Tongue Mounted Interface for Digitally Actuating the Sense of Taste

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Abstract

Most of the systems for generating taste sensations are based on blending different chemicals appropriately, and there are less proven approaches to stimulate the sense of taste digitally. In this paper, a method to digitally stimulate the sense of taste is introduced and demonstrated based on electrical and thermal stimulation on human tongue. Thus, two digital control systems are presented to control taste sensations and their intensities effectively on the tongue. The effects of most persuading factors such as current, frequency, and temperature have been accounted to non-invasively stimulate the tongue. The initial experimental results indicate that sour (strong), bitter (mild), and salty (mild) are the main sensations, which can be evoked while there are evidences of sweet sensation too. Based on the results of the Tongue Mounted Digital Taste Interface, we have then developed another system which named as the Digital Sour Lollipop to effectively control the sour taste digitally. Initial experimental results of this system show the controllability of sour taste up to three levels of intensities using the electrical stimulation on human tongue.

1. Introduction

The technology of wearable computing has evolved ever since the inventions of eyeglass and pocket watch. It had a strong recognition after the invention of personal cassette players (for example the Walkman^{TM}) and the movie Terminator [13]. In wearable systems, one of the key aspects is actuators (output devices). Recently, there are several research works published in literature on advancements of output technologies such as contact lens displays [10, 9] and wearable haptic systems [6, 17].

At present, the digital output (actuating) technologies in wearable computing are only associated with three human senses, the sight, hearing, and touch. As common actuation technologies, head mounted displays, wrist displays, and wrist watch technologies associates with the actuation of sight while earplugs and headsets relates to hearing. Furthermore, the tactile feedback devices such as the cyberglow [6] are used as a common output technology associate with the touch.

Although wearable actuation technologies have mainly advanced on three common senses of sight, hearing, and touch, the senses of taste and smell are also tremendously valuable for the human beings. These two senses are not yet established in the wearable computing area. At present, it is harder to incorporate taste and smell senses in modern digital wearable systems paradigm due to two main difficulties: 1). unawareness of neurological makeup 2). chemical based nature of these two senses.

However, there have been few attempts to develop an integrated and comprehensive approach to stimulate all five main human senses. For example, the virtual reality helmet developed by British scientists can stimulate five human senses. The helmet releases chemicals in order to stimulate both smell and taste, while hearing, sight, and touch senses are stimulated digitally [2]. The main drawback of these solutions is the use of different chemicals to stimulate the smell and taste senses. Thus, the existing approaches are analogues and there are several practical problems associate with them such as manageability, transferability, and scalability of such approaches.

Among these two chemical senses, the taste and smell, we particularly focus on the sense of taste. Taste has a direct relationship with the food we eat and the quality of the food. The ability to taste food is essential for human existence. Feeling taste is not only a common sensation. It prepares your body for digesting food. Tasting food stimulates salivary glands and digestive enzymes. Furthermore, the sense of taste is a pleasurable sensation. People prefer dine together and arrange various food items for events and celebrations in their everyday lives. Therefore, the sense of taste is uniquely valuable to maintain a healthy human body and to maintain stronger relationships. Hence, the sense of taste plays a pivotal role in human lives. The aim of this

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paper is to investigate the possibility of digitally actuating basic taste sensations known as sweet, bitter, sour, salty, and umami. In addition, flavor is a more complex multisensory perception including the sense of smell, which we are not focused in this paper.

In this paper, as a solution for digitizing the sense of taste, we present a novel system, the Tongue Mounted Digital Taste Interface, which digitally stimulate different taste sensations on human tongue. The system is capable of generating taste sensations based on electrical and thermal stimulation on the tip of human tongue. It is designed as two main modules: the tongue interface and the digital control system. The digital control system and the process of stimulating (electrical and thermal) different taste sensations are the main novelties of this technology. We expect to gain the digital controllability over the sense of taste through this technology, let alone to develop effective communication, digital amplification, and optimization techniques.

