Taste Retargeting via Chemical Taste Modulators

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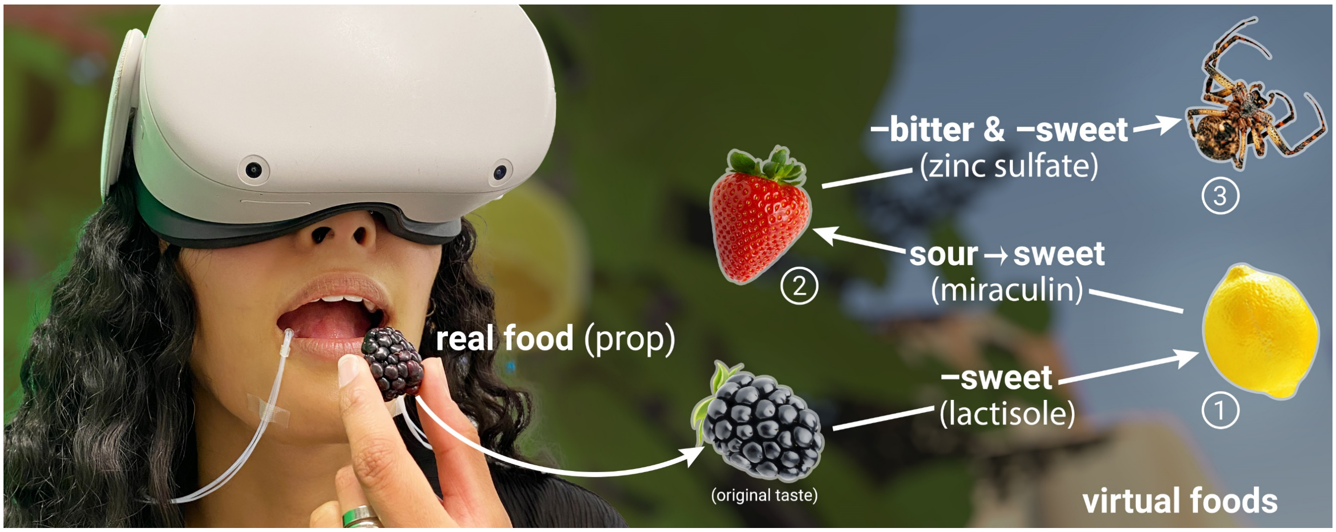

Figure 1: *Taste retargeting* selectively changes taste perception using *taste modulators*—chemicals that temporarily alter the response of taste receptors to foods and beverages. As our technique can deliver droplets of modulators *before* eating or drinking, it is the first interactive method to selectively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

ABSTRACT

Prior research has explored modifying taste through electrical stimulation. While promising, such interfaces often only elicit taste changes while in contact with the user's tongue (e.g., cutlery with electrodes), making them incompatible with eating and swallowing real foods. Moreover, most interfaces cannot selectively alter basic tastes, but only the entire flavor profile (e.g., cannot selectively alter bitterness). To tackle this, we propose *taste retargeting*, a method of altering taste perception by delivering chemical modulators to the mouth before eating. These modulators temporarily change the response of taste receptors to foods, selectively suppressing or altering basic tastes. Our first study identified six accessible taste modulators that suppress salty, umami, sweet, or bitter and transform sour into sweet. Using these findings, we demonstrated an interactive application of this technique with the example of virtual reality, which we validated in our second study. We found that taste retargeting reduced the flavor mismatch between a food prop and other virtual foods.

CCS CONCEPTS

• **Human-centered computing**; • **Human computer interaction (HCI)**; • **Interaction devices**;

KEYWORDS

Taste, food interaction, multimodal, haptics, props, VR

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1 INTRODUCTION

Taste is a critical aspect of our experiences, from rich sensory and hedonic experiences during eating, to guiding our dietary behaviors. Human taste perception roughly encompasses five basic tastes:

sweet, sour, salty, bitter, and umami (savory). There has been a growing interest in interactive food experiences, especially generating virtual tastes but also *modifying real tastes* through sensory stimulation. Altering taste perception has primarily been achieved by conducting electricity through cutlery ("electrical taste" [48]), adjusting the strength of the taste via electrolytes [43], or adding seasonings to food [85]. Other approaches have explored modifying secondary aspects of the eating experience, such as applying weight on the tongue [22], sound [37], perceived texture [32], or scent [52].

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

In this paper, we propose a new method for modifying taste perception of *real foods during eating*. This method, which we call *taste retargeting*, is based on delivering small drops of liquid taste modulators to the user's mouth before eating and drinking. Taste modulators are chemicals that alter the response of specific taste receptors to flavor stimuli. Modulators change the basic taste of the next bite or sip. For instance, one of the modulators we identified, *zinc sulfate*, can decrease the sweetness of a candy. Modulators achieve their taste effects by binding to taste receptor cells on the user's tongue and temporarily changing how this receptor responds to certain tastes on a molecular level [53]. With these effects, our technique produces selective changes to the user's perception of the five basic tastes. We leveraged insights from basic science to identify six accessible taste modulators: *amiloride* (salt suppression), *clofibric acid* (umami suppression), *gymnemic acid* (sweet suppression), *lactisole* (umami & sweet suppression), *miraculin* (sour-to-sweet transformation), and *zinc sulfate* (sweet & bitter suppression).

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

We validated our technique through two user studies. After identifying a set of six taste modulators, we investigated changes these evoked in basic taste perception. Our first study found that they could suppress salty, umami, sweet, or bitter sensations and transform sour into sweet. Using these findings, we then designed the virtual reality experience, depicted in Figure 1, to study the use of our technique in an interactive context. We found that taste retargeting reduced the flavor mismatch between a food prop and three other distinct virtual foods.

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

2 WALKTHROUGH: ALTERING REAL FOODS

To illustrate our novel technique with an example application, we designed a survival VR eating experience in which we retargeted three real foods (as props) to taste like virtual foods using three modulators, depicted in Figure 2. For this, we engineered a wearable device (i.e., small battery and wireless). The device's tubing attaches to the mouth's corners to deliver modulators to the user, allowing it to change the taste of upcoming bites or sips from a food prop.

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

The user starts the experience by finding berries in a bush, as seen in Figure 3. As they grab a virtual blackberry, they grasp a real, pickled blackberry. They then eat it, savoring the familiar taste of blackberries. Unfortunately, one berry does not replenish their health completely, so they keep foraging.

