Digital Lollipop: Studying Electrical Stimulation on the Human Tongue to Simulate Taste Sensations

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Among the five primary senses, the sense of taste is the least explored as a form of digital media applied in Human–Computer Interface. This article presents an experimental instrument, the Digital Lollipop, for digitally simulating the sensation of taste (gustation) by utilizing electrical stimulation on the human tongue. The system is capable of manipulating the properties of electric currents (magnitude, frequency, and polarity) to formulate different stimuli. To evaluate the effectiveness of this method, the system was experimentally tested in two studies. The first experiment was conducted using separate regions of the human tongue to record occurrences of basic taste sensations and their respective intensity levels. The results indicate occurrences of sour, salty, bitter, and sweet sensations from different regions of the tongue. One of the major discoveries of this experiment was that the sweet taste emerges via an inverse-current mechanism, which deserves further research in the future. The second study was conducted to compare natural and artificial (virtual) sour taste sensations and examine the possibility of effectively controlling the artificial sour taste at three intensity levels (mild, medium, and strong). The proposed method is attractive since it does not require any chemical solutions and facilitates further research opportunities in several directions including human–computer interaction, virtual reality, food and beverage, as well as medicine.

CCS Concepts: • **Human-centered computing → Interaction paradigms**; Interaction devices; • **Hardware** → *Emerging interfaces;*

Additional Key Words and Phrases: Digital Lollipop, taste simulation, digital taste, gustation, user interfaces, virtual reality

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1. INTRODUCTION

Visual and auditory media and simulation appliances have dominated the digital world for a long time. When people mention multimedia, they typically refer to audio and visual sensory simulations. We have televisions, computers, and various mobile devices, which provide immensely creative and exciting experiences. Current technologies have also been incorporating the sense of touch into digital systems. These are commonly known as haptic interfaces [Hayward et al. 2004]. However, at present, both the sense

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of smell and taste are generally stimulated using chemical substances; digital controllability of these two senses has yet to be achieved. For example, a virtual-reality helmet developed by British scientists can simulate five human senses. The helmet releases different chemicals in order to stimulate both the sense of smell and taste while hearing, sight, and touch senses are simulated digitally [Derbyshire 2009]. The main drawback of these solutions is the use of different chemicals to stimulate the senses of smell and taste. These solutions are analogs and associated with manageability, transferability, and scalability issues. Of the two senses, taste is even more underutilized, getting remarkably little attention in the domain of interactive and digital media. Thus, a new methodology is needed to digitally simulate the sensation of taste and enable it as a form of digital media.

Taste, as one of the five basic senses, plays a significant role in human life. When people refer to the sense of taste, they typically refer to the taste of food that they consume. More important, the sensation of taste may change people's mood. Research shows that, when people consume their favorite foods, it stimulates the release of β-endorphins, which is a substance that enhances mood [Drewnowski 1997]. This explains children's preference for candy, because the taste of candy makes them happy. Thus, it is said that if food is nutrition for the body, taste is nutrition for the soul [Drewnowski 1997].

Using chemical substances to improve the taste sensations of food is common in everyday life. For example, artificial taste compounds such as monosodium glutamate (MSG) are used for cooking in order to enhance the taste of umami. However, it has been discovered that overconsumption of MSG may cause unhealthy effects to the human body and brain [Blaycock 1996]. Therefore, digitally simulating taste sensations may reduce the risk of unwanted health effects when compared to chemical-based traditional stimulations. In addition, with the use of digital simulation of taste sensations, some people (e.g., diabetes patients) will have a new way to experience taste sensations (e.g., the sweet taste) without any serious health concerns.

Currently, there are several research projects being conducted on the electronic sensing of taste (e.g., the electronic tongue presented in Robertsson et al. [2007]). However, remarkably few reports are available regarding such work in literature related to electronic taste actuation. As a result, based on our initial research on electrical and thermal stimulation of taste sensations (previously published in Ranasinghe et al. [2011a, 2011b, 2011c]), we have developed the Digital Lollipop. The Digital Lollipop is an innovative electronic solution that we believe will supersede traditional chemical-based lollipops to create new interactions in the future. For example, we may be able to manipulate the taste of the Digital Lollipop through a smartphone application in the future. The Digital Lollipop can also be employed as a reward system in a computer game and send taste messages remotely.

At present, the system consists of a control system and a tongue interface, as shown in Figure 1. The properties of an electric current (frequency, magnitude, polarity) and the sensitivity of different regions on the human tongue are experimentally examined in order to simulate different sensations and control the levels of intensity of those sensations. Several basic taste sensations were reported from the experiments, such as sourness, saltiness, bitterness, and sweetness. The specific contributions of this article are as follows:

—Studying the possibility of generating basic taste sensations on different regions of the human tongue.
—Studying the possibility of generating basic taste sensations by inverting the direction of the applied current on the same position.
—Comparing and evaluating the differences between natural and artificial taste sensations, focusing especially on sour taste.

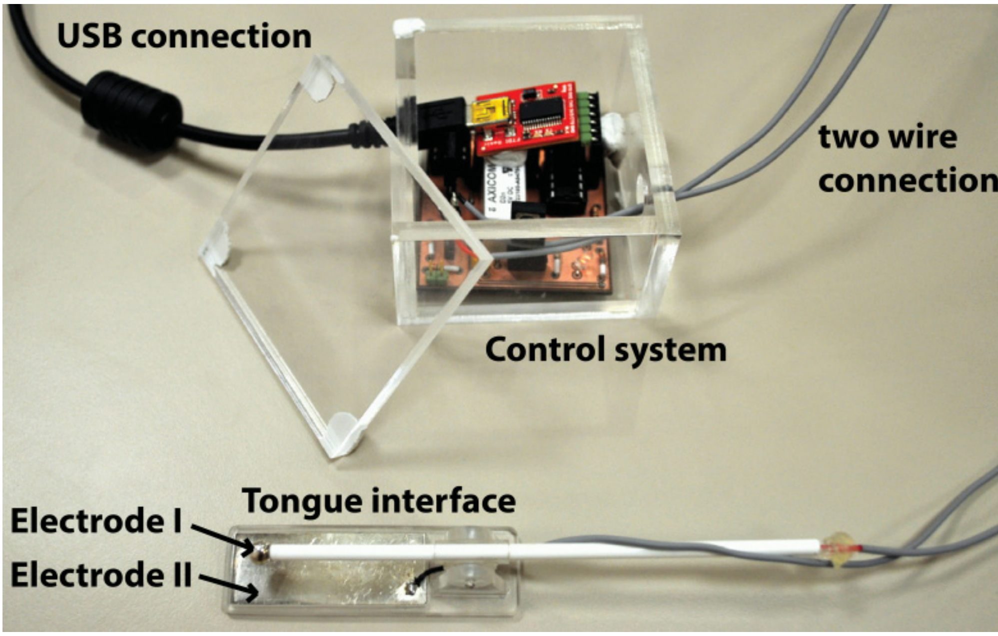

Fig. 1. Main components of the Digital Lollipop.

Furthermore, the studies presented in this article focus mainly on simulating primary taste sensations known as saltiness, sourness, bitterness, sweetness, and umami. The concept of flavor is beyond the scope of this research at present. Flavor is a complex perception. It is recognized as a combination of both taste and smell sensations [Firestein 2001], and is infinite and cognitive. Conversely, taste is a sensory function directly associated with the human tongue and sensitive to chemical stimuli.

The rest of the article is organized as follows. In Section 2, we present work related to chemical-based taste interactions and nonchemical taste interactions. In Section 3, we describe the design process of the system. We then present the system description of the Digital Lollipop and technical measurements of the device in Section 4. Section 5 provides supporting user experiments on an electronic tasting test. Sections 6 summaries the findings and limitations of the current system. We present our conclusions in Section 7.

2. PREVIOUS WORK

Several interactive systems can be found in the literature for simulating taste sensations, especially in the area of Human–Computer Interaction (HCI). However, these solutions mostly use an array of edible chemicals to produce different taste sensations. One example of a solution that uses chemicals to stimulate taste sensations is the TasteScreen [Maynes-Aminzade 2005]. The TasteScreen system, which is attached to the top of the user's computer screen, holds 20 different chemical flavoring cartridges that are mixed and sprayed toward the display. The user is capable of enjoying the dispensed taste by licking the computer screen. However, this approach is questionable in two aspects. The use of the computer screen as the delivery method is not ideal as the liquid may damage the screen. Second, the authors did not consider the users' behavior. Most users may find this process distasteful since it requires them to lick their screens.

