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Wearable and Portable Electric Taste Device and the Characterization of the Electrical Taste Sensations Produced

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Abstract: This paper introduces a wearable and portable computer interface designed to produce virtual taste sensations on the human tongue without the use of chemicals. The device achieves this by delivering electrical stimulation, and the intensity and type of taste sensations can be adjusted by modifying parameters such as frequency, duty cycle, and voltage intensity of the output signal. Our study demonstrates that this compact system can reliably evoke statistically significant sour and salty taste sensations, with over 50 participants also reporting experiences of spicy, bitter, metallic, electric, and pressure sensations. Increased voltage amplitude resulted in more intense sensations, while lower duty cycles produced lingering cold feelings, and higher duty cycles generated pressure and discomfort. Interestingly, the intensity of metallic taste sensations remained consistent across varying duty cycles and frequencies. This research highlights the potential of wearable digital taste technology to revolutionize virtual sensory experiences, opening new opportunities for applications in immersive media, health, and entertainment.

Keywords: virtual taste, digital taste, taste characterization, taste receptors, electrical stimulation of taste, taste communication

1. Introduction

Taste sensation is produced when a chemical substance reacts with taste receptor cells located on taste buds in the oral cavity, and the tongue. Taste buds are the primary sensory unit of the taste system and are composed of 150 to 300 tightly packed cylindrical cells of epithelial origin (taste cells). Evidence now suggests that each taste modality is mutually exclusive to a subset of individual taste cells [1]. Regarding the biology of human taste, taste cells get stimulated and send signals through cranial nerves (facial, glossopharyngeal, and vagus) to taste regions in the brainstem. Such impulses are then directed to the thalamus, which relays sensory information to other brain regions, such as the frontal lobe gustatory cortex and the amygdala implicated in taste perceptions. Notably, the sense of taste not only enables us to choose and enjoy the food required for our existence but also represents a sensory channel that helps us interpret our environment regarding specific contexts, as in the case of social interactions.

The concept of producing taste sensations using electrical stimulation of the tongue was first brought up in the 1960s in the medical field. In particular, previous studies addressed the aspect of sensing the taste ability of patients and termed it as "electrogustometry (EGM)" [2]. Compared to the other methods used in the field, such as thermal taste stimulation [3], this method enables targeting an exact area on the tongue and provides a more controlled approach regarding the possibility of varying stimulation parameters. Therefore, the use of EGM is widespread in research and clinical settings.

The Internet of Things and virtual reality (VR) represent emerging technologies with the potential to profoundly influence how we interact with our environment and other individuals. Therefore, endowing such systems capable of producing sensations covering the full range of human senses represents a relevant issue for developing ecological systems. Focusing on taste and using chemical substances to elicit sensations represents a limitation within digital and virtual contexts. Therefore, developing non-chemical approaches that may naturally be embedded into VR technologies and thus have implications for their ecological validity and sense of immersion is highly relevant.

The work described in this paper is a part of the authors' long-term research project on developing digital taste and smell actuation technologies. In 2011, the first digital taste actuation technology based on electrical stimulation was presented in a conference [4]. Another thermal stimulation-based digital taste technology which produces sweet taste sensations was recently published in the IEEE TVCG journal [3]. Furthermore, an early prototype with some preliminary test results was published in a non-peer-reviewed book chapter, but it lacked the comprehensive study findings presented in this work [5].

The electric taste device generates rectangular wave pulses of different frequencies, duty cycles, and duration to elicit different taste sensations, as illustrated in Figure 1.

In fact, given the complexity of electric-induced taste sensations, we expected a proper description of its characteristics based on taste properties and a collection of taste-related and non-taste-related sensations. To our knowledge, this is the first study

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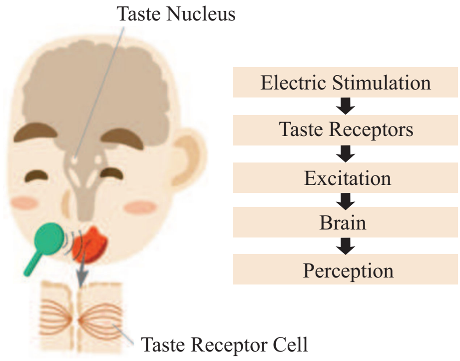
Figure 1
Approach to digital taste stimulation



that addresses the characterization of induced electric taste using taste and non-taste sensations. In particular, the present study characterizes electric taste and reports how different characteristics of electrical stimuli give place to different electric taste sensations.

Experiments conducted by using the electric taste device revealed following findings: The device produced different taste sensations including salty and sour with some non-taste sensations such as electric and carbonation on human subjects. The user study results showed that sour and salty sensations are statistically significant. In addition, over 50% of the subjects mentioned feeling pressure, metallic, electric, spicy, and bitter. We also found that higher voltage amplitudes result in more intense sensations. Moreover, higher duty cycle values lessened pressure and unpleasantness while lower duty cycle values produced lingering, cold sensations.

The remaining sections of this paper are organized as follows: In Section II, we discuss previous electrogustometry studies dealing with electrical stimulation of the tongue. In Section III, we provide a detailed description of the developed technology. In Section IV, we discuss user experiment procedures and results. Finally, Section V will discuss our findings, future work, and potential applications.

In 1754, Sulzer reported that placing the tongue between lead and silver electrodes gives rise to sensations similar to ferrous sulfate. In 1786, Alessandro Volta investigated how electrical stimulation affected human senses, especially touch, taste, and sight. He was able to feel salty by placing two coins (made of different metals) on the upward and downward surfaces of his tongue and connecting them with a wire [5].

EGM is a technique based on presenting anodal currents (100 μA) to anterior taste bud fields. EGM was introduced in the 1950s for the clinical assessment of taste function. Since then, it has been routinely used in clinical practice as a valid tool to identify taste dysfunctions and test the integrity of gustation and sensory pathways [6]. Importantly, EGM can elicit salty, sour, metallic, or sour/metallic sensations [7]. Recent advancements in EGM and electrogustatory stimulation have expanded its applications beyond clinical diagnostics, encompassing sensory rehabilitation, virtual environments, and wearable device development [8–29]. These developments have demonstrated that electrical stimulation can reliably evoke taste sensations, including sour, salty, metallic, and pressure-related experiences, paving the way for innovative applications in both clinical and technological contexts.

