Chemical interfaces: new methods for interfacing with the user's senses

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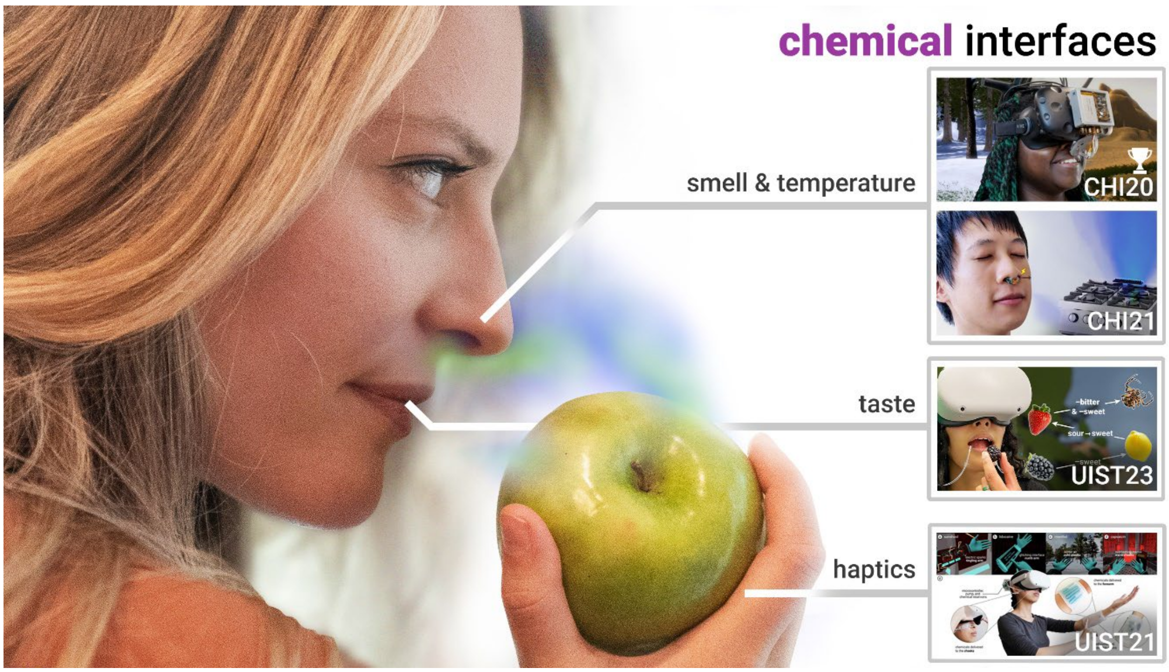

Figure 1: My research aims to incorporate the untapped and critical senses of smell, taste, and temperature into computer interfaces by delving into a class of devices I refer to as *chemical interfaces*. In turn, these interfaces provide a potential foundation to influence how we perceive and engage with the very air we breathe and the foods we consume.

Abstract. Since the advent of computer interfaces, significant advances have been made toward delivering high-fidelity visual, auditory, and haptic experiences, notably propelled by the rise of virtual and augmented reality. Yet, the stimulation of new senses like smell, taste, and temperature has severely stagnated over the last decades. I argue that this stems from the predominant reliance on actuators from mechanical and robotic engineering, which are not scalable or adaptable for these senses. I posit that completely new interfacing techniques are needed to fully engage users' senses. As such, I explore the integration of these crucial senses by proposing a new class of devices, which I call "chemical interfaces." These devices interface directly with the chemical dimension of our sensory pathways – tapping into our smell receptors, taste receptors, and even temperature receptors. Through the precise delivery of specific chemicals to areas like the user's skin or tongue, I have dramatically increased the level of immersion of virtual (and real) experiences by adding temperature, smell, and taste. My findings reveal that, in contrast to conventional methods originating from robotics or mechanical engineering, chemical interfaces offer distinct benefits and advantages. These include a significant reduction in power consumption for temperature feedback (CHI'20 Best Paper), rich skin sensations like tingling, stinging, numbing, and hot or cold (UIST'21), the ability to modify the taste of virtual and real foods (UIST'23), and endowing users with new abilities, such as sensing

harmful gases when they inhale (CHI'21). My approach paves the way for richer digital interactions (e.g., in VR or AR), but also lays the groundwork for future health interventions, such as for helping people with smell and taste disorders.