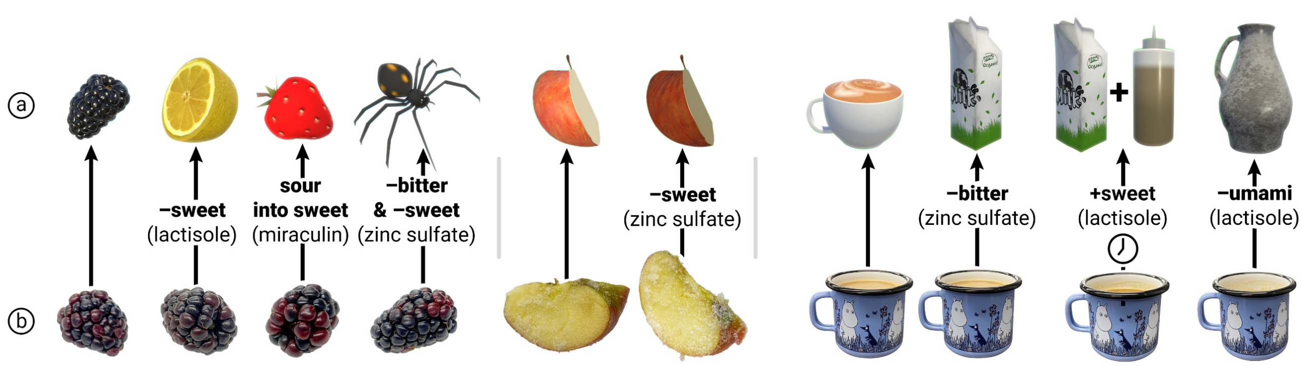

Figure 2: Timeline of (a) the virtual foods the user tastes and (b) the taste retargeted props they actually eat.

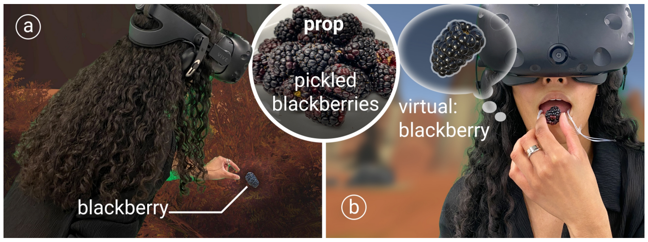

Figure 3: The user eats a blackberry (pickled blackberry prop).

While the user forages through trees (Figure 4), our device delivers *lactisole* droplets to suppress the prop's sweetness and retarget it to the next virtual food: a lemon. They then spot a small lemon on a tree. Once they put it in their mouth and chew it, they recognize the sour flavor of the lemon. In reality, the user ate *another pickled blackberry*.

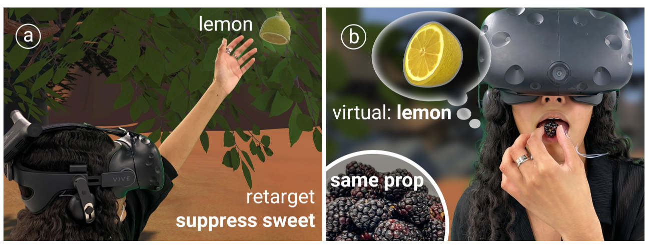

Figure 4: (a) The user grabs a lemon. (b) The same prop now tastes like a sour lemon after suppressing sweetness.

Our device then delivers *miraculin* to transform the next prop's sourness into sweetness. As the user reaches out for a virtual strawberry they came across, they grab the same blackberry prop yet again. This time, it tastes sweeter, approximating the strawberry's taste (Figure 5).

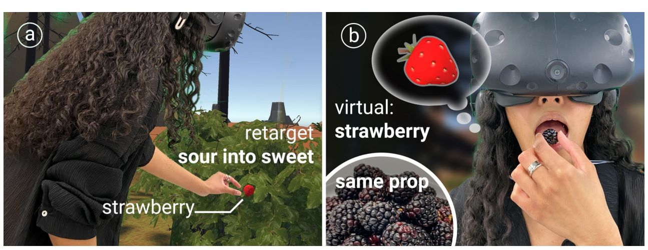

Figure 5: (a) The user picks a strawberry. (b) The same prop retargets by transforming the citric acid into sweetness.

Unfortunately, the user runs out of fruit to forage and must eat small spiders to heal. Our device drips *zinc sulfate* to suppress the upcoming prop's remaining sweet or bitter notes, removing almost all taste to highlight the prop's unique *texture* (the bumpiness of a blackberry). This transformation retargets the prop to match a plump spider, which the user finds and chews (Figure 6). With little taste remaining, the texture comes through bursting and gushing like a bug. This entire time, the user ate the *same* food prop four times yet experienced the tastes of *four* distinct foods.

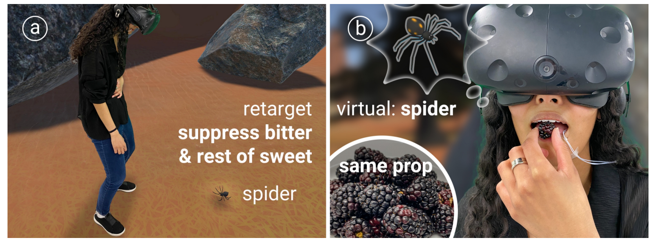

Figure 6: (a) They must eat a spider. (b) So, the prop retargets by suppressing bitterness and the rest of the sweetness.

Later, our user comes across an abandoned campsite in the sands (Figure 7). They search for food and find apple slices: our second *real food* prop. They eat a slice, tasting its sweetness from the granulated sugar coating.

Figure 7: (a) The user finds apple slices. (b) They eat the prop (sugar-coated apple) and taste the virtual sweet apple.

Suddenly, a powerful sandstorm kicks up (Figure 8), during which our device drips *zinc sulfate* to suppress the granulated sugar's sweetness. The user must then eat the remaining slice covered in sand. As they do, they notice the gritty texture of sand, which comes from the granulated sugar that no longer has a taste and is simply texture.

Figure 8: (a) A sandstorm kicks up and blows sand onto the second apple slice. (b) We suppress the prop's sweetness to render the sand grit using the (now) tasteless granulated sugar.

Next, we depict that some modulators, and even the delivery order of modulators, can produce even more complex effects. The user stumbles across and searches an abandoned cabin for hydration

(Figure 9). They find an empty cup and grab it. In reality, they grabbed a cup with a latte: our third food prop. In the cabin, they find a coffee maker and press a button to prepare a small virtual latte to quench their thirst.

Figure 9: (a): The user sees a recently abandoned cabin. (b) They find an old, but working, latte machine and restore some of their hydration by (c) drinking a bit of latte (prop).

The user searches for more drinks while our device drips *zinc sulfate* to suppress bitterness. The user finds virtual milk, which they pour into their empty cup and drink. Without its bitterness, the prop latte's milky (umami) taste is brought forward, retargeting the latte prop to a sip of milk.

While the user searches the kitchen cabinets, our device delivers *lactisole* to create a taste "after-effect" specific to liquids known as *sweet water taste* [19]. This effect is well-known and elicited by water following the removal of lactisole from the receptors. The sweet water taste effect resembles "after-images," patterns that become visible after looking away from an image being fixated on for too long [87]. We use this effect to retarget the user's next sip. The user finds syrup and adds it to the remains of their milk. *Lactisole's* sweet water taste effect adds sweetness, and the user now savors virtual sweetened milk (Figure 10).