A sour taste elicited by weak electrical current delivered to the tongue's surface was documented in 1996 [30]. Nevertheless, recent reports have shown that electrogustometry relates to an ability to sense all four tastes: sour, sweet, salt, and bitter. The observation that electrogustometry is correlated with all four taste qualities was reported in 2007 [31]. In particular, the authors proposed that there is a direct depolarizing mode of action of the sensory-neural tongue aspects. By performing both anodic and cathodic stimulation on a single human tongue, the papilla of five subjects, Plattig and Innitzer [32], reported a sour taste (22.2%) and some small responses for the bitter (3.8%) and salty (1.8%). Also, it was emphasized a sour and sweet combined sensation (8.9%) under cathodic stimulation and 9.3% sour and salty, 12.09% sour and bitter sensations under anodic stimulation. Moreover, Lawless et al. [33] were able to elicit a metallic taste from electrical and chemical stimulation. In particular, the authors reported that the intensity of taste was dependent upon the sulfate solution used for stimulation and the voltage intensity in areas dense in fungiform papillae and that such intensity was not affected by nasal occlusion.

As previously indicated [34], several researchers invented equipment for sweet tastes. Research has concentrated on creating a sweet or any previous major taste [35]. Karunanayaka et al. [3] and other researchers developed an interface that produces sweetness by warming the mouth. They continued by stating that chilling the tongue results in a minty and pleasant sensation, while quickly reheating it gives a sweet and greasy sensation. Excellent research was done on digital taste by Ranasinghe et al. [36]. They produced the four fundamental tastes of sweet, sour, bitter, and salty on the tongue's surface by applying electrical and thermal stimulation.

Based on the idea of developing an EGM technology for daily use, some of us introduced the first stimulation device for electric taste in 2011 [4]. In the same year, Nakamura and Miyashita [37] addressed the aspect of augmented gustation by applying electric current through isotonic drinks and juicy foods to change the taste perception.

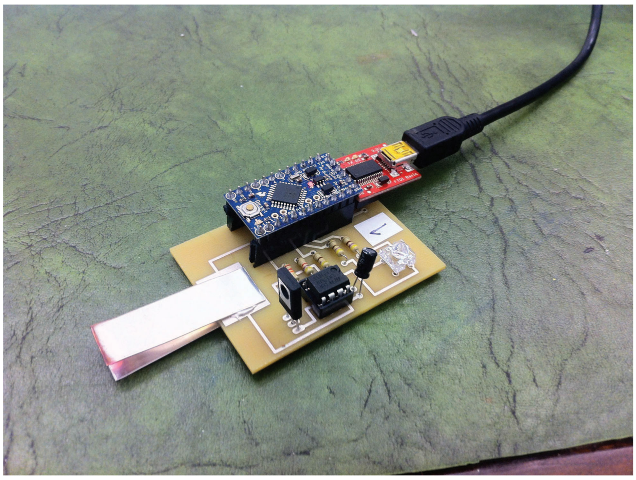
Through EGM, researchers have discovered that electrical and thermal stimulation can elicit various taste sensations, including sweet, sour, bitter, salty, and even metallic [38]. The Digital Lollipop, also known as the Digital Taste Interface, was developed in 2016 to simulate primary taste sensations through electrical and thermal stimulation on the human tongue [39]. Overall, research has shown that electrical and thermal stimulation can evoke various taste sensations.

However, these techniques for electrical and thermal stimulation of the tongue predominantly produce metallic or acid sensations, limiting their ability to simulate other taste sensations accurately [40]. Furthermore, stimulating gustatory fibers through electrical means or bypassing the tongue's taste buds raises questions about the accuracy and complete simulation of taste experiences, as taste is not solely determined by the activation of taste buds but also by complex neural interactions and cognitive processes [41]. Overall, the use of electrical and thermal stimulation on the human tongue has shown potential in simulating primary taste sensations, although there are limitations in accurately replicating the full range of taste experiences and avoiding metallic or acidic sensations [41].

1.1. Principle of electric taste stimulation

Electrical stimulation of the tongue induces taste perceptions through direct activation of taste receptor cells and neural pathways. The human tongue contains taste buds composed of specialized taste receptor cells, which transduce chemical stimuli into neural signals. However, research has demonstrated that these cells can also be excited by electrical currents, leading to taste perceptions independent of chemical stimuli. When an electrical stimulus is applied to the tongue, it depolarizes the taste receptor cells, activating ion channels such as epithelial sodium channels

Figure 2
Digital taste interface device



(ENaCs) for salty sensations and proton-sensitive channels for sour perceptions. The generated bioelectric signals are transmitted via the facial (cranial nerve VII), glossopharyngeal (cranial nerve IX), and vagus nerves (cranial nerve X) to the brainstem's solitary nucleus, where taste signals are processed and relayed to the thalamus and the gustatory cortex in the insula and frontal operculum.

EGM studies suggest that cathodal stimulation tends to elicit sour and metallic sensations, whereas anodal stimulation is associated with salty and bitter perceptions, potentially due to differences in ion migration and the direct activation of specific taste-related ion channels. Additionally, electrical stimulation can activate mechanoreceptors and nociceptors in the tongue, leading to secondary sensations such as tingling, pressure, and irritation [19]. This interaction between taste receptors, neural pathways, and mechanosensitive fibers underpins the ability of electrical stimulation to evoke complex and multi-modal taste experiences.

2. System Description

The prototype developed is shown in Figure 2. This device provides low-intensity electric pulses based on a particular frequency and PWM. The electric pulses were generated based on the user's input and outputted to the tongue membrane, where the tongue makes physical contact with the device. The current travels across the tongue, which excites the taste cells that may, in turn, activate brain regions engaged in taste perception.

The printed circuit board was designed using Eagle software, and Figure 3 shows the board diagram of the device. It was equipped with an Arduino Pro Mini microcontroller, constant current circuit, silver electrode, and LED indicator. The microcontroller was chosen due to its flexibility, low cost, and small size. Since the microcontroller board does not have a built-in USB circuitry, a FTDI Basic Breakout Board and a USB Mini-B cable were used to set up the communication with the computer. There are two versions of the microcontroller board: one at 5 V and one at 3.3 V. However, when the device operates at 5 V, it creates stronger pulses and increases sensations with higher intensity. Therefore, we decided to use 5 V FTDI converter boards for the device. Based on the control commands, it generates square wave pulses with different frequencies and PWM values. The device was designed to operate in six modes: digital high, digital low, 20 Hz/50% duty cycle, 1200 Hz/50% duty cycle, 500 Hz/39% duty cycle, and 500 Hz/94% duty cycle. Digital high maintains the voltage value at 3 V, while digital low at 0 V. For 39% duty cycle mode, the signal is on 39% of the time and off 61% of the time. Similarly, for 94% duty cycle mode, the signal is on 94% of the time and off 6% of the time. The maximum current used for this experiment is 0.67 mA, and the frequency ranges from 0 Hz to 1200 Hz. Each signal pattern generated by the device is shown in Figure 4. The signal was measured by a Keithley DMM7510 Sampling Multimeter using the two-probe method. From the signal, we can see negative spikes at the falling edge due to stray inductance.