1 INTRODUCTION

Smell, taste, and temperature shape our enjoyment of life – through pleasure, flavor, and memory – **and our survival** in detecting hazards or health risks [48]. Since the advent of computer interfaces, significant strides have been made toward providing high-fidelity visual and auditory experiences, as contemporary smartphones and virtual reality headsets demonstrate. We have even begun to master haptic feedback like vibrations [28] or force-feedback [32], courtesy of advancements from robotics, mechanical engineering, and medical devices. Despite these advancements in delivering high-fidelity audiovisual and now tactile experiences, **stimulating smell, taste, and temperature has stagnated over the last century**, relying on borrowed methods from mechanical and robotic engineering [54, 55] or early 20th-century Heating, Ventilation, and Air Conditioning (HVAC) advancements [14].

My research aims to incorporate these untapped, critical senses by delving into a new class of devices I call "chemical interfaces," devices that manipulate human senses by interfacing with our perceptions' biochemical cascades through carefully selected chemicals. As these senses are *fundamentally* rooted in chemical reactions that translate to perceived sensations (e.g., molecules binding to olfactory receptors), chemical interfaces provide a promising pathway to interfacing with them and offer unique affordances unavailable to traditional techniques derived from robotics or mechanical engineering. In each paper, I explored these affordances: from reduced power consumption for thermal feedback, to versatile and miniaturized feedback mechanisms for haptic wearables, to chemical selectivity producing new interactions for taste. I have even applied my research approach to traditional actuators, unlocking new sensations like stereo-smell. I am incredibly excited about this research providing a potential foundation to influence how we perceive and engage with our food and the air we breathe as well as its potential for assistive technologies.

2 CHEMICAL INTERFACING IS POWER-EFFICIENT (CHI'20 BEST PAPER)

Haptic feedback allows virtual reality experiences to match our sensorial expectations beyond visual realism [2, 45]. Today, researchers focus on engineering wearable devices that deliver realistic haptic sensations, such as touch [2, 5], force feedback [19, 24], but also thermoception—the sense of temperature changes [39]. The latter has proven extremely hard to miniaturize into wearable devices. Researchers must *physically* produce a temperature change to create a temperature sensation, whether through air conditioning [55] or direct skin stimulation [41], which means these devices must consume an *equivalent, substantial amount of power.*

In my first paper [11], I developed an interactive wearable device that releases tiny puffs of specifically chosen scents. These fragrances stimulate not only the olfactory bulb but also the trigeminal nerve's temperature receptors, tricking the body into perceiving a temperature change. For example, mint can be used for cooling or capsaicin (peppers) for heating. The device achieves this temperature illusion with low-powered electronics (0.25 W), enabling the miniaturization of simple temperature sensations, as seen in Figure 2. **These illusions bypass physical limitations and are 52-1000 times more power efficient than traditional, power-intensive mechanisms** like thermoelectric (Peltier) elements [40, 42] or heat lamps [55], making the illusion a new alternative for thermal feedback.

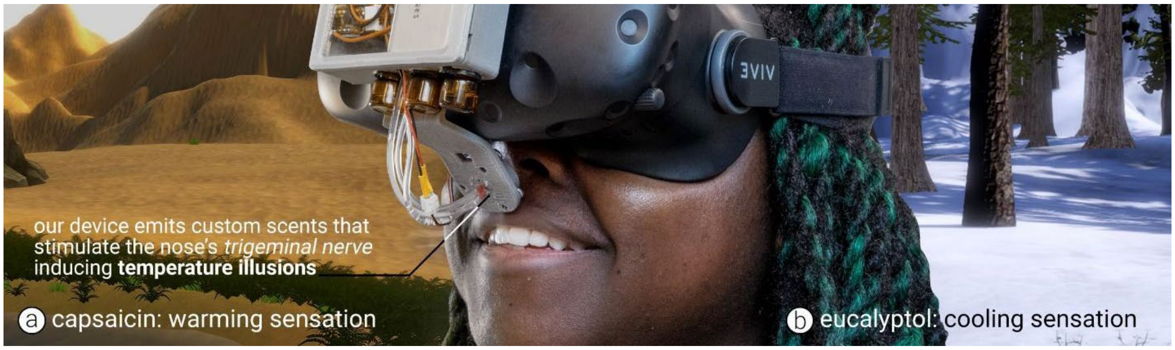

Figure 2: I engineered a thermal display that does not physically heat or cool but instead creates an illusion of temperature by stimulating the nose's trigeminal nerve with different scents. This nerve detects temperature shifts but also chemicals like menthol or capsaicin, which are why breath mints feel cold and chilis feel hot. This work received a CHI 2020 Best Paper Award.