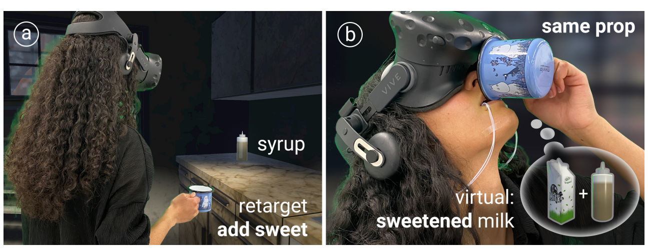

Figure 10: (a) The user sees a bottle of syrup. Our device retargets the prop to – initially – have sweetness, allowing the user to add syrup to their milk and (b) taste the sweetened milk.

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

Moreover, the order of modulators can also produce different experiences. Figure 11 depicts alternative experiences depending on the interactive order of the modulators. If the user finds syrup instead of milk (after drinking the initial latte in the abandoned kitchen), our device will deliver *lactisole* instead of *zinc sulfate*. Due to *lactisole*'s sweet water taste effect, this order will sweeten the latte instead of the milk. Once this effect fades, the latte prop would lose its umami notes (*lactisole*) and taste closer to a virtual coffee. Finally, after *zinc sulfate* suppresses the prop's bitterness, they would experience the same stale water taste as in the first version.

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

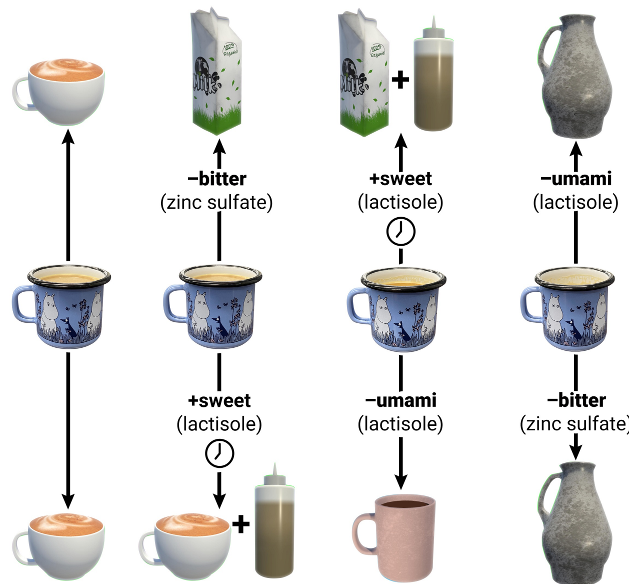

Figure 11: By swapping the order of two modulators (lactisole and zinc sulfate), the tastes of two additional virtual foods are available: sweetened latte and coffee (bottom row).

2.1 Contrast to naïve solution

At this point, the reader might wonder why use modulators instead of simply adding additives with basic tastes (e.g., sugary water to enhance sweetness or an acidic powder to enhance sourness). While this idea has some merit in theory, it exhibits fundamental issues that taste retargeting avoids.

First, this naïve solution can only *add* tastes to food without the ability to suppress or modify, which taste retargeting achieves. Second, sustaining this added taste requires frequently and repeatedly delivering a solution or powder, which might result in bursts of the added taste that will disrupt the experience. In contrast, taste retargeting produces a sustained, smooth change, as demonstrated in Study 1. Moreover, adding powders or liquids while chewing or drinking can unintentionally alter the foods texture or dilute its taste [21]. Taste retargeting avoids this since modulators are delivered in tiny amounts before eating or drinking.

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

3 CONTRIBUTION, BENEFITS, & LIMITATIONS

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

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

As the first exploration of a novel technique, its limitations are significant to discuss, revealing future research directions. (1) Taste retargeting is not currently suitable for short taste alterations. Our Study 1 results provide information on modulator offset times so that designers can design their experiences around this limitation. More research is needed to modify or dose the modulators to accelerate their offset time. (2) Some modulators may have their own taste (e.g., zinc sulfate). We provide potential methods to address this issue (see Study 2's Discussion). (3) As with any technique based on chemicals, there might be cross-modulator interactions. Currently, only lactisole diminishes the strength of miraculin's effect [36], and we did not notice additional cross-modulator interactions in our pilots and studies. (4) Additional effects require uncovering additional modulators. For instance, we chose our modulators because they are accessible and because most are food-safe, which leaned towards suppression and not enhancement. (5) Taste retargeting is a *taste* technique and does not solve the smell or texture incongruencies of food props in VR. However, it is easily combinable with other techniques that alter texture or smell. Also, in the case of VR props, it is worth noting that taste retargeting requires some considerations with the prop since the technique only modulates *existing* flavors. The prop's initial flavor must already contain facets matching each virtual food. However, this is as much a limitation as a tradeoff, as taste retargeting provides a key benefit in exchange: using readily available foods as props with little to no preparation.

4 RELATED WORK

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

4.1 Producing tastes

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

Chemical taste interfaces. A common design for interfaces that simulate a flavor involves chemical stimuli delivery. For instance, the *TasteScreen* drips flavoring agents onto a screen for the user to lick [41]. *TTTV* refines this concept by spraying taste solutions for each basic taste on a saran-covered screen [45]; the device sprays taste solutions on a 2D picture of the intended food item [44]—unfortunately, this is a one-off device that users cannot use in any other way (e.g., this would not work in VR, AR, etc.). Vi et al. engineered a game interface that delivers basic taste stimuli (e.g., sugary water) to the user through a straw [81]. *LOLLio* is an interactive device with a lollipop that provides a passive sweet taste and that pumps citric acid into the mouth through the lollipop for sourness [47]. Even the method of chemical delivery alters taste perception, as shown in *TastyFloats*, which levitated small foods to the mouth [82]. Finally, the *Food Simulator* applies a force to the user's teeth while pumping basic taste solutions into the mouth to roughly simulate a food [25].

Thermal taste interfaces. Ranasinghe & Do [59] and Samshir et al. [63] developed thermal interfaces for sweet stimulation, leveraging how the TRPM5 sweet receptor responds to thermal stimulation. Both devices involved a Peltier element attached to a cooling system for which users must stick their tongues out to touch the Peltier.

Electrical taste interfaces. Electrical stimulation of the tongue is the most popular technique to induce taste sensations in HCI. Ranasinghe et al. [58] leverage direct electrical stimulation of the user's taste receptors to evoke perceived taste sensations in a virtual cocktail experience. Miyashita's *Norimaki Synthesizer* device [43] combines these approaches by differentially exposing the user's tongue to combinations of five tastes. The taste compounds are suspended in semi-permeable gels, for which electrical currents through each gel determine the intensity of the perceived taste.

