-specific  $\pm\text{JND}$  levels. The  $\pm\text{JND}$  levels were derived from the mean JND values estimated for each odorant in Study 1, computed separately for cooling and heating, and then rounded to the nearest  $0.5^\circ\text{C}$  to match the resolution of our thermal control setup. Specifically, the temperature values used in Study 2 were  $5.0^\circ\text{C}$  (cooling) and  $6.5^\circ\text{C}$  (heating) for Cherry Blossom,  $4.0^\circ\text{C}$  (cooling) and  $6.5^\circ\text{C}$  (heating) for Sweet Orange, and  $4.0^\circ\text{C}$  (cooling) and  $5.5^\circ\text{C}$  (heating) for Wasabi Oil. The  $\pm 2^\circ\text{C}$  levels were included as moderate temperature changes, informed by prior work reporting nasal temperature variations during chemosensory stimulation [26], to provide a mid-range stimulation level within a safe and comfortable regime, and to examine whether milder sub-JND thermal cues

Please rate the perceived intensity of each odor quality dimension (1 = not at all, 7 = extremely)

Condition: Baseline

<b>W1</b> Fragrant, Floral, Perfumery, Sweet, Rose, Aromatic, Light, Cologne, Herbal, Green, Cut grass, Violets 0 1 2 3 4 5 6 7	<b>W6</b> Minty, Peppermint, Cool, Cooling, Aromatic, Anise (Licorice), Fragrant, Medicinal, Spicy, Sweet, Eucalyptus, Camphor 0 1 2 3 4 5 6 7
<b>W2</b> Woody, Resinous, Musty, Earthy, Moldy, Cedarwood, Herbal, Green, Cut grass, Fragrant, Aromatic, Light, Heavy, Spicy, Burnt, Smoky 0 1 2 3 4 5 6 7	<b>W7</b> Sweet, Vanilla, Fragrant, Aromatic, Chocolate, Malty, Almond, Caramel, Light, Warm 0 1 2 3 4 5 6 7
<b>W3</b> Fruity (Other than citrus), Sweet, Fragrant, Aromatic, Light, Pineapple, Cherry (Berry), Strawberry, Perfumery, Banana 0 1 2 3 4 5 6 7	<b>W8</b> Popcorn, Burnt, Smoky, Peanut butter, Nutty, Oily, Fatty, Almond, Heavy, Warm, Musty, Earthy, Moldy, Woody, Resinous 0 1 2 3 4 5 6 7
<b>W4</b> Sickening, Putrid, Foul, Decayed, Rancid, Sweaty, Sour, Vinegar, Sharp, Pungent, Acid, Fecal, Sour milk, Musty, Earthy, Moldy, Heavy 0 1 2 3 4 5 6 7	<b>W9</b> Sickening, Garlic, Onion, Heavy, Burnt, Smoky, Sulfidic, Sharp, Pungent, Acid, Household gas, Putrid, Sewer, Burnt rubber 0 1 2 3 4 5 6 7
<b>W5</b> Chemical, Etherish, Anaesthetic, Medicinal, Disinfectant, Carbolic, Sharp, Pungent, Acid, Gasoline, Solvent, Paint, Cleaning fluid, Alcoholic, Turpentine 0 1 2 3 4 5 6 7	<b>W10</b> Lemon, Fruity, Citrus, Fragrant, Orange, Light, Sweet, Cool, Cooling, Aromatic, Herbal, Green, Sharp, Pungent, Acid 0 1 2 3 4 5 6 7

(a)

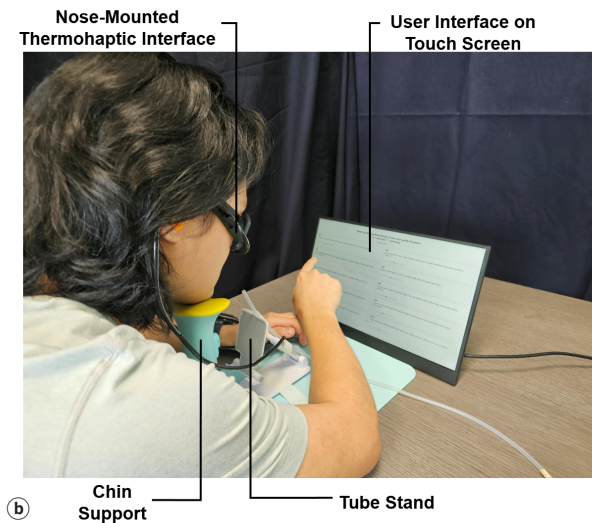


Figure 9: (a) Graphical user interface for rating the perceived intensity of odor quality dimensions (W1–W10) on 7-point Likert scales; and (b) experimental setup, similar to Study 1.

might still bias odor-quality ratings. This design yielded 15 odor-thermal conditions (3 odors  $\times$  5 thermal levels) and 150 ratings per participant (10 dimensions per condition).

To reduce order effects while maintaining perceptual continuity, odor presentation followed a counterbalanced order. Within each odorant block, the baseline condition ( $\Delta T = 0^\circ\text{C}$ ) was always presented first to establish a stable perceptual anchor, followed by the remaining four thermal conditions in randomized order. Baseline ratings for each odorant were retained as an explicit reference so that participants could judge subsequent conditions relative to a consistent internal standard. Thermal conditions were computer-controlled, and participants were not informed of the specific temperature manipulation applied in each trial.

## 5.3 Procedure

Upon arrival, participants were briefed on the procedure and safety precautions, after which written informed consent was obtained.

They completed a short demographic questionnaire and a nasal health assessment [73] to confirm the absence of acute nasal discomfort that could affect odor perception; short breaks were provided if needed. Participants were then introduced to the odor quality rating task and descriptor dimensions via a touchscreen GUI. A brief familiarization phase followed, during which participants experienced a baseline odor presentation without thermal stimulation to establish a perceptual reference; no responses were recorded.

The formal experiment was organized by odorant. For each odorant, participants first completed a baseline trial ( $\Delta T = 0^\circ\text{C}$ ) and rated all ten dimensions on a 7-point Likert scale. The GUI stored and displayed these baseline ratings as a visual reference during subsequent trials for the same odorant. Participants then completed four additional trials under the remaining thermal conditions ( $\pm 2^\circ\text{C}$  and  $\pm\text{JND}$ ), with baseline ratings kept visible to support relative judgment. When moving to the next odorant, stored baseline ratings were cleared and the procedure repeated.

Each trial followed a fixed sequence: after participants initiated the trial, a 3 s countdown was shown, thermal stimulation began, and odor delivery occurred during the stable temperature phase after reaching the target temperature. Participants then completed the ten-dimensional ratings. To reduce adaptation and fatigue, a mandatory 3-min rest was enforced after every two conditions; between trials, odor delivery was stopped and filtered air was supplied. Participants were instructed to breathe normally and avoid intentional sniffing outside stimulus periods.

After completing all conditions, participants took part in a short exit interview on their perceptual experience and task understanding. Each participant finished the study in a single 1.5–2 hour session including familiarization, trials, and the interview.

