Sensing and Modulating the Feel of a Drink: A Personalized Approach via Laryngeal Thermal Feedback

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Abstract

The sensation of a drink in the throat is a salient example of the internal bodily feelings that shape our eating experiences. Computationally modeling these sensations would enable their redesign and inform technologies that augment how we eat. However, methods for quantifying such subjective, internal states from objective cues remain underdeveloped. This paper introduces a computational approach to bridge this gap. A first study ($N = 31$) models subjective ratings from laryngeal skin temperature and ingested volume, revealing distinct, individual Interoceptive Profiles. Informed by these findings, we developed a wearable device that provides thermal feedback to the larynx. A second study ($N = 20$) demonstrates that this intervention can alter drink sensations, contingent on the user's sensory profile. Based on these findings, we highlight the potential of the larynx as a site for bidirectional interaction (sensing and modulating) and propose a novel approach for personalized sensory augmentation.

CCS Concepts

• **Human-centered computing → Human computer interaction (HCI)**; *Interaction paradigms.*

Keywords

Flavor perception; Human Food Interaction; Pseudo-physiological reaction; Thermal sensation; Physiological sensing

ACM Reference Format:
Mai Kamihori, Kouyou Otsu, and Yuichi Itoh. 2026. Sensing and Modulating the Feel of a Drink: A Personalized Approach via Laryngeal Thermal Feedback. In *Proceedings of the 2026 CHI Conference on Human Factors in Computing Systems (CHI '26), April 13–17, 2026, Barcelona, Spain.* ACM, New York, NY, USA, 18 pages. https://doi.org/10.1145/3772318.3790510

1 Introduction

The experience of consuming food and beverages is multisensory, where gustatory, olfactory, and somatosensory cues are integrated to form a unified perception of flavor [64]. Consequently, quantifying these subjective sensory experiences with objective metrics presents a significant challenge. However, bridging this gap between subjective feeling and objective data is fundamental to the HCI goal of computationally mediating human experience. The ability to model flavor perception would unlock new possibilities for interactive technologies that could augment, personalize, and even digitally transmit our culinary experiences, contributing to the design of novel gustatory interfaces. In particular, the crucial sensation experienced as a beverage passes through the pharynx—a "throat feeling"—contributes significantly to the overall evaluation of a drink. However, its scientific mechanisms are not well understood, and a method for its quantitative measurement has yet to be established.

To address this challenge, recent studies have attempted to infer internal emotional states from peripheral physiological indicators, such as changes in facial skin temperature [3, 22, 26, 30, 32, 63]. These studies are based on the finding that subjective emotional feelings are localized to specific body parts [14], and they report that thermal changes on the facial skin surface can serve as a proxy for internal physiological and emotional states. However, while facial thermal changes may reflect systemic states, they have limitations in capturing sensory experiences that are strongly tied to a specific location, such as the sensation of a drink passing down the throat.

The "throat feeling" is a localized sensory experience that occurs in the pharyngeal region as a beverage passes, significantly contributing to the drink's overall hedonic evaluation. Crucially, this pharyngeal area, and specifically the laryngeal region, possesses heightened sensorial significance, setting it apart from the oral cavity, which primarily initiates flavor processing. The larynx not only plays a critical mechanical role in swallowing but also hosts a dense network of receptors, such as TRP channels, sensitive to both the temperature and chemical properties of ingested materials [1, 68]. This dual mechanical and sensorial function positions the larynx as a key site for detecting a substance's properties immediately prior to final ingestion and for shaping the resultant sensation. Therefore, we hypothesize that measuring the physiological state of the larynx is a uniquely effective and targeted approach for computationally modeling and understanding this essential dimension of flavor perception.

Parallel to efforts in sensing, research in HCI has explored technological interventions to modulate gustatory experiences. It is known that taste can be reproduced through various chemical substances [8, 9] or altered using chemical taste modulators [5]. Beyond chemical approaches, taste perception can also be altered through cross-modal effects, using techniques such as electrical stimulation of the tongue [42, 43] or leveraging interactions with visual, auditory, and olfactory cues [29, 48–50, 52, 56, 74–76, 80]. Thermal stimulation has emerged as a particularly relevant modality

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CHI '26, Barcelona, Spain

ACM ISBN 979-8-4007-2278-3/26/04
https://doi.org/10.1145/3772318.3790510

in this domain. Related work has demonstrated that presenting temperature to facial areas, including the nose, tongue, and lower lip, can significantly influence flavor perception [23, 25, 67]. It has also been shown that thermal stimulation of the posterior neck can specifically alter the perceived temperature of food [31].

While various approaches have been explored, technological interventions targeting the localized sensory experience of "throat feeling," which occurs in the pharyngeal region as a beverage passes through, have not been examined. As noted earlier, this sensation arises specifically in the pharyngeal area, and the larynx contains receptors such as TRP channels that respond to temperature[1, 68]. Based on this principle, applying thermal stimulation to the laryngeal skin located directly above the region where the sensation is perceived may enable modulation of flavor perception. This localized, sensory-source approach offers significant structural and functional advantages over the conventional sites explored in related work. In contrast to conventional approaches that rely on cross-modal perception induced from peripheral sites, this method can act directly on the sensory source. Therefore, interventions applied to the pharyngeal region are expected to be at least as effective as, if not more effective than, previously studied sites for enhancing eating and drinking experiences. In addition, the pharyngeal region is expected to suitable as a target site for designing wearable devices that sense or augment food and beverage experiences. Because the larynx is located on the neck, where accessories such as necklaces and chokers are commonly worn, devices placed here are likely to be more socially acceptable than those attached to unadorned areas of the face [73]. Moreover, devices in this area do not interfere with eating or speaking, making it a practical location for continuously sensing consumption behaviors or providing interventions.

Therefore, our research focuses on the larynx as the direct site of both sensation and intervention. In this paper, we refer to the five basic tastes perceived by the user as "taste perception," while other sensations such as the "throat feeling," "deliciousness," and "comfort" are collectively termed "flavor perception."

To this end, this paper presents a two-part study to computationally model and modulate the sensation of a drink:

- **Sensing (Study 1):** We first explore a method to model individual sensory characteristics by combining laryngeal skin temperature, which reflects the physical phenomena of swallowing, with ingested volume, a key behavioral indicator. This initial study aims to uncover the relationship between these objective measures and subjective perceptual ratings.
- **Intervention (Study 2):** Building upon the insights from our sensing study, we investigate the influence of external thermal presentation on the laryngeal region. Based on the premise explored in Study 1—that laryngeal temperature is a salient feature for modeling flavor perception—we hypothesize that this region is a locus of thermal sensation and that applying thermal stimuli can actively modulate this perception. We designed a wearable device to deliver controlled thermal stimuli and evaluated its effect, specifically testing if the intervention's efficacy is dependent on the individual Interoceptive Profiles identified in Study 1.

Through this work, we offer the following contributions to the field of Human-Computer Interaction:

- We present a computational methodology for modeling an individual's flavor perception from laryngeal temperature and intake volume. This approach quantitatively reveals the existence of distinct Interoceptive Profiles and provides a foundation for technologies that can personalize eating experiences.
- We demonstrate, through the design, implementation, and evaluation of a novel wearable system, that beverage sensations can be modulated via targeted thermal feedback to the larynx.
- We provide empirical evidence validating the effectiveness of personalized sensory intervention and offer design guidelines for the future of personalized food and beverage experiences.

2 Related Work

2.1 Quantification of Flavor Perception with Physiological and Behavioral Indicators

The sensory evaluation of flavor perception has traditionally relied on descriptive analysis and subjective questionnaires [40]. However, as flavor perception is influenced by individual characteristics and psychological contexts, these methods are limited in their ability to capture temporal dynamics and individual differences. To overcome this challenge, recent research has shifted toward identifying physiological indicators associated with sensory experiences. Neuroimaging techniques such as electroencephalography (EEG) [51], magnetoencephalography (MEG) [79], and functional magnetic resonance imaging (fMRI) [18, 20, 53] have revealed neural activities related to taste and olfaction. While powerful, these techniques often impose significant constraints; for instance, fMRI and MEG require participants to remain immobile in a large apparatus, and even more mobile techniques like EEG are susceptible to motion artifacts. Such restrictions on movement and posture are ill-suited for studying the nuances of natural eating and drinking behaviors. The wearable approach in our work, however, is designed to capture precisely these kinds of ecologically valid sensory experiences without such constraints.

To capture sensory experiences in more ecologically valid settings, research has increasingly turned to physiological and behavioral measurements from peripheral body sites. Exploring autonomic nervous system (ANS) activity has become a vital approach to objectively assess the affective dimensions of eating experiences. ANS responses, such as heart rate variability (HRV) and electrodermal activity (EDA), offer a window into the physiological underpinnings of emotion, particularly arousal and valence [33]. For instance, studies in sensory science have demonstrated that basic taste stimuli elicit distinct ANS patterns, with unpleasant tastes like quinine bitterness inducing significantly larger heart rate changes compared to pleasant tastes [61]. More specifically, pleasant flavors have been shown to increase vagal activity—a response potentially preparing the body for digestion—whereas unpleasant flavors trigger sympathetic activation [44].

In parallel with ANS measurements, automated facial expression analysis has emerged as a powerful, non-invasive method for capturing spontaneous affective responses. As facial muscle movements are direct outputs of the brain's emotional centers, they can reveal moment-by-moment reactions to sensory stimuli [17]. This has led to the development of systems that can, for instance, distinguish between different beverage samples based on subtle facial cues [13] or correlate expressions of "happiness" and "disgust" with subjective liking of foods [15]. Facial thermography provides another lens into these peripheral responses. The trigeminal nerve is known to influence facial blood flow, causing localized changes in skin temperature that can be captured with thermal imaging. This mechanism has been used to infer emotional and hedonic states, with variations in nasal skin temperature being associated with emotional arousal [32, 63] and gustatory-related pleasure [3, 26]. Furthermore, oral movements such as mastication induce measurable thermal changes due to muscle activity [22] and are correlated with changes in stress levels [30].

These findings collectively suggest that thermal variations on the body's surface can serve as a valuable indicator of internal sensory states. While these methods have established the utility of physiological sensing, the laryngeal region—the anatomical site where the "throat feeling" originates—remains unexplored. Prior work has focused on facial or systemic responses, but not the direct locus of this specific sensation. Our work addresses this gap by positing that measuring thermal dynamics directly at the site of swallowing provides a more specific and direct proxy for this unique perceptual experience.

2.2 Modulating Flavor Perception via Sensory Presentation

The field of HCI has a growing interest in technologies that augment or digitally mediate food experiences. One approach involves the use of chemical compounds to reproduce taste sensations [4, 39, 43]. However, this method presents challenges related to the management and formulation of chemicals, and potential adverse health effects from long-term use of artificial compounds like monosodium glutamate have been noted [45]. As an alternative, electrical stimulation applied to the tongue has been explored to present basic tastes [2, 42, 46, 57]. While electrical control is more straightforward than chemical delivery, accurately replicating the complexity of real flavors remains a significant challenge.

A substantial body of research has focused on altering flavor perception through cross-modal interactions. In the visual domain, Narumi et al.'s "Meta Cookie" demonstrated that changing the appearance and scent of a plain cookie can induce different perceived tastes [49]. They also explored controlling food intake by altering the apparent size of food with an HMD [48]. Others have used AR to dynamically change a food's appearance [47] or used virtual colors to influence the perception of beverages [50]. Auditory cues have also been employed, from creating playful experiences with sound-emitting ice cream cones [74] to altering food texture perception with modified chewing sounds presented via bone-conduction headphones [29]. Furthermore, various factors of drinking containers reportedly affect flavor perception: the type [7], material [69], shape [10, 58], texture [6, 54], color and weight [41, 62], shape and design [77], tactile feel [36, 55, 59, 72], and softness [34]. In addition, the material of the rim that comes into direct contact with the mouth has also been shown to be a significant factor [24].

Among these modalities, thermal stimulation has been a key area of investigation. It is well-established that the temperature of food itself affects flavor perception, influencing the taste and aroma of coffee [65], the saltiness of soup [27], the aroma of wine [60], and the sensory profiles of cheese [16] and rice [78]. Building on this principle, HCI research has explored applying localized thermal stimuli to facial areas. Suzuki et al.'s "Affecting Tumbler" showed that thermal cues to the perinasal area could alter a drink's flavor [67]. Others have reported that warming the tip of the tongue can elicit sweetness, while cooling it can produce sour or salty sensations [12, 25]. More recently, thermal presentation to the lower lip was also found to modulate flavor perception [23]. Furthermore, it has been demonstrated that applying cold stimuli to the posterior neck synchronized with swallowing can enhance the perception of food's coldness [31]. Kyogoku et al.'s "PhantomFeel Dots" is a proposed wearable system designed to augment the eating experience by applying coordinated thermal and vibrotactile stimuli to the cheeks and throat, aiming to evoke a thermal phantom sensation of warmth flowing from the mouth to the throat[35].

These studies collectively demonstrate the potential of sensory augmentation, particularly through thermal means, to modulate the experience of food and drink. However, existing interventions have primarily targeted peripheral regions such as the oral cavity, face, and posterior neck [12, 23, 25, 31, 35, 67]. While some approaches have proposed multi-site stimulation on the cheek and throat to induce phantom sensations[35], they often lack empirical evaluation of flavor modulation. Furthermore, most prior works rely on simple event synchronization rather than physiological modeling. Consequently, the laryngeal region—which constitutes the anatomical locus of the "throat feeling"—remains largely uninvestigated as a site for both physiological sensing and targeted thermal intervention. The relationship between subjective experience and physiological response is bidirectional; just as bodily changes reflect experiences, the facial feedback hypothesis posits that physiological changes can influence feelings[66]. Drawing an analogy, we hypothesize that the natural thermal fluctuations in the larynx during drinking are integral to the "throat feeling," and that externally applying thermal stimuli to this region could actively modulate flavor perception.