The properties of electric current (the frequency and magnitude of current) as well as the change of temperature, on tip of the tongue are explored to effectively control the taste sensations and intensity level of the sensation. In this paper, we describe two systems developed based on this technology. First system was developed for initial user experiments and the second as an application based on the results from the first system. The tip of the anterior tongue is used in the experimental evaluations with both systems due to the high sensitivity of that area of human tongue [14]. Although there are several taste sensations were reported during initial studies with the first system, the second system is developed to explore more on the controllability of digital sour taste.

A wearable system that could stimulate the sense of taste digitally has potential applications in various domains including remote multisensory communication, gaming, virtual reality, and entertainment. By using this technology for gaming and virtual reality technologies, it would be possible to provide a taste of a virtual food item. Furthermore, it will help to introduce the theorized concepts such as the next generation World Wide Web (WWW) with embedded multisensory interactions.

In the rest of the paper, in section 2, we discuss related research on different experiments and approaches on generating taste sensations. We then describe the design of electrical stimuli and the other factors related to the design of Tongue Mounted Taste Interface in section 3. Followed by the design, we present two systems in sections 4 and 5. We conclude with future possibilities of the presented technology and solutions in section 6.

2. Related Work

The Tongue Mounted Digital Taste Interface draws on two aspects of related work, wearable computing and taste interfaces.

2.1 Wearable Computing

There are few wearable systems developed on mouth based interactions mainly for people with physical disabilities. Those interfaces generally use the movements of user's tongue as an alternative input methodology for computers.

For example, Huo et al. presents an approach to use human tongue as an input device [3]. The authors attach a magnet on the tongue and observe the changes in the magnet field using Hall Effect sensing, when the user changes the position of his/her tongue. The information then transfer to the computer through the head mounted processing unit. Similarly, in "Development of a tongue-operated switch array as an alternative input device" Kim et al. describes a tongue based switch array as a hands-free alternative communication method between human and machines [5].

In addition, Sampaio et al. in "Brain plasticity: 'visual' acuity of blind persons via the tongue" uses the tongue as an actuator [15]. The authors present a tongue display (TDU) unit with an array of electrical stimulators (144 points) to stimulate the 'visual' acuity of blind persons. The wearable TDU is connected to a camera through a computer, which transform the visual images from the camera into the TDU coordinates.

2.2 Taste Interfaces

Related to taste interfaces there have been few works conducted on generating taste sensations by mixing few chemicals together. In addition to the virtual reality helmet [2] discussed in section 1, Iwata et al. presents a food simulator which uses chemical and mechanical linkages to simulate food chewing sensations. The system provides flavoring chemicals, biting force, chewing sound, and vibration to the user [4]. It is designed to fit the users' mouth to deliver the force of a virtual bite.

In addition, there are few experimental results can be found on electrical stimulation on human tongue mainly in the field of medicine, especially in electrophysiology. Lawless et al. presents a study on the metallic taste generation from electrical and chemical stimulation [8]. The presented study was designed to observe the similarities and differences of stimulation with metals, electrical stimulation, and solutions of divalent salts and ferrous sulphate in particular. In this experiment, they have investigated sensations occurred across oral locations using electrical stimulation with different metal anodes and cathodes. They have presented evidences of sour and salty sensations on users' tongues through electrical stimulation.

Moreover, In "Taste qualities elicited by electric stimulation of single human tongue papillae", a single human tongue papillae was electrically stimulated (84 trials) with a silver electrode using five young subjects [11]. They used electrical pulses of both negative and positive with the frequency range of 50 - 800 Hertz. The results provided some exciting and effective responses for the sour sensations (22.2%) and smaller number of responses for the bitter (3.8%) and salty (1.8%) sensations.

Additionally, in "Thermal stimulation of taste" Cruz et al. studies the effects on temperature change (heating and cooling) and perceptions of taste sensations [1]. They experimented on anterior edge of the tongue and found evidences on sweet, sour, and salty sensations.