3 CHEMICAL ACTUATORS ARE VERSATILE & COMPACT (UIST'22)

As physical touch is essential to interacting with our physical world, haptic researchers have placed much emphasis on rendering physical sensations [21, 41, 46, 47]. Unfortunately, two key factors limit the application of haptic devices that provide varied sensations beyond simple vibrations or pressure. First, most actuators capable of creating tingling, tickling, or temperature are large (e.g., *ChillyChair*'s desktop-sized actuators [18]) or – as mentioned earlier – power-hungry, making them unsuitable for wearables. Second, standard approaches to producing varied sensations require a unique actuator per distinct sensation [31].

Expanding on my earlier paper, a colleague and I introduced ***chemical haptics*** [33]. This novel haptics approach delivers topical stimulants to the skin. We engineered a **compact, versatile wearable capable of producing *several* haptic sensations using just *one* actuator**, unlike traditional interfaces that require a separate, larger actuator for each sensation. By stimulating skin receptors with different chemicals (see Figure 3), we elicited tingling, stinging, warming, cooling, and even numbing sensations – the last being usually impossible for standard actuators. Since this paper's publication, other researchers have explored chemical haptics, such as chemically-inducing the thermal grill effect [20] or combining chemical haptics *with* Peltier elements [26].

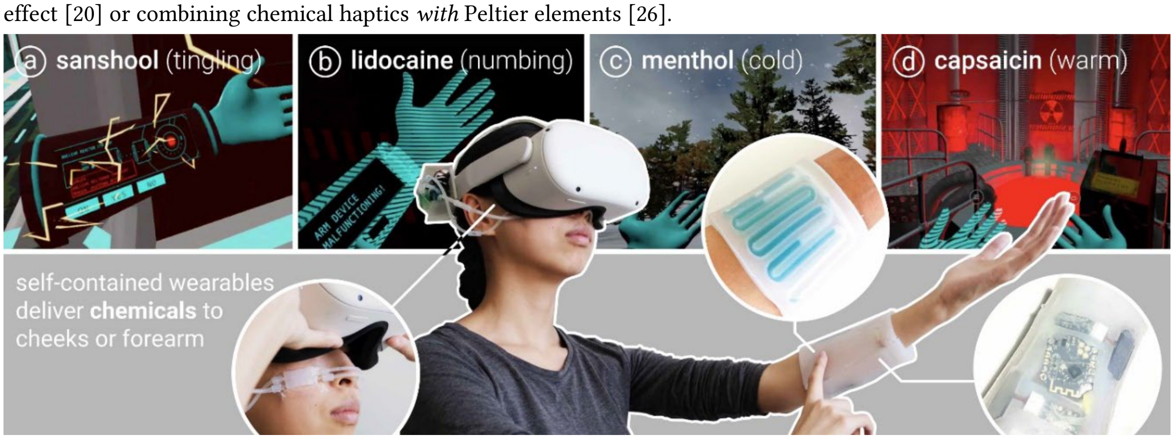

Figure 3: *Chemical haptics* leverages topical stimulants, chemicals that activate targeted skin receptors to render distinct haptic sensations. With one actuator, but different chemicals, the user can feel (a) tingling with sanshool, (b) numbing with lidocaine, (c) cooling with menthol, (d) warming with capsaicin, and even stinging with cinnamaldehyde.

4 CHEMICAL SELECTIVITY ENABLES NEW INTERACTIONS (UIST'23)

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" [35]), adjusting the strength of the taste via electrolytes [34], or adding seasonings to food [53]. Other approaches have explored modifying secondary aspects of the eating experience, such as applying weight on the tongue [22], sound [30], perceived texture [29], or scent [37].

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 my most recent paper, I introduced *taste retargeting* [6], a novel technique to interactively alter taste perception using chemical taste modulators. These compounds temporarily and selectively change how taste receptors respond to other foods. While prior techniques relied on electrical stimulation via cutlery and could only affect the overall flavor while in contact with the tongue [1, 36, 43], **taste retargeting can selectively alter basic tastes (sweet, sour, salty, bitter, umami) of real foods without hindering eating or impacting the food's consistency**. An interactive application of this technique retargeted three food props in a virtual reality experience to taste like 12 different virtual foods, marking a *four-fold* increase in distinct tastes. Figure 4 illustrates such a retargeting sequence.

In my work on chemical interfaces, 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. This work exemplifies my research exceptionally well, in which chemicals provide unique methods of interfacing with the human body to unlock new interactive possibilities.