Building upon these related studies, our work advances the field through three methodological distinctions: First, we move beyond using sensing merely for event detection to computationally modeling subjective experience. Prior work has employed sensing solely to identify the timing of feedback (e.g., synchronizing stimulation with a swallow). In contrast, our study employs laryngeal thermal dynamics and ingested volume to computationally model the user's subjective hedonic rating. This establishes a new methodology for quantifying an individual's eating and drinking state rather than just detecting the act itself.

Second, we validate the efficacy of localized thermal intervention directly targeting the laryngeal site. While existing studies have explored multisite stimulation and illusion-based approaches to enhance food and drink experiences, our work targets the anatomical origin of the "throat feeling." We hypothesize that the larynx can serve as a direct intervention site that contributes fundamentally to sensory formation, offering a robust alternative to cross-modal illusions from peripheral sites.

Third, and critically, we propose a data-driven personalization framework. By utilizing a computationally derived "Interoceptive Profile" (i.e., the SHAP-based model) to inform the intervention, we surpass the limitations of pre-defined or simple event-triggered stimulation patterns used in related work. This approach addresses the high inter-individual variability inherent in sensory responses, providing a scalable method for tailoring gustatory interfaces.

3 Study 1: Modeling Subjective Sensation from Laryngeal Thermal Dynamics

The primary objective of this study was to investigate how laryngeal skin temperature and ingested volume relate to the subjective evaluation of beverages, focusing on individual differences. We aimed to build computational models to predict ratings of "throat feeling," "deliciousness," and "comfort" from these objective measures.

3.1 Method

3.1.1 Participants. A total of 31 healthy university students (15 male, 16 female; age: 21.3 ± 1.37 years) were recruited for this study. Participants were required to have no dislike of apple juice, no apple allergy, and to be able to consume the caffeine solution. The experiment was approved by our university's research ethics committee.

3.1.2 Acquisition of Laryngeal Skin Temperature and Ingested Volume. Laryngeal skin temperature was measured using a made neck belt fitted with four thermistors (103JT-025, SEMITEC Corporation). The thermistor used has a zero-load resistance at 25 °C (R_{25}) of 10 kΩ with a tolerance of ±1 %, and a B-value ($B_{25/85}$) of 3435 K with a tolerance of ±1 %. To measure the temperature, a voltage divider circuit was constructed with the thermistor and a 10 kΩ fixed resistor. The output voltage was digitized using the 14-bit analog-to-digital converter of an Arduino Uno R4. This setup provided a theoretical temperature resolution of approximately 0.0063 °C within the measurement range of 25–40 °C. A cross-sectional diagram and a photograph of the device are shown in Figure 1(a) and (b), respectively. The thermistors were affixed to a sponge puff using thermally conductive adhesive tape to ensure stable contact with the skin and accurate temperature measurement. Temperature data was acquired at a sampling rate of approximately 315 Hz. Ingested volume was measured using a digital scale (0.1 g resolution) placed under the beverage cup. A button was placed on the desk for participants to press during ingestion. Figure 1(c) illustrates the experimental setup. Participants were seated at a desk while wearing the custom-made neck belt. A beverage cup and a button were placed on the desk in front of them.

3.1.3 Stimuli. The experiment involved five beverage conditions. These were: three conditions using water from Suntory Holdings Limited (Cooled (**cw**) at 5–10 °C, Room-temperature (**nw**) at 24 °C, and Warmed (**hw**) at 50–60 °C); a Caffeine solution (**cff**) with 50 mg of caffeine (SSP Co., Ltd.) dissolved in 100 mL of room-temperature water; and room-temperature Apple juice (**aj**, Ehime Beverage Co., Ltd.).

3.1.4 Procedure. All participants provided written informed consent prior to their participation. Participants completed a total of 250 trials (50 trials for each of the 5 beverage conditions). To manage participant fatigue from this large number of trials, the experiment was conducted over two days. The 250 trials were structured into 5 identical sets. Each set consisted of 5 blocks, with one block corresponding to 10 trials of a single beverage (i.e., 1 set = 10 trials × 5 beverages = 50 trials). Participants completed either two sets (100 trials) or three sets (150 trials) on the first day, and the remaining sets on the second day. The presentation order of the beverage conditions (blocks) within each set was randomized across participants to mitigate order effects. Within each block (10 trials), participants took a short pause (approximately 15-30 seconds) between each trial to complete the VAS ratings, minimizing immediate perceptual carryover. Furthermore, between blocks (i.e., after 10 trials of one beverage type), participants rinsed their mouths with water and took a minimum rest of three minutes to ensure palate cleansing and prevent sensory fatigue. Immediately before handing the cup to a participant, the beverage's temperature was measured to confirm it was within the target range (±0.5 °C for nw). In each trial, 100 g of a beverage was provided, and participants were allowed to consume any amount they wished. They were instructed to press a button from the moment the beverage touched their lips until swallowing was complete; this period was defined as the "ingestion interval." After each trial, participants provided subjective ratings for four items using a 100 mm visual analog scale (VAS). After each trial, participants provided subjective ratings for four items using a 100 mm visual analog scale (VAS). We operationalized these constructs as follows:

- **Throat Feeling:** Participants were instructed to rate the hedonic quality (i.e., how good or bad) of the overall sensation experienced as the beverage passes down the throat.
- **Deliciousness:** This measured the participant's subjective hedonic rating of the *beverage itself.*
- **Comfort:** This measured the comprehensive hedonic quality reflecting the pleasantness or soothing nature of the *overall drinking experience.*

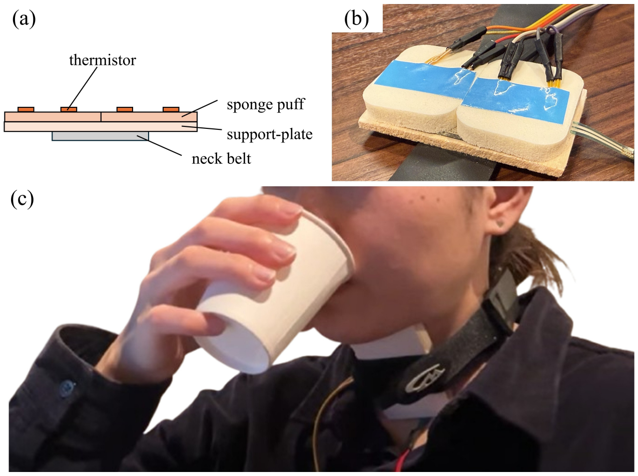


Figure 1: The thermal sensing device and experimental setup. (a) Schematic of the sensing unit. (b) The custom-made thermal sensing belt. (c) The device worn by a participant during the experiment.

- **Thirst:** This was measured to assess its relationship with the primary hedonic ratings and its change throughout the experiment.

For "throat feeling," "deliciousness," and "comfort," the VAS anchors ranged from 0 ("Very bad") to 100 ("Very good"). For "thirst," the anchors ranged from 0 ("Not at all thirsty") to 100 ("Extremely thirsty").

3.1.5 Thermal Data Processing and Feature Extraction. Laryngeal skin temperature was continuously recorded throughout each trial. From the recorded data, we extracted the temperature during the ingestion interval and a subsequent post-ingestion interval of equal duration. First, for each thermistor, a baseline was calculated as the average temperature over the 3 seconds preceding the onset of ingestion. Next, we removed outliers from the data, including samples that deviated by more than 0.4 °C from the previous value and those detected by the interquartile range (IQR) method. Subsequently, thermal displacement was calculated as the difference between the temperature at each time point and the baseline. Trials in which the absolute thermal displacement exceeded 0.4 °C for more than 20% of the ingestion interval were considered noisy and excluded from the analysis. This 0.4 °C threshold is based on the reported perceptual threshold for cold sensation (-0.40 ± 0.30 °C) when the skin temperature is around 31 °C [19]. Finally, to denoise the signal, a moving average with a 50-frame window was applied to the resulting thermal displacement for smoothing.

From the processed data, we computed multiple features for both the ingestion and post-ingestion intervals of each trial. These features included the mean, variance, maximum, and minimum temperature; the maximum thermal displacement [3]; the rate of change between the start and end of the ingestion interval; the rate of change from the start to the extreme values (maximum or minimum); and the rate of change between the minimum and maximum values within the ingestion interval.

3.2 Analysis

We analyzed the effects of beverage type using Linear Mixed-Effects Models (LMMs) and examined the interrelations between subjective ratings and ingested volume using Spearman correlation coefficients. To predict subjective ratings, we trained and evaluated several personalized regression models (e.g., Random Forest, Support Vector Regression, Backpropagation Neural Networks) for each participant. We compared three feature sets: (1) laryngeal temperature features only, (2) ingested volume only, and (3) a combination of both. To assess the reliability of the mapping between features and subjective ratings, the predictive performance for each model was evaluated using a stratified 5-fold cross-validation procedure. We report the coefficient of determination (R^2) and Root Mean Squared Error (RMSE) from this cross-validation as the primary metrics of model performance. Finally, we used SHAP (SHapley Additive exPlanations) to interpret the model outputs and identify key contributing features.

3.3 Results

3.3.1 Effect of Beverage Type on Subjective Ratings and Ingested Volume. We analyzed the subjective ratings (throat feeling, deliciousness, comfort, thirst) and ingested volume from 31 participants across five beverage conditions. To evaluate the influence of beverage type, we applied a linear mixed-effects model for each subjective item and for ingested volume, with beverage condition as a fixed effect and participant as a random effect. A significant main effect of beverage condition was confirmed for all flavor perception ratings and for ingested volume (all $p < 0.001$). As shown in Figure 2(a), apple juice (aj) and cooled water (cw) were consistently rated high across ingested volume and flavor perception items, whereas the caffeine solution (cff) had the lowest ingested volume and received the lowest ratings for flavor perception.

To investigate the relationship between subjective ratings and ingested volume, we calculated Spearman's correlation coefficients between the four flavor perception ratings and ingested volume for each participant ($n = 31$). A 5x5 correlation matrix was constructed for each participant based on all 250 trials, and Fisher's z-transformation was applied to each matrix element. The mean correlation coefficients were then calculated by the z-transformed coefficients across participants and applying the inverse transformation. The resulting correlation matrix for all participants is shown in Figure 2(b). As a result, "throat feeling," "deliciousness," and "comfort" showed strong correlations with each other ($r = 0.77 \sim 0.85$) and each was positively correlated with ingested volume ($r = 0.66 \sim 0.67$). These results indicate that participants tended to consume more of a beverage when they evaluated it more favorably. To assess the statistical reliability of this relationship, p-values were calculated for each pairwise correlation for each participant and corrected for multiple comparisons within the correlation matrix using the Bonferroni method. The results showed that for 30 out of 31 participants, the correlations between "throat feeling," "deliciousness," "comfort," and ingested volume were significantly positive (corrected $p < 0.05$). This indicates that the observed relationship is not driven by a few individuals but reflects a consistent pattern across the group.

3.3.2 Effect of Beverage Temperature on Laryngeal Skin Temperature. To investigate the effect of the beverage temperature itself on the thermal response of the larynx, we analyzed trials from three different water temperature conditions (cw: 5-10 °C, nw: 24 °C, hw: 50-60 °C). For each thermal feature, we applied a linear mixed-effects model with temperature condition as a fixed effect and participant as a random effect. The results, shown in Figure 3 for features with significant differences, revealed no simple monotonic relationship between beverage temperature and skin temperature response. Specifically, room temperature water yielded a significantly higher mean temperature during ingestion than warmed water ($p = 0.020449$). Cooled water showed a significantly greater variance in temperature than both nw ($p = 0.023787$) and hw ($p = 0.007494$), indicating higher instability in the thermal response. Furthermore, the minimum temperature during ingestion was significantly lower for cw compared to nw ($p = 0.020102$). However, no consistent pattern was observed in slope-based features that would indicate linear cooling or warming effects. This suggests that the temperature of the beverage does not have a direct, straightforward impact on the laryngeal skin temperature.