3. Stimuli Design

As described, the system uses both electrical stimulation and thermal stimulation on the tip of the tongue to generate different taste sensations. In this section, we describe the stimulus protocol for both electrical and thermal stimulation. Then we present the finalized architecture of the Tongue Mounted Taste Stimulation system, including tongue interface and control system in section 4.

3.1 Protocol

During the design phase of the system, we realized the importance of finalizing the stimulus protocol for both electrical and thermal stimulation. Two main factors were considered for the final protocol design: threshold of the stimulus to obtain expected perceptions and the comfort level of users.

3.1.1 Electrical Stimulation

In electrical stimulation, the magnitude of current and the frequency of electric pulses are controlled. Primarily, based on literature [12, 8, 16, 11], we finalized the range of frequencies and the magnitudes of current as follows,

- Frequency range: 50Hz - 1000Hz (since lower frequencies have a clear effect on human tissues)
- Magnitude of current: 20μA to 300μA and further revised based on the study presented in section 4.1.

As in the initial phase and to simplify the control system, we were only interested in square wave electrical pulses on the human tongue. The effects of sine, triangle, and sawtooth waveforms will be studied in later stages of this research.

3.1.2 Thermal Stimulation

In thermal stimulation, based on [1], temperature is controlled (both heating and cooling) within 20°C - 35°C. In addition, it is noted that the time required to achieve a distinct temperature change is essential thus implemented a mechanism based on pulse width modulation (PWM) technique to manipulate the time required.

Apart from the above experimental design considerations, the material of electrodes (which are contacting with the user's tongue) are equally important for the user experiments. For the presented prototypes, silver (95%) electrodes were used since it has high thermal and electrical conductivity. In this paper, we only considered stimulating the tip of the tongue. The effects from other areas of the tongue surface are not considered. Two electrodes were used for the electrical stimulation: one as the anode and the other as the cathode. Furthermore, we understood the ethical issues behind this research and secured the necessary approval from the University Institutional Review Board (Approval No: NUS 1049) before the experiments.

4. Tongue Mounted Digital Taste Interface

To observe the effectiveness of this approach, the Tongue Mounted Digital Taste Interface is developed with two main modules as shown in Figure 2. They are the control system, which controls the output based on stimuli design in section 3.1 and the tongue interface, which finally actuates the user's tongue as in Figure 1. Furthermore, we implemented a mechanism to control the output of the digital taste interface through a computer. The computer controls the output of digital taste interface using Bluetooth[1] communication.

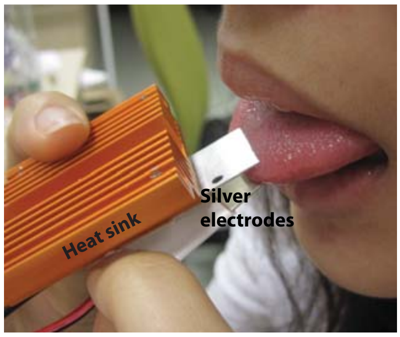

Figure 1. The tongue interface attached to the user's tip of the tongue

The control system consists of three subsystems as in Figure 2. First subsystem is designed for electrical stimu-