Due to impedance differences on different persons' tongue, we improved our circuit to provide a constant current source using an operational amplifier and an NPN transistor. The operational amplifier

Figure 3
Schematic diagram of the electric taste device

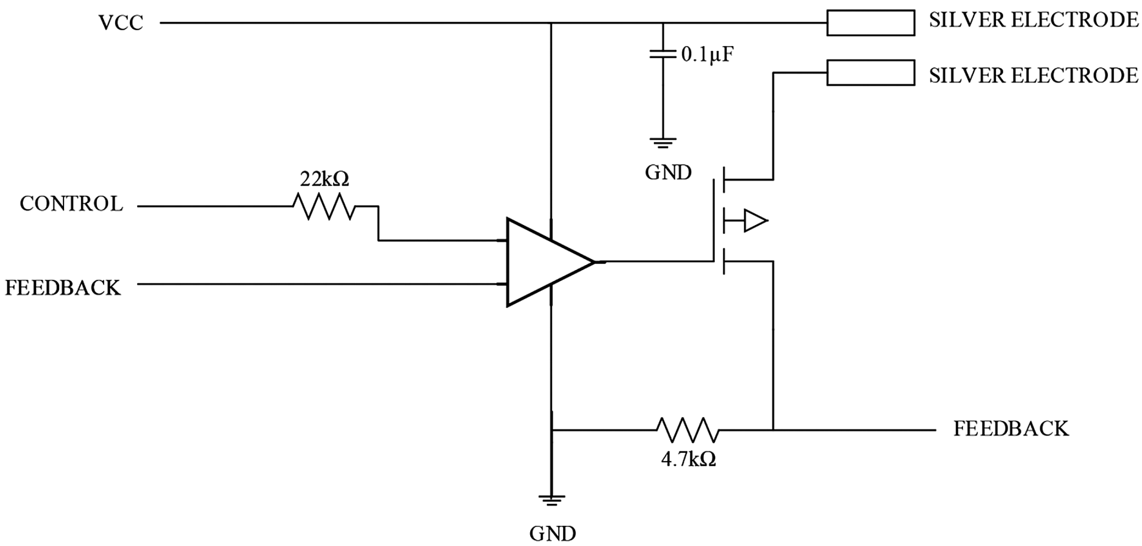
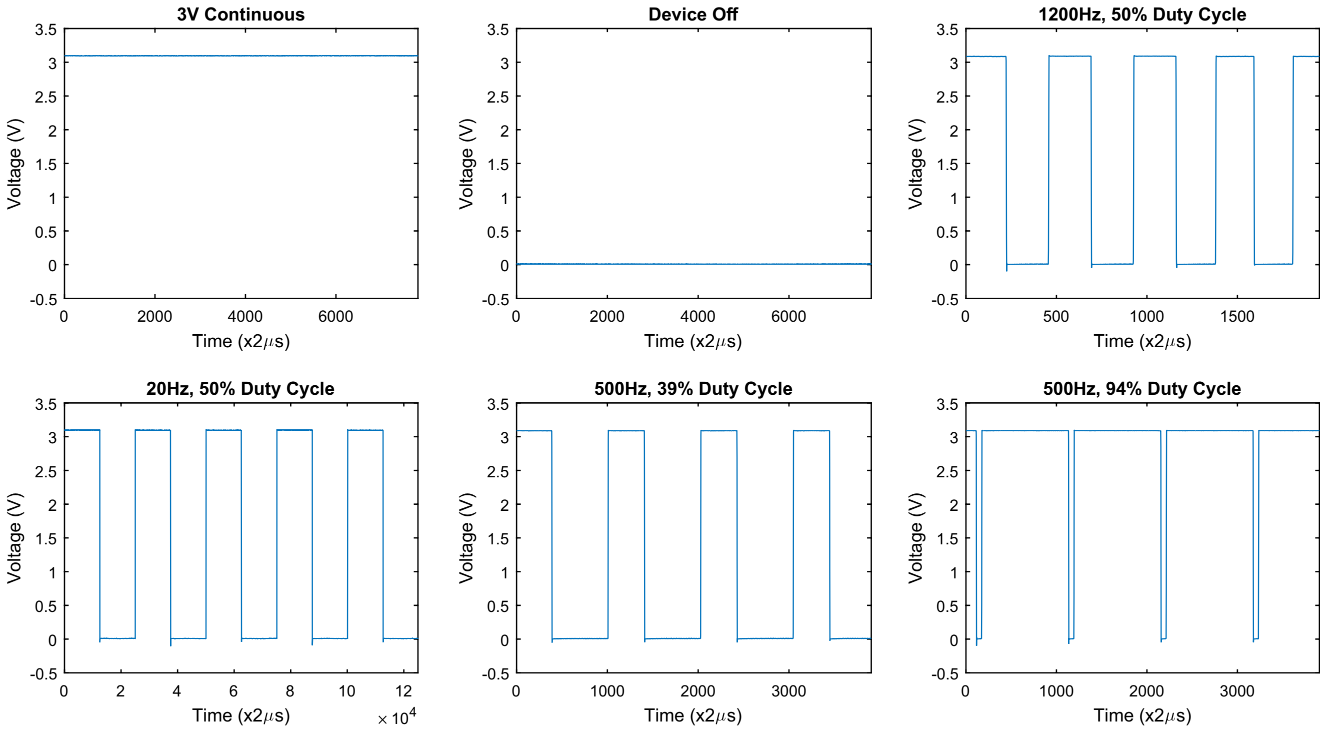


Figure 4
Different stimulation signals generated by the device when it is operating at 3.3 V



has negative feedback and balances the $V+$ and $V-$ terminals to approximately the same potential. By having this circuit, the current is kept constant through the transistor, so the output to the silver electrode is maintained even with the addition of a negligible amount of current from the output of the operational amplifier.