## 5.4 Participants

A group of 12 healthy adult participants (six males, six females; age  $M=24.75$ ,  $SD=4.19$ ) took part in Study 2. None of them attended Study 1 before. Nasal health assessment results indicated low levels of nasal congestion and airflow obstruction across participants. The study was approved by the institutional ethics review board.

## 5.5 Results

Unlike Study 1, which tested perceptual modulation of odor intensity, Study 2 examined semantic descriptor ratings rather than basic intensity judgments. We treat these analyses as exploratory with respect to how thermal stimulation reshapes odor-quality interpretation across dimensions. In total, we collected 15 conditions  $\times$  10 dimensions  $\times$  12 participants = 1,800 odor-quality ratings. Following Kamihori et al. [37], we analyzed each odorant separately using Friedman tests to assess overall differences across thermal stimulation levels, followed by pairwise Wilcoxon signed-rank tests with Benjamini-Hochberg False Discovery Rate (FDR) correction to identify condition-specific contrasts (i.e.,  $p < 0.05$ : significant difference).

**5.5.1 W4 (Sickening, Putrid, Rancid) Ratings.** For Wasabi Oil, ratings at  $-JND$  ( $M = 3.33$ ,  $SD = 1.61$ ) were significantly lower than at  $+JND$  ( $M = 5.00$ ,  $SD = 1.13$ ,  $p = 0.039$ ). Similarly, ratings at  $-2^\circ\text{C}$  ( $M = 3.50$ ,  $SD = 1.51$ ) were significantly lower than at  $0^\circ\text{C}$  ( $M = 4.25$ ,  $SD = 1.42$ ,  $p = 0.039$ ) and  $+JND$  ( $p = 0.039$ ). Ratings at

$+2^\circ\text{C}$  ( $M = 3.92$ ,  $SD = 1.08$ ) were significantly lower than at  $+JND$  ( $p = 0.039$ ). For Cherry Blossom and Sweet Orange, no significant differences were observed.

**5.5.2 W6 (Minty, Cooling, Eucalyptus) Ratings.** For Cherry Blossom, ratings at  $-JND$  ( $M = 3.92$ ,  $SD = 1.93$ ) were significantly higher than at  $0^\circ\text{C}$  ( $M = 2.83$ ,  $SD = 1.64$ ,  $p = 0.026$ ),  $+2^\circ\text{C}$  ( $M = 2.75$ ,  $SD = 1.54$ ,  $p = 0.026$ ), and  $+JND$  ( $M = 2.25$ ,  $SD = 1.42$ ,  $p = 0.026$ ). Similarly, ratings at  $-2^\circ\text{C}$  ( $M = 3.58$ ,  $SD = 1.44$ ) were significantly higher than  $0^\circ\text{C}$  ( $p = 0.026$ ),  $+2^\circ\text{C}$  ( $p = 0.026$ ), and  $+JND$  ( $p = 0.026$ ). For Sweet Orange, ratings at  $-2^\circ\text{C}$  ( $M = 3.42$ ,  $SD = 1.51$ ) were significantly higher than  $0^\circ\text{C}$  ( $M = 2.75$ ,  $SD = 1.36$ ,  $p = 0.039$ ) and  $+2^\circ\text{C}$  ( $M = 2.75$ ,  $SD = 1.54$ ,  $p = 0.039$ ). For Wasabi Oil, no significant differences were observed.

**5.5.3 Ratings of Other Dimensions.** We did not observe any significant differences in other dimensions (i.e., except for W4 and W6) across all three odorants. However, we also found some thermal stimulation may induce some minor change on some specific dimensions, such as W10 (Citrus, Lemon, Fresh) of Cherry Blossom, but not significant.

**5.5.4 Subjective Feedback.** Participants' brief verbal comments during the exit interviews suggested that mild thermal stimulation produced limited changes in perceived odor quality relative to baseline. The  $+2^\circ\text{C}$  condition was most often described as indistinguishable: ten out of twelve participants reported ratings close to baseline, commonly noting that neither warmth nor odor quality felt clearly altered. As P3 stated, "I didn't really feel obvious warmth, and the smell didn't seem to change much, so I rated it the same as baseline." The  $-2^\circ\text{C}$  condition was slightly more noticeable, though its impact on odor quality varied across individuals. As P6 noted, "I could feel a bit of cooling, but the odor itself almost didn't change for me."

Participants also reported that thermal stimuli made effects on a limited subset of rating dimensions rather than distributed across all ten. All described that they relied on only a few dimensions when comparing conditions, with others perceived as stable or irrelevant. As P10 explained for Wasabi Oil, "I only really felt changes in W6, W8, and W9. The other dimensions didn't really feel different." Several participants noted that if a dimension was absent in the baseline odor, nasal thermal modulation did not introduce it. Finally, all participants reported that the nose-mounted interface remained comfortable and did not interfere with sustained odor evaluation.

**5.5.5 Summary and Analysis of Thermal Effects on Odor Quality.** Baseline comparisons indicated that cooling significantly increased W6 ratings for Cherry Blossom and Sweet Orange, while reducing W4 ratings for Wasabi Oil. Heating-related baseline effects were limited, with no significant changes observed in baseline comparisons. Specifically, for the two pleasant and familiar odors (Cherry Blossom and Sweet Orange), cooling consistently shifted perception toward freshness- and sharpness-related qualities by increasing minty/cooling/eucalyptus-like impressions (W6). Especially for Cherry Blossom, stronger thermal offsets (e.g.,  $-JND$ ) produced more pronounced qualitative changes than weaker offsets (e.g.,  $-2^\circ\text{C}$ ) in cooling, suggesting a potential magnitude-dependent effect. On the other hand, the trigeminally dominant odor Wasabi Oil exhibited a different pattern, with thermal modulation primarily