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

4.2 Modifying the taste of existing food

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

Pseudo-taste interfaces. Considering that taste is also a multimodal experience, many have tackled altering taste by influencing *secondary* aspects of flavor perception such as sound, smell, temperature, or texture [69, 71]. Narumi et al. referred to the later as pseudo-gustatory or pseudo-taste displays [52]. For instance, researchers have experimented with audio to induce flavor changes. Some examples include, *Chewing jockey,* which augments the texture of food via auditory feedback [37], an auditory-augmented wine glass [42], or *Auditory Seasoning Filters,* which alters chewing sounds, influencing perceived flavor and crispiness of potato chips [31]. In a different vein, *MetaCookie* delivers inhaled smells to influence the taste of a basic cookie [51, 52]. *LeviSense* added smells and lighting to influence the taste of levitating food [80]. Similarly, *TransFork* diffuses odors while the user holds their eating utensil close to their mouth [38]. Unfortunately, these techniques focus on orthonasal (inhaled odors) delivery instead of retronasal (exhaled odors), of which the later contributes more to flavor perception through oral referral once food is in the mouth [6, 8, 70]. Finally, researchers have also experimented with tactile and thermal modifications. *Gravitamine Spice* alters the flavor of food by shifting the eating utensil's center of gravity [22]. *Affecting tumbler* uses thermal feedback around the nostrils (when the beverage lid is held up for drinking) to modify perceived flavor [75].

Chemical taste interfaces. Three devices have focused on the modulation of flavor via seasoning, affecting both olfactory and gustatory elements. *Yaminabe YAMMY* modifies the flavor profile of a hot pot by dropping flavoring agents into the pot according to the emotional associations of a user's email or photo [85]. *GustaCine* drops seasonings onto a bowl of popcorn based on the emotional content of a movie [30]. These modifications to food items are irreversible: once a seasoning is added, it cannot be removed.

Miyashita expands this approach by combining it with his prior work, resulting in the *TTTV2* [46], which sprays basic taste solutions ("seasoning") onto foods that serve as a substrate (e.g., tofu, rice, or sliced bread). While more controlled than prior seasoning-based approaches, current demonstration examples focus on using bland foods as bases (e.g., cold tofu sprayed to taste like mapo tofu), may be prone to non-uniform seasoning (e.g., only seasoning a particular patch and not the food item in general), can only add taste to the food item, and – like prior literature – modify the food's flavor profile irreversibly.

Electrical taste interfaces. The predominant approach to alter real food tastes is electrical stimulation. For instance, Ranasinghe et al. developed electric cutlery that could slightly increase the sourness or saltiness of unsalted mashed potatoes and only slightly increase the sourness of unsalted miso soup [57]. While these are promising they also have three key limitations. (1) The foods or beverages altered are often simple in taste profile (mashed potatoes, biscuits, broth, sugary or salty water, etc.). Moreover, suppression techniques only work for electrolyte liquids, as suppression works through ionic migration [2, 3, 43]. This latter point essentially prevents suppression of real foods that are not soups or beverages. (2) Electrical stimulation is still typically deployed through *cutlery* [12, 48, 49], which means the experience stops once the utensil's electrodes are no longer in contact with the tongue (e.g., during chewing and swallowing). In contrast, Aoyama et al. showed that electrical galvanic tongue stimulation (with electrodes at the chin and back of the neck) can induce, inhibit, or enhance the food's taste intensity [2, 3]. Building off of this finding, Ueno et al. [79] demonstrated such stimulation can produce alterations to a beverage's aftertaste in combination with and beyond a utensil's stimulation window. Unfortunately, this leads to the fourth limitation: both Aoyama et al. and Ueno et al. did not produce selective taste alterations. (4) Only the *overall* taste intensity could be impacted instead of individual basic tastes like bitter or sweet.

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

4.3 Redirection and props for virtual reality

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

Redirecting techniques. At its core, *redirection* of human movement involves offsetting a user's virtual body to produce a different virtual and real movement, helping overcome the limitations of limited tracking spaces or prop-based haptics. Examples include redirected walking [60], haptic and hand retargeting [4, 35, 56], etc. In our case, taste retargeting applies the same core concept of redirection but to flavor perception by altering the perceived taste of foods with modulators, circumventing the limitation of food props for virtual reality.

Props. Props are physical stand-ins for virtual objects typically employed to enhance realism [13, 73, 77]. Virtual eating experiences can also use *food props*: foods that serve as *edible stand-ins* for virtual foods. In its most straightforward application, a food prop can match the virtual counterpart (e.g., seeing and eating a lemon). For instance, *Aerobanquets RMX*, an interactive gastronomy experience, had diners wear VR headsets to eat real dishes recontextualized in a whimsical virtual world [11]. However, preparing one prop per virtual food becomes cumbersome and laborious as the number of foods increases. A *useful prop* is one that can be reused for as *many* virtual items as possible. This is difficult for foods due to their distinctive flavors (e.g., lemon does not taste like a cucumber), the need for replenishment after every bite, and the abundance of cues (e.g., the smell, size, weight, and texture of a lemon is different from that of a cucumber). Weidner et al. explored this tension and demonstrated that one cannot simply transform a "neutral" (nearly tasteless and odorless) food into a more complex food (e.g., a banana) using visuals and smells alone [84]. Our technique advances food props by retargeting a food item's taste into many.

4.4 Chemical Interfaces in Human-Computer Interaction

Smell and taste interfaces are often fundamentally *chemical interfaces* in that they stimulate these senses using chemical stimuli like fragrance oils, flavoring agents, or foods. Recent research in HCI has explored using chemicals to influence human perception by identifying sensory mechanisms that can be stimulated with carefully selected compounds. [7] demonstrated that an olfactory interface can be an alternative to Peltier elements by selecting odor molecules that chemically stimulate the same receptors that respond to temperature to produce a temperature illusion. *Chemical Haptics* extended this to identify chemical alternatives to vibromotors and electrotactile stimulation [39]. Research has continued to explore these effects in haptics [20, 26]. Taste retargeting sets itself apart by using chemicals to modulate receptors (and, thus, alter their response to other stimuli) instead of stimulating those receptors to produce a sensation.

5 MODULATORS USED FOR TASTE RETARGETING

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

5.1 Gymnemic acids: sweet suppressor

Gymnema acids allows us to achieve **sweet suppression**. This is a chemical isolated from the leaves of Gymnema sylvestre. This leaf powder is commonly available as a dietary supplement and thus food-safe; ours was purchased from *Best Naturals*. We use a concentration of 1.0% w/v based on Okamoto et al. [54].

Taste alteration mechanism: Of our chosen modulators, this may be the most well-known, second only to miraculin. This sweet suppression has been attributed to its triterpene glycosides [5, 74]. More recently, Sanematsu et al. found that these gymnemic acids bind to the human sweet taste receptor hT1R3 to produce its sweet-suppressing effect [64].