3.3.3 Predicting Subjective Ratings with Within-Individual Regression Models. To determine whether flavor perception could be predicted from physiological and behavioral features, we evaluated the

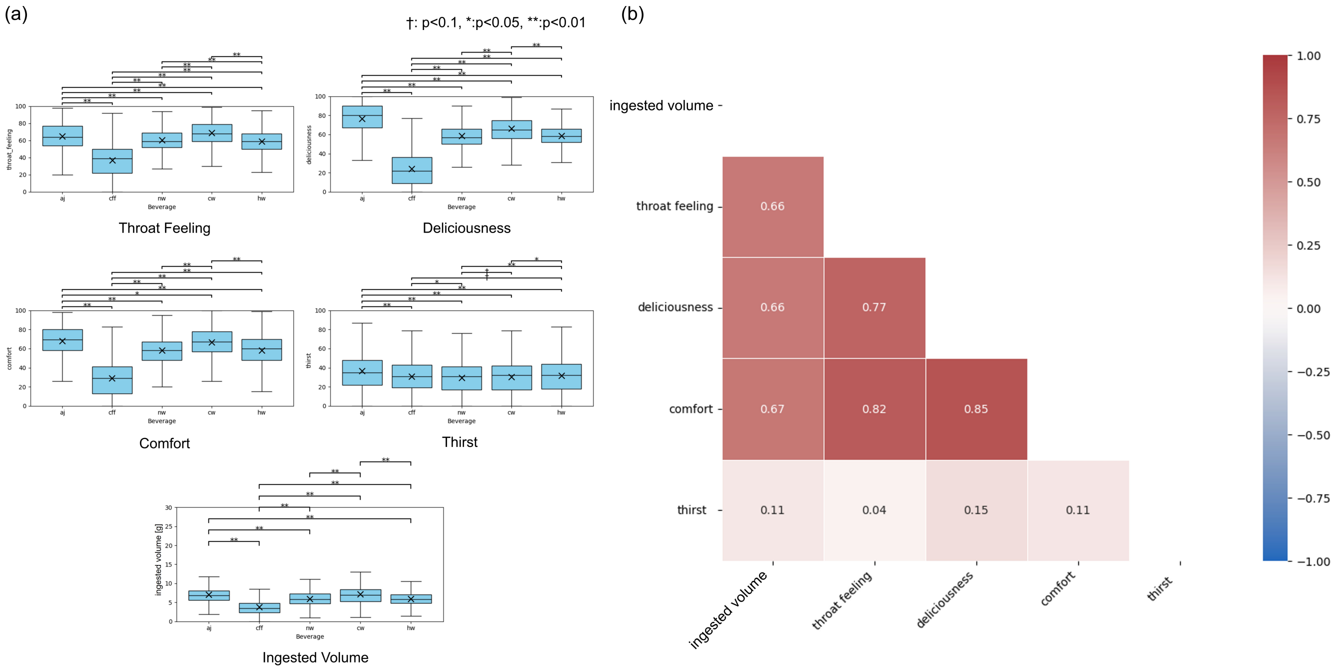
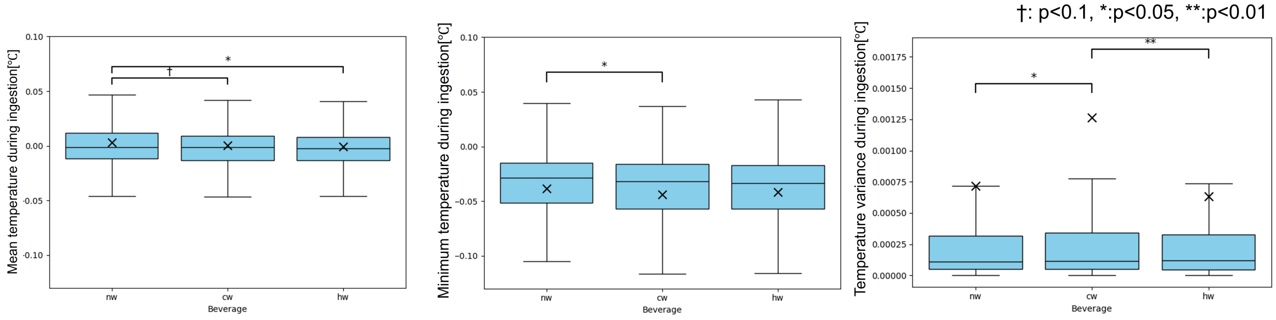


Figure 2: Subjective ratings and ingested volume across different beverage conditions. (a) Subjective ratings and ingested volume for the five beverage conditions. (b) Mean correlation matrix between subjective ratings and ingested volume.



(a) Mean temperature during ingestion (b) Minimum temperature during ingestion (c) Temperature variance during ingestion

Figure 3: Laryngeal thermal dynamics across different water temperatures. Box plots compare thermal features across three water conditions: (a) mean temperature displacement, (b) minimum temperature displacement, and (c) temperature variance.

performance of several regression algorithms using stratified 5-fold cross-validation within each individual. We compared three feature combinations: (1) laryngeal temperature only, (2) both temperature and ingested volume, and (3) ingested volume only. Performance was assessed using the coefficient of determination (R^2) and Root Mean Square Error (RMSE). The results are summarized in Table 1.

Overall, the combination of both laryngeal temperature and ingested volume features yielded the highest predictive performance. The Random Forest (RF) model, in particular, demonstrated high mean R^2 values of 0.6989 for "throat feeling," 0.6456 for "deliciousness," and 0.6653 for "comfort," showing the best accuracy in many categories. In contrast, the performance using only laryngeal temperature features was substantially lower, with the best model (nonlinear SVR) achieving R^2 values of only around 0.10 to 0.33. When using only ingested volume as a feature, the Backpropagation Neural Network (BPNN) model showed very high performance for "throat feeling" with an R^2 of 0.6993. However, for many other models such as Random Forest, linear SVR, k-NN, and XGBoost, combining laryngeal temperature and ingested volume features improved accuracy. This suggests that laryngeal temperature features provide complementary information to the ingested volume data.

Table 1: Performance of personalized regression models for subjective ratings across different feature sets.

(1) Features: Temperature only

Model	**Throat Feeling** R^2 **(RMSE)**	**Deliciousness** R^2 **(RMSE)**	**Comfort** R^2 **(RMSE)**	**Thirst** R^2 **(RMSE)**
BPNN	0.1302 (19.5855)	0.0664 (23.7847)	0.0911 (22.4140)	0.2265 (17.6706)
RF	0.1488 (19.0023)	0.0700 (23.2262)	0.1186 (21.6665)	0.3229 (15.8150)
Linear SVR	0.1627 (18.9629)	0.0940 (23.1106)	0.1418 (21.6048)	0.3116 (16.1715)
Nonlinear SVR	**0.1702 (18.8427)**	**0.0989 (23.0321)**	**0.1477 (21.5049)**	**0.3280 (15.9482)**
k-NN	0.1247 (19.6986)	0.0521 (24.1695)	0.1002 (22.4103)	0.2837 (16.4839)
XGBoost	0.1018 (20.5313)	0.0398 (25.2098)	0.0745 (23.5083)	0.2527 (17.1767)
LightGBM	0.1016 (20.4896)	0.0445 (24.9624)	0.0781 (23.3083)	0.2736 (16.8380)

(2) Features: Temperature + Volume

Model	**Throat Feeling** R^2 **(RMSE)**	**Deliciousness** R^2 **(RMSE)**	**Comfort** R^2 **(RMSE)**	**Thirst** R^2 **(RMSE)**
BPNN	0.6104 (12.8443)	0.5347 (16.3248)	0.5739 (15.0007)	0.3143 (16.4062)
RF	**0.6989 (11.1567)**	**0.6456 (14.0791)**	**0.6653 (13.1672)**	**0.4493 (14.1969)**
Linear SVR	0.5408 (13.9838)	0.4661 (17.5200)	0.5122 (16.1432)	0.3736 (15.3730)
Nonlinear SVR	0.5293 (14.1014)	0.4595 (17.9164)	0.5045 (16.3561)	0.3804 (15.2388)
k-NN	0.6821 (11.5183)	0.6318 (14.4179)	0.6381 (13.7778)	0.3830 (15.2245)
XGBoost	0.6530 (12.0952)	0.5857 (15.4308)	0.6033 (14.5356)	0.3786 (15.4411)
LightGBM	0.6643 (11.8974)	0.6040 (15.0643)	0.6270 (14.0500)	0.4061 (14.9989)

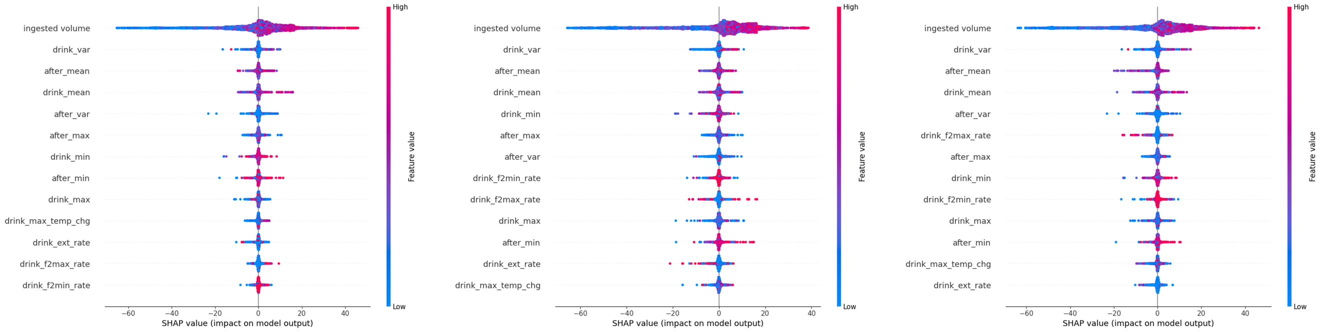
(3) Features: Volume only

Model	**Throat Feeling** R^2 **(RMSE)**	**Deliciousness** R^2 **(RMSE)**	**Comfort** R^2 **(RMSE)**	**Thirst** R^2 **(RMSE)**
BPNN	**0.6993 (11.1499)**	**0.6460 (14.0718)**	**0.6656 (13.1617)**	**0.4484 (14.2090)**
RF	0.6499 (12.1596)	0.6051 (15.0252)	0.6100 (14.3866)	0.3416 (15.9591)
Linear SVR	0.5398 (14.0062)	0.4651 (17.5482)	0.5113 (16.1663)	0.3714 (15.4047)
Nonlinear SVR	0.6419 (12.4217)	0.5788 (15.7456)	0.6038 (14.6029)	0.3977 (15.0366)
k-NN	0.6695 (11.7720)	0.6146 (14.8301)	0.6234 (14.0979)	0.3595 (15.5361)
XGBoost	0.6247 (12.7109)	0.5785 (15.6972)	0.5853 (15.0020)	0.2996 (16.9390)
LightGBM	0.6784 (11.5794)	0.6300 (14.4511)	0.6358 (13.8096)	0.3687 (15.3945)

3.3.4 Analysis of Feature Importance with SHAP. To understand how laryngeal temperature and ingested volume contribute to flavor perception, we first defined a set of features for our regression models. These included the ingested volume (`ingested_volume`) and twelve thermal features derived from the laryngeal temperature data, calculated for both the ingestion and post-ingestion phases. For the ingestion phase, we extracted the mean (`drink_mean`), variance (`drink_var`), maximum (`drink_max`), and minimum (`drink_min`) temperature change from baseline. We also calculated several rates of change: between the maximum and minimum temperatures (`drink_ext_rate`), from ingestion onset to the maximum temperature (`drink_f2max_rate`), and from onset to the minimum temperature (`drink_f2min_rate`). Similarly, for the post-ingestion phase, we calculated the mean (`after_mean`), variance (`after_var`), maximum (`after_max`), and minimum (`after_min`) temperature change. Finally, we included the maximum absolute temperature change across both phases (`drink_max_temp_chg`).

We then interpreted the output of each participant's model using SHAP to assess the contribution of these features [37]. We validated these SHAP interpretations by cross-checking them against observable patterns in the raw data. First, as our primary validation (N=31), SHAP (Figure 4) consistently identified ingested_volume as the most influential feature for all hedonic ratings. This interpretation was robustly confirmed by our findings in Sec 3.3.1 (Figure 2(a), 2(b)), which show that ingested volume had a strong, statistically significant correlation ($r = 0.66 \sim 0.67$, $p < 0.05$ for 30/31 participants) with these exact ratings, and clearly reflected preferences (e.g., low volume for 'cff', high for 'aj'). Second, we validated the importance of secondary physiological features in the same manner. This process is exemplified in our case study analysis (see Section 5.2.2 and Figure 8(a)), where the SHAP importance of drink_var for Participant N was confirmed by their significantly higher drink_var for the unpleasant 'cff' stimulus in the raw data. Across all participants, ingested volume was the most influential feature for the ratings of "throat feeling," "deliciousness," and "comfort," followed by the temperature variance during drinking, the mean temperature after drinking, and the mean temperature during drinking (Figure 4).

For ingested volume, there was a clear trend where higher flavor perception ratings were associated with larger ingested volumes, and lower ratings with smaller volumes. This result suggests that ingested volume functions as a fundamental indicator of hedonic



Throat feeling Deliciousness Comfort

Figure 4: SHAP summary plots for the subjective ratings of throat feeling, deliciousness, and comfort.

evaluation. However, the analysis also revealed that the directional impact of laryngeal temperature features on the ratings varied among individuals. This points to underlying differences in individual sensory characteristics, suggesting that individuals process different sensory input patterns as "favorable" or "unfavorable" based on past experiences, genetic backgrounds, or psychological states.

4 System Design: A Wearable Device for Laryngeal Thermal Feedback

The results from Study 1 indicated that thermal displacements at the larynx are potentially associated with flavor perception, such as the 'throat feeling'. Complementing this, related work has established that thermal presentation to specific areas, including the tongue[12, 25], nose[67], lower lip[23], and posterior neck[31], can modulate flavor perception. Based on these findings, this chapter outlines a device designed to investigate whether thermal presentation to the larynx can similarly alter flavor perception.