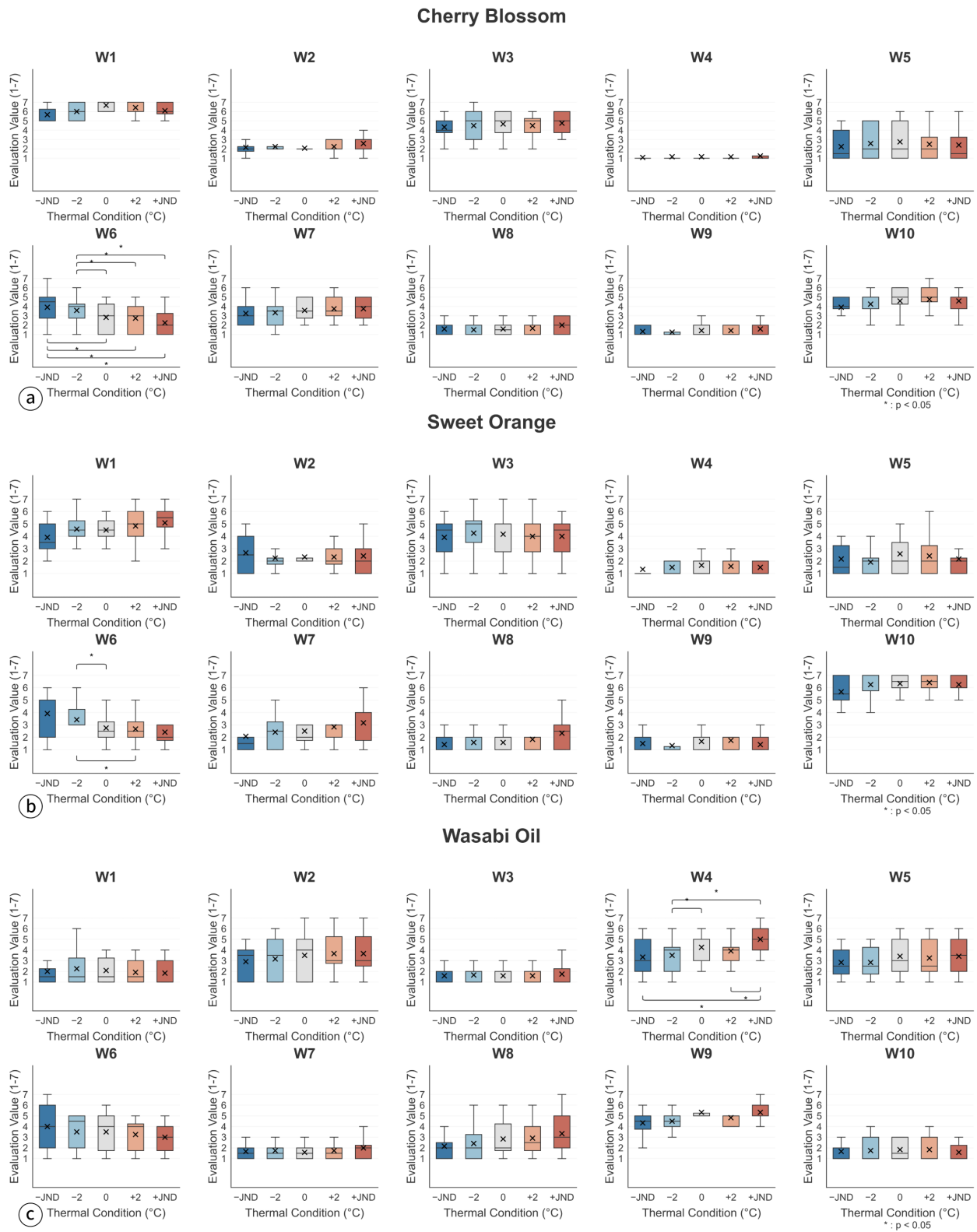


Figure 10: Box plots of odor quality ratings (W1–W10) across five thermal levels for (a) Cherry Blossom, (b) Sweet Orange, and (c) Wasabi Oil with pairwise comparisons (Wilcoxon signed-rank tests, FDR Corrected).

influencing irritation- and aversion-related dimension (e.g., Sickening/Putrid/Rancid, W4). Cooling reduced the salience of these aversive attributes.

## 6 Discussion

Across two controlled studies, we show that localized nasal thermal stimulation can (1) bias perceived odor intensity and (2) reshape qualitative odor perception in an odor- and direction-dependent manner. By combining psychophysical threshold estimation with semantic profiling in a structured descriptor space, our results clarify how thermal cues interact with olfaction at multiple perceptual levels and suggest that nasal temperature can function as a controllable, non-chemical modulation signal.

### 6.1 Reflections on Two Studies

**6.1.1 Study 1: Quantifying intensity modulation and asymmetric sensitivity.** Study 1 provides psychophysical evidence that nasal heating and cooling near the nostrils bias perceived odor intensity: heating generally increased perceived intensity, whereas cooling attenuated it. Using a one-up/two-down adaptive staircase, we quantified JNDs for thermally induced intensity changes across three odorants. This extends prior work that has reported thermal influences on chemosensory experience at a descriptive or coarse level [30] by providing threshold-level measurements that support direct comparison across participants, odors, and stimulation directions.

We also observed that participants required smaller temperature offsets to detect cooling-induced intensity changes than heating-induced changes (i.e., JND: 4.33°C cooling vs. 6.15°C heating). One possible explanation is asymmetry in trigeminal thermosensation. Prior work suggests that cold-sensitive TRPM8-positive fibers may be more abundant in nasal mucosa than heat-sensitive TRPV1-positive fibers [40]. This asymmetry also echoes findings in thermal perception and thermohaptic interaction, where cooling is often detected more readily than warming under comparable conditions [6, 8, 34, 53]. Importantly, our results suggest that this perceptual asymmetry extends to crossmodal thermal-olfactory modulation, although the temperature offsets needed to modulate odor intensity are larger than those reported for other nasal tasks [3].

Comparing our thresholds to Brooks et al.'s work [3], which quantified nasal thermal stimulation effects on breathing (heating threshold  $\sim 1.5^\circ\text{C}$ ; cooling threshold  $\sim 3.9^\circ\text{C}$ ), our JNDs are higher. We attribute this to at least two design-relevant factors. First, our stimulation targeted the external nasal sidewalls region rather than intranasal sites (e.g., septum), which exhibit stronger thermal sensitivity [81]. Second, our thermal profile emphasized a rapid transition followed by a stabilized temperature plateau to overlap with odor sampling, rather than being coupled to respiration. Together, differences in stimulation site and temporal coupling likely reduced thermal salience and required larger offsets to bias odor intensity. These observations highlight that *where* and *when* thermal cues are applied may be as important as the temperature magnitude when designing nasal thermohaptic modulation.

**6.1.2 Study 2: Dimension-specific reweighting of odor quality.** Study 2 moves beyond intensity to examine how nasal thermal stimulation reorganizes odor quality perception across semantic dimensions in a structured human odor descriptor space [9]. A key outcome

is that thermal modulation does not produce a uniform shift in odor quality. Instead, it yields *dimension-specific reweighting*: some descriptor dimensions may change under heating or cooling, while others remain relatively stable or minor change.

Some prior thermal-olfactory work report odor-dependent changes in holistic impressions such as freshness, pleasantness, or heaviness under nasal warming or cooling [17, 62]. Our results further refine it by showing *how* these holistic impressions may arise: thermal cues selectively modulate specific descriptor dimensions, partially redistributing perceptual emphasis rather than shifting all qualities together. The directionality of these effects also accords with everyday temperature-flavor associations, where warmth is linked to richer and sweeter experiences and cooling is associated with freshness and clarity [55]. In this sense, nasal thermal cues may act as contextual signals that guide attention toward different semantic facets of an odor without altering the chemical stimulus itself.