5.2 Clofibric acid: sweet and umami suppressor

Clofibric acid allows us to achieve simultaneous **sweet & umami suppression**. Clofibric acid (PubChem CID: 2797, Catalog #: 21608) was purchased from *Cayman Chemical Company* at its highest available purity (≥98%). We use a dose of 51.45 mg, based on Kochem & Breslin [33], well below its acute oral toxicity (LD_{50}) of 897 mg/kg [90].

Taste alteration mechanism: Clofibric acid has been shown to be an antagonist for the sweet taste receptor (hT1R2-hT1R3), which also contributes to umami perception. In other words, clofibric acid binds and inhibits this receptor's activity. This inhibition diminishes sweet and umami perception in humans [33, 34, 40].

5.3 Lactisole: sweet and umami suppressor

Lactisole (PubChem CID: 16231, Catalog #: 18657) was purchased from *Cayman Chemical Company* at its highest available purity (≥98%). We use a dose of approximately 3.75 mg, based on Sclafani and Pérez [68]. This modulator is approved for use in foods at levels up to 150 ppm (approximately 150 mg) per food item [9]. Lactisole is a commonly used sweet modulator in industrial food processing [68]. The food industry typically uses lactisole to avoid perceiving an increase in sweetness when additional sugar is introduced for texture-purposes (e.g., softness).

Taste alteration mechanism: Lactisole achieves its sweet and umami suppression by blocking the activation of the hT1R2-hT1R3 receptor [33, 34].

5.4 Miraculin: sweet modulator

Miracle berry tablets are a commonly available food supplement derived from berries (*Synsepalum dulcificum*, known as "miracle fruit"). We source ours from the off-the-shelf product *mberry*. We use 200 mg of miracle berry dissolved in water. The key active ingredient, *miraculin*, produces the taste alteration. Miraculin is not associated with any safety concerns and does not represent a risk of allergy or toxicity to humans [76].

Taste alteration mechanism: Of our modulators, miraculin is the most recognizable as it is commercially advertised as a "party trick" [16]. Miraculin binds to human sweet taste receptor hT1R2-hT1R3. While miraculin acts as an inhibitor at neutral pH environments, it functions as a strong agonist in the presence of acidic pH environments [36]. In other words, miraculin causes acidic stimuli to activate a sweet taste receptor. This is why it is used as a "party trick" with acidic foods, such as making a lemon taste sweet. In addition, the perceived sourness of acidic stimuli is diminished, with mostly the sweet signal reaching the primary taste area [86]. The exact mechanism of miraculin interaction with taste receptors remains unknown. However, miraculin interacts with lactisole, with psychophysical findings showing that lactisole diminishes the pH-dependent sweet response produced by miraculin [24, 36].

5.5 Zinc sulfate: sweet & bitter suppressor

Zinc sulfate (PubChem CID: 24424) is a chemical commonly available in food supplements and has the U.S. Food and Drug Administration's "Generally Regarded as Safe" status for food and beverages. We source it from an off-the-shelf product by *Triquetra Health*. We use a dose of 4 mg derived from pilots. Zinc sulfate's acute oral toxicity (LD_{50}) is 1,538 mg/kg.

Taste alteration mechanism: Zinc sulfate is a sweet inhibitor [27, 28] and selective bitter inhibitor [29]. The exact mechanisms by which zinc ions affect sweet and bitter taste are still unknown, but Keast et al. suggests that they bind to taste receptors, altering their binding properties [27].

5.6 Amiloride: salty suppressor

Amiloride (PubChem CID: 16231, Catalog #: 14409) was purchased from *Cayman Chemical Company* at its highest available purity (≥98%). We use a dose of 1.722 mg, based on Schiffman et al.'s [65]. This modulator's acute oral toxicity (LD_{50}) of this modulator is 300 mg/kg [89].

Taste alteration mechanism: Amiloride has been used as a specific inhibitor of sodium transport (reducing saltiness). The psychophysical findings that amiloride reduces the intensity of taste perception of sodium and lithium salts is consistent with its action in which the fluxes of sodium and lithium are molecularly blocked [65].

6 HARDWARE IMPLEMENTATION

To help the readers replicate our design, we provide the necessary technical details bellow. We additionally provide all source code, firmware, and hardware for our implementation online.[1] Figure 12 shows our complete and self-contained 3-channel prototype, including its battery, liquid-safe pumps, and reservoirs.

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

[1] https://github.com/humancomputerintegration/taste-retargeting

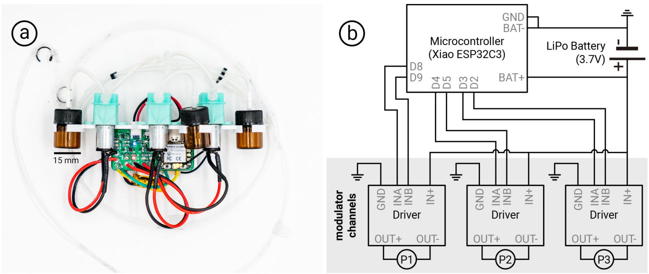

Figure 12: (a) Our device is comprised of a printed circuit board, pumps, vials, tubing, and cuffs. (b) High-level schematic.

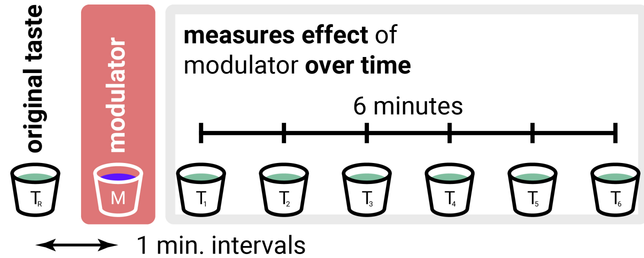

Figure 13: Study protocol to measure the effect of a modulator on a target basic taste over time.

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

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

7 STUDY 1: MEASURING THE EFFECT OF MODULATORS

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

7.1 Participants

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

7.2 Modulators and taste solutions

We used the taste modulators detailed in earlier: amiloride (0.1148 mg/mL), clofibric acid (3.43 mg/mL aka saturation), gymnema powder (1.0% w/v), lactisole (0.25 mg/mL), miraculin (13.33 mg/mL), and zinc sulfate (0.266 mg/mL). We then used medium-intensity solutions of basic taste stimuli (*tastants*) prepared according to Hoehl et al. [23]: 8.00 g/L sodium chloride for salty, 48.00 g/L sucrose for sweet, 1.08 g/L caffeine for bitter, 2.40 g/L citric acid for sour, and 4.00 g/L monosodium glutamate for umami. All solutions used room-temperature filtered tap water as a solvent.