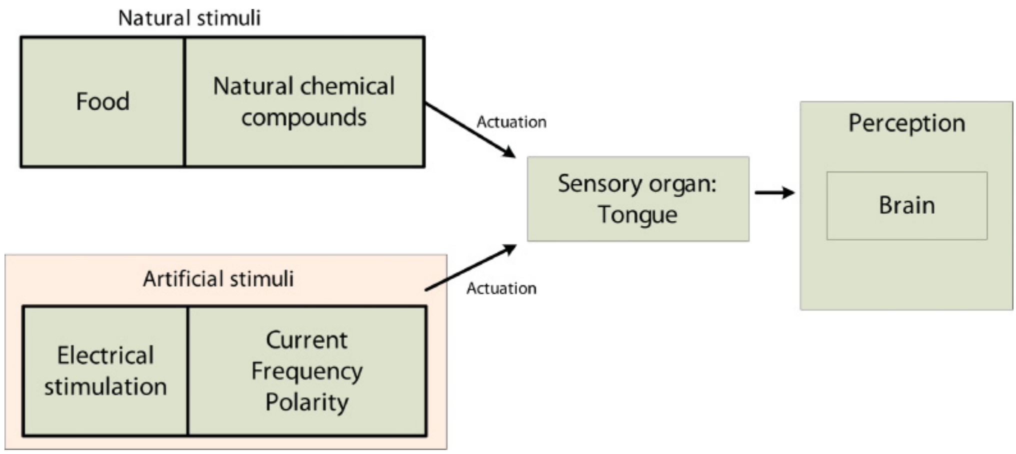

Fig. 2. Correspondence between natural and artificial stimuli to actuate the sensation of taste in the human tongue.

Moreover, using chemicals in an interactive system is unrealistic since a set of chemicals is difficult to store and manipulate. Furthermore, the chemical stimulation of taste is analogous in nature, making it impractical to use this approach for digital interactions. Therefore, it is evident that a new nonchemical approach is required to achieve digital control over taste. By examining the anatomy of taste, we have found two possible nonchemical stimulation techniques: tongue stimulation and brain stimulation. In the initial phase, a direct tongue-stimulation technique was explored to simulate the sensation of taste through electrical and thermal stimulation methods, as shown in Figure 2. At present, we are interested only in simulating primary taste sensations known as sweet, salty, sour, bitter, and umami through this method. However, we also explained a possible future brain-stimulation method through a novel mechanism of pulse magnetic flux nozzle (a magnetically induced deep-brain electrical stimulation system) in Ranasinghe et al. [2011c] to simulate more complex flavors.

Currently, nonchemical taste stimulation methods are the least explored in interactive systems. A few experimental results have been presented in the literature on electrical stimulation of the tongue and the different taste sensations that can result, particularly in medicine and physiology, and especially in electrophysiology. In Plattig and Innitzer [1976], a single human tongue papilla was electrically stimulated (84 trials) with a silver electrode using five subjects. They used both negative and positive electrical pulses in the frequency range of 50Hz to 800Hz. The results provided some exciting and effective responses for the sour taste (22.2%) and some small responses for the bitter (3.8%) and salty (1.8%) sensations. However, this experiment was conducted in a controlled laboratory environment in which they used only a single papilla of the tongue. Additionally, the study did not consider the controllability aspects of the stimuli or sensation.

In recent years, there have been several studies that have shed some light on virtual taste systems related to HCI. For example, Narumi et al. [2010] describe a pseudo-gustatory display based on the virtual color of a real drink. They used a wireless Light-Emitting Diode (LED) module embedded in the bottom of a plastic cup to superimpose the virtual color of the drink. The results of their experiments show that different colors induce users to attribute different flavors to the same drink. The motivation behind this research was to study the cross-sensory effects of visual feedback and the interpretation of the flavor of real drinks.

Nakamura and Miyashita [2011] demonstrated using electricity for augmented gustation. They applied an electric current through isotonic drinks (which contains electrolytes) and food, such as juicy vegetables and fruits, to change the taste perception of those drinks or food items. In this study, they were mainly concerned about the level of voltage and augmented sensations of food items.

From this review, it can be seen that there are several different approaches for the nonchemical stimulation of taste. However, it is noteworthy that in recent systems such as Narumi et al. [2010] and Nakamura and Miyashita [2011], they are still incorporating chemical substances to augment the taste sensations. Simulating different taste sensations directly on the tongue (e.g., using a tongue wearable system) without chemicals or organic substances is discussed only briefly in Volta [1800] and Plattig and Innitzer [1976]. These studies are at an early experimental stage in the medical domain. Therefore, before introducing the electrical stimulation method as a means of actuating the sensation of taste, many aspects of this approach need to be carefully studied. The most significant aspect is the controllability of generating taste sensations through electrical stimulation. Thus, it is desirable to propose a digital control system to simulate the sensation of taste through electrical stimulation, in order to introduce the sense of taste as a new digital media element.

In our previous research [Ranasinghe et al. 2011a, 2011b, 2011c, 2012], we presented several exploratory experiments and reported our initial findings on electrical and thermal stimulation methodologies to simulate the sensation of taste. Based on those exploratory results, we designed the Digital Lollipop, which uses an electrical stimulation methodology to digitally simulate taste sensations. In addition to our previous research findings, this article specifically evaluates regional differences on the human tongue for electrical stimulation. We have also developed an inverse-current mechanism to study the effects on taste sensation.

3. DESIGN CONCEPTUALIZATION

This section introduces the main design factors that we took into consideration (in relation to both stimuli and device design) for the development of the Digital Lollipop.

3.1. Stimuli Design

It is necessary to design the parameters of stimuli before developing the control system. Two main properties of electric currents were considered: magnitude of current and frequency. The experimental range of frequency and magnitude of current was finalized as follows based on Pleasonton [1970], Lawless et al. [2005], Stillman et al. [2003], Loucks and Doty [2004], and Plattig and Innitzer [1976], and the initial experiments conducted in Ranasinghe et al. [2011a, 2011b, 2011c],

- The frequency range selected was within 50Hz to 1200Hz, since lower frequencies have a clear effect on human tissues. Furthermore, in the case of higher frequencies (>1200Hz) the heat effect may reduce the effectiveness of electrical stimulation (due to this heat effect, the Electrosurgery technique uses higher frequencies [Haag and Cuschieri 1993]). On the other hand, very low frequencies (<50Hz) cause only vibration effects on the tongue.
- The magnitude of current was controlled from 20μA to 200μA, which is well accepted and considered safe based on Dalziel and Lee [1968].
- Square wave pulses were used for experiments with different levels of frequency and magnitudes of current as discussed earlier. We used square wave pulses for several reasons: (1) ease of implementation, (2) power efficiency, and (3) repetitive square wave may give both DC and AC effects to the tissues [Ratner 2009]. However, the

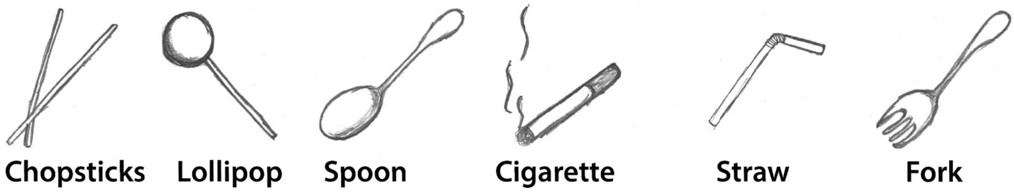

Fig. 3. Everyday objects people use to interact with the mouth. .

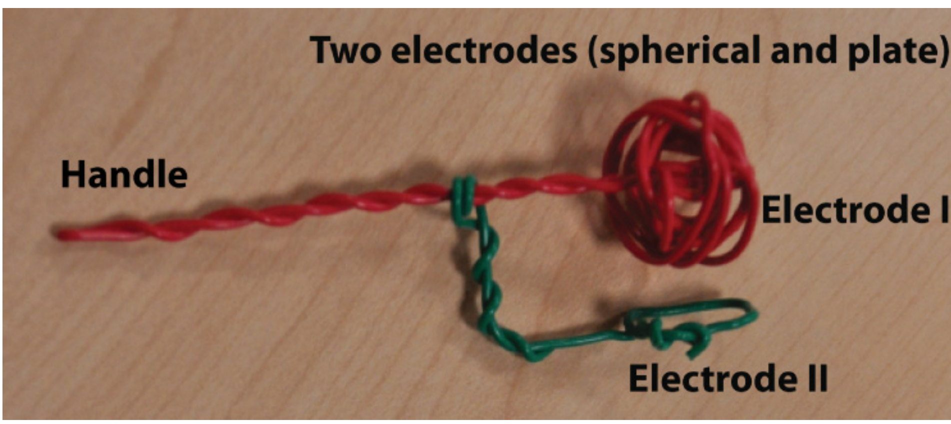

Fig. 4. The wire model of the final design of the tongue interface.

effects of other waveforms (such as sine, sawtooth, triangular) are equally important and will be studied in future experiments.