**6.1.3 Bridging the two studies: multi-level modulation and mechanisms.** Taken together, our results suggest that nasal thermal modulation operates at multiple perceptual levels. At the level of intensity, we observe robust and quantifiable thresholds with clear psychophysical regularities (including a cooling-heating asymmetry). At the level of odor quality, modulation is evident yet more nuanced, expressed as selective shifts in particular semantic dimensions and varying with odor identity and stimulus magnitude. This dissociation mirrors broader multisensory findings in which lower-level sensory measures often show stronger regularities than higher-level semantic judgments, which tend to be more context- and interpretation-dependent [15]. For example, a study by DeLong and Noppeney [15] on audiovisual binding showed that spatial congruency effects—reflecting low-level sensory integration—can persist even when visual stimuli are rendered subjectively invisible, whereas semantic congruency modulates multisensory integration only when stimuli are consciously perceived. Based on this, we suppose that nasal thermal cues may shape olfaction via relatively automatic pathways (e.g., trigeminal contributions or other chemosensory effects) and higher-level interpretive pathways (e.g., reweighting semantic descriptors), yielding structured yet odor- and context-dependent qualitative changes. However, elucidating these mechanisms will require comprehensive physiological and psychological studies that can disentangle trigeminal, olfactory, and cognitive contributions.

### 6.2 Nasal Thermal Modulation as a Cross-Modal Interaction

Our results reinforce the view that temperature is not only a physical sensation but also a contextual cue that can shape chemosensory perception [3, 30, 81]. The nasal region is a particularly plausible site for such cross-modal effects: it exhibits high thermosensitivity, and trigeminal pathways that convey thermal and irritation signals are anatomically and functionally intertwined with olfactory processing [4, 81]. Consistent with this coupling, prior work has shown that intranasal thermal stimulation can alter perceived airflow and breathing effort without any chemical manipulation [3], suggesting that localized temperature changes can meaningfully bias perception in the nasal domain. Building on this foundation, our work suggests that controlled thermal stimulation applied to the nasal

sidewalls can give rise to cross-modal perceptual shifts associated with odor intensity and odor-quality judgments, as reflected in Study 1 and Study 2.

Importantly, this cross-modal interaction approach decouples *odor delivery* from *odor modulation*. Whereas most olfactory interfaces control experience by manipulating the odorant medium (e.g., diffusion, concentration, blending, or switching mechanisms) [29, 57, 66, 70, 85], we instead apply temperature as a perceptual control signal directly to the user. This is distinct from thermal aroma displays that use heat to vaporize or release scent materials [41, 77]. By acting on perception rather than chemistry, nasal thermal modulation can be rapid, reversible, and residue-free, offering a complementary interaction pathway for shaping olfactory experience under the practical constraints of dynamic multisensory systems.

We think that the observed perceptual changes are likely shaped by multiple interacting pathways rather than a single isolated thermal-olfactory effect [50, 78]. Local nasal cooling/heating may engage trigeminal thermosensation, which is closely coupled with nasal chemosensory processing and could contribute to the cooling-heating asymmetry and odor-dependent effects [4, 81]. In addition, thermal stimulation can also bias airflow perception and breathing effort [3], potentially altering how odors are sampled and judged. Localized nasal thermal stimulation may further introduce additional non-olfactory contextual influences, such as thermal comfort, attentional processes, or affective associations, that further shape participants' responses [4, 16, 75, 81]. Finally, crossmodal associations between thermal and chemosensory perception (e.g., cool-fresh vs. warm-rich/sweet) may guide higher-level interpretation, causing dimension-specific semantic shifts in crossmodal perception [55, 71]. Therefore, we suppose that the olfactory modulation bias may be caused by cross-modal perceptual shifts induced by nasal thermal stimulation, rather than as evidence for one specific underlying mechanism. However, as our studies were not designed to isolate these mechanisms, we frame them as hypotheses. Future work should combine targeted manipulations and physiological measures to disentangle trigeminal, airflow, and cognitive contributions.

### 6.3 Implications for Multisensory HCI and Design

While the current work was conducted under controlled laboratory conditions with a limited set of odorants, by showing that thermal cues can influence reported odor intensity and produce selective shifts in odor-quality judgments without altering odor chemistry, our results potentially suggest design opportunities that reduce reliance on expanding scent libraries or changing concentration. One potential design direction is immersive media such as VR/AR, where odor delivery is often constrained by slow dissipation and residual mixing. Thermal-based modulation can support contextual adaptation: a single odor source could be perceived as stronger or weaker, warmer or sharper, depending on narrative context or environmental cues. As a lightweight multisensory channel, this approach can enhance realism, affect, and engagement while avoiding the engineering complexity [48, 54, 69, 86].

More broadly, our findings suggest an alternative framing for olfactory interface design and evaluation. Rather than aiming for uniform or deterministic perceptual outcomes, nasal thermal modulation expands the expressive design space by enabling subjective redistribution of odor qualities across perceptual dimensions. This human-centered approach operates near perceptual thresholds, enabling subtle and controllable shifts rather than sensory extremes. It aligns with emerging HCI perspectives that frame sensory interfaces not only as output channels, but as interaction techniques that present both quantitative and qualitative control over sensory stimulation [30, 54, 61].

### 6.4 Application Scenarios Design

Motivated by our empirical findings, we outlined four envisioned use cases that suggest how nasal thermal modulation could be incorporated into future multisensory interaction design (Fig. 1).

*Attenuating Pungency in Food Experiences* (Fig. 1c): This scenario targets foods with challenging or pungent odors. By applying cooling near the nose, users may reduce perceived intensity and mitigate irritation-related impressions, improving approachability while preserving the underlying odor identity. Such selective attenuation suggests applications in everyday food consumption, sensory accessibility, and cross-cultural flavor exploration—particularly in situations where users wish to engage with strong smells without sensory overload.

*Selective Qualitative Tuning of Odor Experience* (Fig. 1d): This scenario illustrates personalization of real-world scent experience through dimension-level modulation. Users can bias an existing ambient scent toward preferred qualitative facets (e.g., suppressing minty/cooling notes) without changing the odor source. Such tuning can support individualized comfort and preference, enabling perceptual personalization without reformulating scent mixtures or increasing chemical load.

*VR: Contextual Adaptation and Scent Reuse* (Fig. 1e): We designed VR scenarios of combining nasal thermal stimulation with visual context for rich multisensory experiences. In such a use case, coordinated visual cues together with nasal heating or cooling might bias how the same physical odor is interpreted, for example, making a chocolate scent more readily associated with ice cream under cooling or with hot chocolate under heating. From this perspective, nasal thermal modulation could potentially serve as a semantic mediator between sensory input and contextual meaning, suggesting one possible route toward flexible multisensory design without increasing odor hardware complexity.

*Ambient Well-being and Attention Shaping* (Fig. 1f): This scenario highlights a wellness-oriented use case in which nasal temperature varies smoothly over time to produce gradual, continuous shifts in perceived odor quality (e.g., from sharper to richer impressions). Rather than serving as a discrete notification, wave-like thermal modulation can function as a low-intrusion, ambient cue for relaxation, meditation, or attentional regulation, where continuous sensory change guides internal state without requiring sustained focal attention.