The silver electrodes were custom-made and contain 99% pure silver. We have selected silver since it provides very few metallic taste sensations. Therefore, we can ensure that the sensation produced by the device is due to electric pulses and not due to the natural metallic taste of the metal. The distance separation between both electrodes was maintained throughout the experiment, and each electrode had a thickness of 0.45 *mm*. When the two silver electrodes are connected through the external circuit by means of tongue contact, the circuit will close and flow the current. The pulses generated by the circuit are delivered to the silver electrodes placed on the top and bottom of the tongue. The electrodes were fixed to the PCB using a special conductive epoxy that can conduct current from the PCB to the electrodes with very low resistance.

The LED indicator was designed to ensure the type of signal produced by the circuit. Each stimulation mode has a unique light indication: continuous purple for digital high, continuous red for digital low, continuous green for 500 *Hz*/94% duty cycle, and continuous blue for 500 *Hz*/39% duty cycle. Blinking blue LED will show for 20 *Hz*/50% duty cycle and 1200 *Hz*/50% duty cycle, with the blinking rate depending on its frequency value.

3. User Evaluation

3.1. Prescreening of participants

Participants were pretested to ensure that they did not suffer from any taste disorder and could identify and differentiate between four basic tastes: sweet, sour, salty, and UMAMI. We purposely omitted the UMAMI taste as it is not common for most of our participants. First, subjects were asked to answer a simple questionnaire. Therefore, we intended to identify if subjects suffer from any known taste disorder or from any temporary disability in relation to taste perception (ex., Losing the sensation of taste after an accident). Importantly, subjects were notified not to eat or drink anything 30 min before the experiment, and distilled water was used to rinse the mouth before each trial. Afterwards, we placed five different taste solutions with known concentrations in front of the subject, which represent the four basic considered tastes (sweet, sour, bitter, and salty (labeled as A, B, C, and D)). Stimuli were prepared in aqueous solution of distilled water, including coarse sugar 15 *g*/*l*, Coarse Salt 3.325 *g*/*l*, citric acid 5 *g*/*l*, and paracetamol 2.5 *g*/*l*. These weights were selected by testing solutions with different concentrations with 10 lab members. The selected concentrations reflect the minimum values that all 10 members were able to correctly sense and differentiate with regard to the four considered tastes.

After preparing the solutions mentioned above, we moved into the pre-screening of participants. Participants first tasted a solution by keeping 10 *ml* of the solution in their mouth for 10 s. The experimental setup is depicted in Figure 5.

Later, they were asked whether they perceived any taste and the type of taste in case of an affirmative answer. The order of presentation of taste solutions was counterbalanced across participants. After analyzing the results, participants who correctly differentiated all five basic tastes and reported no taste-related disorders on the questionnaire were selected for the main experiment.

The six sets of experimental parameters for the pilot experiment were selected by evaluating different voltage, frequency, and duty cycle combinations that produced distinguishable taste sensations. These parameters, which included variations in voltage (0 V and 5 V), frequency (0 Hz, 20 Hz, 500 Hz, and 1200 Hz), duty cycle

Figure 5
Experiment setup with a participant

Table 1
Different stimulation parameters used for the pretest experiment

Stimuli No	Voltage (V)	Frequency (Hz)	Duty cycle	Duration(s)
1.	0 V	0 Hz	0%	10 s
2.	5 V	0 Hz	100%	10 s
3.	5 V	20 Hz	50%	10 s
4.	5 V	1200 Hz	50%	10 s
5.	5 V	500 Hz	39%	10 s
6.	5 V	500 Hz	94%	10 s

(ranging from 0% to 100%), and a constant stimulation duration of 10 s, are detailed in Table 1.

These parameters were designed to cover a broad range of electrical stimulation conditions, ensuring that the final selection for the main study included the most effective stimuli.

Importantly, the 20 participants in the pilot study and the 40 participants in the main study were completely independent groups. All participants were general public volunteers, recruited separately to ensure unbiased results. There was no overlap between the two groups to prevent prior exposure from influencing taste perception.

While increasing the number of participants could enhance statistical significance, the study was constrained by practical limitations. The experiments required several months to complete, involving significant time and resources. Despite these constraints, the statistical analyses (Kruskal-Wallis and Mann-Whitney U tests) confirmed that the collected data provided meaningful insights into electrically induced taste perceptions. Future studies may increase participant numbers or employ alternative methodologies to further validate these findings.

3.2. Main study

This study's main objective was to understand the virtual taste sensations produced by the introduced computer taste interface. Specifically, we stimulate participants' tongues with selected stimulation parameters and document their taste perception. By analyzing the results, we wanted to describe electric taste sensations based on known tastes and sensations. We employed several stimulation parameter combinations that the device could generate to do so. Specifically, we selected only four frequencies that produce various taste sensations. As the first step, we did a pretest with 20 lab members and tested 6 different sets of stimulation parameters. We selected the best four sets of parameters that provide different sensations based on the pretest results. The following are the main factors that determine the stimuli the device produces.

Table 2
Different stimulation parameters used for the main experiment

Stimuli No	Voltage (V)	Frequency (Hz)	Duty cycle	Duration (s)
1.	0 V	0 Hz	0%	10 s
2.	5 V	0 Hz	100%	10 s
3.	5 V	20 Hz	50%	10 s
6.	5 V	500 Hz	94%	10 s

Voltage: The device enabled selection of either 3.3 *V* or 5.0 *V*. This can be done by selecting the 3.3 *V* or 5 *V* FTDI breakout board. We tested 10 lab members with two different sensations produced 5 *V* and 3.3 *V*, and all reported that 5 *V* elicits more intense sensations. Therefore, we decided to select 5 *V* for the pretest and main study.

Frequency: By considering that frequency generates different taste and non-taste-related sensations. We decided to focus on four different frequencies (0 *Hz*, 20 *Hz*, 500 *Hz*, and 1200 *Hz*) for the pretest and 3 different frequencies (0 *Hz*, 20 *Hz*, and 500 *Hz*) for the main study.

Duty cycle: Duty cycle is another crucial parameter leading to different sensations. The following duty cycles were used during the experiments (0%, 39%, 50%, 94%, and 100%).