Modulators' effects were measured on taste(s) they effected in prior literature. Following this, we tested nine modulator-tastant pairs: amiloride on salty, clofibric acid on umami, gymnema powder on sweet, lactisole on sweet, lactisole on umami, miraculin on sour, zinc sulfate on sweet, and zinc sulfate on bitter.

7.3 Procedure

Participants performed a multi-sip, multi-attribute time-intensity test for each modulator-taste pairing, as depicted in Figure 13. In other words, each participant drank a tastant at the start, then the modulator, then the tastant six more times (multi-sip) and evaluated its taste each time (multi-attribute time-intensity). The examiner pre-poured all solutions (same volume at 3 mL) and told participants that every tastant could be different or identical to avoid any expectation bias. Participants drank a cup each minute and were asked to maintain a consistent sip size. For the modulator, participants were asked to swish the solution in their mouth for 5 seconds before swallowing to ensure proper coverage of the oral cavity. After each drink, they then rated the solution's taste intensity across five attributes (salty, sweet, sour, bitter, and umami) using a Likert scale ranging from 0 (not at all) to 10 (the most).

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

7.4 Results

As reference ratings for the tastants vary across untrained individuals, we used the relative change (difference between a time point T and the reference T_R) to determine the modulator's impact on taste perception. We summarize the results for each modulator below and illustrate their impact in Figure 14.

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

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

Lactisole. Surprisingly, lactisole did not appear to strongly affect the sweet solution despite prior literature demonstrating an effect (see *Discussion*). In contrast, lactisole successfully suppressed the umami of an umami solution. Lactisole-induced umami suppression steadily strengthens over time, with a maximal relative change in umami intensity of −2.5 but no trend back towards neutral within this timeframe. Lactisole also produced a sweet sensation (+1.4) that faded after 200 seconds. A similar phenomenon occurred for umami during the sweet solution.

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

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

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

7.5 Discussion

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

Zinc sulfate reducing sourness. While some participants mistook bitterness for sourness, sour-bitter confusion is well-documented [55, 61]. When we account for this confusion, this "sour" decrease pointed to the further efficacy of zinc sulfate at suppressing bitterness over time.

Zinc sulfate's change in mouthfeel. Participants sometimes reported a brief (within the first 10-20 seconds) change in mouthfeel with zinc sulfate. This aligns with prior literature suggesting that zinc may bind to the salivary protein responsible for oral lubrication, reducing salivation [28].

Lactisole and sweet water effect. While our results on the effect of lactisole on a sweet solution may seem mild, they point towards a secondary effect that lactisole has on liquids like water—the sweet water effect. As seen by the bump in the perceived sweetness for an umami solution, exposure to lactisole causes a "sweet water taste", in which water tastes sweet for some time after exposure (does not apply to solids) [1]. Most likely, the lactisole *suppresses* sweetness, but the sweet water taste initially counteracts this effect.

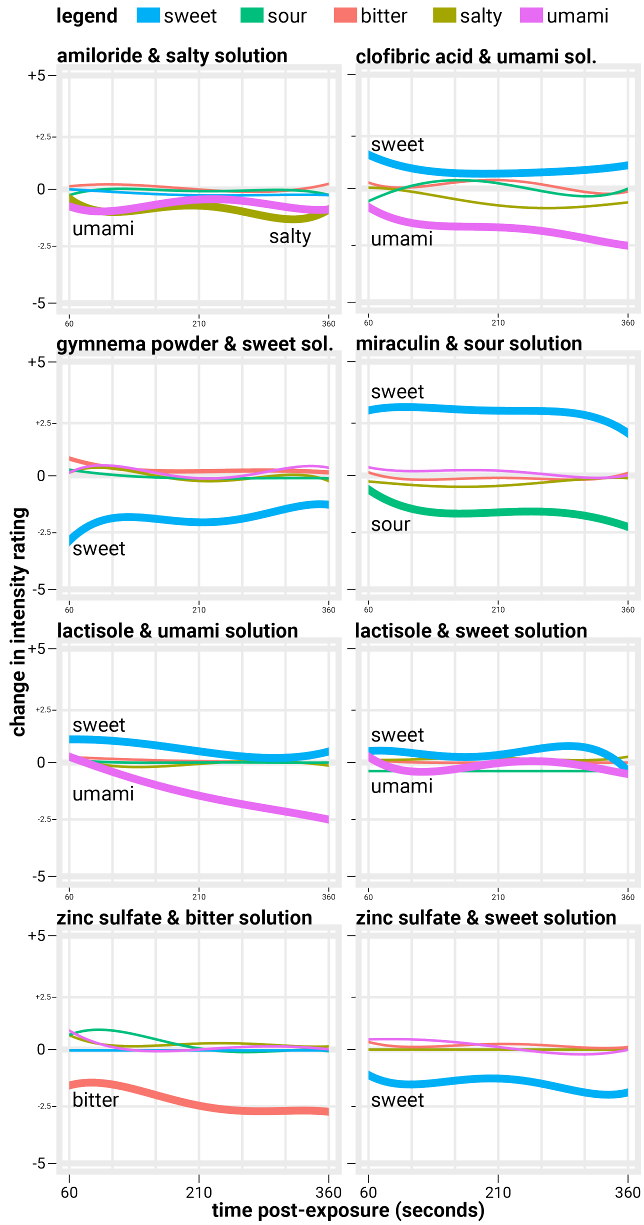

Figure 14: Plots of the relative change in intensity of basic tastes measured under the effect of each modulator. For clarity, we bolded the polynomial fits for basic tastes that are relevant to the modulator and taste solution of each plot.

For this reason, we do not completely rule out lactisole's well-known sweet suppression but embrace the sweet water taste effect as another opportunity for taste retargeting.

Taste modulation onset. Given our study protocol, we did not characterize each modulator's effect during the first 59 seconds post-exposure. However, prior literature for each modulator establishes that their effect is (1) noticeable and (2) comes into effect shortly after or immediately upon exposure. Rated as "immediate effect" are lactisole [68], zinc sulfate [27], miraculin [10], and gymnema sylvestre tea [83]. While clofibric acid's effect was measured

75 seconds post-exposure [33], our pilots suggested clofibric acid's effect on umami occurred almost immediately after exposure. Likewise, while recent literature on amiloride suppression of saltiness was unclear on how quickly (<60 seconds) the effect started [65], our pilots suggested the change was noticeable around 30 seconds after exposure.

8 STUDY 2: USE IN A VR INTERACTIVE APPLICATION

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

8.1 Participants

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

8.2 Tasks

For this study, we adapted one portion of the VR experience describe in our *Walkthrough*. Similar to the study design in [7], we designed the VR scene so that participants took at least 40 seconds to find new food items. This gap ensured that our device had time to drip the modulators. Any virtual foods that users could interact with appeared at the closest suitable location (but out of view) only after delivery was complete.