4.1 Implementation

4.1.1 Hardware and Control System. Figure 5(a) and (b) show the thermal presentation device. To deliver thermal stimuli to the larynx, we mounted two Peltier devices and a thermistor (103JT-025) onto a neck belt. To control the temperature of the Peltier devices, we used a motor driver (TA8429HQ, TOSHIBA CORPORATION) with an Arduino. The TA8429HQ is an H-Bridge driver, which allowed us to reverse the direction of the current, enabling both heating and cooling from the same Peltier elements. A PID control system was implemented to drive the Peltier devices, using the thermistor for feedback control. Specifically, the PID controller in the Arduino generated a Pulse Width Modulation (PWM) signal to the motor driver. This precisely adjusted the voltage applied to the Peltier elements, allowing us to maintain the target temperature based on the continuous feedback from the thermistor. In the subsequent experiment, the Peltier devices needed to be activated during drinking. Therefore, we configured the system to be manually controlled by the participant using an external mouse placed on the desk. The first click of the mouse button activated the Peltier devices, and a second click deactivated them.

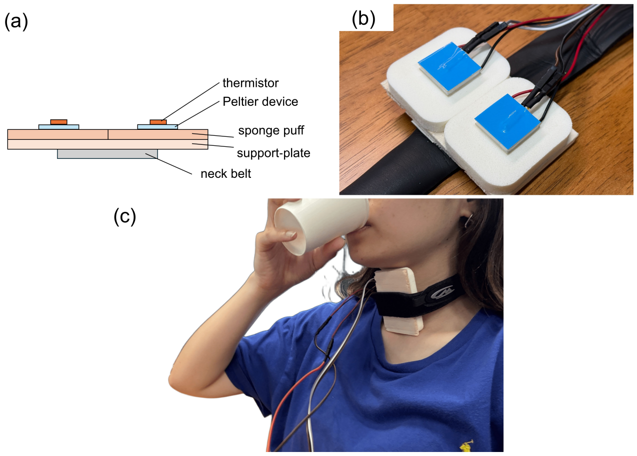


Figure 5: Thermal presenting device and experimental setup. (a) Schematic of the thermal device. (b) The custom-made thermal belt. (c) A participant wearing the device during a trial.

4.1.2 Stimulation Parameters. Based on related work [23, 67], we set the maximum temperature difference (the PID setpoint) to ±2 °C relative to a baseline. The baseline was defined as the participant's laryngeal skin temperature, calculated as the average temperature over a 3-second resting period. Crucially, to ensure participant safety, an absolute upper temperature limit was hard-coded into the control software, which cut power to the motor driver if the thermistor reading exceeded 39°C. This conservative threshold ensures the device always operated well within safe physiological limits for skin temperature. Due to the implementation constraint of not having an active heat dissipation mechanism (e.g., a heatsink or fan), the achievable cooling was limited. Consequently, the system achieved a maximum temperature reduction of -1.25 °C in the cooling condition.

4.2 Device Performance

Figure 6 shows a representative example of the laryngeal skin temperature change recorded by the device. To reduce signal noise, the

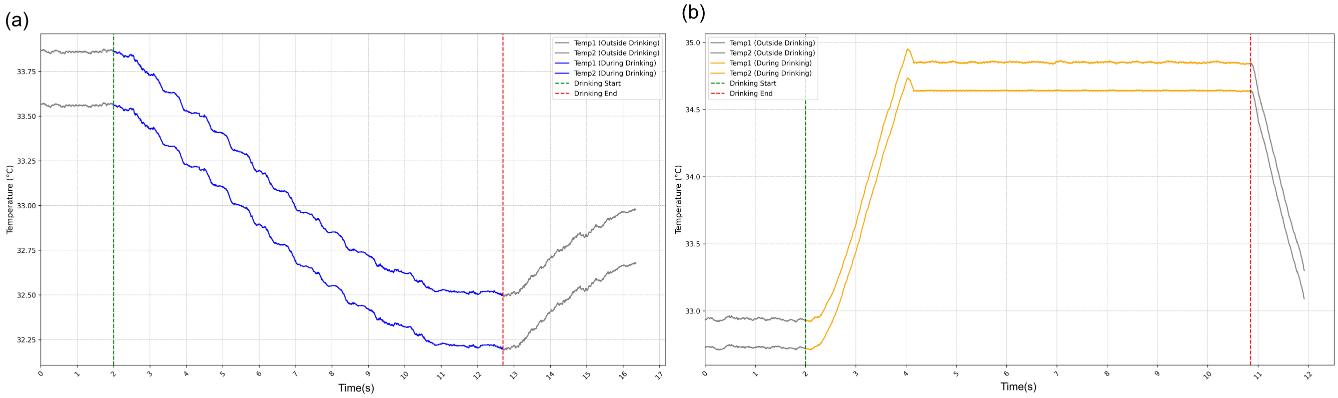


Figure 6: The temperature change at the larynx when the device was worn. (a) The cooling condition. (b) The warming condition.

raw data was processed with a 50-frame moving average filter. Figure 6(a) depicts the cooling condition, and (b) shows the warming condition. The highlighted interval on the plots indicates the drinking period, which was marked by the participant pressing a button at the start and end of the action. Although drinking duration varied among participants, the shortest recorded time in the experiment was 2.5 seconds. The plots confirm that both cooling and warming stimuli were successfully delivered within this timeframe.

5 Study 2: Evaluating the Effect of Laryngeal Thermal Presentation

This study aimed to investigate whether thermal presentation to the larynx, using the device described in the previous chapter, could modulate flavor perception.

5.1 Method

5.1.1 Participants. A subset of 20 participants (11 male, 9 female; mean age 21.7 ± 1.08 years) from Study 1 took part in this experiment. Before the experiment, participants were briefed on the procedure and provided written informed consent. They were informed that the study involved tasting beverages and that they could withdraw at any time. We confirmed that they had no dislike of or allergies to the beverages being served.

5.1.2 Experimental Conditions and Stimuli. Referencing related work on how thermal cues in perinasal areas and on the rim of a cup can alter flavor perception [23, 67], we designed a factorial experiment with three conditions. We used four types of beverages: apple juice, orange juice (both produced by Ehime beverage Co., Ltd.), green tea (produced by Kirin Beverage Co., Ltd.), and water (produced by Suntory Spirits Limited). These were served at three different temperatures (cooled: 5 °C, room temperature: 24 °C, and warm: 60 °C). Two laryngeal thermal presentation conditions were applied: a cooling condition (max -1.25 °C from baseline) and a warming condition (max +2 °C from baseline). This resulted in a total of 24 unique conditions (4 beverages × 3 beverage temperatures × 2 laryngeal temperatures).

5.1.3 Procedure. All participants provided written informed consent prior to their participation. To avoid having thirst confound the flavor perception ratings, participants first rated their level of thirst on a VAS from 0 (“not thirsty at all”) to 100 (“very thirsty”). If the rating was 70 or higher, they were given a sip of water before starting the experiment.

The experiment was conducted using a paired-stimulus format based on themagnitude estimation method. First, the participant consumed a standard stimulus (a beverage with no thermal presentation to the larynx). Immediately after, they consumed the comparison stimulus (the same beverage with either cooling or warming applied). For each pair, participants rated five items. For “throat feeling,” “deliciousness,” and “comfort,” they were asked to assign a value of 1 to the sensation of the standard stimulus and then rate the intensity of the comparison stimulus in proportion to it. For the perceived temperature on the laryngeal skin surface and the perceived temperature of the beverage itself, we established separate references for “warmth” and “coldness,” following [23]. For example, if the perceived warmth did not change, it was rated as “1”; if the perceived coldness felt 1.5 times stronger, it was rated as “1.5.” To mitigate perceptual carryover and sensory fatigue across trials, participants were required to rinse their mouth with room-temperature water and rest for a minimum of 30 seconds after completing the ratings for each pair (two trials).

Participants were instructed to press a button at two time points: just before the cup touched their lips and again after swallowing. For the comparison stimulus, the first button press triggered the activation of the Peltier elements, and the second press deactivated them. This sequence constituted one set, and each participant completed one set for all 24 conditions. Each beverage was presented in a 50 g serving, and its temperature was measured with an infrared thermometer just before presentation. The order of beverages and laryngeal thermal conditions was randomized across participants to control for order effects. To minimize participant fatigue, the experiment was completed in a single session lasting approximately 90 minutes, including breaks and setup.

5.2 Results

5.2.1 Overall Effects of Thermal Intervention. The data obtained from the magnitude estimation method were first log-transformed. To account for differences in scale use among individuals, the values for each participant were standardized to have a mean of 0 and a standard deviation of 1. The standardization was performed by calculating the mean and standard deviation of all of a participant's data, subtracting the mean from each rating, and then dividing by the standard deviation. A Shapiro-Wilk test on the standardized evaluation data showed that not all items were normally distributed. Consequently, we used the non-parametric Friedman test for analysis, followed by Bonferroni correction for multiple comparisons to examine significant differences among the evaluation data. The results of the experiment are shown in Figure 7.

Perception of Thermal Stimuli. The thermal stimulation on the larynx was clearly perceived by the participants. When a warming stimulus was applied while drinking warm orange juice ($p = 0.0076$) and warm water ($p = 0.0116$), participants reported feeling significantly more warmth on their larynx compared to the baseline. Similarly, when a cooling stimulus was applied while drinking cooled beverages, participants felt significantly more coldness on their larynx for orange juice ($p = 0.043$), apple juice ($p = 0.0116$), and green tea ($p = 0.043$).

The laryngeal stimulation also tended to influence the perception of the beverage's temperature itself. When a warming stimulus was applied while drinking warm beverages, there was a trend towards perceiving the beverage itself as warmer for orange juice ($p = 0.099$), green tea ($p = 0.09$), and water ($p = 0.012$). Likewise, applying a cooling stimulus to the larynx while drinking cooled beverages tended to increase the perceived coldness of the beverage itself for apple juice ($p = 0.075$) and water ($p = 0.043$).

Effects on Flavor Perception. Applying a cooling stimulus to the larynx while drinking cooled beverages was found to increase the "throat feeling" ($p < 0.1$ or $p < 0.05$). In conditions where a warming stimulus was applied during the consumption of room-temperature orange juice ($p = 0.068$), cooled water ($p = 0.075$), and room-temperature water ($p = 0.043$), the "throat feeling" was found to decrease compared to the cooling stimulus.

For "deliciousness," cooling the larynx increased the rating for cooled and room-temperature juices and for cooled green tea ($p < 0.1, p < 0.05$). For "comfort," cooling the larynx increased the rating for cooled juices and green tea ($p < 0.1, p < 0.05$), while warming the larynx decreased comfort for room-temperature juices and water ($p < 0.1, p < 0.05$). Conversely, when drinking warm orange juice ($p = 0.068$) and warm green tea ($p = 0.027$), warming the larynx increased the feeling of comfort.

In summary, it was found that laryngeal cooling tended to enhance positive sensory evaluations, especially for cool or room-temperature beverages. In contrast, the effect of laryngeal warming was more complex and depended on the temperature of the beverage being consumed, sometimes decreasing and sometimes increasing comfort.

5.2.2 Relationship with Study 1: Personalized Effects. To investigate if the individual differences in the intervention's effects observed in Study 2 could be predicted, we conducted a quantitative analysis correlating them with the individual Interoceptive Profiles derived from Study 1. Here, an individual's sensory profile was quantitatively defined by the mean absolute SHAP values for each feature from their personalized model built in Study 1. This was followed by an analysis of illustrative case studies to provide qualitative context.

Quantitative Analysis of Personalized Effects. To investigate if the individual differences in response to the thermal intervention could be systematically predicted by the Interoceptive Profiles identified in Study 1, we conducted a correlation analysis across all 20 participants. For each participant, we quantified their individual sensory profile by calculating the mean absolute SHAP value for each feature from their personalized model in Study 1. Based on the overall feature importance analysis (see Figure 4), we focused on the three most influential thermal features: mean temperature post-ingestion (after_mean), mean temperature during ingestion (drink_mean), and variance of temperature during ingestion (drink_var). The magnitude of the intervention's effect in Study 2 was defined as the change from the baseline, calculated as rating -1 from the Magnitude Estimation data.

We calculated both Pearson's product-moment correlation coefficient (r) to assess linear relationships and Spearman's rank correlation coefficient (r_s). The results are summarized in Table 2.