Stimulation time: We have selected a constant time period for the stimulation. For both the pretest and main study, we used 10 s. The pretest results helped refine the stimulation parameters for the main experiment. The main experiment focused on three specific voltage and frequency combinations (0 *Hz*, 20 *Hz*, and 500 *Hz*), with a duty cycle set at either 50% or 94%, and a stimulation duration of 10 s. These finalized parameters are summarized in Table 2.

Based on the pretest results, the stimulus that provided the best sensations was selected for the main study.

The order of stimulation conditions presentation for trials between participants was counterbalanced. There were about 50 participants recruited for the user study. Participants' experiences were recorded in each trial using visual analogue scales numbered from 0 (none) to 10 (Strongest) for 20 different taste elements. They are Sweet, Sour, Bitter, Salty, UMAMI, Carbonation, Metallic, Chemical, Electric, Fatty (Oily), Spicy, Numbing, Lingering, Pressure, Pain, Cold/Warm, Pleasant/Unpleasant. On the response recording sheet, we have provided English and two other native languages, which makes it easier for the participant to understand.

3.2.1. Participants

Participants selected for the experiment were mainly recruited from a nearby university. 40 participants participated in this study (23 females, mean age 24). The majority of the participants were university students aged 20 to 23, however few adults also taking part in the experiment. Also, some participants who didn't experience this device before were called for the experiment. This experiment was approved by the Institute's internal review board and conducted according to their standards. All the participants in the study were paid for the time they spent using standard rates.

3.2.2. Procedure of the experiment

Subjects were asked not to eat or drink anything 30 min before the experiment. Distilled water was used to rinse the mouth of the subject before each trial. The idea was to leave the last tasted sensation from electric stimulation by tasting water. This is a general practice for taste experiments that allows the reset of taste receptors in the tongue. After rinsing the mouth with water, an electric taste device was placed on the tip of the participant's tongue and stimulated using one of the following stimulation parameters. After the stimulation, the participant was asked to describe his/her electric taste experience by rating the elements on the paper on the visual analogue scale provided (from 4 (none) to 10 (Strongest)). Also, the participant was asked to write down the experiences which are not listed and rate their intensity. Further, there is a space to describe the experience using words. Next, the participant rinsed the mouth with distilled water and experienced the next stimulation. These steps continued until the participant was done with all the parameters for four trials. So, this experiment consisted of 16 trials in total (4 stimulation parameters * 4 trials). The order of the stimulation parameters was counterbalanced across participants.

It is not necessary to preheat the silver electrode before placing it in the participant's mouth. The high thermal conductivity of silver ensures that it rapidly equilibrates to oral temperature within seconds, reducing any potential discomfort. Additionally, the human oral cavity naturally adapts to minor temperature variations through blood flow and saliva circulation. More importantly, electric stimulation itself is the primary factor influencing taste perception, as demonstrated in EGM studies. Introducing preheated electrodes could introduce uncontrolled experimental variables, making it difficult to standardize conditions across trials. Furthermore, saliva acts as a natural insulator, further minimizing any transient thermal sensation. Given these factors, heating the electrodes is unnecessary and does not impact the accuracy of the experiment.

4. Results and Discussion

Figures 6 and 7 show the mean intensities of taste-related and non-taste-related sensations reported by the participants during the trials. Figures 8 and 9 show the percentage of participants who reported taste-related and non-taste-related sensations during the four trials. For most of the sensations, there is a clear difference between the control trial and other three stimulation trials for both taste-related and non-taste-related sensations.

Table 3 displays the summary statistics of the Kruskal-Wallis test on Virtual Taste Sensations among respondents with different Stimulation groups. In the case of Virtual Taste Sensations (Sour, salty, Metallic, Electric, Spicy, Lingering, pain, and Pressure), Chi-square values are 27.751, 25.557, 17.452, 13.009, 10.039, 9.311, 12.624, and 9.412. Obtained p-values 0.000, 0.000, 0.001, 0.005, 0.018, 0.025, 0.006, and 0.024 are significant at 5% level (p-values <0.05).

In order to determine gender differences in Virtual Taste Sensations, we conducted another statistical analysis. Mann-Whitney U Test is a non-parametric statistical test carried out to measure the differences in Virtual Taste Sensations between genders. Table 4 shows the summary statistics of the Mann-Whitney U Test. The Z-values for Virtual Taste Sensations (Salty. Sour, Electric, Pressure and pain) (−4. 183, −3.774, −2. 161, −3.231, and −2.632) are significant at 5% level (p-values <0.05). Therefore, this concludes that male and female respondent does differently in their Virtual Taste Sensations.

Our results showed that the introduced digital taste device significantly affected several taste sensations, including sour, salty, metallic, electric, spicy, lingering, pain, and pressure. Stimulations with 20 *Hz* and 50% duty cycle produced the strongest taste sensations compared to other stimulation parameters, and the strongest sensation produced by this parameter is salty, with a mean rank of 77.47. On the other hand, 3 *V* continuous stimulations yield

Figure 6
Intensity of taste-related sensations for different stimulation conditions. Range: 0–10 (strongest)