Participants entered a deserted forest and were tasked with foraging food to survive. As they teleported through the forest, they could find a blackberry, then a lemon, a strawberry, and – now that no other food was available – a dead spider. For these transformations, we delivered lactisole (blackberry to lemon), miraculin (blackberry to strawberry), and finally, zinc sulfate (strawberry to spider). Before they could eat any virtual item, participants had to "wash" any virtual food they found in a virtual pot of water. Only then could the participant use their hand to grab the virtual food from the pot, which aligned with a physical prop in the room. Following, the participant always grabbed the same pickled blackberry prop from a physical bowl. We did this to reduce the visual mismatch from tracking the real food item.

8.3 Apparatus

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

Participants wore an early prototype delivery system in a backpack, with the same tubing outlets comfortably hooked at the mouth corners. Through pilots, we calibrated the delivery system to go unnoticed by two authors. Our device delivered solutions at a drip of 0.05 mL per 6 seconds to reduce perceiving the modulator solution's taste and delivery. For reference, humans swallow 0.46±0.31 mL of saliva every 60.8±39.0 seconds [62].

8.4 Conditions

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

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

8.5 Procedure

We took into consideration the experimental protocol discussion from *DeepTaste*. In it, Nakano et al. reported that some participants said they would have experienced something closer to the virtual food had they not seen the original prop [50]. Following, we hid all food props from the participants' view whenever they were not in VR to avoid reducing the strength of manipulation in both conditions.

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

8.6 Quantitative Results

We conducted a two-way ANOVA. Figure 15 depicts our main findings. We found a statistically significant effect of the food item [$F(3,75) = 27.08$, $p < 0.001$] and condition [$F(1,75) = 19.95$, $p < 0.001$] on the flavor matching score. A Tukey post-hoc test revealed that taste retargeting resulted in higher matching on average than in the baseline condition.

For visual clarity, we report the statistical differences from post-hoc pair-wise comparisons that used Benjamini-Hochberg-corrected t-tests in Table 1.

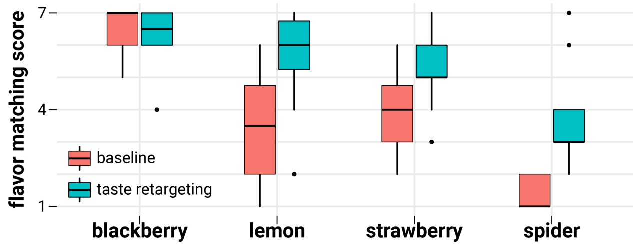

Figure 15: Flavor matching scores between conditions.

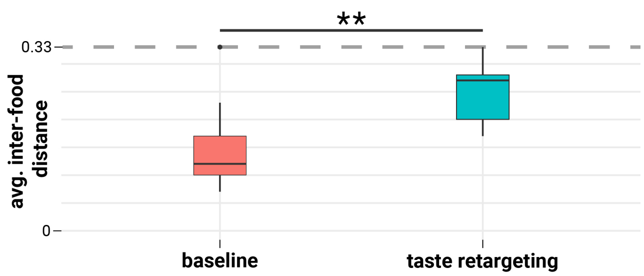

Figure 16: The average inter-flavor distance between all four food items for baseline and taste retargeting. The maximum possible result would be a spacing of 0.33 between four foods.

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

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

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

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

8.7 Qualitative Results

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

Flavor matching. Most participants commented that taste retargeting led to better flavor matching to the intended virtual taste. For instance, after both conditions, P2 believed the taste retargeting condition was better than the baseline and added that the change in taste surmounted the little discrepancies left. "When I taste the lemon, I can feel that it's more sour, [...] I have illusion that makes me think, 'it's lemon"' (P2). Likewise, P9 reported that the sourness of the lemon came out very noticeably with lactisole's sweet suppression and that, for the miraculin transformation, the virtual strawberry was "very strawberry-like as if it were a sweet strawberry." Many participants commented on the retargeted spider (P1-7, P9-11). To illustrate this: P9, who debated rating it a six or seven, voiced, "a seven would be disingenuous because [they] never had a spider before, but it was the energy for what a spider *would* taste like." P1 had a visceral reaction to the spider in the taste retargeting condition only, screaming loudly and rating it as six in flavor matching. They later stated that the baseline "was okay, but the [taste retargeting] time... perfect spider taste: it blocked everything else and had just a little bitter [...] now I can brag about, you know, eating a spider."

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

Incongruencies. While taste retargeting improved the flavor matching and distinct taste of the virtual foods, three participants noted incongruencies with smell (P10) and texture (P7, P8). P10 stated that the lemon's citrus taste was clearly present during taste retargeting, but there was also "a hint of some floral note [prop

Table 1: Summary of post-hoc pair-wise comparisons.

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

taste]" that would not typically be in a lemon. P7 noted that the blackberry's texture was still noticeable despite the flavors matching more in the taste retargeting condition. Instead, P8 recognized the texture of the blackberry when grabbing berries. Surprisingly, given the differences between the virtual foods and prop, no further incongruencies were reported.

Prop's identity. While most participants were unsure if the prop was a blackberry (with some asking to have it revealed after the study), they often did not discuss the prop itself. As mentioned above, P7 and P8 were outliers that recognized the prop as a blackberry from grasp or texture. In fact, P6 initially thought they knew the prop's real identity but started questioning themselves as the modulators kicked in, "When I ate the blackberry, it felt like a perfect match, but later, [I was] less and less convinced it was a blackberry."

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

8.8 Discussion

Overall, the quantitative and qualitative results from Study 2 confirm both of our initial hypotheses. First, the addition of taste modulators reduced the sensory mismatch between the blackberry prop and each of its virtual counterparts (H1), as seen in Figure 15. Moreover, even if the flavor increased but did not match perfectly, taste retargeting made the taste of virtual foods more distinct (H2), as seen in Figure 16. These results are especially exciting because the complexity of retargeting a prop increases as the prop undergoes additional transformations. Moreover, as previously mentioned, taste retargeting modulates *existing* flavors. Thus, the prop's initial flavor profile must contain facets matching *each* virtual food. This consideration is not so much a limitation as a tradeoff, as taste retargeting provides a benefit in exchange: using readily available foods as props with little to no preparation. Finally, future research might address zinc sulfate's taste (noted by three participants) with techniques like mixture suppression (e.g., adding a sweetener to diminish the initial slight bitter taste of zinc sulfate).

9 FURTHER APPLICATIONS

Our exploration of taste retargeting to reduce flavor mismatching between a food prop and virtual foods represents only one of its possible applications. Alongside opportunities for taste retargeting to potentially support future immersive experiences (e.g., online co-creation of foods or reliving food memories [14]), we highlight four potential scenarios where one might expect our technique to find further applications.