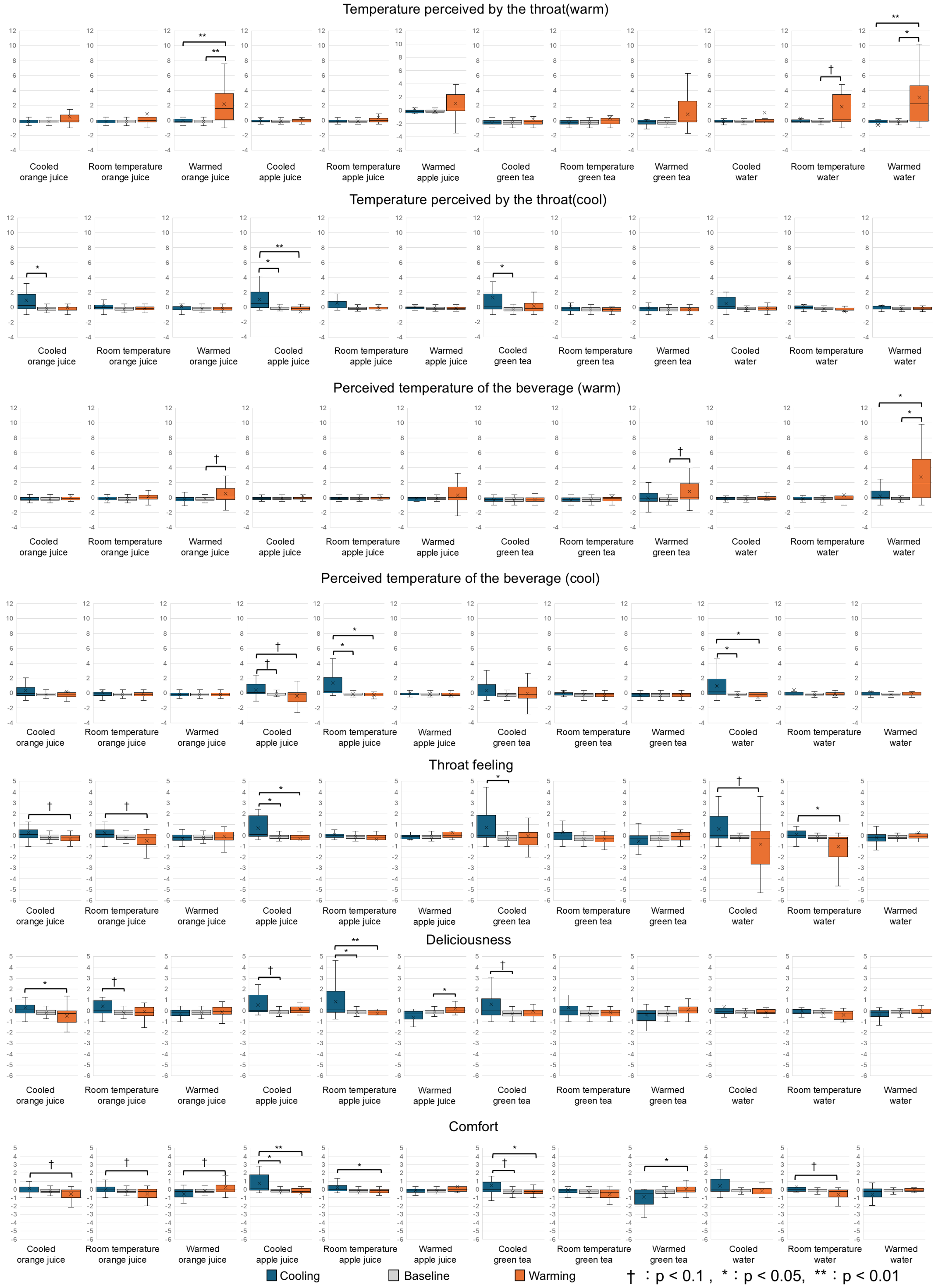
The analysis revealed a statistically significant positive linear correlation between the SHAP value for mean temperature post-ingestion and the effect of the cooling intervention on the "throat feeling" rating ($r = 0.542, p = 0.014$). However, the corresponding Spearman's rank correlation was not significant ($r_s = 0.137, p = 0.563$). Furthermore, a non-significant trend was observed in the Spearman correlation between the SHAP value for mean temperature post-ingestion and the effect of cooling on the "comfort" rating ($r_s = 0.382, p = 0.097$), suggesting a potential, albeit weaker, monotonic relationship for this dimension. No other correlations approached statistical significance.

Illustrative Case Studies. To further illustrate the divergent individual responses suggested by the quantitative analysis, we present a detailed analysis of two participants, N and W, who exemplify these differences.

For each participant, we analyzed the data from the magnitude estimation method to examine changes in flavor perception across the laryngeal thermal conditions (cooling, baseline, warming). As a Shapiro-Wilk test indicated that the data were not normally distributed, we performed a Friedman test, followed by post-hoc comparisons using the Bonferroni method to test for significant differences. The results for participants N and W are shown in Figure 8(b).

As shown in Figure 8(a), Participant N, in the sensing experiment, showed a significantly larger variance in laryngeal temperature during the ingestion interval when consuming the unpleasant stimulus (caffeine solution) compared to other beverages. In Study 2, Participant N's flavor perception was significantly altered by the laryngeal thermal presentation (Figure 8(b)). Specifically, cooling the larynx significantly improved their ratings of "throat feeling," "deliciousness," and "comfort" compared to the baseline.

In contrast, Participant W showed no statistically significant effect of beverage type on any of the laryngeal temperature features in the sensing experiment. Correspondingly, in the thermal presentation experiment, Participant W showed no significant change in flavor perception as a result of the laryngeal thermal presentation.


Temperature perceived by the throat(warm)

Temperature perceived by the throat(cool)

Perceived temperature of the beverage (warm)

Perceived temperature of the beverage (cool)

Throat feeling

Deliciousness

Comfort

Figure 7: Overall results of Study 2.

Table 2: Correlation between sensory profile features (mean absolute SHAP values from Study 1) and the effect of laryngeal thermal intervention (from Study 2) on subjective ratings.

		Laryngeal Cooling Effect		Laryngeal Warming Effect	
Subjective Rating	**Sensory Profile Feature**	Pearson's r	Spearman's r_s	Pearson's r	Spearman's r_s
Throat Feeling	after_mean	**0.542 (p=.014)**	0.137 (p=.563)	0.083 (p=.728)	-0.073 (p=.761)
	drink_mean	-0.155 (p=.513)	-0.002 (p=.995)	-0.082 (p=.730)	-0.026 (p=.912)
	drink_var	0.229 (p=.332)	0.182 (p=.441)	-0.142 (p=.549)	-0.015 (p=.950)
Deliciousness	after_mean	0.021 (p=.932)	0.190 (p=.422)	0.058 (p=.810)	0.151 (p=.524)
	drink_mean	0.042 (p=.861)	0.125 (p=.598)	0.160 (p=.501)	0.085 (p=.721)
	drink_var	0.076 (p=.750)	-0.004 (p=.987)	0.093 (p=.697)	0.126 (p=.596)
Comfort	after_mean	0.064 (p=.788)	**0.382 (p=.097)**	0.149 (p=.529)	0.292 (p=.212)
	drink_mean	0.000 (p=.999)	0.173 (p=.466)	0.016 (p=.947)	0.051 (p=.833)
	drink_var	-0.069 (p=.774)	0.200 (p=.399)	-0.130 (p=.584)	0.069 (p=.771)

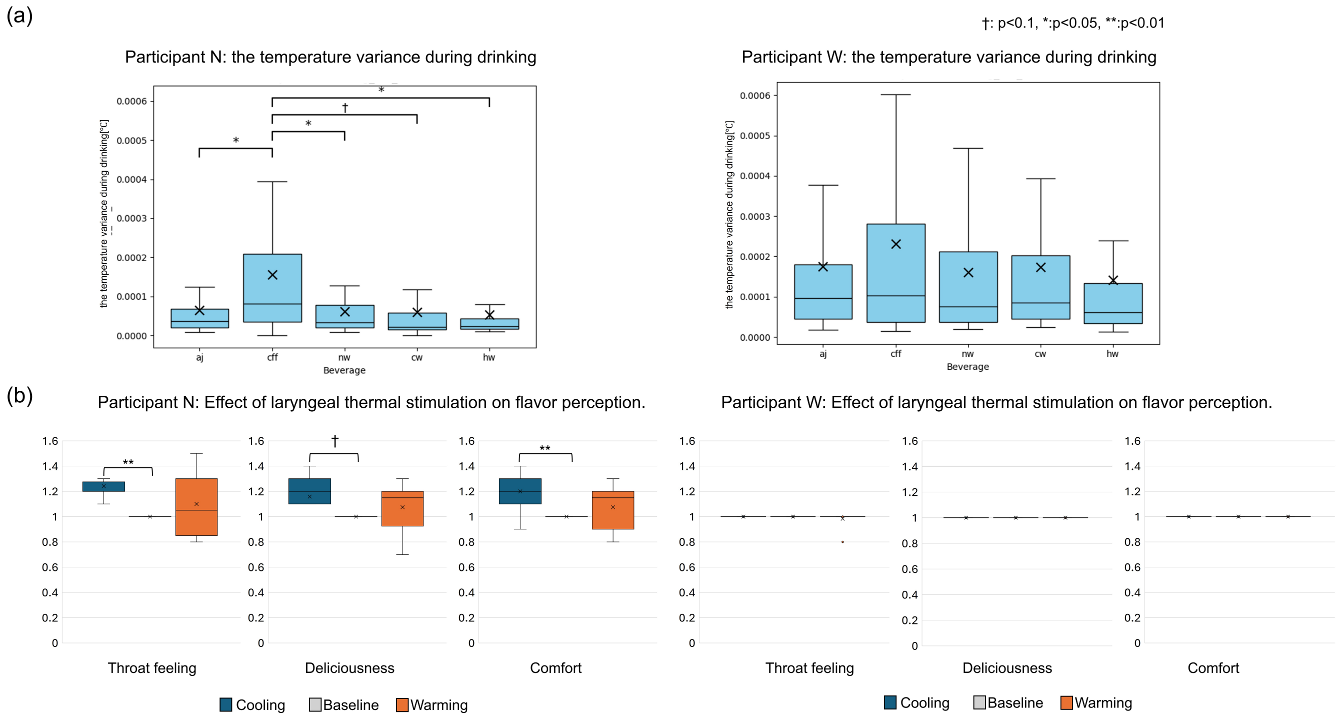


Figure 8: Contrasting responses to laryngeal thermal stimulation for two participants. (a) Laryngeal temperature variance during drinking (Study 1). (b) Effect of thermal stimulation on flavor perception (Study 2).

6 Discussion

6.1 Interpretation of Study 1: Individual Differences in Sensory Models

This study demonstrates that subjective sensory experiences during beverage consumption—most notably *throat feeling*—can be quantitatively predicted from a combination of laryngeal skin temperature and ingested volume. The within-individual machine-learning models achieved high predictive accuracy (mean $R^2 = 0.65$–0.70). This performance is competitive with previous studies that have used more complex, multi-modal biosignals to estimate emotional states. For instance, the DEAP dataset reported binary classification accuracies around 57-67% for arousal, valence, and liking using EEG and other peripheral measures [28]. Similarly, prior work on gustatory responses using nasal thermography reported correlation coefficients corresponding to an R^2 of up to 0.49 [3]. Our approach, using a combination of laryngeal thermal dynamics and behavioral cues, yielded higher coefficients of determination, suggesting it is a viable and low-burden method for estimating affective states in this context.

A primary finding is that ingested volume was the most powerful predictor of positive ratings for "throat feeling," "deliciousness," and "comfort." This result empirically supports the principle that consumption volume is a robust behavioral correlate of hedonic evaluation, as people tend to consume more of what they find pleasant [21]. The strong inter-correlations among these three ratings

(Figure 2b) further suggest they form a coherent hedonic dimension that is reflected in ingestive behavior. This finding provides empirical support for our selection of subjective measures. Given that we defined all three items ("throat feeling," "deliciousness," and "comfort") as measures of hedonic quality, their high inter-correlation ($r = 0.77 \sim 0.85$, as shown in Figure 2b) serves as an internal cross-check on the measurement indicators. The consistency of results suggests that participants consistently processed them as interrelated components of a unified, positive hedonic dimension. However, this consistency is primarily considered a supporting observation, and not a definitive validation of complete psychological construct coverage.

Our results also show that laryngeal thermal dynamics provide complementary information that significantly improves predictive accuracy for several models (Table 1). This suggests that while behavioral metrics offer a broad estimate of preference, physiological signals—likely reflecting factors such as the beverage's properties and the physiological work of swallowing [68]—are essential for capturing the nuanced sensory qualities that constitute that preference. The utility of this thermal data appeared to be model-dependent; for models like Random Forest, thermal features consistently provided complementary information, whereas for a powerful non-linear model like a BPNN, the single strong feature of ingested volume may have been sufficient to learn the predictive relationship.

Finally, the SHAP analysis revealed that while ingested volume was the primary driver of predictions, the way in which thermal features contributed to the models varied considerably across individuals. This suggests that individuals have different Interoceptive Profiles, weighing cues like thermal stability or dynamic changes differently when forming their subjective evaluations. This finding provides a clear theoretical grounding for our key construct. While "sensory profiling" in consumer science typically uses consumer-based methods to characterize products[70], our computational approach aims to create a profile of the *individual's perceptual model* itself. We posit that our computationally-derived Interoceptive Profiles (i.e., the SHAP values) are a novel, HCI-based operationalization of an established psychological concept: *individual differences in interoceptive weighting* [11]. Specifically, the profile quantifies how strongly an individual's subjective hedonic judgment (e.g., "comfort") depends on specific physiological cues (e.g., the thermal mean, or dynamic changes like the `drink_var`).

6.2 Interpretation of Study 2: Overall Effects of Thermal Intervention

Consistent with related work demonstrating that thermal presentation to specific facial areas can alter taste and flavor perception [12, 23, 25, 67], our study revealed that thermal presentation to the larynx also modulates flavor perception.

The thermal stimulus applied to the larynx was perceived more strongly only when its direction was congruent with the beverage's temperature. This might be because participants' attention was primarily directed toward evaluating the beverage's temperature, making them less attentive to unexpected thermal changes (e.g., thermal stimulation with a room-temperature beverage). Furthermore, a comparison of the median ratings of perceived temperature on the larynx showed that the "warmth" from the warming stimulus was rated more strongly than the "coldness" from the cooling stimulus. This is consistent with prior research on the asymmetry of thermal thresholds; for instance, for skin temperatures in the range observed in our experiment (33–36°C), warming stimuli (threshold: +0.5°C) are more easily detected than cooling stimuli (threshold: -1.8°C) [19]. The lower perception of the cooling stimulus could also be attributed to differences in the absolute magnitude and rate of temperature change. The warming stimulus may have been perceived more strongly because the temperature increased more rapidly.