## 7 Limitations and Future Work

We also identified some limitations for our work. First, the experimental results of studies showed substantial inter-individual variability and did not manifest as strong group-level significant effects along some semantic dimensions. This variability reflects a broader challenge in olfactory research, where higher-level perceptual judgments are strongly shaped by personal experience, cultural background, and semantic interpretation [1, 46]. However, our participants were young, healthy adults recruited from a university population and tested under controlled laboratory conditions, limiting demographic diversity and potentially underrepresenting age- or culture-related differences in olfactory and thermal sensitivity. We also focused on short-term responses, leaving long-term adaptation and learning unexamined; this is important because olfactory adaptation and thermal habituation operate on different timescales [39, 68]. Future work should recruit larger, more diverse and stratified samples and conduct longitudinal evaluations to assess how prolonged nasal thermal modulation affects perceptual stability, sensitivity, and comfort.

Second, the present studies focused on a limited set of odorants, concentrations and temperature ranges to maintain experimental control and participant comfort. Although the selected odors span distinct perceptual categories, they do not represent the full diversity of olfactory space. Moreover, all odorants were tested at a single concentration, and effects may differ at other concentration levels, which limits the quantification of perceived intensity of odors under different concentrations. Future work could explore a broader range of odor types, concentrations, and temperature offsets, including trigeminal-dominant, affectively charged, or culturally specific scents, to further examine how odor chemistry, concentrations and semantic structure interact with thermal stimulation, and to test whether suprathreshold thermal offsets produce different effects on odor-quality judgments.

We also notice that the presented order of stimuli may influence the perceptual effects. In Study 2, we presented the baseline condition first within each block to establish a perceptual anchor for subsequent testing; however, this design may also introduce anchoring and learning effects. As a result, later ratings may partly reflect the influence of an established internal reference, in addition to the thermal manipulation itself. Future protocols could counterbalance baseline placement (or include occasional hidden-baseline trials) to better disentangle true modulation effects from possible order-related biases.

In addition, for comfort and simplicity, neither study monitored breathing patterns or synchronized odor and thermal delivery to participants' inhalation cycles. As a result, the temporal alignment between inhalation, odor arrival, and extranasal thermal stimulation likely varied across participants and trials, which may have introduced additional variability in olfactory judgments. Future work could incorporate respiration monitoring (e.g., nasal airflow sensing) and implement breath-synchronized thermal/odor delivery to test whether tighter phase alignment yields stronger and more consistent perceptual effects.

Finally, our work focused more on perceptual effects rather than user task performance or behavioral change. Facial thermal stimulation could also influence non-olfactory perceptual factors such as

thermal comfort [74], attentional processes [5], and general nasal sensations [3, 4, 81]. Therefore, some of the observed rating shifts may reflect broader contextual influences rather than odor-only effects alone. Future studies could investigate how nasal thermal modulation influences these factors, such as comfort, decision-making, memory, affect, or behavior in applied scenarios such as food choice, learning environments, or stress regulation, for broader cross-modal contextual effects.

## 8 Conclusion

In this paper, we investigated localized nasal thermal modulation as an experimental probe for shaping olfactory experience under controlled conditions. We introduced a wearable, nose-mounted thermohaptic interface that delivers precise, closed-loop thermal stimulation to modulate odor perception. In a psychophysical study, we quantified perceptual thresholds for thermal offsets that bias perceived odor intensity. We further showed that thermal cues selectively reshape odor quality within a structured descriptor space, producing dimension-specific and odor-dependent shifts in semantic profiles. Together, these results indicate that localized nasal thermal stimulation may provide a stable, reversible, and non-chemical means of modulating olfactory perception under controlled conditions. We envision thermal-based odor modulation as a complementary design primitive for future olfactory interfaces, enabling contextual adaptation and personalized scent experiences without increasing chemical load.

## 9 Acknowledgment

This project was supported by the Ministry of Education, Singapore, under the Academic Research Fund Tier 1 (FY2024) Award 25-0156-A0001. This research was partially supported by the CDE4301 capstone module from Innovation & Design Programme (iDP), Engineering Design and Innovation Centre (EDIC). We thank Quanhao Gan for VR scene development. We used large language models (e.g., OpenAI GPT-5, Google Gemini 3), to polish the academic writing. The authors take full responsibility for all outputs produced by the AI and for their use in this research.

## References

- [1] Judith Amores and Pattie Maes. 2017. Essence: Olfactory interfaces for unconscious influence of mood and cognitive performance. In *Proceedings of the 2017 CHI conference on human factors in computing systems*. 28–34.
- [2] Yossiri Ariyakul and Takamichi Nakamoto. 2011. Improvement of olfactory display using electroosmotic pumps and a SAW device for VR application. In *The 21st international conference on artificial reality and telexistence*. 15–21.
- [3] Jas Brooks, Alex Mazursky, Janice Hixon, and Pedro Lopes. 2024. Augmented Breathing via Thermal Feedback in the Nose. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology*. 1–11.
- [4] Jas Brooks, Steven Nagels, and Pedro Lopes. 2020. Trigeminal-based temperature illusions. In *Proceedings of the 2020 CHI conference on human factors in computing systems*. 1–12.
- [5] M Catherine Bushnell, Gary H Duncan, Ronald Dubner, Richard L Jones, and William Maixner. 1985. Attentional influences on noxious and innocuous cutaneous heat detection in humans and monkeys. *Journal of Neuroscience* 5, 5 (1985), 1103–1110.
- [6] Joseph C. Stevens and Kenneth K. Choo. 1998. Temperature sensitivity of the body surface over the life span. *Somatosensory & motor research* 15, 1 (1998), 13–28.
- [7] Shaoyu Cai, Zhenlin Chen, Haichen Gao, Ya Huang, Qi Zhang, Xinge Yu, and Kening Zhu. 2025. ViboPneumo: A Vibratory-Pneumatic Finger-Worn Haptic Device for Altering Perceived Texture Roughness in Mixed Reality. *IEEE Transactions on Visualization & Computer Graphics* 31, 07 (2025), 3957–3972.
- [8] Shaoyu Cai, Pingchuan Ke, Takuji Narumi, and Kening Zhu. 2020. Thermairglove: A pneumatic glove for thermal perception and material identification in virtual