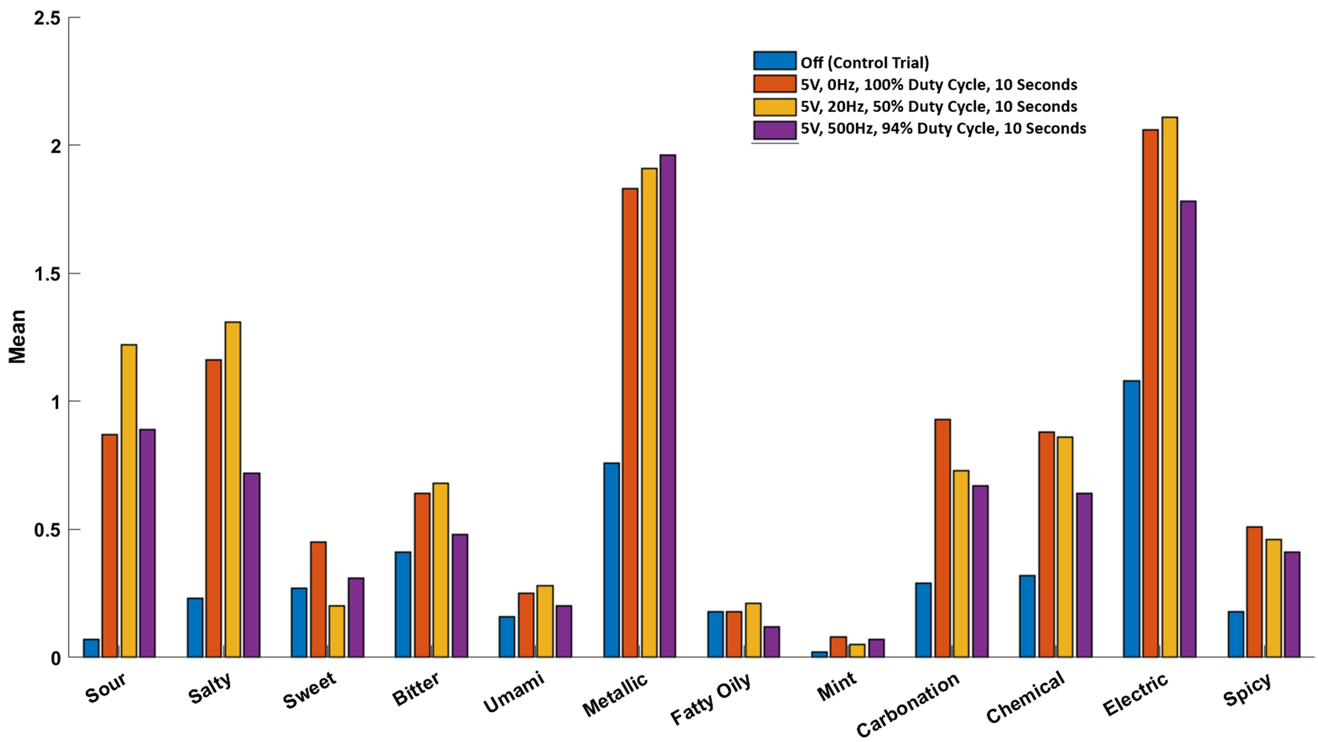


Figure 7
Intensity of non-taste-related sensations for different stimulation conditions. Range: 0–10 (strongest)

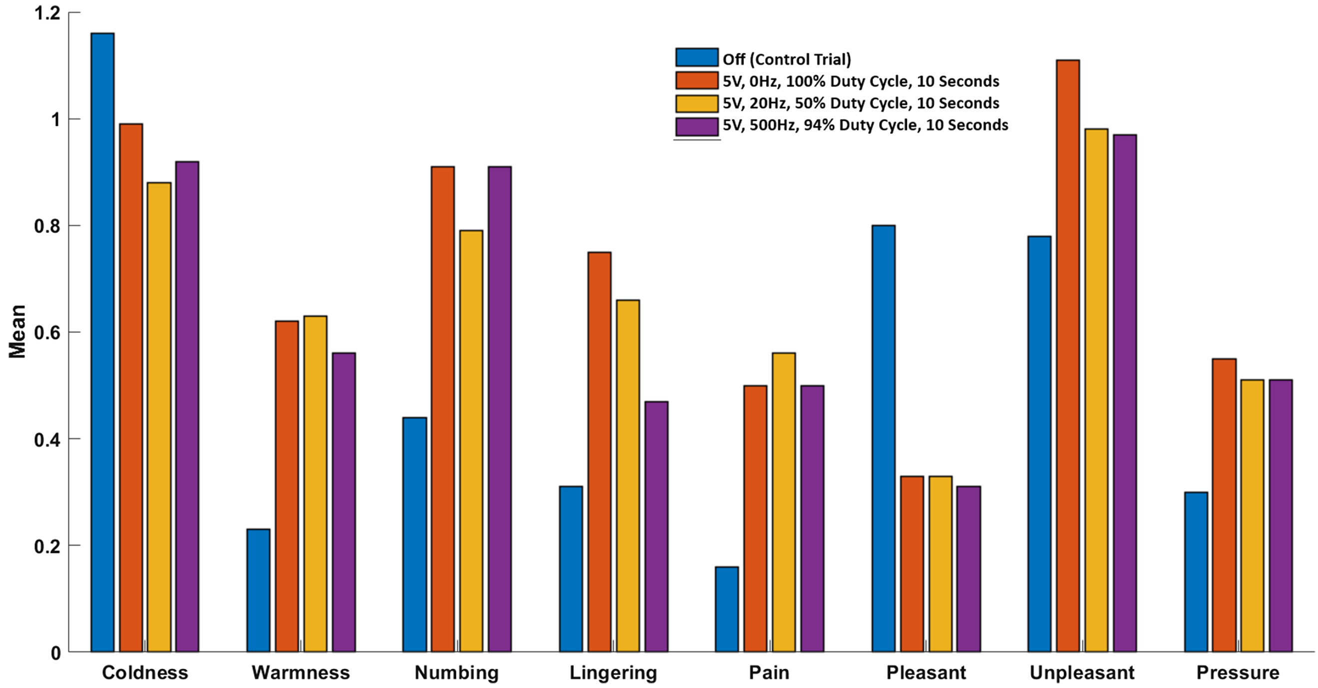


Figure 8
Proportion of participants reporting taste-related sensations across stimulations