Apart from these experimental design considerations, the material of the electrodes (which are to be in contact with the user's tongue) is equally important. For the presented prototype, silver (95%) electrodes were used since it has high electrical conductivity. Two electrodes were used for the electrical stimulation: one as the anode and the other as the cathode. We understood the ethical issues behind this research and obtained the necessary approval from the University Institutional Review Board (Approval No: NUS 1049).

3.2. Device Design

The current version of the Digital Lollipop consists of two main components: the control system and the tongue interface. The control system configures the output stimuli of the tongue interface. These two components were developed as two separate modules and subsequently attached by a two-wire connection. As the electrical stimulation of the tongue for generating different taste sensations is a particularly new technology, most people are not familiar with it. Therefore, it was a challenge to propose a comfortable preliminary design for the system (especially for the tongue interface). Furthermore, the system should be simple and user-friendly. After considering several household objects that people use to interact with their mouths—such as spoons, chopsticks, cigarettes, and lollipops (as displayed in Figure 3)—we designed a modified form of a lollipop as the tongue interface, shown in Figure 4.

Interacting with a lollipop is a familiar concept for most people in their everyday lives. The hollow ball (electrode I) and the bottom plate (electrode II) are the two electrodes that connect to the tongue, as shown in Figure 5. The wires are located

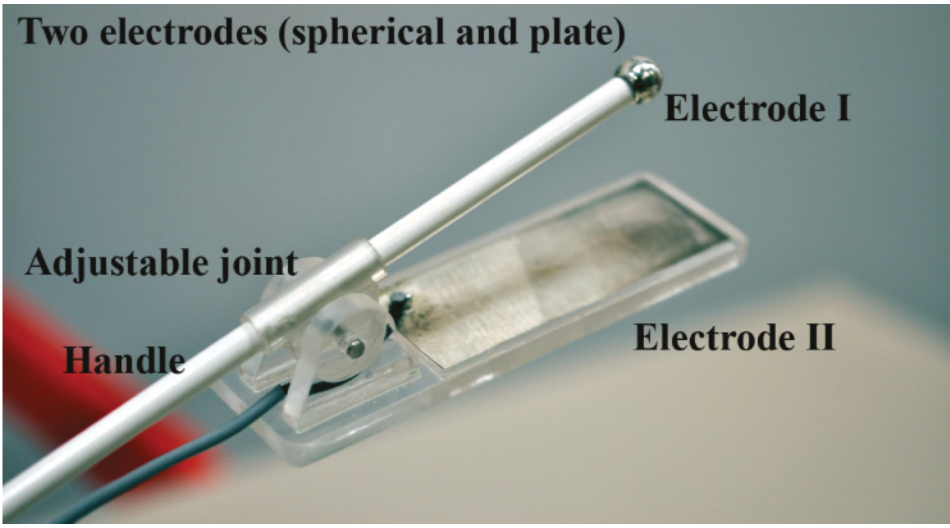

Fig. 5. The implementation of the lollipop tongue interface.

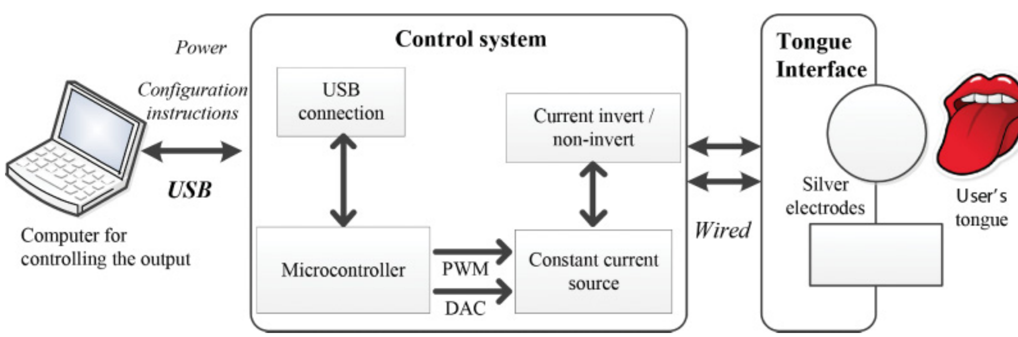

Fig. 6. The system architecture of the Digital Lollipop.

inside the hollow handle and are connected to the controller at the end of its handle. We had to change the original form of the lollipop to attach an additional electrode, as seen in Figure 4, since it is necessary to connect two electrodes on the top and bottom surfaces of the tongue. Furthermore, the handles of this model move independently, enabling users to play with the tongue interface by rotating (or spinning) and licking the spherical electrode, similar to a real lollipop. We used the form of a lollipop as the curved shape makes it safe to use inside the mouth.

4. SYSTEM DESCRIPTION

Two separate modules of the Digital Lollipop (the tongue interface and the digital control system) are illustrated in Figure 6. As per the design, the tongue interface consists of two silver electrodes: one in the shape of a sphere and the other in the form of a plate. The tongue is placed between these two silver electrodes: the sphere at the top and the other electrode on the bottom of the tip of the tongue, as displayed in Figure 7. Different electrical stimuli are then supplied through silver electrodes to the tongue in order to simulate primary taste sensations.

The control system module consists of a digital-to-analog converter, which supplies a variable voltage proportional to the input settings. This module controls the magnitude

Fig. 7. A close-up of the tongue interface that connects with the participant's tongue.

of the current, the frequency and polarity of the stimuli (i.e., direction of current) on the tongue interface. The electronic control system provides square wave pulses to the silver electrodes with a magnitude of current from 20μA to 200μA and a frequency of 50Hz to 1200Hz.

A PIC microcontroller (16F1824[1]) with a 4MHz built-in clock is used to implement the control system. This low-power microcontroller also has additional features that are useful for our implementation, such as a built-in USART for digital communication, two pulse-width modulation (PWM) peripherals, a 10b ADC, and a 5b rail-to-rail resistive digital-to-analog control (DAC) with positive and negative reference selection.

DAC technology is used to control the magnitude of current in discrete steps in order to stimulate the human tongue. To adjust the frequency of electric pulses, we used a timer-interrupt–based PWM technique. Furthermore, to control the output parameters, a computer is connected to the control system through a USB connection. Currently, for user experiments (to configure the output current and frequency), control commands are given using the RealTerm[2] serial terminal program. Moreover, an inverse-current mechanism is implemented using a relay for conducting experiments involving both anodic (noninverted) and cathodic (inverted) stimulations.

The resistance of a human tongue varies due to the differences in the density of papillae on the surface of the tongue [Lackovic and Stare 2007]. Therefore, to normalize the results of experiments, a constant current source has to be implemented for tongue stimulation. In addition, the control system is configured to output step-by-step magnitudes of current from 20μA to 200μA with intervals of 20μA during experiments. 20μA steps were chosen as the majority of the participants were able to sense the difference between 20μA step sizes. However, the human tongue could differentiate even smaller changes depending on the sensitivity of the individual's tongue [Stillman et al. 2000].

The linear increment of DAC and output current values of the system are depicted in Figure 8. We have observed a slight variation between the measured output current and the expected output (average current error is approximately $\pm 3\mu$A). This variation is

[1]http://www.microchip.com/wwwproducts/en/PIC16F1824.
[2]http://realterm.sourceforge.net/.

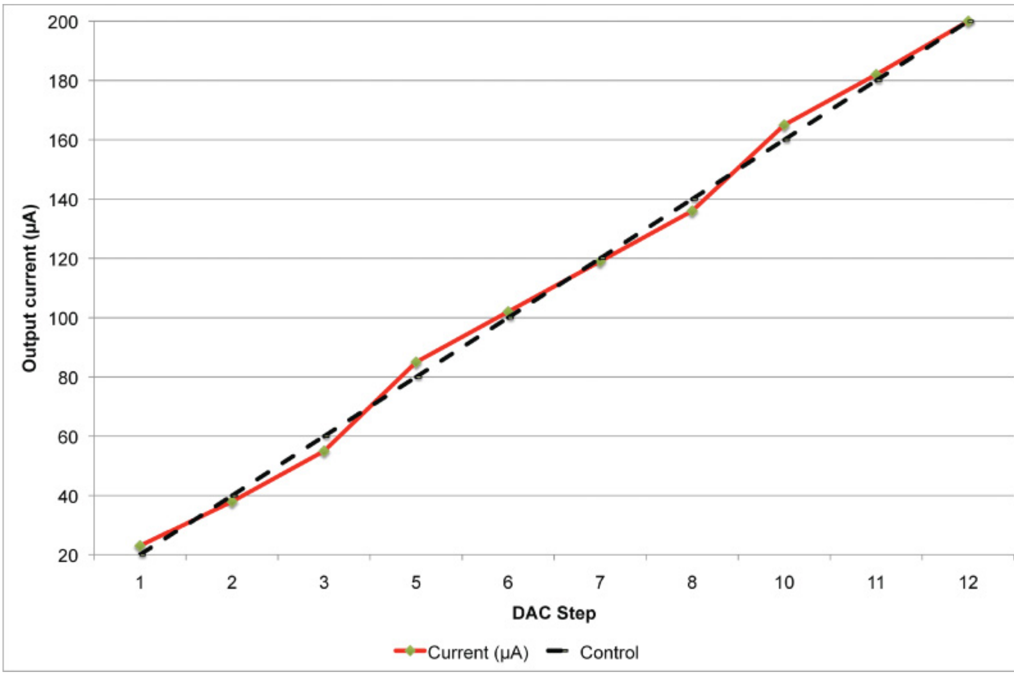

Fig. 8. The linear increment of output current based on DAC step values.