- reality. In *2020 IEEE conference on virtual reality and 3D user interfaces (VR)*. IEEE, 248–257.
- [9] Jason B Castro, Arvind Ramanathan, and Chakra S Chennubhotla. 2013. Categorical dimensions of human odor descriptor space revealed by non-negative matrix factorization. *PLoS one* 8, 9 (2013), e73289.
  - [10] Sergio Cervera-Torres, Maria Eleonora Minissi, Alberto Greco, Alejandro Callara, Saideh Ferdowsi, Luca Citi, Luna Maddaloni, Irene Alice Chicchi Giglioli, and Mariano Alcañiz. 2023. Modulating virtual affective elicitation by human body odors: advancing research on social signal processing in virtual reality. In *International Conference on Human-Computer Interaction*. Springer, 317–327.
  - [11] Nisha Charkoudian. 2003. Skin blood flow in adult human thermoregulation: how it works, when it does not, and why. In *Mayo clinic proceedings*, Vol. 78. Elsevier, 603–612.
  - [12] M Chastrette, T Thomas-Danguin, and E Rallet. 1998. Modelling the human olfactory stimulus-response function. *Chemical senses* 23, 2 (1998), 181–196.
  - [13] Aleph Campos Da Silveira, Eduardo C Rodrigues, Estevao B Saleme, Alexandra Covaci, Gheorghita Ghinea, and Celso AS Santos. 2023. Thermal and wind devices for multisensory human-computer interaction: an overview. *Multimedia Tools and Applications* 82, 22 (2023), 34485–34512.
  - [14] Pamela Dalton. 2000. Psychophysical and behavioral characteristics of olfactory adaptation. *Chemical senses* 25, 4 (2000), 487–492.
  - [15] Patrycja Delong and Uta Noppeney. 2021. Semantic and spatial congruency mould audiovisual integration depending on perceptual awareness. *Scientific Reports* 11, 1 (2021), 10832.
  - [16] Carolina Diaz-Piedra, Emilo Gomez-Milan, and Leandro L Di Stasi. 2019. Nasal skin temperature reveals changes in arousal levels due to time on task: An experimental thermal infrared imaging study. *Applied Ergonomics* 81 (2019), 102870.
  - [17] Yuichi Fujino, Haruka Matsukura, Daisuke Iwai, and Kosuke Sato. 2019. Odor modulation by warming/cooling nose based on cross-modal effect. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 929–930.
  - [18] Haichen Gao, Shaoyu Cai, Yuhong Wu, and Kening Zhu. 2024. ThermOuch: a wearable thermo-haptic device for inducing pain sensation in virtual reality through thermal grill illusion. In *SIGGRAPH asia 2024 conference papers*. 1–12.
  - [19] Jose Gabriel Grajales-Reyes, Bandy Chen, David Meseguer Garcia, and Marc Schneeberger Pane. 2024. How does our brain process positive and negative thermosensory cues? *Physiology* (2024). <https://api.semanticscholar.org/CorpusID:268722761>
  - [20] David Marvin Green, John A Swets, et al. 1966. *Signal detection theory and psychophysics*. Vol. 1. Wiley New York.
  - [21] Sebastian Günther, Florian Müller, Dominik Schön, Omar Elmoghazy, Max Mühlhäuser, and Martin Schmitz. 2020. Terminator: Understanding the interdependency of visual and on-body thermal feedback in virtual reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–14.
  - [22] Sebastian Günther, Alexandra Skogseide, Robin Buhlmann, and Max Mühlhäuser. 2024. Assessing the Influence of Visual Cues in Virtual Reality on the Spatial Perception of Physical Thermal Stimuli. *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (2024). <https://api.semanticscholar.org/CorpusID:269748891>
  - [23] Nicolas S Herrera and Ryan P McMahan. 2014. Development of a simple and low-cost olfactory display for immersive media experiences. In *Proceedings of the 2nd ACM international workshop on immersive media experiences*. 1–6.
  - [24] Rachel S Herz. 2003. The effect of verbal context on olfactory perception. *Journal of Experimental Psychology: General* 132, 4 (2003), 595.
  - [25] Koichi Hirota, Yoko Ito, Tomohiro Amemiya, and Yasushi Ikei. 2013. Presentation of odor in multi-sensory theater. In *International conference on virtual, augmented and mixed reality*. Springer, 372–379.
  - [26] Asano Hiroto, Mizuno Tota, Nozawa Akio, and Ide Hideto. 2009. Comparison with Amount of Gustatory Sense and Nasal Skin Temperature. *Journal of Robotics and Mechatronics* 21, 1 (2009), 81–87. doi:10.20965/jrm.2009.p0081
  - [27] Ya Huang, Jingkun Zhou, Pingchuan Ke, Xu Guo, Chun Ki Yiu, Kuanming Yao, Shaoyu Cai, Dengfeng Li, Yu Zhou, Jian Li, et al. 2023. A skin-integrated multi-modal haptic interface for immersive tactile feedback. *Nature Electronics* 6, 12 (2023), 1020–1031.
  - [28] Daisuke Iwai, Mei Aoki, and Kosuke Sato. 2018. Non-contact thermo-visual augmentation by ir-rgb projection. *IEEE transactions on visualization and computer graphics* 25, 4 (2018), 1707–1716.
  - [29] Charles Javerliat, Pierre-Philippe Elst, Anne-Lise Saive, Patrick Baert, and Guillaume Lavoué. 2022. Nebula: An affordable open-source and autonomous olfactory display for vr headsets. In *Proceedings of the 28th ACM symposium on virtual reality software and technology*. 1–8.
  - [30] Chao Jia, Yonghua Rong, Xiaoying Geng, Menghan Wang, Zhicheng Zhang, Shengnan Han, and Xihao Bie. 2023. People’s psychological and physiological responses to the combined smell-thermal environments. *Building and Environment* 241 (2023), 110510.
  - [31] Han-Gue Jo, Olga Wudarczyk, Marcel Leclerc, Christina Regenbogen, Angelika Lampert, Markus Rothermel, and Ute Habel. 2021. Effect of odor pleasantness on heat-induced pain: An fMRI study. *Brain Imaging and Behavior* 15, 3 (2021), 1300–1312.