Moreover, laryngeal warming stimulation made warm beverages feel even warmer, and cooling stimulation made cool beverages feel even cooler. This suggests that the external, supplementary information augmented the perception of the primary sensation (the beverage's temperature). This principle aligns with previous findings where applying cold stimuli to the posterior neck synchronized with swallowing was shown to enhance the perception of food's coldness [31]. Our study demonstrates that this effect can also be induced at the larynx, a region more directly involved in the swallowing process. This sensory congruence appears to be linked to hedonic evaluation. When the sensation expected from the beverage and the external stimulus were congruent (e.g., a cooled beverage with a cooling stimulus), the sensation was enhanced, leading to positive evaluations such as improved "throat feeling," "deliciousness," and "comfort." The beverages used in this experiment reflect a cultural context where they are generally preferred cold. Our findings suggest the possibility of creating or enhancing the perceptual experience of a "cool and delicious" beverage through external sensory input, without physically altering the beverage itself. This strong dependency on the beverage's own properties and the observed high inter-individual variability lead to a critical insight. For example, the mixed results observed for the warming intervention may be partly attributed to the fact that the study was conducted during the summer, a season when cooling sensations are generally preferred. Applying a warming stimulus to room-temperature or chilled beverages may have therefore created a sensory incongruence that participants perceived as unpleasant. This dependency suggests that universal interventions (e.g., always cooling) are suboptimal because they disregard not only situational context but also individual sensory weighting (as identified in Study 1). Thus, interventions targeting the larynx imply dependence not only on individual characteristics but also on the broader context in which beverages are consumed. Context-adaptive approaches that account for users' sensory preferences, cultural norms surrounding beverages, and environmental factors like ambient temperature are likely more effective at enhancing the perceptual experience than universal interventions that disregard these situational and individual factors.

6.3 Interpretation of Study 2: Personalized Effects of Thermal Intervention

The correlation analysis between the Interoceptive Profiles from Study 1 and the intervention effects from Study 2 provides quantitative evidence for the personalized nature of laryngeal thermal feedback. The significant Pearson correlation for the "throat feeling" with cooling suggests a linear relationship for a subset of individuals. The discrepancy between the significant Pearson correlation and the non-significant Spearman correlation suggests that this linear relationship is likely driven by a small number of participants who were highly sensitive to this feature and responded strongly to the intervention, rather than a consistent monotonic trend across the entire sample. This indicates that the personalized effect is highly specific: it is most pronounced for the "throat feeling" dimension, is linked primarily to the cooling intervention, and is predictable based on an individual's sensitivity to post-ingestion thermal cues.

The case studies of Participants N and W help to illustrate these divergent responses. Participant N likely represents one of the highly responsive individuals that drove the significant Pearson correlation observed in our analysis. Their clear and significant improvement in flavor perception with cooling aligns with their sensory profile from Study 1, which showed high sensitivity to thermal variance. In contrast, Participant W, whose sensory profile was not sensitive to thermal features, showed no significant change in flavor perception. This response is representative of the general trend in the data, where no consistent monotonic relationship was found, as indicated by the non-significant Spearman correlations.

However, it is important to note that participants exhibiting distinctive characteristics like Participant N in Study 1 were few. Furthermore, some participants who showed characteristic thermal changes could not participate in Study 2, highlighting the need for further investigation with a larger sample to generalize these findings. It is also possible that our model has not yet captured other physiological or psychological factors that mediate the effect of our intervention. For instance, the static nature of the thermal stimuli in Study 2 (constant cooling/warming) may not align with the Interoceptive Profiles of all individuals, some of whom may be more responsive to dynamic temperature changes, as suggested by the importance of the temperature variance feature in Study 1.

6.4 Synthesizing a Potential Framework for Personalized Sensation Augmentation

Taken together, our two studies suggest the potential for a computational approach to personalizing sensory experiences. While our results indicate that this personalization is not yet achievable for all individuals, our work points toward a potential framework consisting of three stages:

1. **Sensing:** Objectively measure relevant physiological and behavioral signals during a baseline experience.
2. **Modeling:** Use machine learning to build a personalized model that maps these signals to subjective perception, thereby identifying an individual's unique sensory profile.
3. **Intervention:** Design and apply a targeted intervention based on the individual's model to achieve a desired perceptual outcome.

This "Sensing → Modeling → Intervention" pipeline suggests a possible direction for a systematic, data-driven approach to understanding and augmenting subjective experiences, moving beyond generic interventions towards truly personalized technology.

To realize the full potential of the larynx as a bidirectional interface, as implicitly suggested by the sequential nature of our studies, the integration of these three stages into a continuous, real-time closed-loop system is essential.

Toward True Bidirectional Feedback. In this paragraph, we discuss the design of a novel integrated system with personalized feedback, which can be realized by synthesizing the findings from Study 1 and Study 2. Such a system would function as a closed loop by continuously predicting the user's subjective hedonic state (e.g., a predicted "comfort" score) using real-time laryngeal thermal data and ingestion cues. When the predicted hedonic rating falls below a personalized threshold (indicating an unfavorable sensory trend), the system would immediately activate the thermal actuator according to the individual's Interoceptive Profile (e.g., initiating cooling for an individual who is highly sensitive to the `after_mean` thermal feature). The core challenge for realizing this true bidirectional feedback lies in connecting the predictive output of the Modeling stage directly to the Intervention input with minimal latency. Overcoming this latency allows the system to act as a responsive, homeostatic regulator of the sensory experience, dynamically adjusting the physical stimulus (temperature) based on the inferred internal state (hedonic rating) in real time. The implementation of this closed-loop control would establish the larynx as a functional, bidirectional HCI interface for consumption.

7 Limitations and Design Implications

7.1 Limitations

Our research has several limitations. A primary challenge is that the precise physiological mechanisms underlying our findings remain unclear. The mechanism by which flavor perception influences laryngeal temperature, and conversely, how thermal presentation to the larynx modulates flavor perception, is not yet understood. Our measurements are correlational and do not establish causality. Furthermore, skin-surface temperature is an indirect proxy for the actual thermal events occurring within the pharynx. The intervention is also limited to thermal stimuli delivered to the skin surface, which may not fully replicate the internal sensation of a drink.

Another significant limitation is the participant pool. Our conclusions are based on a relatively small group of university students from a single cultural background. It is known that cultural background and past experiences play a significant role in flavor perception and its cross-modal modulation [64, 71]. Therefore, the generalizability of our findings requires further validation with a broader and more diverse participant pool, comprising individuals of different age groups, nationalities, and dietary habits. Similarly, our conclusions regarding personalization in Study 2 are based on illustrative case studies, which necessitate a larger-scale study to establish statistical significance across different Interoceptive Profiles.

A further constraint relates to the subjective nature of the hedonic ratings. Although all analyses relying on subjective scales, such as correlations and predictive modeling, are performed within-subjects, thereby mitigating the issue of absolute scaling differences between individuals, the fundamental challenge of semantic interpretation remains. Specifically, the interpretation of verbal anchors (e.g., whether "Very good" represents the same hedonic intensity for all participants) may still vary. Since we rely on self-reported data to model the physical predictors, the observed predictive power may be influenced by these inherent inconsistencies in semantic interpretation.

One of the primary conceptual frameworks of this paper is the bidirectionality of the larynx as an interface. Our work demonstrates the potential of this bidirectionality by presenting two independent studies: sensing (Study 1) and intervention (Study 2). A key limitation is that these systems are not integrated; the current studies do not involve real-time, closed-loop control connecting the two. The integration of these sensing and actuation systems is a critical next step. Future work must unite these two components to function in concert as a truly bidirectional interface.

In this paper, we focused on modeling holistic, hedonic ratings (e.g., "deliciousness," "comfort") as they strongly correlate with ingestive behavior (volume). However, we did not include more analytical sensory dimensions, such as perceived texture, viscosity, or specific flavor attributes (e.g., sweetness, bitterness). Including these dimensions, would undoubtedly broaden the profiling space and could reveal more nuanced relationships between laryngeal physiology and specific sensory inputs.

Finally, both studies were conducted under controlled laboratory conditions rather than in an ecologically valid, "in-the-wild" setting. Our primary goal was to establish the fundamental feasibility and effectiveness of the larynx as a sensing and actuation site, which required minimizing environmental noise and controlling variables strictly. However, this controlled setting limits the generalizability of our findings to real-world eating contexts (e.g., noisy restaurants, social gatherings, or while walking). The short-term nature of the experiments also means we have not assessed long-term usability, user acceptance, or potential novelty effects. While we propose the larynx offers higher social acceptability, we did not validate this hypothesis, nor did we assess how wearing the device impacts social communication during a meal. Research on face-worn olfactory displays, for instance, suggests that placing devices near existing adornment practices (e.g., jewelry, piercings) maximizes social acceptance, whereas placing them on "unadorned" sites like the cheek can deviate from social norms and cause resistance [73]. Although the neck benefits from this adornment association (e.g., necklaces, chokers), further study is required to validate the long-term social acceptability of a functional laryngeal device in real-world social dining.

7.2 Design Implications for HCI

Despite these limitations, our work offers several design implications for HCI.

7.2.1 Adaptive Strategy Design in Food Augmentation. Our findings provide a novel framework for engineering adaptive food augmentation systems. The results from Study 2, demonstrating that the intervention efficacy is dependent on beverage context and individual profiles, suggest that a simplistic, universal intervention strategy (e.g., always cooling) is inherently suboptimal. Instead, intervention design requires a hierarchical approach to adaptation: First, our findings support a general principle of sensory congruence as a baseline strategy. As shown in Fig. 7, thermal feedback that aligns with the beverage's inherent temperature (e.g., cooling for cold beverages) consistently enhances the positive sensory experience across participants. This implies that preserving the congruency between external stimuli and the beverage's properties serves as a robust default strategy when minimal intervention is sufficient. Second, to maximize effect across diverse conditions, systems must implement dual adaptation that simultaneously considers: (1) context-awareness (e.g., adapting stimulus polarity based on beverage temperature and environmental factors), and (2) individual adaptation (e.g., adjusting intensity based on the user's Interoceptive Profile from Study 1). Third, while creating a unique profile for every user is resource-intensive, our case studies suggest the potential for scalable personalization. Future Human-Food Interaction(HFI) systems can cluster users into groups based on similar physiological response patterns and apply group-based Interoceptive Profiles to achieve effective personalization at scale, which warrants further investigation. The integration of this dual (context + individual/group) adaptation within our proposed "Sensing-Modeling-Intervention" framework provides a new direction for engineering truly personalized HFI experiences.

7.2.2 The Larynx as an Unobtrusive Interface Site for Bio-Sensing and Actuation. Our work advocates for the larynx as an optimal site for interfaces targeting eating and drinking, demonstrating its viability for both sensing and actuation. The viability of using laryngeal temperature to capture ingestion actions and physiological features, as shown in Study 1, suggests that laryngeal sensing, when combined with behavioral data (ingested volume), provides high predictive performance for flavor perception, positioning it as a highly effective site for consumption monitoring. Crucially, the larynx enables precise synchronization with swallowing without interfering with eating or speaking. Furthermore, unlike facial devices, the neck location allows the device to be discreetly concealed by clothing (e.g., a turtleneck or collar) or worn as an accessory. These functional and social advantages position the larynx as a key area for next-generation consumption interfaces.

7.2.3 Objective and Real-Time Sensory Evaluation Tools. The "Sensing-Modeling" approach proposed in this work can be developed into a novel tool to augment traditional sensory evaluation methods, which typically rely on subjective reporting and descriptive analysis. By providing objective, real-time data on physiological cues (laryngeal thermal dynamics) and correlating them with ingestion behavior (volume) and hedonic ratings, our methodology can offer food scientists and product developers a richer, quantitative understanding of consumer perception. This objective profiling capability has the potential to accelerate and enrich the product design cycle by providing granular insight into the individual variability of sensory responses. Furthermore, the physiological sensing capabilities of the larynx can be expanded by integrating modalities such as laryngeal pressure sensing [38], which offers precise information about swallowing kinematics. Integrating multiple sensors (e.g., thermal and pressure) presents a promising direction for future research in capturing comprehensive, multimodal physiological indicators of food consumption.

7.3 Future Work

Future work will focus on developing a closed-loop system that connects the sensing model to the intervention in real-time. Specifically, we will integrate the sensing system from Study 1 with the intervention system from Study 2. This integrated system will first predict the user's subjective flavor perception in real-time based on laryngeal temperature changes and intake volume. Based on this predictive data, the thermal presentation to the larynx will dynamically adjust its temperature to achieve a desired perceptual outcome. For example, the system could create a pleasant sensation by applying cooling to the larynx when an unpleasant sensation is detected, allowing for dynamic adaptation of the stimulus based on the user's ongoing physiological state. To achieve the required context-awareness for this closed-loop system, future efforts must focus on dynamically integrating the properties of the consumed item. Specifically, this involves measuring or inferring the beverage's initial state (e.g., precise temperature and type) in real-time through complementary sensing modalities, such as integrating temperature sensors into tableware and cutlery or utilizing computer vision to identify the item. The algorithm will then use this contextual information to determine the optimal polarity (cooling vs. warming) and intensity of the thermal stimulus, ensuring the intervention is congruent with the beverage's properties and the user's sensory profile.