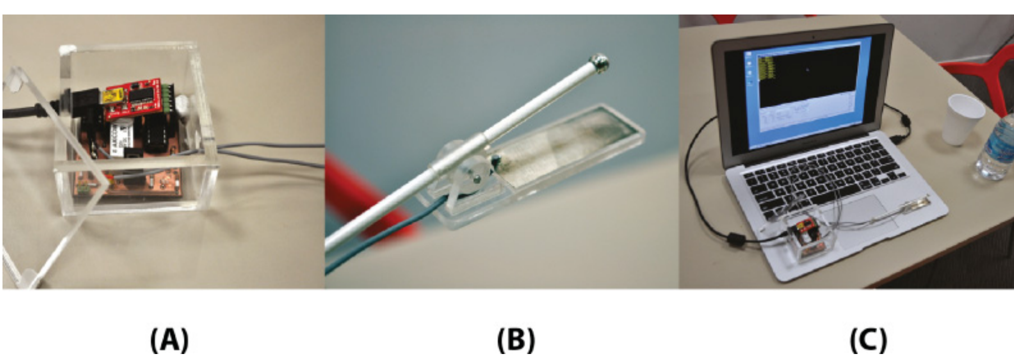

Fig. 9. The implementation of the Digital Lollipop. (A) Control system, (B) tongue interface (which has a spherical electrode with 5mm diameter and flat electrode with 40mm * 15mm * 0.2mm), and (C) typical configuration with a computer.

acceptable since the human perception is not sensitive enough to detect this particular degree of difference in resolution.

Figure 9 displays the implementation of two main components of the Digital Lollipop: the control system (A) and the tongue interface (B). The control system is connected to the silver electrodes of the tongue interface using two strands of wire, as shown in Figure 9 (C).

It was noted that when the tongue was connected to the tongue interface, the voltage across the tongue changed. Figure 10 shows the voltage across the tongue when the tongue was connected. The characteristics of the signal convey that the signal was low-pass filtered, possibly due to the capacitive effect and the inductance of the human

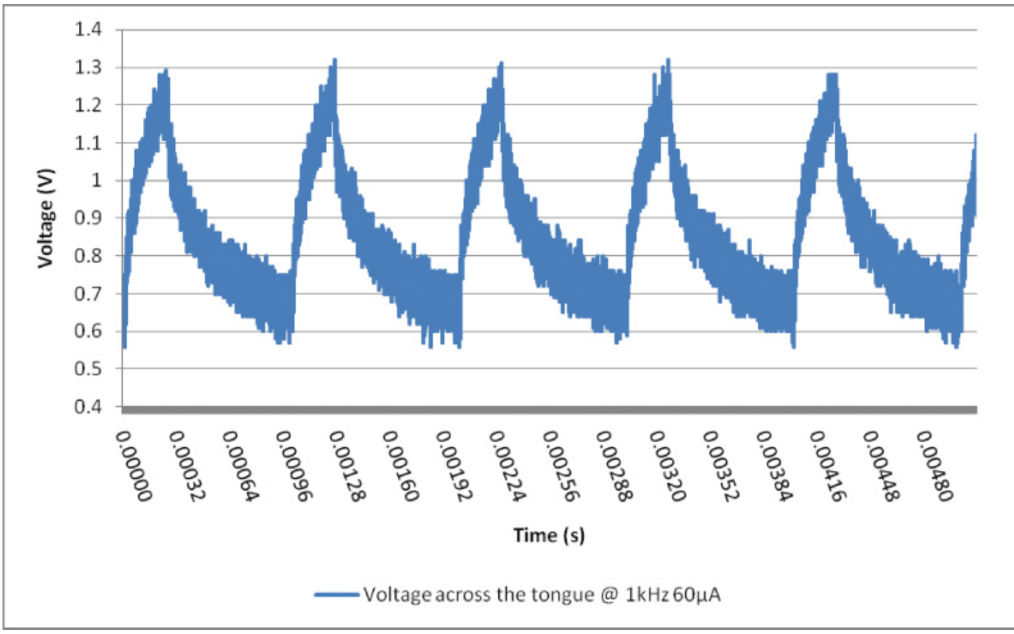

Fig. 10. The noninverted output voltage across the tongue when the tongue is connected.

tongue. However, more experiments should be conducted in the future to confirm this phenomenon.

5. SUPPORTING USER EXPERIMENTS

Two user experiments were conducted to experimentally evaluate the Digital Lollipop. The first experiment studied the responses from different regions of the tongue. The second study was conducted to evaluate the effectiveness of the system and compare the virtual sour taste with real or natural sour tastes. For the second experiment, the sour taste was selected for additional focus since it received the largest number of responses from the first study. For the second study, the tip of the tongue was selected due to its increased sensitivity. The experimental setup of the Digital Lollipop is depicted in Figure 11.

Before conducting formal user experiments, the developed prototype system was used to conduct an informal pilot experiment with five subjects. Based on their feedback and taste responses, the system was adjusted and the experimental protocol was modified. The formal experiment was then conducted to determine (1) taste sensations from different regions of the tongue and (2) the controllability of virtual sourness with regard to natural sour taste sensations. In both experiments, participants were instructed to rate the level of intensity of any taste sensation that they perceived. The level of intensity was recorded at three levels: 1, mild; 2, medium; and 3, strong.

5.1. Participants

All participants were in good health. No issues regarding their sense of taste and smell were reported. All were asked not to smoke, not to eat strongly spiced meals, and not to consume alcoholic beverages prior to the experiment as this may have affected the results. Participants were asked to describe their experience after each experiment, and include any relevant additional information.

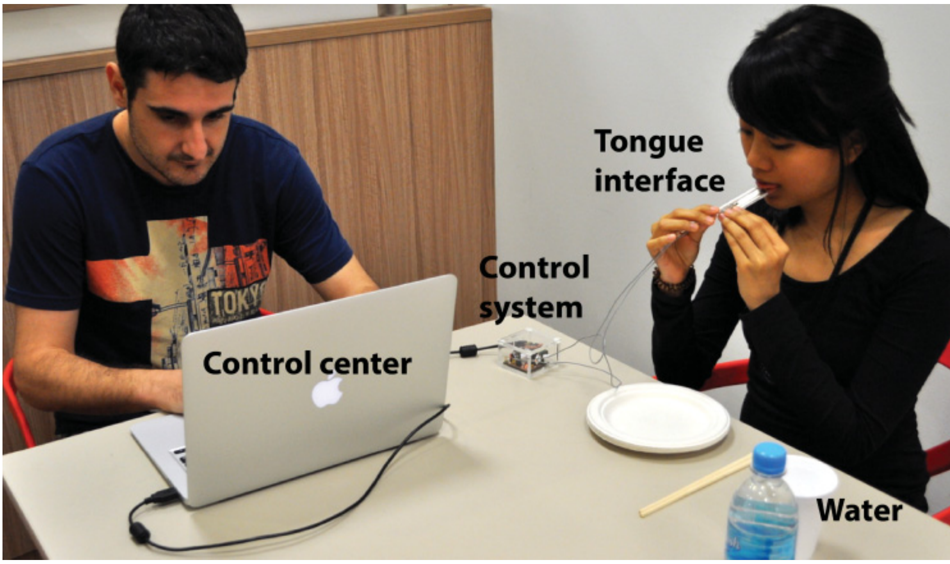

Fig. 11. The experimental setup of the Digital Lollipop.