  - [32] Takuya Jodai, Lynette A. Jones, Masahiko Terao, and Hsin-Ni Ho. 2024. Perceiving Synchrony: Determining Thermal-Tactile Simultaneity Windows. *IEEE Transactions on Haptics* 17 (2024), 850–859. <https://api.semanticscholar.org/CorpusID:272370716>
  - [33] Lynette A Jones and Michal Berris. 2002. The psychophysics of temperature perception and thermal-interface design. In *Proceedings 10th symposium on haptic interfaces for virtual environment and teleoperator systems. HAPTICS 2002*. IEEE, 137–142.
  - [34] Lynette A Jones and Hsin-Ni Ho. 2008. Warm or cool, large or small? The challenge of thermal displays. *IEEE Transactions on Haptics* 1, 1 (2008), 53–70.
  - [35] Lynette A. Jones and Hsin-Ni Ho. 2022. Incorporating Thermal Feedback in Cutaneous Displays: Reconciling Temporal and Spatial Disparities. In *Haptic and Audio Interaction Design*. <https://api.semanticscholar.org/CorpusID:251815220>
  - [36] Lynette A Jones and Hong Z Tan. 2012. Application of psychophysical techniques to haptic research. *IEEE transactions on haptics* 6, 3 (2012), 268–284.
  - [37] Mai Kamihori, Shinsuke Kitanaka, Kiyoshi Suzuki, and Yuichi Itoh. 2025. Effects of material and softness of the rim of cups on flavor perception. *Applied Food Research* 5, 1 (2025), 100672.
  - [38] Subhankar Karmakar, Anindita Kesh, and Manivannan Muniyandi. 2023. Thermal illusions for thermal displays: a review. *Frontiers in human neuroscience* 17 (2023), 1278894.
  - [39] Makiko Kashio and Makoto Tominaga. 2022. TRP channels in thermosensation. *Current Opinion in Neurobiology* 75 (2022), 102591.
  - [40] Siew M Keh, Paul Facer, Ahmed Yehia, Guri Sandhu, Hesham A Saleh, and Praveen Anand. 2011. The menthol and cold sensation receptor TRPM8 in normal human nasal mucosa and rhinitis. *Rhinology* 49, 4 (2011), 453.
  - [41] Dong Wook Kim, Yeong Hee Cho, Kazushi Nishimoto, Yusuke Kawakami, Susumu Kunifujii, and Hiroshi Ando. 2009. Development of aroma-card based soundless olfactory display. In *2009 16th IEEE International Conference on Electronics, Circuits and Systems-ICECS 2009*. IEEE, 703–706.
  - [42] Hojoong Kim, Young-Tae Kwon, Hyo-Ryoung Lim, Jong-Hoon Kim, Yun-Soung Kim, and Woon-Hong Yeo. 2020. Recent Advances in Wearable Sensors and Integrated Functional Devices for Virtual and Augmented Reality Applications. *Advanced Functional Materials* 31 (2020). <https://api.semanticscholar.org/CorpusID:225134092>
  - [43] Seung-Won Kim, Sung Hee Kim, Choong Sun Kim, Kyoungsoo Yi, Jun-Sik Kim, Byung Jin Cho, and Youngsu Cha. 2020. Thermal display glove for interacting with virtual reality. *Scientific reports* 10, 1 (2020), 11403.
  - [44] Sven G. Kratz and Anthony Dunnigan. 2017. ThermoTouch: a New Scalable Hardware Design for Thermal Displays. *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces* (2017). <https://api.semanticscholar.org/CorpusID:22640187>
  - [45] Seohu Lee, Seongkwan Jang, and Youngsu Cha. 2024. Soft wearable thermo-tactile haptic interface for virtual reality. *iScience* 27, 12 (2024).
  - [46] Jiayin Li, Kehua Zou, Weifang Li, Gen Wang, and Weihua Yang. 2019. Olfactory characterization of typical odorous pollutants part I: Relationship between the hedonic tone and odor concentration. *Atmosphere* 10, 9 (2019), 524.
  - [47] Tao Lin, Quanhao Gan, Fuxi Ouyang, Yiming Luo, Yushan Pan, Yushi Li, and Shaoyu Cai. 2025. AromaCanvas: A wearable olfactory display for Chinese painting appreciation and learning in virtual reality. *Computers & Education: X Reality* 7 (2025), 100109.
  - [48] Yiming Liu, Chun Ki Yiu, Zhao Zhao, Wooyoung Park, Rui Shi, Xingcan Huang, Yuyang Zeng, Kuan Wang, Tsz Hung Wong, Shengxin Jia, et al. 2023. Soft, miniaturized, wireless olfactory interface for virtual reality. *Nature Communications* 14, 1 (2023), 2297.
  - [49] Neil A Macmillan. 2002. Signal detection theory. *Stevens’ handbook of experimental psychology: Methodology in experimental psychology* 3 (2002), 43–90.
  - [50] Carla Masala, C Käehling, F Fall, and T Hummel. 2019. Correlation between olfactory function, trigeminal sensitivity, and nasal anatomy in healthy subjects. *European Archives of Oto-Rhino-Laryngology* 276, 6 (2019), 1649–1654.
  - [51] Daiki Mayumi, Yugo Nakamura, Yuki Matsuda, Shinya Misaki, and Keiichi Yasumoto. 2023. Kaolid: a Lid-type Olfactory Interface to Present Retronasal Smell towards Beverage Flavor Augmentation. In *Proceedings of the 13th International Conference on the Internet of Things*. 1–8.
  - [52] Katie McLellan, Jerrold S Petrofsky, Gurinder Bains, Grenith Zimmerman, Michelle Prowse, and Scott Lee. 2009. The effects of skin moisture and subcutaneous fat thickness on the ability of the skin to dissipate heat in young and old subjects, with and without diabetes, at three environmental room temperatures. *Medical engineering & physics* 31, 2 (2009), 165–172.
  - [53] Duška Meh and Miro Denišlić. 1994. Quantitative assessment of thermal and pain sensitivity. *Journal of the neurological sciences* 127, 2 (1994), 164–169.
  - [54] Miguel Melo, Guilherme Gonçalves, Pedro Monteiro, Hugo Coelho, José Vasconcelos-Raposo, and Maximino Bessa. 2020. Do multisensory stimuli benefit the virtual reality experience? A systematic review. *IEEE transactions on visualization and computer graphics* 28, 2 (2020), 1428–1442.