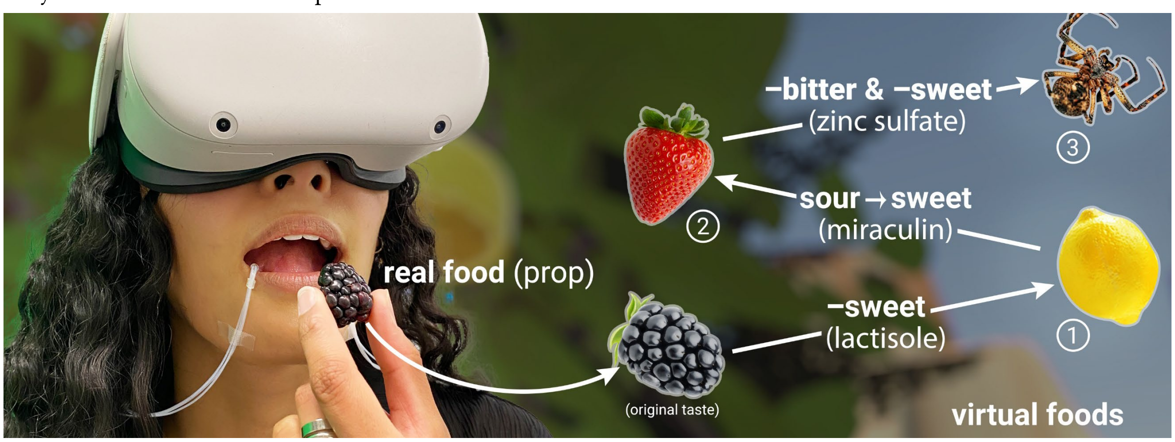

Figure 4: *Taste retargeting* **selectively changes taste perception** using taste modulators—chemicals that temporarily alter the response of taste receptors to foods and beverages. As our technique delivers modulators before eating or drinking, it is the first interactive method to selectively alter the basic tastes of real foods *without obstructing eating or impacting the food's consistency.*

5 CHEMICAL APPROACH INSPIRES NEW SENSATION WITH TRADITIONAL METHODS (CHI'21)

My approach to chemical interfaces involves careful consideration of the target sense's anatomical location, physiology, and biochemical responses. I applied this methodology towards digitizing smell sensations. Prior efforts relied on deep, invasive electrical stimulation with little [13] to no success [23, 49, 52]. Instead, I leveraged that what we perceive as smell is the perceptual fusion of olfactory bulb *and trigeminal* nerve sensations. As shown in Figure 5, I engineered a device to electrically stimulate the trigeminal nerve at an easily accessible location (septum), reproducing stereo-smell (directional odor sensations) and enabling users to find virtual odor sources like real ones [12].

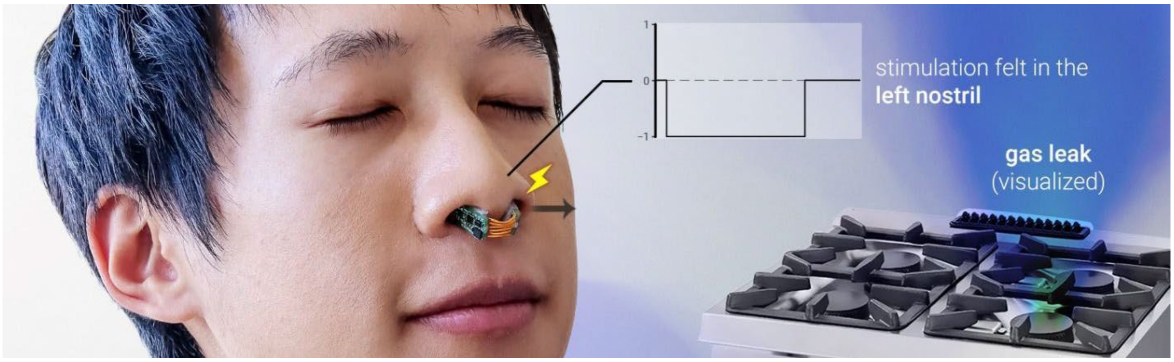

Figure 5: I proposed a novel smell device that renders stereo-smell sensations (directional odor cues) by electrically stimulating the trigeminal nerve [11]. To realize this, I engineered a self-contained apparatus worn as a nose clip across the septum. This work received a 2021 Fast Company Innovation by Design Honorable Mention.

6 RESEARCH STATUS

I have published four papers on my dissertation topic, a fifth paper investigating low-fidelity prototyping for smell at CHI 2023 [8] (see Figure 6), and two papers on haptics more broadly [25, 50]. Alongside my publications, I spend time fostering a community for researchers studying smell, taste, and temperature interfaces by leading and co-organizing the "Smell, Taste, and Temperature Interfaces" workshops, which took place at CHI 2021 [9] and 2023 [7], alongside co-organizing a panel on smell in HCI [10] at CHI 2023. Currently, I am working to "close the loop" and focus on how chemical interfaces intersect with sensing technologies and methodologies.