[1] http://www.bluetooth.com

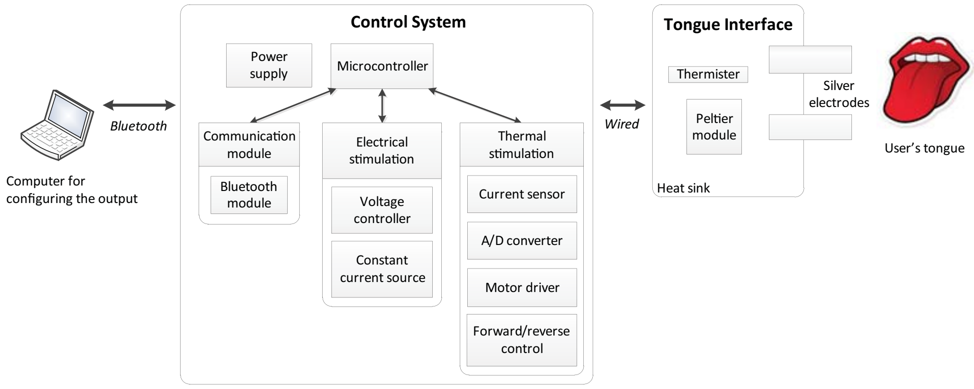

Figure 2. System architecture of Tongue Mounted Digital Taste Interface. The connection between the computer and control system is implemented using Bluetooth

lation, second for thermal stimulation, and third for communication with the control computer. In electrical stimulation subsystem, a digital potentiometer is used (voltage controller) with a constant current source to provide a constant current to all the participants. A constant current source is implemented since the impedance of the tongue is varying person to person due to the differences in types and density of papillae on the tongue surface [7]. The electrical stimulation module provides square wave pulses to the tongue module with diverse current from 20μA to 300μA and frequency from 50Hz to 1000Hz. The frequency is changed based on the PWM output of the Microcontroller. In thermal stimulation subsystem, a Peltier[2] semiconductor module is used (Peltier Junctions) to change the temperature of the tongue. The thermal stimulation module controls (both cooling and heating) the Peltier module, which attached to silver electrodes within 20°C - 35°C. The output parameters can be configured using the computer attached.

Additionally, the tongue interface consists of two silver electrodes (each has dimensions of 40mm x 15mm x 0.2mm) for electrical stimulation, a Peltier module, and a thermister for thermal stimulation. In addition, it requires a heat sink for effective temperature control through the Peltier module. The tongue interface and the control system are connected with a six wire connection, which carries two control signals and power connection for the peltier module. The final implementation of the Tongue Mounted Digital Taste Interface is shown in Figure 3.

4.1 Comfort Level

A pilot user experiment was conducted for electrical stimulation to determine the comfort level of the participants. The experiment was designed to measure the comfort level of user's tongue over the magnitude of current supplied. Eleven participants were recruited for the experiment and asked to contact two silver electrodes (of the tongue interface) on the tip of the tongue (bottom and top ends as in Figure 1), while the control system increases the magnitude of current supplied. The magnitude of current was changed from 20μA to 300μA in 20μA intervals. Participants were asked to hold the tongue interface on their tongues till it gets uncomfortable. The results of this experiment were plotted in Figure 4 and used to configure the output of the system to be well within the safety margins and especially in the comfort zone for end users. For user experiments on taste perceptions, the system is configured to be within 20μA to 200μA.

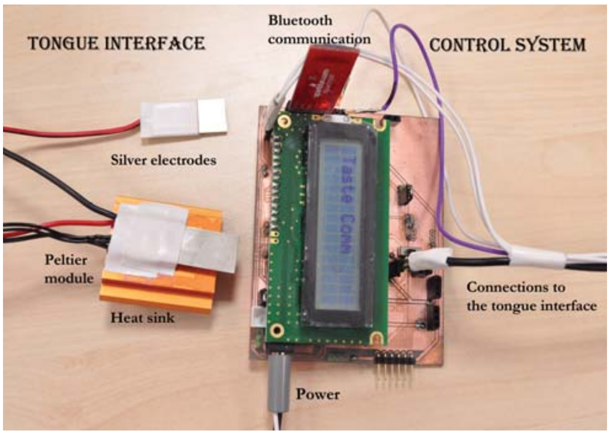

Figure 3. Implementation of the Tongue Mounted Digital Taste Interface

[2] http://www.peltier-info.com

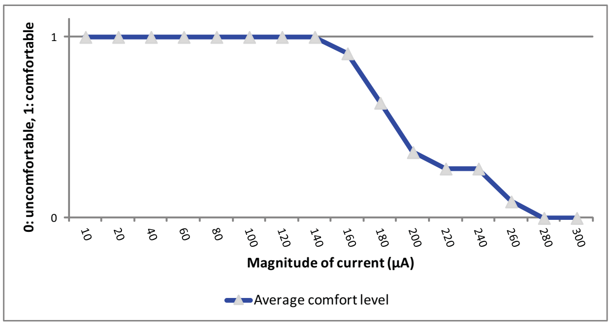

Figure 4. Comfort level of the users when experimenting on electrical stimulation using the Digital Taste Interface (n = 11)