5.2. Apparatus

The experiments were conducted in a quiet and air-conditioned (24°C) meeting room inside the laboratory in order to eliminate possible interruptions from other sensory inputs such as heat, sound (noise), and vision. A computer was configured as the command control center for the Digital Lollipop. Before each session, both electrodes were rinsed using tap water, sterilized using 70% isopropyl alcohol swabs, then rinsed again using deionized water [Dobrin 1984].

We conducted a trial session with each subject before the experiment (with the magnitude of 40μA). Furthermore, for the experiments explained in this article, we configured the frequency at a constant value. From the previous experiments presented in Ranasinghe et al. [2011a, 2011b, 2011c], we found a minimum contribution from the frequency of the stimuli to simulate different sensations. Lackovic and Stare [2007] also observed that the tongue impedance decreases with an increase in frequency. The decrease in impedance might slightly increase the magnitude of the current, thus affecting the susceptibility of taste perception. Therefore, the frequency was configured at 1000Hz in order to achieve optimal results.

5.3. Stimulating Different Regions on the Tongue

We conducted an experimental study using 31 participants (6 females, 25 males, ages 22–39y, M = 24y, SD = 3.17y) on three different regions of the human tongue to study the perception of primary taste sensations when applying electrical stimulation. A relatively narrow age group was chosen as an individual's age may affect one's perceptions of taste sensations. As shown in Figure 12, we used three main regions on the anterior portion of the human tongue to explore the ways in which electrical stimulation creates different types of sensations with varying intensities. These three regions were selected from the anterior portion of the tongue, as this portion is easily accessible with an external interface (similar to using eating utensils). Moreover, the tip of the tongue is considered to be the most sensitive region for chemical taste stimulation [Brown and McNeill 1966].

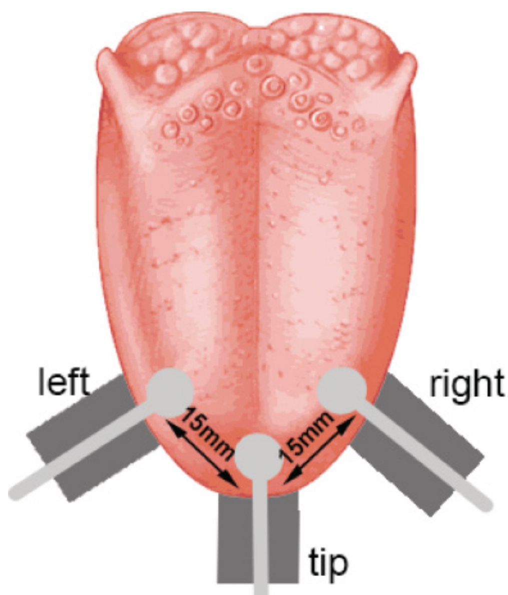

Fig. 12. Different placements of the Digital Lollipop on the human tongue during the experiments.

5.3.1. Procedure. At the beginning, participants were informed of the experimental procedure. First, we asked them to hold and touch the tongue interface on the tip of the tongue. Then, the stimulus was gradually increased from 20μA to 200μA in steps of 20μA intervals. They were instructed to disconnect the tongue interface immediately if the stimulation was too strong or uncomfortable. Participants were instructed to rest 5min and rinse their mouth with deionized water between each stimuli to prevent bias and counterbalancing. After each stimulation, we asked the participants to report the taste sensation and the level of intensity, if they perceived any.

We then continued the experiments on other regions (approximately 15mm to the left of the tip and approximately 15mm to the right of the tip, as depicted in Figure 12) of their tongues. We closely monitored the correct placement of the lollipop interface on the tongue and advised the participants to rearrange it if they had placed it incorrectly.

Once each step was completed (tip, left, and right), the participants were interviewed in order to gain feedback regarding their perceived sensations and the usability of the interface (as described in Section 6). Since this was an early experimental evaluation, we allowed the participants to freely explore the tongue interface while providing feedback. As this technology introduced a new and unfamiliar interaction, we believed that more insightful feedback would be gained by allowing the users to become familiar with the interface in this manner. During these informal interviews, users were also asked to provide feedback regarding the wearability of the interface, the nature of the sensations experienced while using it, and any potential refinements to improve the overall device.

5.3.2. Results and Discussion. The results obtained from initial studies are encouraging and suggest that varying intensities of distinct taste sensations are associated with specific regions of the human tongue when applying electrical stimulation. Approximately 90% of the participants tasted the sourness, which was the most dominant among other sensations, such as saltiness (approximately 70%), bitterness (approximately 50%), and sweetness (approximately 5%). More interestingly, there is evidence

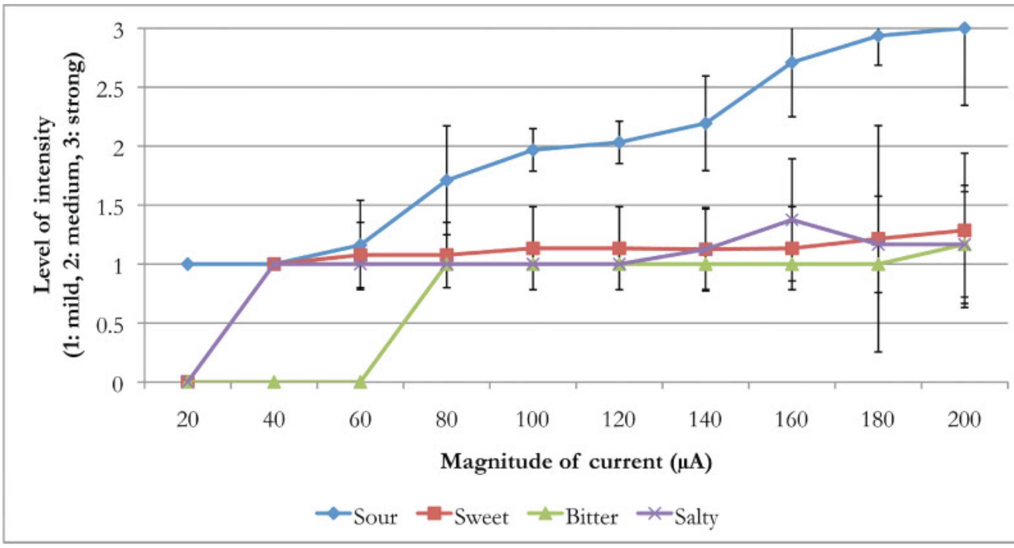

Fig. 13. Reported taste sensations and their intensity levels observed from the tip of the tongue when current is noninverted.

of the sweet sensation being perceived from the anode electrode when the current was inverted. This finding will be examined in greater depth in future studies. As these results are from initial studies, we did not conduct thorough statistical evaluations to compare perceived taste sensations as well as regions of excitation on the tongue. This is mainly because we collected only verbal feedback from the participants in these initial studies without proper comparison with real sensations.

Figure 13 depicts the taste sensations and mean intensity levels obtained from the tip of the tongue when the current was noninverted. One of the compelling phenomena that we observed from the results was the increasing intensity of the sour taste when the current was increased. In addition, several participants mentioned that higher current levels may cause a tingling, or "pineapple"-like, sensation on the tongue.

Similarly, in Figure 14, recorded taste sensations and intensity levels are displayed after inverting the current. It is worth noting that the perceived intensity of sweet sensation increased when the current was inverted. We received several comments about this fact, and many participants noted a subtle change when the current was inverted on the tip of the tongue. We noticed that some people perceive this phenomenon as a change of taste, which was interesting. Approximately 5% identified it as a sweet taste, while 2% identified it as a bitter taste. A few mentioned that, when the polarity was changed, they could feel an atypical experience, which they described as similar to experiencing two taste sensations from the top and bottom electrodes. It was a new observation that we obtained from the inverted current experiment. A slight deviation in the increment between $100\mu A$ to $160\mu A$ can be seen, and it appears that the more intense sweet sensation may weaken the perception of a sour taste.