Figure 6: An overview of prototyping with *Smell & Paste* (lo-fi) versus current practices (hi-fi). Our technique leverages low-fidelity materials to make low-fidelity prototyping of smell experiences approachable and fast for novices and experts alike. In contrast, steps in current practice are costly and time-consuming: a single iteration can take hours, days, or – in some extremes – months.

7 BROADER IMPACTS AND FUTURE WORK

Over the last century, since visionaries like theatrical impresario Samuel "Roxy" Rothafel installed a scent delivery system into a major cinema in 1917 [56, 57], the successful integration of smell, taste, and temperature into interfaces has been notably stagnant. In my papers, I have proposed, explored, and engineered **chemical interfaces as a promising pathway toward incorporating these rich senses into our digital interactions**. I believe these interfaces open exciting new interactive uses.

Smell is often leveraged to detect hazardous situations, such as expired food or chemical risks. Unfortunately, **an individual with anosmia (loss of olfactory function) cannot detect gas, smoke, or fire through their sense of smell** [3, 38]. In Keller and Malaspina's reports, 72% of their subjects reported fearing exposure to dangers due to their olfactory dysfunction [27]. The main concern was the inability to detect a fire, volatile compounds, or a gas leak. (The latter stems from people with anosmia not being able to smell the compound – methyl mercaptan – added to odorize natural gas, which is ordinarily odorless.) Bonfils et al. reported similar results from incidents with their survey population [4]. These consequences ripple across many aspects of a person's life, such as active avoidance of housing with natural gas, food poisoning, prolonged exposure to hazardous volatile chemicals, reduced quality of life from lack of flavor, and more. In contrast to their olfactory dysfunction, **people with anosmia often retain trigeminal function**, though it may be dampened in sensitivity [16, 17]. Soon, I aim to explore leveraging **my trigeminal devices as an assistive technology for people with anosmia, as they could enable them to sense gases in the air**.

Likewise, ***taste retargeting* may be a promising tool for dietary interventions or nutritional education**, as sensory properties (taste, smell, sound) strongly influence food choice and intake [15]. Our device could decrease the sweetness or saltiness of unhealthy foods to help users reduce their intake of added sugars or ultra-processed foods [51]. 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.

Taste retargeting could also help a person use *their tongue* to interactively understand the impact of basic tastes (or even compounds) on the flavor of *any* food, *anywhere*. For example, a user wants to understand how 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 their beverage's sweetness, umami, or saltiness 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 [44].

In the future, I plan to expand my research to broadly rethink how we perceive and interact with our food and the very air we breathe in our everyday lives.

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REFERENCES

[1] Aoyama, K., Sakurai, K., Morishima, A., Maeda, T. and Ando, H. 2018. Taste controller: galvanic chin stimulation enhances, inhibits, and creates tastes. *ACM SIGGRAPH 2018 Emerging Technologies* (Vancouver British Columbia Canada, Aug. 2018), 1–2.

[2] Benali-Khoudja, M., Hafez, M., Alexandre, J.-M. and Kheddar, A. Tactile interfaces: a state-of-the-art survey. 9.

[3] Blomqvist, E.H., Brämerson, A., Stjärne, P. and Nordin, S. 2004. Consequences of olfactory loss and adopted coping strategies. *Rhinology*. 42, 4 (Dec. 2004), 189–194.

[4] Bonfils, P., Faulcon, P., Tavernier, L., Bonfils, N.A. and Malinvaud, D. 2008. Accidents domestiques chez 57 patients ayant une perte sévère de l'odorat. *La Presse Médicale*. 37, 5 (May 2008), 742–745. DOI:https://doi.org/10.1016/j.lpm.2007.09.028.

[5] Borst, C.W. and Volz, R.A. 2005. Evaluation of a Haptic Mixed Reality System for Interactions with a Virtual Control Panel. *Presence: Teleoper. Virtual Environ.* 14, 6 (Dec. 2005), 677–696. DOI:https://doi.org/10.1162/105474605775196562.

[6] Brooks, J., Amin, N. and Lopes, P. 2023. Taste Retargeting via Chemical Taste Modulators. *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA, 2023).