- [55] Kosuke Motoki, Toshiaki Saito, Rui Nouchi, and Motoaki Sugiura. 2020. Cross-modal correspondences between temperature and taste attributes. *Frontiers in Psychology* 11 (2020), 571852.
- [56] Fumitaka Nakaizumi, Haruo Noma, Kenichi Hosaka, and Yasuyuki Yanagida. 2006. SpotScents: A novel method of natural scent delivery using multiple scent projectors. In *IEEE Virtual Reality Conference (VR 2006)*. IEEE, 207–214.
- [57] Takamichi Nakamoto and Hai Pham Dinh Minh. 2007. Improvement of olfactory display using solenoid valves. In *2007 IEEE Virtual Reality Conference*. IEEE, 179–186.
- [58] Takuji Narumi, Shinya Nishizaka, Takashi Kajinami, Tomohiro Tanikawa, and Michitaka Hirose. 2011. Augmented reality flavors: gustatory display based on edible marker and cross-modal interaction. In *Proceedings of the SIGCHI conference on human factors in computing systems*. 93–102.
- [59] Simon Niedenthal, William Fredborg, Peter Lundén, Marie Ehrndal, and Jonas K Olofsson. 2023. A graspable olfactory display for virtual reality. *International journal of human-computer studies* 169 (2023), 102928.
- [60] Marianna Obrist. 2017. Mastering the senses in HCI: Towards multisensory interfaces. In *Proceedings of the 12th Biannual Conference on Italian SIGCHI Chapter*. 1–2.
- [61] Marianna Obrist, Carlos Velasco, Chi Thanh Vi, Nimesha Ranasinghe, Ali Israr, Adrian D Cheok, Charles Spence, and Ponnampalam Gopalakrishnakone. 2016. Touch, taste, & smell user interfaces: The future of multisensory HCI. In *Proceedings of the 2016 CHI conference extended abstracts on human factors in computing systems*. 3285–3292.
- [62] Yoshihiro Okamoto, Haruka Matsukura, and Kosuke Sato. 2021. Modulation of Olfactory Perception by Presenting Heat Sensation: Effects of Different Methods on Degree of Olfactory Perception Modulation. In *International Conference on Human-Computer Interaction*. Springer, 145–152.
- [63] Jonas K Olofsson. 2014. Time to smell: a cascade model of human olfactory perception based on response-time (RT) measurement. *Frontiers in psychology* 5 (2014), 33.
- [64] Shriniwas Patwardhan, Anzu Kawazoe, David Kerr, Masashi Nakatani, and Yon Visell. 2019. Dynamics and Perception in the Thermal Grill Illusion. *IEEE Transactions on Haptics* 12 (2019), 604–614. <https://api.semanticscholar.org/CorpusID:76663088>
- [65] Jiaming Qi, Longteng Yu, Eng Tat Khoo, Kian Wei Ng, Yujia Gao, Alfred Wei Chieh Kow, Joo Chuan Yeo, and Chwee Teck Lim. 2024. Bridging the digital-physical divide using haptic and wearable technologies. *Nature Electronics* 7, 12 (2024), 1098–1110.
- [66] Katsunori Saiki, Osamu Fukazawa, Hideyo Asaka, and Sadayuki Takagi. 1994. T&T olfactometer for standardized olfactory test and its uses. In *Olfaction and Taste XI: Proceedings of the 11th International Symposium on Olfaction and Taste and of the 27th Japanese Symposium on Taste and Smell. Joint Meeting held at Kosei-nenkin Kaikan, Sapporo, Japan, July 12–16, 1993*. Springer, 340–340.
- [67] Angela Sandri, Maria Paola Cecchini, Marianna Riello, Alice Zanini, Riccardo Nocini, Mirta Fiorio, and Michele Tinazzi. 2021. Pain, smell, and taste in adults: a narrative review of multisensory perception and interaction. *Pain and Therapy* 10, 1 (2021), 245–268.
- [68] Codrut Sarafoleanu, Corina Mella, M Georgescu, and C Perederco. 2009. The importance of the olfactory sense in the human behavior and evolution. *Journal of Medicine and life* 2, 2 (2009), 196.
- [69] Emily Shaw, Tessa Roper, Tommy Nilsson, Glyn Lawson, Sue VG Cobb, and Daniel Miller. 2019. The heat is on: Exploring user behaviour in a multisensory virtual environment for fire evacuation. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–13.
- [70] Yatharth Singhal, Haokun Wang, Hyunjae Gil, and Jin Ryong Kim. 2021. Mid-air thermo-tactile feedback using ultrasound haptic display. In *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*. 1–11.
- [71] Charles Spence. 2020. Temperature-based crossmodal correspondences: Causes and consequences. *Multisensory research* 33, 6 (2020), 645–682.
- [72] Richard J Stevenson. 2010. An initial evaluation of the functions of human olfaction. *Chemical senses* 35, 1 (2010), 3–20.
- [73] Michael G Stewart, David L Witsell, Timothy L Smith, Edward M Weaver, Bevan Yueh, and Maureen T Hannley. 2004. Development and validation of the Nasal Obstruction Symptom Evaluation (NOSE) scale. *Otolaryngology—Head and Neck Surgery* 130, 2 (2004), 157–163.
- [74] Yunuo Su, Emma O'Donnell, Sven P Hoekstra, and Christof A Leicht. 2025. Facial cooling improves thermal perceptions and maintains the interleukin-6 response during passive heating: A sex comparison. *Temperature* 12, 1 (2025), 40–54.
- [75] Chie Suzuki, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. 2014. Affecting tumbler: affecting our flavor perception with thermal feedback. *Proceedings of the 11th Conference on Advances in Computer Entertainment Technology* (2014). <https://api.semanticscholar.org/CorpusID:17589434>
- [76] Yuhi Takeo, Masayuki Hara, Naofumi Otsuru, Takeru Taihei, Ryushin Kawasoe, and Hisato Sugata. 2025. Modulation of thermal perception by VR-based visual stimulation to the embodied virtual body. *Behavioural Brain Research* 480 (2025), 115395.
- [77] Akira Tiele, Siddharth Menon, and James A Covington. 2019. Development of a thermal-based olfactory display for aroma sensory training. *IEEE Sensors Journal* 20, 2 (2019), 631–636.
- [78] Cécilia Tremblay and Johannes Frasnelli. 2018. Olfactory and trigeminal systems interact in the periphery. *Chemical Senses* 43, 8 (2018), 611–616.
- [79] Alisha Vabba, Marina Scattolin, Giuseppina Porciello, Maria Serena Panasiti, and Salvatore Maria Aglioti. 2025. From feeling chilly to burning up: How thermal signals shape the physiological state of the body and impact physical, emotional, and social well-being. *Neuroscience & Biobehavioral Reviews* 169 (2025). <https://api.semanticscholar.org/CorpusID:275357522>
- [80] Chuhong Wang and James A Covington. 2023. The development of a simple projection-based, portable olfactory display device. *Sensors* 23, 11 (2023), 5189.
- [81] Susanne Weise, Pauline Hanslik, Coralie Mignot, Evgenii Glushkov, Arnaud Bertsch, Romain Dubreuil, Moustafa Bensafi, Susanne Fuessel, and Thomas Hummel. 2024. Hot topic: Mapping of the human intranasal mucosal thermal sensitivity: A clinical study on thermal threshold and trigeminal receptors. *Plos one* 19, 8 (2024), e0304874.
- [82] Yannick Weiss, Marlene Eder, Oguzhan Cesur, and Steeven Villa. 2025. Quantifying the Effect of Thermal Illusions in Virtual Reality. *Proceedings of the 2025 31st ACM Symposium on Virtual Reality Software and Technology* (2025). <https://api.semanticscholar.org/CorpusID:281079969>
- [83] Reto Wettach, Christian Behrens, Adam Danielsson, and Thomas Ness. 2007. A thermal information display for mobile applications. In *Proceedings of the 9th international conference on Human computer interaction with mobile devices and services*. 182–185.
- [84] Graham A. Wilson, Stephen Anthony Brewster, Martin Halvey, and Stephen A. Hughes. 2012. Thermal icons: evaluating structured thermal feedback for mobile interaction. *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services* (2012). <https://api.semanticscholar.org/CorpusID:16133287>
- [85] Yasuyuki Yanagida, Shinjiro Kawato, Haruo Noma, Akira Tomono, and N Tesutani. 2004. Projection based olfactory display with nose tracking. In *IEEE Virtual Reality 2004*. IEEE, 43–50.
- [86] Zixuan Zhang, Xinge Guo, and Chengkuo Lee. 2024. Advances in olfactory augmented virtual reality towards future metaverse applications. *nature communications* 15, 1 (2024), 6465.
- [87] Kening Zhu, Simon Perrault, Taizhou Chen, Shaoyu Cai, and Roshan Lalintha Peiris. 2019. A sense of ice and fire: Exploring thermal feedback with multiple thermoelectric-cooling elements on a smart ring. *International Journal of Human-Computer Studies* 130 (2019), 234–247.