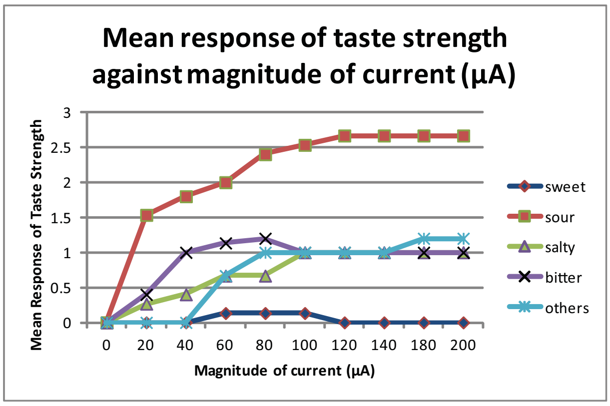

Figure 5. Taste intensity against the magnitude of current (μA)

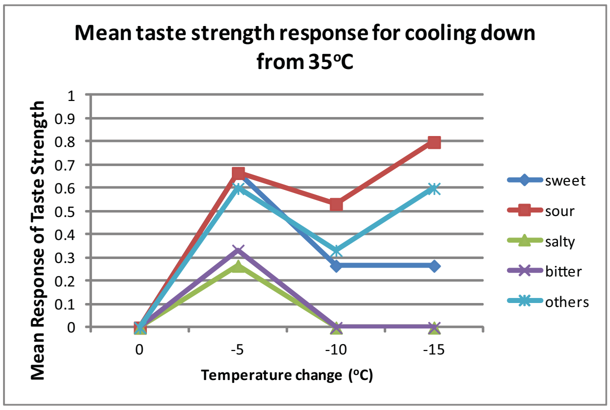

Figure 6. Taste Intensity responses (35°C - 20°C)

4.2 Preliminary Experiment and Results

To investigate and analyze the effectiveness of the approach an initial user experiment was conducted with eighteen subjects (ten males and eight females, age range from 21-27). Participants were not trained before the experiment and they were in normal health condition. Electrical pulses with predetermined magnitude of current (20, 40, 60, 80, 100, 120, 140, 180, 200μA), frequency (50, 100, 200, 400, 600, 800, 1000Hz), and temperature (cooling and heating between 20°C - 35°C) of the stimulation were then applied to the tongue through the electrodes to produce different sensations. Subjects rinsed their mouth with deionized water between each stimulus. The sensations were recorded along with intensity levels. Participants were asked to describe perceived taste intensity in three levels: mild representing 1, medium means 2, and 3 corresponds to strong.

Figure 5 reveals the intensities of taste sensations reported during the electrical stimulation. The results suggest that the strength of sour, bitter, and salty sensations are increased when the magnitude of current increased. Furthermore, responses from all the participants were quite similar and continuous for sour sensation. Average of 62% indicated that the sour sensation is increased when the magnitude of current is increased. All the participants indicated that the change of frequency did not have a clear effect on their perceived sensations.

Although the rate of successful generation of sweet sensation was low, it implied the possibility of being able to produce the sweet sensation using the thermal stimulation (Figure 6). Furthermore, several subjects reported that they felt the minty taste, refreshing taste (when cooling down from 35°C - 20°C), and also slight spiciness (when heating up from 20°C to 35°C).