[7] Brooks, J., Bahremand, A., Lopes, P., Spackman, C., Amores Fernandez, J., Ho, H.-N., Inami, M. and Niedenthal, S. 2023. Sharing and Experiencing Hardware and Methods to Advance Smell, Taste, and Temperature Interfaces.

Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems (Hamburg Germany, Apr. 2023), 1–6.
[8] Brooks, J. and Lopes, P. 2023. Smell & Paste: Low-Fidelity Prototyping for Olfactory Experiences. *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg Germany, Apr. 2023), 1–16.
[9] Brooks, J., Lopes, P., Amores, J., Maggioni, E., Matsukura, H., Obrist, M., Lalintha Peiris, R. and Ranasinghe, N. 2021. Smell, Taste, and Temperature Interfaces. *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama Japan, May 2021), 1–6.
[10] Brooks, J., Lopes, P., Obrist, M., Amores Fernandez, J. and Kaye, J. 2023. Third Wave or Winter? The Past and Future of Smell in HCI. *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg Germany, Apr. 2023), 1–4.
[11] Brooks, J., Nagels, S. and Lopes, P. 2020. Trigeminal-based Temperature Illusions. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu HI USA, Apr. 2020), 1–12.
[12] Brooks, J., Teng, S.-Y., Wen, J., Nith, R., Nishida, J. and Lopes, P. 2021. Stereo-Smell via Electrical Trigeminal Stimulation. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama Japan, May 2021), 1–13.
[13] Cheok, A.D. and Karunanayaka, K. 2018. *Virtual Taste and Smell Technologies for Multisensory Internet and Virtual Reality*. Springer International Publishing.
[14] Clepper, C. 2016. *The Rigged House: Gimmickry, Exhibition, and Embodied Spectatorship in Mid-Century American Movie-Going*. Northwestern University.
[15] Forde, C.G. and de Graaf, K. 2022. Influence of Sensory Properties in Moderating Eating Behaviors and Food Intake. *Frontiers in Nutrition*. 9, (Feb. 2022), 841444. DOI:https://doi.org/10.3389/fnut.2022.841444.
[16] Frasnelli, J., Schuster, B. and Hummel, T. 2007. Interactions between Olfaction and the Trigeminal System: What Can Be Learned from Olfactory Loss. *Cerebral Cortex*. 17, 10 (Oct. 2007), 2268–2275. DOI:https://doi.org/10.1093/cercor/bhl135.
[17] Frasnelli, J., Schuster, B., Zahnert, T. and Hummel, T. 2006. Chemosensory specific reduction of trigeminal sensitivity in subjects with olfactory dysfunction. *Neuroscience*. 142, 2 (Oct. 2006), 541–546. DOI:https://doi.org/10.1016/j.neuroscience.2006.06.005.
[18] Fukushima, S. and Kajimoto, H. 2012. Chilly chair: facilitating an emotional feeling with artificial piloerection. *ACM SIGGRAPH 2012 Emerging Technologies on - SIGGRAPH '12* (Los Angeles, California, 2012), 1–1.
[19] Gu, X., Zhang, Y., Sun, W., Bian, Y., Zhou, D. and Kristensson, P.O. 2016. Dexmo: An Inexpensive and Lightweight Mechanical Exoskeleton for Motion Capture and Force Feedback in VR. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2016), 1991–1995.
[20] Hamazaki, T., Kaneda, M., Zhang, J., Kaneko, S. and Kajimoto, H. 2022. Chemical-induced Thermal Grill Illusion. *2022 IEEE Haptics Symposium (HAPTICS)* (Mar. 2022), 1–6.
[21] Han, T., Wang, S., Wang, S., Fan, X., Liu, J., Tian, F. and Fan, M. 2020. Mouillé: Exploring Wetness Illusion on Fingertips to Enhance Immersive Experience in VR. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu HI USA, Apr. 2020), 1–10.
[22] Hirose, M., Iwazaki, K., Nojiri, K., Takeda, M., Sugiura, Y. and Inami, M. 2015. Gravitamine spice: a system that changes the perception of eating through virtual weight sensation. *Proceedings of the 6th Augmented Human International Conference on - AH '15* (Singapore, Singapore, 2015), 33–40.
[23] Holbrook, E.H., Puram, S.V., See, R.B., Tripp, A.G. and Nair, D.G. 2019. Induction of smell through transethmoid electrical stimulation of the olfactory bulb. *International Forum of Allergy & Rhinology*. 9, 2 (2019), 158–164. DOI:https://doi.org/10.1002/alr.22237.
[24] Hollerbach, J. and Jacobsen, S.C. 1995. Haptic Interfaces for Teleoperation and Virtual Environments. *in Proc. of First Workshop on Simulation and Interaction in Virtual Environments, Iowa City* (1995), 13–15.
[25] Je, S., Lim, H., Moon, K., Teng, S.-Y., Brooks, J., Lopes, P. and Bianchi, A. 2021. Elevate: A Walkable Pin-Array for Large Shape-Changing Terrains. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama Japan, May 2021), 1–11.
[26] Jiang, C., Chen, Y., Fan, M., Wang, L., Shen, L., Li, N., Sun, W., Zhang, Y., Tian, F. and Han, T. 2021. Douleur: Creating Pain Sensation with Chemical Stimulant to Enhance User Experience in Virtual Reality. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*. 5, 2 (Jun. 2021), 66:1-66:26. DOI:https://doi.org/10.1145/3463527.
[27] Keller, A. and Malaspina, D. 2013. Hidden consequences of olfactory dysfunction: a patient report series. *BMC Ear, Nose and Throat Disorders*. 13, 1 (Dec. 2013), 8. DOI:https://doi.org/10.1186/1472-6815-13-8.
[28] Kim, L.H., Castillo, P., Follmer, S. and Israr, A. 2019. VPS Tactile Display: Tactile Information Transfer of Vibration, Pressure, and Shear. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*. 3, 2 (Jun. 2019), 1–17. DOI:https://doi.org/10.1145/3328922.