We also plan to expand this research to a wider variety of beverages and food textures to understand how different physical properties interact with our sensing and intervention methods. In doing so, we aim to incorporate the analytical sensory dimensions (e.g., viscosity, texture, specific flavor attributes) discussed in our limitations. This will allow us to build more comprehensive models that untangle how different physical properties (e.g., a beverage's viscosity) and specific sensory inputs (e.g., bitterness) distinctively influence laryngeal thermal dynamics and the overall "throat feeling." A key priority is to conduct studies with a larger and more diverse participant pool to examine the generalizability of our findings and further explore the influence of factors like age and cultural background. This will not only serve to examine the generalizability of our findings (e.g., across different ages and cultural backgrounds) but also to explore the feasibility of clustering participants into distinct sensory profile groups, as discussed in our Design Implications. This grouping could enable more scalable, group-based personalization as a practical alternative to fully individualized models. Furthermore, to address the limitations of our lab-based studies, we plan to conduct long-term, "in-the-wild" evaluations. This will allow us to understand how the device performs amidst the complexities of daily life and to assess factors such as comfort, social acceptability, and robustness to motion artifacts. Finally, integrating other physiological sensors, such as electromyography (EMG) to measure muscle activity during swallowing, could enhance model accuracy and provide deeper mechanistic insights.

8 Conclusion

This study proposed a framework for sensing and modulating flavor perception by focusing on the laryngeal region. We first demonstrated that flavor perception can be quantified by combining laryngeal skin temperature and ingested volume. Second, we showed that thermal presentation to the larynx can modulate flavor perception. Finally, our findings suggest that the effect of this thermal intervention may be linked to an individual's characteristic laryngeal temperature changes during drinking. This work presents a step toward realizing personalized beverage experiences by computationally modeling and intervening in the sensation of the "throat feeling."

Acknowledgments

We also thank Prof. Hideki Sunahara (Keio University) and Prof. Takeshi Ikenaga (Kyushu Institute of Technology) for their valuable advice and fruitful discussions. This work was partially supported by JSPS KAKENHI Grant Numbers JP22K18424 and JP24KJ1917, as well as by JST, ACT-X Grant Number JPMJAX24M3, Japan.

References

[1] Keiko Aihara, Yoko Inamoto, Eiichi Saitoh, Seiko Shibata, Yuriko Sato, Maki Harada, and Yohei Otaka. 2023. Development and validation of a device for monitoring laryngeal motion during swallowing. *Frontiers in Robotics and AI* Volume 10 - 2023 (2023). https://doi.org/10.3389/frobt.2023.1259257

[2] Kazuma Aoyama, Kenta Sakurai, Satoru Sakurai, Makoto Mizukami, Taro Maeda, and Hideyuki Ando. 2017. Galvanic tongue stimulation inhibits five basic tastes induced by aqueous electrolyte solutions. *Frontiers in Psychology* 8 (12 2017). https://doi.org/10.3389/fpsyg.2017.02112

[3] Hirotoshi Asano, Tota Mizuno, Akio Nozawa, and Hideto Ide. 2009. Comparison with amount of gustatory sense and nasal skin temperature. *Journal of Robotics and Mechatronics* 21, 1 (2009), 81–87. https://doi.org/10.20965/jrm.2009.p0081

[4] James C. Boudreau. 1980. Taste and the taste of foods. *Naturwissenschaften* 67 (1980), 14–20. https://doi.org/10.1007/BF00424498

[5] Jas Brooks, Noor Amin, and Pedro Lopes. 2023. Taste retargeting via chemical taste modulators. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 106, 15 pages. https://doi.org/10.1145/3586183.3606818

[6] Fabiana M. Carvalho, Valentina Moksunova, and Charles Spence. 2020. Cup texture influences taste and tactile judgments in the evaluation of specialty coffee. *Food Quality and Preference* 81 (2020), 103841. https://doi.org/10.1016/j.foodqual.2019.103841

[7] Annachiara Cavazzana, Maria Larsson, Eileen Hoffmann, Thomas Hummel, and Antje Haehner. 2017. The vessel's shape influences the smell and taste of cola. *Food Quality and Preference* 59 (2017), 8–13. https://doi.org/10.1016/j.foodqual.2017.01.014

[8] Alan Chalmers, Daniel Zholzhanova, Tarunya Arun, and Ali Asadipour. 2023. Virtual Flavor: High-fidelity simulation of real flavor experiences. *IEEE Computer Graphics and Applications* 43, 2 (2023), 23–31. https://doi.org/10.1109/MCG.2023.3242316

[9] Shulin Chen, Yizhen Jia, Bowen Duan, Tzu-Li Liu, Qi Wang, Xiao Xiao, Prasad Nithianandam, Xi Tian, Chunyu Yang, Changsheng Wu, Zhaoqian Xie, and Jinghua Li. 2025. A sensor-actuator–coupled gustatory interface chemically connecting virtual and real environments for remote tasting. *Science Advances* 11, 9 (2025), eadr4797. https://doi.org/10.1126/sciadv.adr4797

[10] Violeta Corona, Ivette Cruz, Gustavo Lujan Moreno, Jose Albors, P. García-Segovia, and Omar Rojas. 2022. Sensory expectations from aesthetic perceptions of coffee beverages presented in different mugs. *Journal of Culinary Science & Technology* 20, 3 (2022), 213–238. https://doi.org/10.1080/15428052.2020.1824834 arXiv:https://doi.org/10.1080/15428052.2020.1824834

[11] A D Craig. 2013. An interoceptive neuroanatomical perspective on feelings, energy, and effort. *Behav. Brain Sci.* 36, 6 (Dec. 2013), 685–6; discussion 707–26.

[12] Alberto Cruz and Barry Green. 2000. Thermal stimulation of taste. *Nature* 403 (03 2000), 889–92. https://doi.org/10.1038/35002581

[13] Lukas Danner, Liudmila Sidorkina, Max Joechl, and Klaus Duerrschmid. 2014. Make a face! Implicit and explicit measurement of facial expressions elicited by orange juices using face reading technology. *Food Quality and Preference* 32 (2014), 167–172. https://doi.org/10.1016/j.foodqual.2013.01.004 Special Issue: 5th European Conference on Sensory and Consumer Research (Eurosense) 2012 "A sense of inspiration".

[14] Steven Davey, Jamin Halberstadt, and Elliot Bell. 2021. Where is emotional feeling felt in the body? An integrative review. *PLoS One* 16, 12 (Dec. 2021), e0261685.

[15] René A. de Wijk, Valesca Kooijman, Rob H.G. Verhoeven, Nancy T.E. Holthuysen, and Cees de Graaf. 2012. Autonomic nervous system responses on and facial expressions to the sight, smell, and taste of liked and disliked foods. *Food Quality*

and Preference 26, 2 (2012), 196–203. https://doi.org/10.1016/j.foodqual.2012.04.015

[16] Maryanne Drake, Michele Yates, and P.D. Gerard. 2005. Impact of serving temperature on trained panel perception of cheddar cheese flavor attributes. *Journal of Sensory Studies* 20 (05 2005), 147 – 155. https://doi.org/10.1111/j.1745-459X.2005.00013.x

[17] Paul Ekman. 1992. An argument for basic emotions. *Cogn. Emot.* 6, 3-4 (May 1992), 169–200.

[18] Sally Eldeghaidy, Luca Marciani, Francis McGlone, Tracey Hollowood, Joanne Hort, Kay Head, Andrew J. Taylor, Johanneke Busch, Robin C. Spiller, Penny A. Gowland, and Susan T. Francis. 2011. The cortical response to the oral perception of fat emulsions and the effect of taster status. *Journal of Neurophysiology* 105, 5 (2011), 2572–2581. https://doi.org/10.1152/jn.00927.2010 arXiv:https://doi.org/10.1152/jn.00927.2010 PMID: 21389303.

[19] Davide Filingeri, Hui Zhang, and Edward A Arens. 2017. Characteristics of the local cutaneous sensory thermoneutral zone. *J. Neurophysiol.* 117, 4 (April 2017), 1797–1806.

[20] Léa Gagnon, Martin Vestergaard, Kristoffer Madsen, Helena G Karstensen, Hartwig Siebner, Niels Tommerup, Ron Kupers, and Maurice Ptito. 2014. Neural correlates of taste perception in congenital olfactory impairment. *Neuropsychologia* 62 (2014), 297–305. https://doi.org/10.1016/j.neuropsychologia.2014.07.018

[21] Oliver Genschow, Leonie Reutner, and Michaela Wänke. 2012. The color red reduces snack food and soft drink intake. *Appetite* 58, 2 (2012), 699–702. https://doi.org/10.1016/j.appet.2011.12.023

[22] Nakamura Hidetaka, Hashimoto Kazuyoshi, Seki Takeshi, Takahashi Kei, and Matsuda Hideto. 2021. Changes in masticatory muscle activity over time by facial skin temperature area during gum chewing. *Oral Health and Dental science* 5 (12 2021). https://doi.org/10.33425/2639-9490.1094

[23] Mai Kamihori, Kodai Ito, and Yuichi Itoh. 2025. Effects of ±2 °C cup rim temperature variations relative to beverage temperature on flavor perception. *Applied Food Research* 5, 1 (2025), 100972. https://doi.org/10.1016/j.afres.2025.100972

[24] 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. https://doi.org/10.1016/j.afres.2024.100672

[25] Kasun Karunanayaka, Nurafiqah Johari, Surina Hariri, Hanis Camelia, Kevin Stanley Bielawski, and Adrian David Cheok. 2018. New thermal taste actuation technology for future multisensory virtual reality and internet. *IEEE Transactions on Visualization and Computer Graphics* 24, 4 (April 2018), 1496–1505. https://doi.org/10.1109/TVCG.2018.2794073

[26] Hideaki Kashima, Yuka Hamada, and Naoyuki Hayashi. 2014. Palatability of tastes is associated with facial circulatory responses. *Chemical Senses* 39, 3 (01 2014), 243–248. https://doi.org/10.1093/chemse/bjt074 arXiv:https://academic.oup.com/chemse/article-pdf/39/3/243/1356061/bjt074.pdf

[27] Jeong-Weon Kim, Shilpa S. Samant, Yoojin Seo, and Han-Seok Seo. 2015. Variation in saltiness perception of soup with respect to soup serving temperature and consumer dietary habits. *Appetite* 84 (2015), 73–78. https://doi.org/10.1016/j.appet.2014.09.018

[28] Sander Koelstra, Christian Muhl, Mohammad Soleymani, Jong-Seok Lee, Ashkan Yazdani, Touradj Ebrahimi, Thierry Pun, Anton Nijholt, and Ioannis Patras. 2012. DEAP: A database for emotion analysis using physiological signals. *IEEE Transactions on Affective Computing* 3, 1 (2012), 18–31. https://doi.org/10.1109/T-AFFC.2011.15

[29] Naoya Koizumi, Hidekazu Tanaka, Yuji Uema, and Masahiko Inami. 2011. Chewing Jockey: Augmented food texture by using sound based on the cross-modal effect. In *Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology* (Lisbon, Portugal) *(ACE '11)*. Association for Computing Machinery, New York, NY, USA, Article 21, 4 pages. https://doi.org/10.1145/2071423.2071449

[30] So Koizumi, Susumu Minamisawa, Kenichi Sasaguri, Minoru Onozuka, Sadao Sato, and Yumie Ono. 2011. Chewing reduces sympathetic nervous response to stress and prevents poststress arrhythmias in rats. *Am. J. Physiol. Heart Circ. Physiol.* 301, 4 (Oct. 2011), H1551–8.

[31] Shin'ichi Komiya, Ryota Nitto, Yuki Ban, and Shin'ichi Warisawa. 2024. Enhancing food coldness perception via synchronous posterior neck cold stimulus during swallowing. In *ACM Symposium on Applied Perception 2024* (Dublin, Ireland) *(SAP '24)*. Association for Computing Machinery, New York, NY, USA, Article 13, 9 pages. https://doi.org/10.1145/3675231.3675247

[32] Vladimir Kosonogov, Lucas De Zorzi, Jacques Honoré, Eduardo S Martínez-Velázquez, Jean-Louis Nandrino, José M Martinez-Selva, and Henrique Sequeira. 2017. Facial thermal variations: A new marker of emotional arousal. *PLoS One* 12, 9 (Sept. 2017), e0183592.

[33] Sylvia D. Kreibig. 2010. Autonomic nervous system activity in emotion: A review. *Biological Psychology* 84, 3 (2010), 394–421. https://doi.org/10.1016/j.biopsycho.2010.03.010 The biopsychology of emotion: Current theoretical and empirical perspectives.

[34] Aradhna Krishna and Maureen Morrin. 2007. Does touch affect taste? The perceptual transfer of product container haptic cues. *Journal of Consumer Research* 34, 6 (10 2007), 807–818. https://doi.org/10.1086/523286 arXiv:https://academic.oup.com/jcr/article-pdf/34/6/807/11426183/34-6-807.pdf

[35] Yuma Kyogoku, Kensuke Kobayashi, and Mao Yamamoto. 2025. PhantomFeel Dots: Augmenting the eating experience with thermal and vibrotactile stimuli on the face and throat. In *Adjunct Proceedings of the 38th Annual ACM Symposium on User Interface Software and Technology (UIST Adjunct '25)*. Association for Computing Machinery, New York, NY, USA, Article 66, 3 pages. https://doi.org/10.1145/3746058.3758979

[36] Maider Lago, Jose De la Rosa, and Laura Vázquez-Araújo. 2021. Using tactile stimuli to enhance sweet perception in iced tea samples. *Journal of Sensory Studies* 36, 1 (2021), e12612. https://doi.org/10.1111/joss.12612 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/joss.12612

[37] Scott M. Lundberg and Su-In Lee. 2017. A unified approach to interpreting model predictions. In *Proceedings of the 31st International Conference on Neural Information Processing Systems* (Long Beach, California, USA) *(NIPS'17)*. Curran Associates Inc., Red Hook, NY, USA, 4768–4777.