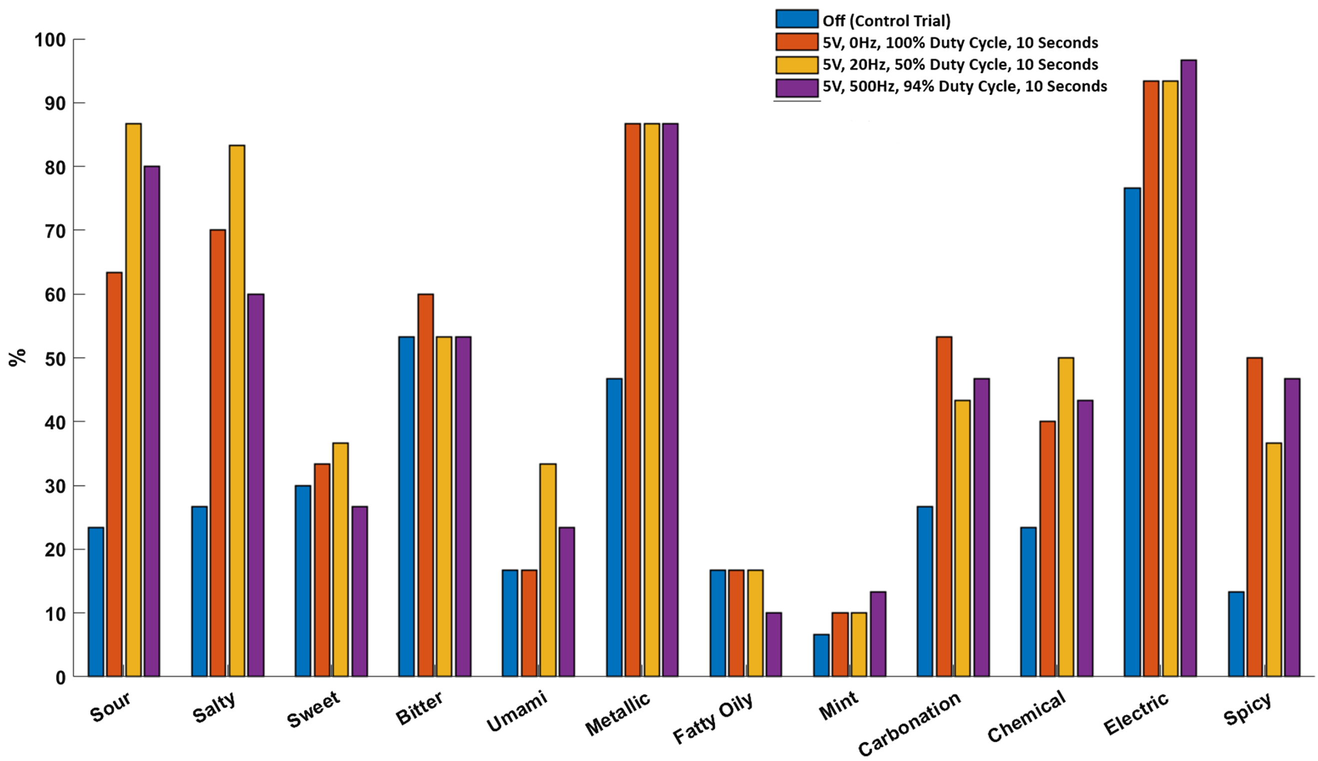


Figure 9
Proportion of participants reporting non-taste-related sensations across stimulations

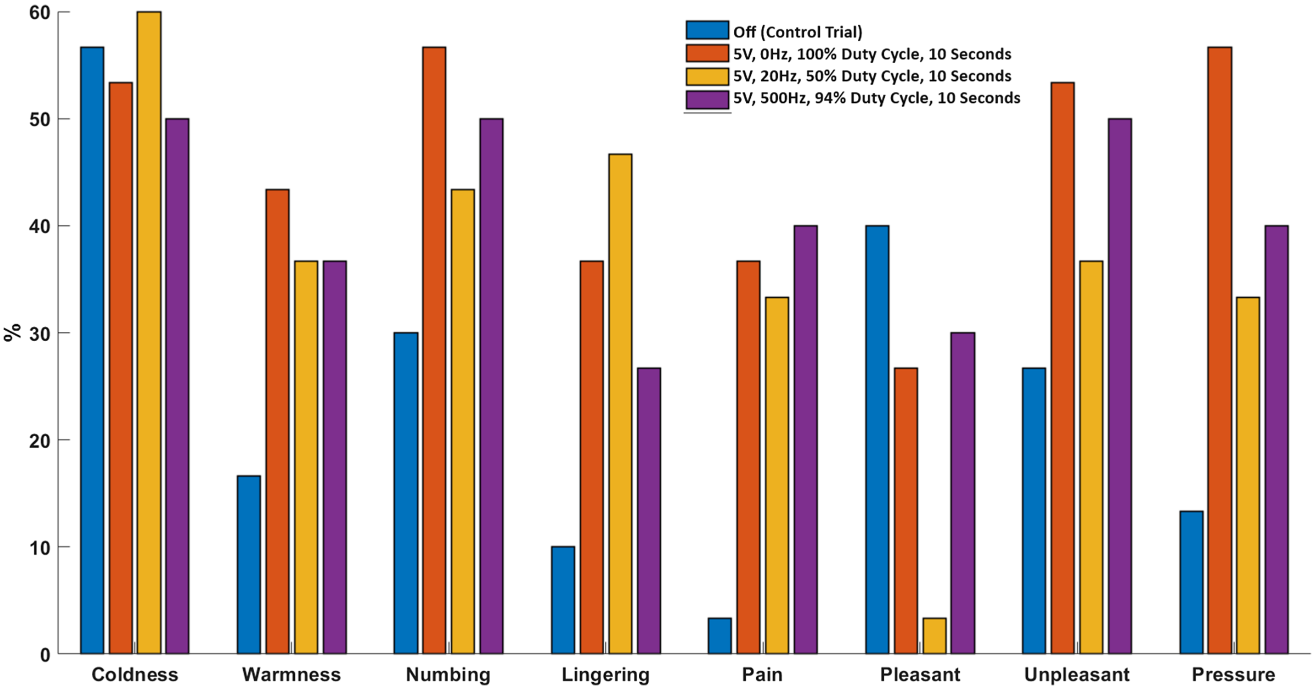


Table 3
Summary statistics of Kruskal-Wallis test on virtual taste sensations among respondents with different stimulation groups

	Sour	salty	Metallic	Electric	Spicy	Lingering	pain	Pressure
Mean Rank off	33.52	36.60	37.77	41.08	46.12	48.50	45.03	47.28
Mean Rank 5 V	62.78	70.27	67.63	66.98	69.02	65.18	65.68	70.20
Mean Rank 20 Hz	76.15	77.47	69.58	70.05	61.95	69.35	64.50	60.87
Mean Rank 94% duty cycle	69.55	57.67	67.02	63.88	64.92	58.97	66.78	63.65
Chi-Square	27.751	25.557	17.452	13.009	10.039	9.311	12.624	9.4125
Asymp. Sig.	0.000	0.000	0.001	0.005	0.018	0.025	0.006	0.024

Table 4
Summary statistics of Mann-Whitney U test on virtual taste sensations between male and female respondents

	Sour	Metallic	Electric	Spicy
Mean Rank Male	74.73	69.58	71.29	69.01
Mean Rank Female	51.03	55.87	54.26	56.40
Mann-Whitney U	1186.000	1495.500	1392.500	1529.500
Z	−4.183	−2.161	−3.231	−2.632
Asymp. Sig. (2-tailed)	0.000	0.031	0.001	0.008

the highest rank for spicy, with a mean rank of 69.02. Hence, this study revealed that the frequency parameter considerably alters the human taste perception from sour and salty to spicy taste. A square wave impulse has a significant direct current component (which depends on the percentage of the duty cycle and the frequency) which makes it difficult to pass the current through the tongue. This may be why the user feels less pain since the low-frequency component will reduce muscle contraction during the stimulation. Further, when the device is in the 'Off' mode, the result reported the lowest mean rank for all taste sensations, which proves that the presence of both frequency and current parameters immensely affect all the taste sensations in the same way.