The results of these initial experiments appear to show that the side regions of the tongue identify a smaller number of sensations when compared to the tip of the tongue. This is reasonable, as it agrees with the existing literature on chemical stimulation [Brown and McNeill 1966]. Also, we have observed that, for noninverted electrical stimulation, the left side reports slightly reduced average intensity levels than the right

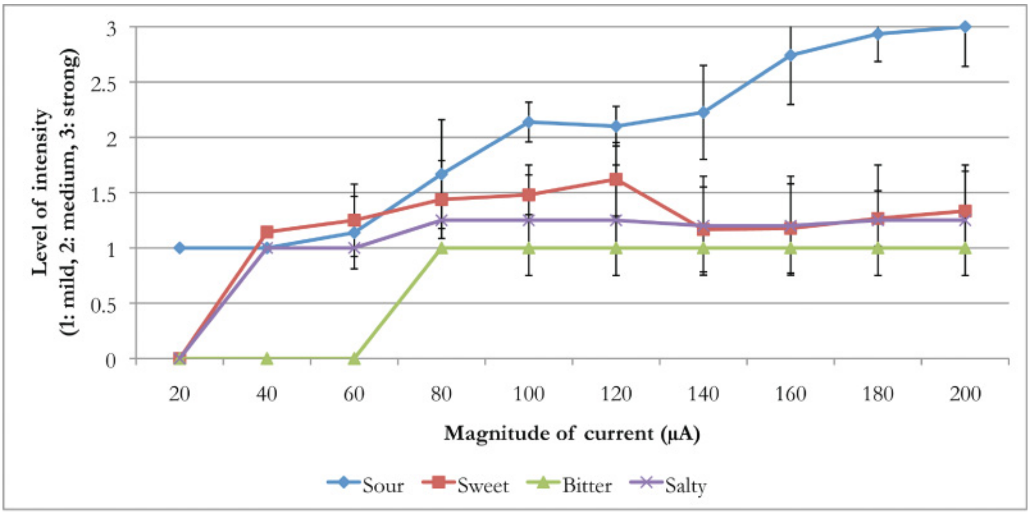

Fig. 14. Reported taste sensations and their intensity levels observed from the tip of the tongue when current is inverted.

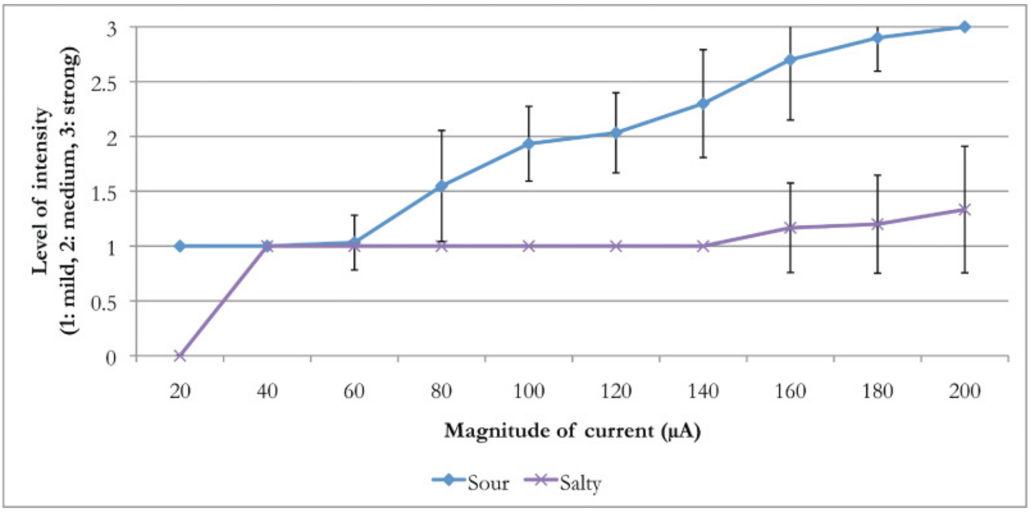

Fig. 15. Reported taste sensations and their intensity levels observed from the left side of the tongue when current is noninverted.

side of the tongue, as shown in Figures 15 and 16. Although there are several pieces of evidence that suggest taste sensations such as sweetness, saltiness, and bitterness, the only sensation consistently reported from the left side of the tongue is sourness (as in Figure 15). However, it can be seen that, compared to the results reported for the tip of the tongue, the level of intensity is slightly decreased (from 20μA to 80μA) for the sour taste. As Figure 16 suggests, there was an increase in the average intensity for the bitter and sour tastes from the right side of the tongue. Results reported for salty and sweet sensations are inadequate and negligible to the findings.

As highlighted in Figures 17 and 18, the left- and right-side stimulations with inverted current have resulted in only sour and salty sensations. Additionally, a few participants highlighted that the inverted current caused slight numbness on the

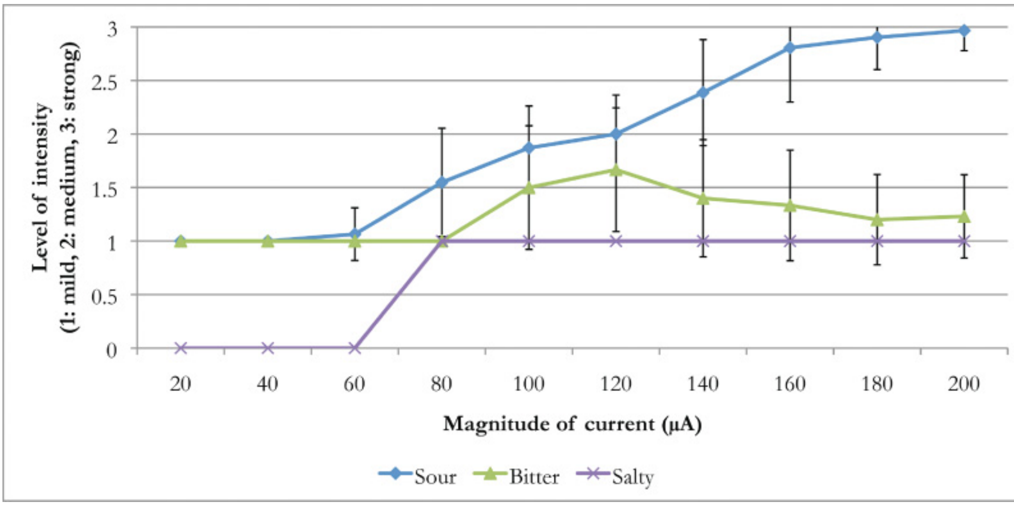

Fig. 16. Reported taste sensations and their intensity levels observed from the right side of the tongue when current is noninverted.

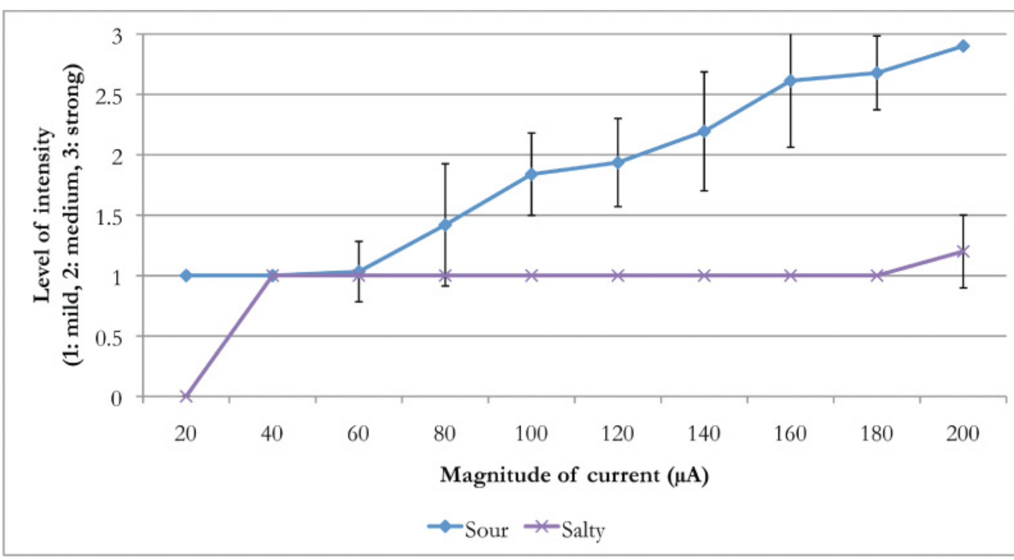

Fig. 17. Reported taste sensations and their intensity levels observed from the left side of the tongue when current is inverted.

bottom surface of the tongue. There were no taste sensations reported from the top surface of the tongue. Almost all of the participants mentioned that, when the electrode was rubbed on the tongue surface, they could perceive the sensations more clearly. This finding also requires further examination in future experiments.