[38] Masanori Maeda, Miyuki Kadokura, Ryoko Aoki, Noriko Komatsu, Masaru Kawakami, Yuya Koyama, Kazuhiro Watanabe, and Michiko Nishiyama. 2023. A fiber-optic non-invasive swallowing assessment device based on a wearable pressure sensor. *Sensors (Basel)* 23, 4 (Feb. 2023), 2355.

[39] Dan Maynes-aminzade. 2005. Edible Bits : Seamless interfaces between people, data and food. *ACM CHI 2005 Extended Abstracts* (2005), 2207–2210. https://cir.nii.ac.jp/crid/1573105976065793920

[40] Morten C Meilgaard, B Thomas Carr, and Gail Vance Civille. 2006. *Sensory evaluation techniques, fourth edition* (4 ed.). CRC Press, Boca Raton, FL.

[41] Line Ahm Mielby, Qian Janice Wang, Sidsel Jensen, Anne Sjoerup Bertelsen, Ulla Kidmose, Charles Spence, and Derek Victor Byrne. 2018. See, feel, taste: The influence of receptacle colour and weight on the evaluation of flavoured carbonated beverages. *Foods* 7, 8 (July 2018), 119.

[42] Homei Miyashita. 2020. Norimaki Synthesizer: Taste display using ion electrophoresis in five gels. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–6. https://doi.org/10.1145/3334480.3382984

[43] Homei Miyashita. 2021. TTTV (Taste the TV): Taste presentation display for "Licking the Screen" using a rolling transparent sheet and a mixture of liquid sprays. In *The Adjunct Publication of the 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 37–40. https://doi.org/10.1145/3474349.3480223

[44] Patrizia Muroni, Roberto Crnjar, and Iole Tomassini Barbarossa. 2011. Emotional responses to pleasant and unpleasant oral flavour stimuli. *Chemosensory Perception* 4, 3 (Sept. 2011), 65–71.

[45] Mitsunobu Nagata, Wataru Suzuki, Seiichi Iizuka, Masahiro Tabuchi, Hirofumi Maruyama, Shuichi Takeda, Masaki Aburada, and Ken-ichi Miyamoto. 2006. Type 2 diabetes mellitus in obese mouse model induced by monosodium glutamate. *Experimental animals / Japanese Association for Laboratory Animal Science* 55 (05 2006), 109–15. https://doi.org/10.1538/expanim.55.109

[46] Hiromi Nakamura and Homei Miyashita. 2013. Controlling saltiness without salt: evaluation of taste change by applying and releasing cathodal current. In *Proceedings of the 5th International Workshop on Multimedia for Cooking & Eating Activities* (Barcelona, Spain) *(CEA '13)*. Association for Computing Machinery, New York, NY, USA, 9–14. https://doi.org/10.1145/2506023.2506026

[47] Kizashi Nakano, Daichi Horita, Nobuchika Sakata, Kiyoshi Kiyokawa, Keiji Yanai, and Takuji Narumi. 2019. Enchanting your noodles: GAN-based real-time food-to-food translation and its impact on vision-induced gustatory manipulation. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Osaka, Japan, 1096–1097. https://doi.org/10.1109/VR.2019.8798336

[48] Takuji Narumi, Yuki Ban, Takashi Kajinami, Tomohiro Tanikawa, and Michitaka Hirose. 2012. Augmented Perception of Satiety: Controlling food consumption by changing apparent size of food with augmented reality. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI '12)*. Association for Computing Machinery, New York, NY, USA, 109–118. https://doi.org/10.1145/2207676.2207693

[49] 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* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 93–102. https://doi.org/10.1145/1978942.1978957

[50] Takuji Narumi, Munehiko Sato, Tomohiro Tanikawa, and Michitaka Hirose. 2010. Evaluating cross-Sensory perception of superimposing virtual color onto real drink: toward realization of pseudo-gustatory displays. In *Proceedings of the 1st Augmented Human International Conference* (Megève, France) *(AH '10)*. Association for Computing Machinery, New York, NY, USA, Article 18, 6 pages. https://doi.org/10.1145/1785455.1785473

[51] Ivan Ninenko, Daria F Kleeva, Nikita Bukreev, and Mikhail A Lebedev. 2023. An experimental paradigm for studying EEG correlates of olfactory discrimination. *Front. Hum. Neurosci.* 17 (May 2023), 1117801.

[52] Masahiro Nishizawa, Wanting Jiang, and Katsunori Okajima. 2016. Projective-AR system for customizing the appearance and taste of food. In *Proceedings of the 2016 Workshop on Multimodal Virtual and Augmented Reality* (Tokyo, Japan) *(MVAR '16)*. Association for Computing Machinery, New York, NY, USA, Article 6, 6 pages. https://doi.org/10.1145/3001959.3001966

[53] J. O'Doherty, E. T. Rolls, S. Francis, R. Bowtell, and F. McGlone. 2001. Representation of pleasant and aversive taste in the human brain. *Journal of Neurophysiology* 85, 3 (2001), 1315–1321. https://doi.org/10.1152/jn.2001.85.3.1315 arXiv:https://doi.org/10.1152/jn.2001.85.3.1315 PMID: 11248000.

[54] Betina Piqueras-Fiszman and Charles Spence. 2012. The influence of the feel of product packaging on the perception of the oral-somatosensory texture of food. *Food Quality and Preference* 26, 1 (2012), 67–73. https://doi.org/10.1016/j.foodqual.2012.04.002

[55] Ragita C. Pramudya, Dipankar Choudhury, Min Zou, and Han-Seok Seo. 2020. "Bitter Touch": Cross-modal associations between hand-feel touch and gustatory cues in the context of coffee consumption experience. *Food Quality and Preference* 83 (2020), 103914. https://doi.org/10.1016/j.foodqual.2020.103914

[56] Nimesha Ranasinghe, Thi Ngoc Tram Nguyen, Yan Liangkun, Lien-Ya Lin, David Tolley, and Ellen Yi-Luen Do. 2017. Vocktail: A virtual cocktail for pairing digital taste, smell, and color sensations. In *Proceedings of the 25th ACM International Conference on Multimedia* (Mountain View, California, USA) *(MM '17)*. Association for Computing Machinery, New York, NY, USA, 1139–1147. https://doi.org/10.1145/3123266.3123440

[57] Nimesha Ranasinghe, David Tolley, Thi Ngoc Tram Nguyen, Liangkun Yan, Barry Chew, and Ellen Yi-Luen Do. 2019. Augmented Flavours: Modulation of flavour experiences through electric taste augmentation. *Food Research International* 117 (2019), 60–68. https://doi.org/10.1016/j.foodres.2018.05.030 Special issue on "Virtual reality and food: Applications in sensory and consumer science".

[58] Michele N. Ribeiro, Iago A. Carvalho, Maísa M. M. de Sousa, Laura M. Coelho, Daniel C. de Rezende, and Ana C. M. Pinheiro. 2021. Visual expectation of craft beers in different glass shapes. *Journal of Sensory Studies* 36, 1 (2021), e12618. https://doi.org/10.1111/joss.12618 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/joss.12618

[59] Paola Risso, Emanuela Maggioni, Roberta Etzi, and Alberto Gallace. 2019. The effect of the tactile attributes of a container on mineral water perception. *Beverages* 5, 1 (March 2019), 23.

[60] Carolyn Ross and Karen Weller. 2008. Effect of serving temperature on the sensory attributes of red and white wines. *Journal of Sensory Studies* 23 (06 2008), 398 – 416. https://doi.org/10.1111/j.1745-459X.2008.00162.x

[61] S Rousmans, O Robin, A Dittmar, and E Vernet-Maury. 2000. Autonomic nervous system responses associated with primary tastes. *Chem. Senses* 25, 6 (Dec. 2000), 709–718.

[62] Asli Sakarya and Ibrahim Taylan Dortyol. 2021. Do we always drink the same coffee? The effect of weight and colour on takeaway coffee perception. *Young Consumers: Insight and Ideas for Responsible Marketers* 23, 1 (2021), 72–89. https://doi.org/10.1108/YC-03-2021-1292

[63] Danila Shelepenkov, Alfred Essel, and Vladimir Kosonogov. 2025. Bodily markers of basic emotions: a thermographic study. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology* 329, 1 (2025), R81–R85. https://doi.org/10.1152/ajpregu.00018.2025 arXiv:https://doi.org/10.1152/ajpregu.00018.2025 PMID: 40380804.

[64] Charles Spence. 2015. Multisensory flavor perception. *Cell* 161, 1 (2015), 24–35. https://doi.org/10.1016/j.cell.2015.03.007

[65] Chloe N. Stokes, Maurice G. O'Sullivan, and Joseph P. Kerry. 2016. Assessment of black coffee temperature profiles consumed from paper-based cups and effect on affective and descriptive product sensory attributes. *International Journal of Food Science & Technology* 51, 9 (2016), 2041–2048. https://doi.org/10.1111/ijfs.13176 arXiv:https://ifst.onlinelibrary.wiley.com/doi/pdf/10.1111/ijfs.13176

[66] F Strack, L L Martin, and S Stepper. 1988. Inhibiting and facilitating conditions of the human smile: a nonobtrusive test of the facial feedback hypothesis. *J. Pers. Soc. Psychol.* 54, 5 (May 1988), 768–777.

[67] Chie Suzuki, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. 2014. Affecting Tumbler: Affecting our flavor perception with thermal feedback. In *Proceedings of the 11th Conference on Advances in Computer Entertainment Technology* (Funchal, Portugal) *(ACE '14)*. Association for Computing Machinery, New York, NY, USA, Article 19, 10 pages. https://doi.org/10.1145/2663806.2663825

[68] Hanako Takatsuji, Kojiro Takahashi, and Junichi Kitagawa. 2015. Physiological and pharmacological actions involved in the pharyngeal and laryngeal sensation. *Folia Pharmacologica Japonica* 145, 6 (2015), 278–282. https://doi.org/10.1254/fpj.145.278

[69] Yangjun Tu, Zhi Yang, and Chaoqun Ma. 2015. Touching tastes: The haptic perception transfer of liquid food packaging materials. *Food Quality and Preference* 39 (2015), 124–130. https://doi.org/10.1016/j.foodqual.2014.07.001

[70] Paula Varela and Gastón Ares. 2012. Sensory profiling, the blurred line between sensory and consumer science. A review of novel methods for product characterization. *Food Research International* 48, 2 (2012), 893–908. https://doi.org/10.1016/j.foodres.2012.06.037

[71] Xiaoang Wan, Andy T Woods, Jasper J F van den Bosch, Kirsten J McKenzie, Carlos Velasco, and Charles Spence. 2014. Cross-cultural differences in crossmodal correspondences between basic tastes and visual features. *Front. Psychol.* 5 (Dec. 2014), 1365.

[72] Qian Janice Wang and Charles Spence. 2018. A smooth wine? Haptic influences on wine evaluation. *International Journal of Gastronomy and Food Science* 14 (2018), 9–13. https://doi.org/10.1016/j.ijgfs.2018.08.002

[73] Yanan Wang, Judith Amores, and Pattie Maes. 2020. On-face olfactory interfaces. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–9. https://doi.org/10.1145/3313831.3376737

[74] Yan Wang, Zhuying Li, Robert S. Jarvis, Angelina Russo, Rohit Ashok Khot, and Florian 'Floyd' Mueller. 2019. Towards understanding the design of playful gustosonic experiences with ice cream. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play* (Barcelona, Spain) *(CHI PLAY '19)*. Association for Computing Machinery, New York, NY, USA, 239–251. https://doi.org/10.1145/3311350.3347194

[75] Yan Wang, Zhuying Li, Rohit Ashok Khot, and Florian 'Floyd' Mueller. 2022. Toward understanding playful beverage-based gustosonic experiences. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 6, 1, Article 33 (mar 2022), 23 pages. https://doi.org/10.1145/3517228

[76] Florian Weidner, Jana E. Maier, and Wolfgang Broll. 2023. Eating, Smelling, and Seeing: Investigating multisensory integration and (in)congruent stimuli while eating in VR. *IEEE Transactions on Visualization and Computer Graphics* 29, 5 (2023), 2423–2433. https://doi.org/10.1109/TVCG.2023.3247099

[77] Su-Chiu Yang, Li-Hsun Peng, and Li-Chieh Hsu. 2019. The influence of teacup shape on the cognitive perception of tea, and the sustainability value of the aesthetic and practical design of a teacup. *Sustainability* 11, 24 (Dec. 2019), 6895.

[78] N.J.N. Yau and J.J. Huang. 1996. Sensory analysis of cooked rice. *Food Quality and Preference* 7, 3 (1996), 263–270. https://doi.org/10.1016/S0950-3293(96)00010-9 Second Rose Marie Pangborn Memorial Symposium.

[79] Takahiro Yoshikawa, Masaaki Tanaka, Akira Ishii, and Yasuyoshi Watanabe. 2014. Suppressive responses by visual food cues in postprandial activities of insular cortex as revealed by magnetoencephalography. *Brain Research* 1568 (2014), 31–41. https://doi.org/10.1016/j.brainres.2014.04.021

[80] Massimiliano Zampini and Charles Spence. 2005. Modifying the multisensory perception of a carbonated beverage using auditory cues. *Food Quality and Preference* 16, 7 (2005), 632–641. https://doi.org/10.1016/j.foodqual.2004.11.004