Additionally, we found gender differences with regard to sensitivity towards the same stimulation parameter. Male participants reported a stronger perception than females of taste sensations such as saltiness, sourness, electricity, pressure, and pain. The highest difference was in the salty taste, with a divergence of 23.7. By observing the sensitivity difference in both males and females, we showed strong support for research that mentioned in previous work that men score higher in discerning salty flavor, and women are sensitive to bitter flavors and prefer higher concentrations and greater quantities of sweet things [42]. The following explanations address the human salty and sour taste receptors, chemical structures, and genes.

Salty taste is commonly elicited by the consumption of NaCl and other minerals. As a result, humans and animals might seek out mineral-rich foods while avoiding overly salty foods in order to preserve ion-water balance. In rats, the channel receptor for salty taste has long been known as the ENaC. These receptors provide a specialized channel for sodium current into the taste cell, if Na+ ions are present inadequate concentration in the oral region. There is some discovery as amiloride was believed to be specific to ENaC. However, amiloride does not inhibit much of human salt taste, which is inhibited by another compound, chlorhexidine, suggesting that the stoichiometry of human ENaCs may differ from rodents or totally different channels are responsible for human salt taste. There is also evidence that the amiloride sensitivity of NaCl taste in humans is specific to the very minor sour component, not the salt itself. At present, the transduction mechanism for human salt taste is unknown.

Acids possess a sour taste and are appealing to humans as well as animals at low quantities, such as in fruits and confectionery. However, it can elicit a natural rejection response if it comes from food ruined by acid-producing microorganisms or unripe fruits, which act as inverse indicators of sugar concentration. Ion channels receive this taste, but the identity of these channels is not firmly established. There are also studies on perceiving sourness as proportional to the concentrations of protons. It impacts a range of pH-sensitive cellular targets, facilitated by their high permeability through various types of ion channels and inter-cellular junctions. The cellular mechanism responsible for transducing sour sensation encompasses several pathways: 1. Direct inhibition of apical K+ channels by protons, 2. Activation of an H+-gated Ca2+ channel, 3. Proton conduction through apical K+ channels 4. A Cl− conductance, inhibited by 5-nitro 2-(3-phenylpropylamine) benzoic acid (NPPB), 5. Stimulation of the proton-gated channel, BNC-1, which belongs to the Na+ channel/degeneration superfamily, 6. Activation of HCN channels due to changes in extracellular pH induced by stimuli, and 7. Direct entry of protons into cells via acid-sensing ion channels.

Throughout fabrication and testing, we found out that the proposed device has several drawbacks. Each stimulation signal can produce a taste sensation. However, the taste intensity is not very strong. Some users get confused about which taste sensation is referred to by the stimulation signal. Consequently, different users provide different responses to the same stimulation signal. This is mainly because different people have different sensitivity towards the taste sensations. Everyone recognizes taste; however, the range of those tastes varies depending on the chemical processing in each person's tongue. People's tastes also differ due to the sensory capacities of the various tastes, which are determined by the structure of the receptors on the taste cells and their ability to excite the process that transmits a taste message. The receptors detect the signal that touches the front of the taste cells and transmit a message within the cell to the nerve terminals surrounding the cells. Everyone's unique structures are determined by their genes. Using those considerations, even if we stimulate a user with the same signal, some may perceive it as a sour and salty taste, while others may perceive it as sour and UMAMI.

In terms of the experimental procedure, cleaning the silver electrode with alcohol was time-consuming. Besides, some users considered the process unhygienic, although we cleaned the electrode properly. Users also hesitate to place the silver plate on top of the tongue due to fear of burning. In future works, we could address this issue by replacing the silver electrode with other disposable conductive materials suitable for this experiment. It will also help to ensure the safety of users from any harmful exposure. Another limitation of this device is the lack of user-friendliness. A computer powers the device through a cable connection, and a keyboard interface triggers the stimulation signal. Hence, it is not portable for frequent use. In future research, we may use a portable power supply to run the circuit and a push-button to stimulate the signal. The experiment can also be improved by having more subjects to provide more accurate information on the variability of percepts. We are also interested in discovering whether this device can reverse the poor sense of taste displayed by some people through electrical stimulations.

To further investigate the optimal stimulus combination, we analyzed individual stimulation parameters separately rather than in combined experimental conditions. This approach ensures rigor by isolating the effects of voltage, frequency, and duty cycle. A factorial statistical analysis revealed that while higher voltage consistently increased perceived taste intensity, the interaction between frequency and duty cycle showed no statistically significant variation in some cases (Figures 6 and 7). This suggests that while voltage strongly influences taste perception, frequency and duty cycle may contribute non-linearly or exhibit saturation effects at higher values. Future work should explore these interactions through a controlled regression model to refine the stimulation design further.

5. Conclusion

This paper presents the development of a wearable and portable digital device capable of stimulating taste receptors on the tongue to produce a variety of taste sensations. The results of the user study demonstrate that electrical stimulation can reliably evoke statistically significant sour and salty sensations, with more than half of the participants also experiencing spicy, bitter, metallic, electric, and pressure sensations. We observed that increasing voltage amplitude generally enhances sensation intensity, while lower duty cycle values produce lingering cold sensations, and higher duty cycle values induce pressure and discomfort.

The compact and portable design of this digital taste device enables seamless integration into various applications, particularly those requiring mobility and user comfort. With advancements to address the noted limitations and improve functionality, this wearable technology holds promise for aiding specific clinical populations, such as individuals with Ageusia who experience diminished food enjoyment due to impaired taste perception. Moreover, its potential to enhance VR experiences is substantial, offering immersive sensory interactions for VR training programs and entertainment.

By incorporating digital taste into VR headsets or other wearable interfaces, users can achieve a safer, more engaging learning experience in hazardous scenarios, such as training in the food manufacturing industry without exposure to spoiled or harmful substances. This innovative approach to human-machine interaction paves the way for breakthroughs in multisensory VR systems, transforming how we engage with digital environments.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Adrian David Cheok: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Emma Yann Zhang:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

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