5.4. Comparison with Real Taste Sensations

Twenty participants were invited to participate in this experiment (ages 21–28y, M = 23.5y, SD = 3.22y). They were selected from the participants of the first experiment, who responded well for the artificial sour taste. Three lime solutions with mild, medium,

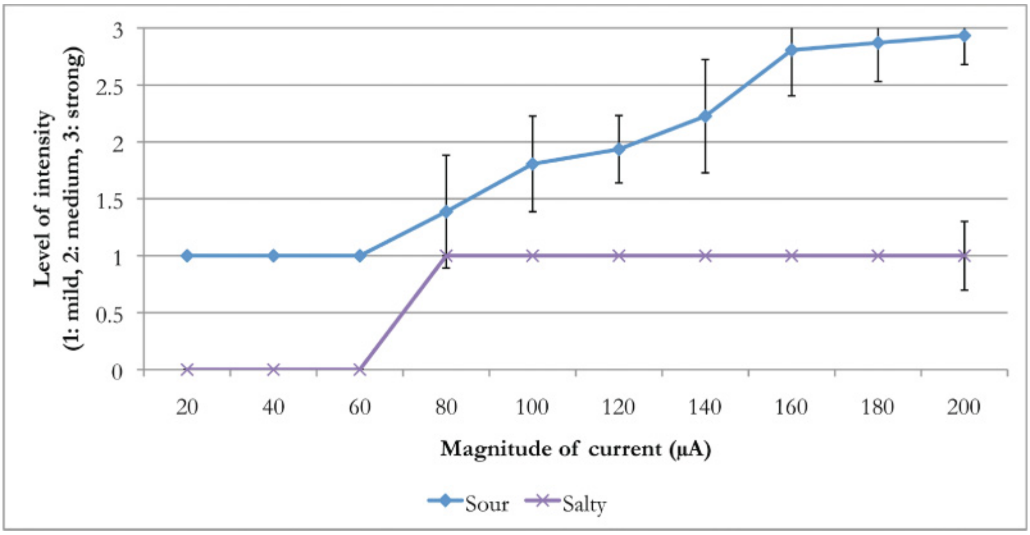

Fig. 18. Reported taste sensations and their intensity levels observed from the right side of the tongue when current is inverted.

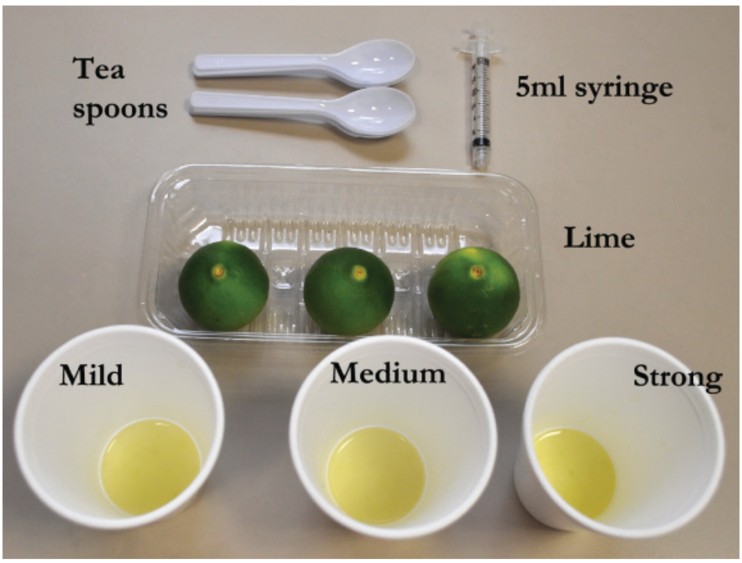

Fig. 19. Preparing three intensities of lime juice: mild, medium, and strong.

and strong intensities were prepared for the comparison between digitally stimulated taste and natural sour taste. Figure 19 shows different equipment used to prepare the three lime solutions. First, three teaspoons of lime juice (5ml $\times$ 3) were squeezed into each cup and mixed with deionized water, 30ml (mild), 16ml (medium), and 5ml (strong), respectively. Then, five users were recruited to evaluate the intensities of the three sour solutions blindly. Based on their feedback, we modified the strong and medium solutions accordingly. The respective final pH values of mild, medium, and strong lime solutions were approximately 2.516, 2.38, and 2.245. The pH values were

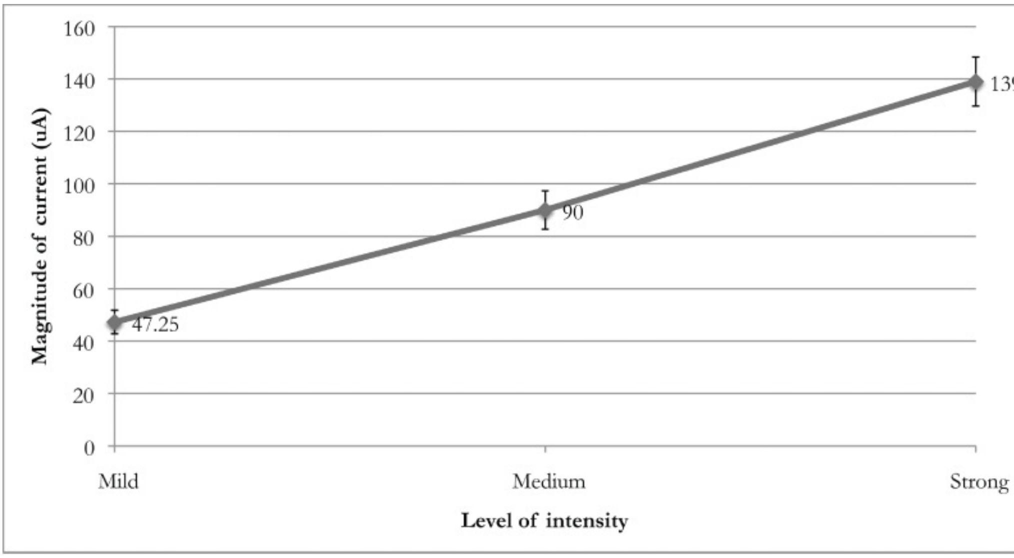

Fig. 20. Mean values of thresholds for three intensities of sour taste (mild, 20μA–38.33μA; medium, 38.33μA–88.75μA; and strong, 88.75μA–140μA).

measured using a Thermo Scientific Orion 4-Star Plus pH/Conductivity Meter[3] and a Thermo Scientific Orion pH Electrode.

5.4.1. Procedure. Before the experiment with the Digital Lollipop, a blind sour taste test was conducted for each participant. They were asked to taste three solutions of lime (2ml per trial), and identify whether the solution had a mild, medium, or strong sour taste. As the smell of the lime solutions might affect the intensity of the sensations, we minimized the exposure of the participants by presenting smaller servings (2ml) of lime solutions on separate spoons.

Participants rinsed their mouth with deionized water and relaxed for 2min between each trial in order to enable a clearer distinction between each level of sour taste. Then, they were asked to hold the lollipop and use the anterior tip of their tongue to touch the silver ball, since it is the most sensitive segment of the human tongue.

During the experiment, the magnitude of the current running through the tongue was increased from 20μA to 200μA in approximately 20μA intervals. The experiment was conducted in three steps for three levels of intensity: mild, medium, and strong. At the beginning of each step, participants were given the natural sour taste. After a 2min interval, the Digital Lollipop was used to simulate a sour taste. The participants were asked to interrupt and inform the researcher once they perceived a similar level of intensity generated by the Digital Lollipop to the natural sour taste that they had perceived. Participants were informed to rest and rinse their mouth if they felt tired or uncomfortable. After all three experimental rounds, they were asked to describe their experiences during the experiments.

5.4.2. Results. We were able to identify the corresponding three intensities (mild, medium, and strong) of digital sour taste similar to the natural sour sensation (lime), as illustrated in Figure 20. This shows the controllability of artificial sour taste through the Digital Lollipop.

[3]https://static.thermoscientific.com/images/D15562~.pdf.

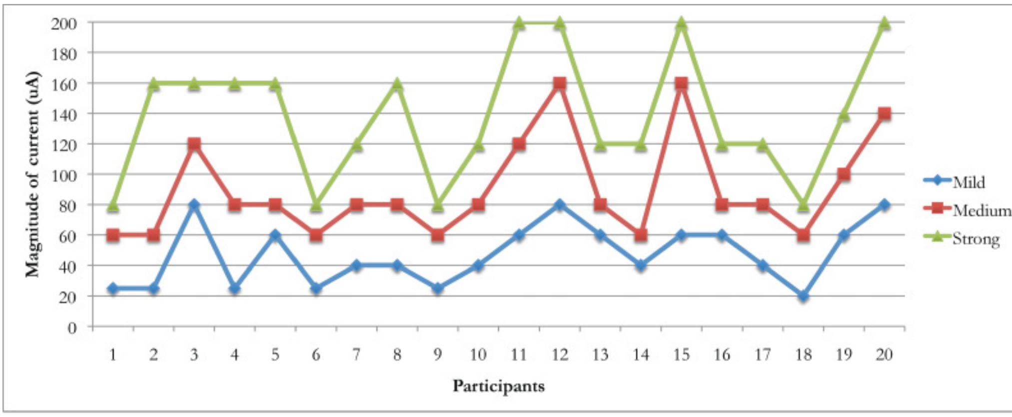

Fig. 21. All sour taste sensations that occurred during the user experiments.