[29] Knoop, J.E., Sala, G., Smit, G. and Stieger, M. 2013. Combinatory Effects of Texture and Aroma Modification on Taste Perception of Model Gels. *Chemosensory Perception*. 6, 2 (Jun. 2013), 60–69. DOI:https://doi.org/10.1007/s12078-013-9141-4.
[30] Koizumi, N., Tanaka, H., Uema, Y. and Inami, M. 2011. Chewing jockey: augmented food texture by using sound based on the cross-modal effect. *Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology - ACE '11* (Lisbon, Portugal, 2011), 1.
[31] Liu, Y., Nishikawa, S., Seong, Y. ah, Niiyama, R. and Kuniyoshi, Y. 2021. ThermoCaress: A Wearable Haptic Device with Illusory Moving Thermal Stimulation. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama Japan, May 2021), 1–12.
[32] Lopes, P., You, S., Cheng, L.-P., Marwecki, S. and Baudisch, P. 2017. Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17* (Denver, Colorado, USA, 2017), 1471–1482.
[33] Lu, J., Liu, Z., Brooks, J. and Lopes, P. 2021. Chemical Haptics: Rendering Haptic Sensations via Topical Stimulants. *The 34th Annual ACM Symposium on User Interface Software and Technology*. Association for Computing Machinery. 239–257.
[34] Miyashita, H. 2020. Norimaki Synthesizer: Taste Display Using Ion Electrophoresis in Five Gels. *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu HI USA, Apr. 2020), 1–6.
[35] Nakamura, H. and Miyashita, H. 2011. Augmented gustation using electricity. *Proceedings of the 2nd Augmented Human International Conference on - AH '11* (Tokyo, Japan, 2011), 1–2.
[36] Nakamura, H. and Miyashita, H. 2011. Communication by change in taste. *Extended Abstracts of the 2011 CHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada, 2011), 1999–2004.
[37] Narumi, T., Kajinami, T., Nishizaka, S., Tanikawa, T. and Hirose, M. 2011. Pseudo-gustatory display system based on cross-modal integration of vision, olfaction and gustation. *2011 IEEE Virtual Reality Conference* (Singapore, Singapore, Mar. 2011), 127–130.
[38] Nordin, S., Hedén Blomqvist, E., Olsson, P., Stjärne, P., Ehnhage, A., and for the NAF2S2 Study Group 2011. Effects of smell loss on daily life and adopted coping strategies in patients with nasal polyposis with asthma. *Acta Oto-Laryngologica*. 131, 8 (Aug. 2011), 826–832. DOI:https://doi.org/10.3109/00016489.2010.539625.
[39] Patapoutian, A., Peier, A.M., Story, G.M. and Viswanath, V. 2003. Sensory systems: ThermoTRP channels and beyond: mechanisms of temperature sensation. *Nature Reviews Neuroscience*. 4, 7 (Jul. 2003), 529–539. DOI:https://doi.org/10.1038/nrn1141.
[40] Peiris, R.L., Feng, Y.-L., Chan, L. and Minamizawa, K. 2019. ThermalBracelet: Exploring Thermal Haptic Feedback Around the Wrist. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19* (Glasgow, Scotland Uk, 2019), 1–11.
[41] Peiris, R.L., Peng, W., Chen, Z., Chan, L. and Minamizawa, K. 2017. ThermoVR: Exploring Integrated Thermal Haptic Feedback with Head Mounted Displays. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17* (Denver, Colorado, USA, 2017), 5452–5456.
[42] Ranasinghe, N., Jain, P., Karwita, S., Tolley, D. and Do, E.Y.-L. 2017. Ambiotherm: Enhancing Sense of Presence in Virtual Reality by Simulating Real-World Environmental Conditions. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (2017), 1731–1742.
[43] Ranasinghe, N., Tolley, D., Nguyen, T.N.T., Yan, L., Chew, B. and Do, E.Y.-L. 2019. Augmented Flavours: Modulation of Flavour Experiences Through Electric Taste Augmentation. *Food Research International*. 117, (Mar. 2019), 60–68. DOI:https://doi.org/10.1016/j.foodres.2018.05.030.
[44] Schroeder, J.A. and Flannery-Schroeder, E. 2005. Use of the Herb Gymnema sylvestre to Illustrate the Principles of Gustatory Sensation: An Undergraduate Neuroscience Laboratory Exercise. *Journal of undergraduate neuroscience education: JUNE: a publication of FUN, Faculty for Undergraduate Neuroscience*. 3, 2 (2005), A59-62.
[45] Sherman, W.R. and Craig, A.B. 2003. *Understanding Virtual Reality: Interface, Application, and Design*. Morgan Kaufmann Publishers Inc.
[46] Srinivasan, M.A. and Basdogan, C. 1997. Haptics in virtual environments: Taxonomy, research status, and challenges. *Computers & Graphics*. 21, 4 (Jul. 1997), 393–404. DOI:https://doi.org/10.1016/S0097-8493(97)00030-7.
[47] Stanley, A.A. and Kuchenbecker, K.J. 2011. Design of body-grounded tactile actuators for playback of human physical contact. *2011 IEEE World Haptics Conference* (Istanbul, Jun. 2011), 563–568.
[48] Stevenson, R.J. 2010. An Initial Evaluation of the Functions of Human Olfaction. *Chemical Senses*. 35, 1 (Jan. 2010), 3–20. DOI:https://doi.org/10.1093/chemse/bjp083.
[49] Straschill, M., Stahl, H. and Gorkisch, K. 1983. Effects of electrical stimulation of the human olfactory mucosa. *Applied Neurophysiology*. 46, 5–6 (1983), 286–289.
[50] Takahashi, A., Brooks, J., Kajimoto, H. and Lopes, P. 2021. Increasing Electrical Muscle Stimulation's Dexterity by means of Back of the Hand Actuation. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama Japan, May 2021), 1–12.