9.1 Interactive dining experiences

Chefs (and researchers) have long sought to surprise and entertain diners through all their senses, leading to new culinary approaches, like molecular gastronomy [72], digital gastronomy [88], and interactive dining experiences [11]. While certain taste modulators are not new to haute cuisine (e.g., miraculin), their interactive delivery and the opportunities for taste retargeting *are*. Taste retargeting could contribute to interactive dining experiences. For instance, Figure 17 depicts a multi-course dinner with an element of surprise: the diners use their smartphone to randomly pick a taste alteration via taste retargeting, yielding different experiences for each person.

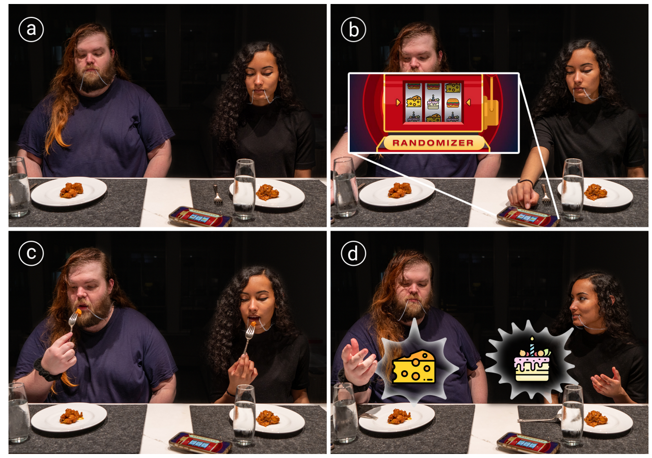

Figure 17: (a) Diners are served a course. (b) They use their smartphone to randomize a taste alteration and (c) eat their dish. (d) Each person thus experiences a different flavor.

9.2 Speeding up recipe development

Developing new food products involves *recipe development*, a process like prototyping in design. Taste retargeting could make recipe development faster and easier, as Figure 18 illustrates. Recipe developers could produce a single test and retarget it to different taste profiles. By previewing several flavor possibilities from a single test, developers could save time and effort, speeding up the recipe development process like rapid prototyping for design.

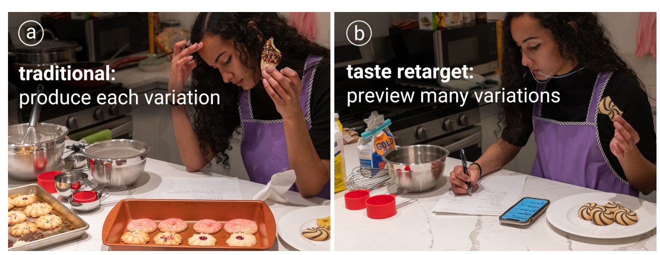

Figure 18: (a) Traditional development requires producing each recipe variation. (b) Taste retargeting could offer previews of flavor variations using a single iteration.

9.3 Embodied understanding of foods

We imagine leveraging taste retargeting so that a user can use *their tongue* to interactively understand the impact of basic tastes (or even compounds) on the flavor of *any* food, *anywhere*. For example, as illustrated in Figure 19, a user wants to understand how the

110 mg of sodium and 20 g of sugar – declared on their cookies' nutritional label – contribute to the sensory experience. They use their phone to scan the beverage's barcode, which accesses a database of nutritional label contents and provides the quantities to our device. By suppressing the sweetness, umami, or saltiness of their beverage interactively, the user can directly experience and understand how these quantities impact the flavor, rather than reading abstract numbers. This interaction could also lead to more playful experiences with everyday foods or better nutritional education. We were inspired by Schroeder & Flannery-Schroeder's class exercise using gymnema tea to experience the contributions of basic tastes to flavor [67].

Figure 19: (a,b) A user scans their bag of cookies' barcode and (c) explores how saltiness or sweetness contribute to the flavor. They suppress the sweetness completely and (d) *taste* how the 20 g of sugar impacts the cookie.

9.4 Dietary interventions

Taste retargeting may also be a promising tool for dietary interventions, as sensory properties (taste, smell, sound) strongly influence food choice and intake [18]. As shown in Figure 20, our device could decrease the sweetness or saltiness of unhealthy foods to help users reduce their intake of added sugars or ultra-processed foods. Already, Turner et al. demonstrated that gymnema sylvestre can reduce the desire for high-sugar sweet foods [78]. Conversely, taste retargeting could enhance the taste of healthier, yet less palatable, foods. For example, suppressing the bitterness of vegetables to make them more appealing to individuals who struggle to consume them regularly.

Figure 20: (a) Our device responds to the user drinking a sugary carbonated beverage by suppressing its sweetness. (b) The user no longer enjoys it and (c) casts the beverage aside.

10 FUTURE WORK

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

10.1 Combining with existing techniques

As tasting represents a multimodal sensory experience, taste retargeting may benefit from combinations with existing techniques to complement with other aspects of flavor like sound, smell, temperature, or texture. For example, Weidner et al.'s results around visual and olfactory modifications [84] or Kleinberger et al.'s *Auditory Seasoning Filters* [31] could pair with taste retargeting to further reduce flavor mismatching between a food prop and virtual foods. Finally, taste sensors, like the TS-5000Z [44], might be able to further measure the effects of modulators on basic taste solutions.

10.2 More delivery mechanisms

While our implementation focused on thin tubes delivering modulators to the corners of the mouth, this is just one of the many ways to achieve taste retargeting. Future work could investigate spraying modulators directly on the food (e.g., combining with *TTTV2* [46] or spraying from a wrist-worn device), dynamically coating cutlery, or even integrating the modulators into an intro-oral device (e.g., a retainer).

10.3 More taste modulators

Given that this paper represents a first step towards using modulators for interactive taste retargeting, we opted for modulators that were readily accessible to most HCI researchers. While most of these modulators function as suppressors, there are more experimental compounds to explore in the future that act as *enhancers*. In literature, *bortezomib* enhances sourness for mice, and in IRB-approved pilots, we noticed that trace amounts of bortezomib could drastically enhance the sourness of foods [53]—to further explore these, we recommend Deepankumar et al.'s review for details on such compounds [15]. Future research can also explore the identification of bitter enhancers, which were otherwise never a research goal in industry or academia. Alternatively, collaborations with clinics could investigate repurposing existing drugs that cause distortions in taste perception [17, 66], including characterizing their alteration and determining whether non-prescription levels of these compounds can produce selective taste alterations.

11 CONCLUSION

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

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

Taste retargeting represents a significant step towards exploring taste modulation in interactive contexts with real foods. We believe this work points to an emerging direction in HCI, in which chemicals provide unique methods of interfacing with the human body to unlock new interactive possibilities. We are excited to see how other researchers in HCI, nutritional & food sciences, and health will build upon and extend our findings. Future research may explore new taste modulators, smaller delivery systems, or even combinations of our technique with existing methods to refine the fidelity and applications of taste retargeting.

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