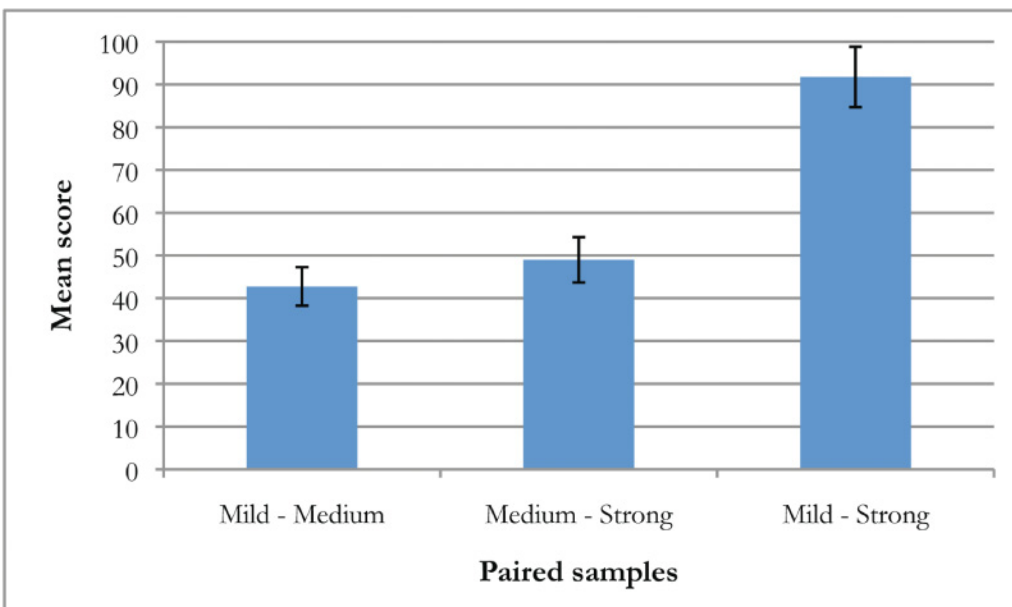

Fig. 22. Mean scores with standard error for three study pairs ($p < .01$).

From the experiment, we found that most of the participants experienced mild sour sensations at around 40μA, medium sensations at around 90μA, and strong sensations at around 140μA. A few participants mentioned that, although they experienced a sour taste, the sensation was less similar to the natural (lime) taste. Figure 21 shows the complete set of digital sour taste occurrences, which are plotted against different intensity levels: mild, medium, and strong. In general, during the comparison study, we observed that the participants could compare the (artificial and natural) sensations and responded quickly when the natural taste was presented.

We also conducted several statistical measurements of the comparison data from this study. The paired sample t-test, as shown in Figure 22, confirms that mild-medium [$t(19) = 9.45$, $p < .01$, $SD = 20.22$, $SE = 4.52$], medium-strong [$t(19) = 9.2$, $p < .01$, SD = 23.81, SE = 5.32], and mild-strong [$t(19) = 13.057$, $p < .01$, SD = 31.42, SE = 7.02] groups are significantly different.

6. DISCUSSION

Many participants remarked that it felt uncomfortable when the current was approximately 180μA and above. Two participants indicated that they could feel vibrations on the tongue at approximately 200μA. One of the most noteworthy comments that we received was that several participants felt that a lower magnitude of current resulted in more realistic sour taste sensations.

The design of the stimuli was one of the critical factors for the efficient results of this technology. During the conducted experiments, there were no uncomfortable situations reported due to the stimuli. Nevertheless, several participants reported experiencing an aftertaste once the experiments were completed. Two female participants mentioned a slight numbness on their tongue after the experiments. We suspect that this may be due to the level of sensitivity of their tongues.

One of the challenges that we faced during the experiments was correctly aligning the tongue interface of the Digital Lollipop on the participant's tongue. We had to monitor and adjust the placement of the electrodes on the tongue during experiments since we used a smaller electrode (5mm diameter) for better handling and to avoid touching other parts of the mouth. Furthermore, we instructed participants to open their mouth and place the tongue slightly out of the mouth to enable close monitoring. Due to this, salivating was one of the problems that we faced during the experiments using the Digital Lollipop.

Moreover, on several occasions, taste qualities elicited were found to be subjective. Gustation or the perception of taste sensations is a complex physiological process; thus, subjectiveness of taste perception is well known even for chemical-based taste sensations. This happens mainly due to the fact that a certain chemical stimulus may be associated with multiple taste qualities based on previous experiences as well as the genetic differences in human beings [Bartoshuk 2000]. Electrical stimulation could also yield similar experiences, thus resulting in different taste qualities reported for the same stimuli, as shown in the results. However, one way to overcome this problem is to calibrate the device according to users' perceptions.

The sensation of taste is perceived through multiple senses. Texture and memory also play a leading role when recognizing taste sensations. However, in our system, presenting taste sensations with the same texture and no previous experience may affect the users' ability to recognize certain taste sensations. Although we did not conduct focused experiments to study this, a training procedure may help to improve the results obtained through user experimentation.

In addition, several participants stated that some sensations were difficult to understand and communicate precisely when we conducted interviews with them. This may be due to a lack of experience with these sensations and not having a sufficient vocabulary to describe different taste sensations. For example, when asked about the umami sensation, almost every participant commented that they did not know how to explain umami. Moreover, participants also mentioned that some of the sensations were mixed, such as salty-sour and salty-bitter.

On the other hand, several participants commented on the look and feel of the current lollipop interface. For example, one such suggestion was "to make it portable and have only one spherical contact point, similar to a real lollipop." Based on this feedback, we are designing the next version of the interface, as illustrated in Figure 23. The next version will incorporate an embedded electronics platform to increase portability and both electrodes will be mounted closer to one another. Moreover, new features will be introduced, including "shake and change" to change the output stimuli, thus changing

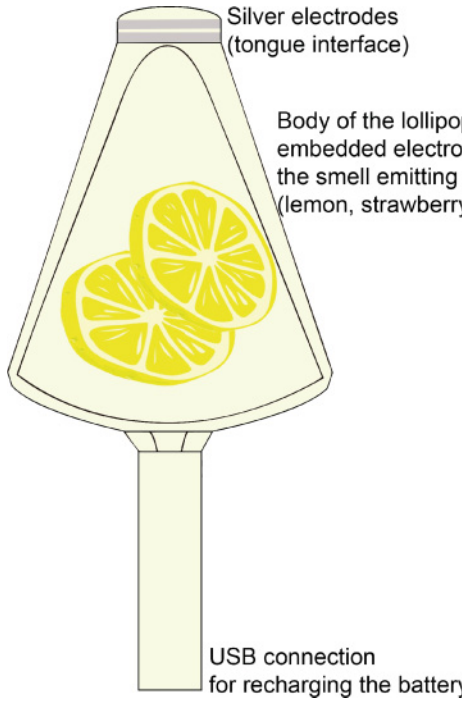

Fig. 23. The next version of the integrated flavor-changing Digital Lollipop.

the virtual taste sensations, and "smell emission" to simulate not only the basic taste sensation but also more flavors.

7. CONCLUSION

In this article, we describe the development of the Digital Lollipop. It was developed with two main modules: the control system and tongue interface. Most important, a complete set of technical measurements of the Digital Lollipop are presented and evaluated. Then, we explain two user experiments conducted using the Digital Lollipop. The first experiment was focused on electrical stimulation on different regions of the human tongue. According to the results, sour, salty, bitter, and sweet sensations were actuated from this experiment. Among these reported sensations, the sour taste was consistently experienced by almost all the participants.

Therefore, a second experiment was conducted to experimentally evaluate and compare digital and natural sour sensations. It is clear that the magnitude of the digital sour sensation is approximately proportional to the magnitude of the current supplied through the tongue interface. Furthermore, based on the user responses, we have categorized the sour sensation into three different categories: mild, medium, and strong. The results have proven that the Digital Lollipop is capable of digitally simulating the sour sensation on the human tongue at three intensity levels (mild, medium, and strong). However, there was a small quantity of feedback describing a slight variation between the artificial sour sensation and the natural sour sensation.

In the future, we believe that this technology has a wide range of applications since the stimulation of the sense of taste is relatively new to the digital domain. The potential applications vary in several domains, including entertainment, communication, as well as medicine. We believe that there are possibilities in the near future to incorporate this technology in gaming, virtual reality, and remote communication. For example, through this technology, people may share a sweet message with a remote friend using mobile devices. Additionally, we are excited to highlight the possibilities of adding the sense of taste into the remote communication paradigm. What if people could share different tastes of their meals remotely through the Internet using the future technologies developed based on the Digital Lollipop?

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