[51] Turner, S., Diako, C., Kruger, R., Wong, M., Wood, W., Rutherfurd-Markwick, K. and Ali, A. 2020. Consuming Gymnema sylvestre Reduces the Desire for High-Sugar Sweet Foods. *Nutrients.* 12, 4 (Apr. 2020), 1046. DOI:https://doi.org/10.3390/nu12041046.
[52] Weiss, T., Shushan, S., Ravia, A., Hahamy, A., Secundo, L., Weissbrod, A., Ben-Yakov, A., Holtzman, Y., Cohen-Atsmoni, S., Roth, Y. and Sobel, N. 2016. From Nose to Brain: Un-Sensed Electrical Currents Applied in the Nose Alter Activity in Deep Brain Structures. *Cerebral Cortex.* 26, 11 (Oct. 2016), 4180–4191. DOI:https://doi.org/10.1093/cercor/bhw222.
[53] Yagi, I., Ebihara, Y., Inada, T., Tanaka, Y., Sugimoto, M., Inami, M., Cheok, A.D., Okude, N. and Inakage, M. 2009. Yaminabe YAMMY: an interactive cooking pot that uses feeling as spices. *Proceedings of the International Conference on Advances in Computer Enterntainment Technology - ACE '09* (Athens, Greece, 2009), 419.
[54] Yanagida, Y. 2012. A survey of olfactory displays: Making and delivering scents. *2012 IEEE Sensors* (Taipei, Taiwan, Oct. 2012), 1–4.
[55] 2016. *An Ancient Roman Experience Enhanced by Using PIPES.*
[56] 1917. Enthusiastic Audience Opens the New Rivoli: Latest Picture Theatre Fulfils All the Rothapfel Promises. *The Evening World.*
[57] 1917. Rivoli Among World's Finest Theater Structures. *The Dramatic Mirror.*