Many participants commented that they enjoyed the new instrument along with the experience. However, one of the main drawbacks we found on this approach was the results which were more subjective in most of the occasions except for sour and bitter sensations. This can be resolved by conducting training sessions and calibrating the device based on individual user's feedbacks. Moreover, several participants recommended two main improvements for the existing design of the tongue interface. First, they mentioned it should be able to extend into the participant's tongue without fully opening their mouth. Thus, enabling the participant to control the salivating as well as dryness on the tongue. Second suggestion is to integrate the tongue interface with control system such that it is capable of being handheld as a single device.

As mentioned, the results provided clear evidence that we were able to obtain more realistic results for sour and bitter sensations using electrical stimulation. Based on this, a more simplified system was developed using electrical stimulation to study more on digital sour sensation. Thus, this system is named as the Digital Sour Lollipop.

5. Digital Sour Lollipop

The Digital Sour Lollipop is based only on electrical stimulation. The aim of this system is to achieve clearer and precise control over the magnitude of current and the sour taste generated. Most of the features of this system are inspired by the Tongue Mounted Digital Taste Interface although the shape of the tongue interface is changed to be more user friendly.

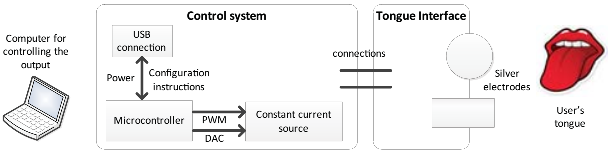

Figure 7. The system architecture of the digital sour lollipop

We adopt the concept (shape, form and operation) of a lollipop as the tongue interface, since it is one of the common/familiar objects people use every day. As can be seen in Figure 8, the sphere shape is one of the electrodes and the base plate is another. Furthermore, the handles are independently moving and the users have the feasibility of enjoying the interface as a real lollipop.

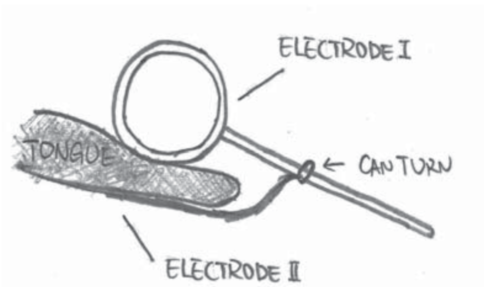

Figure 8. Design of the digital sour lollipop with rotatable electrodes

The design of digital sour lollipop is similar to the Tongue Mounted Digital Taste Interface. It consists of the control system module and the tongue interface (the lollipop) as depicted in Figure 7. The implementation of the digital sour lollipop is shown in Figure 9. Digital-to-analog control (DAC) mechanism is used to control the magnitude of current in discrete steps in order to actuate human tongue. The pulse width modulation (PWM) is used to adjust the frequency of the electric pulses. Thus, the electrical control system provides square wave pulses to the silver electrode (magnitude of current from 10μA to 200μA and frequency from 50Hz - 1200Hz). Different output current values and corresponding DAC steps are plotted in Figure 10.

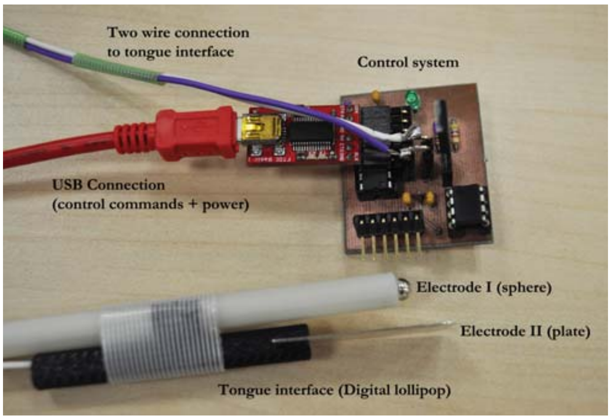

Figure 9. The implementation of the digital sour lollipop

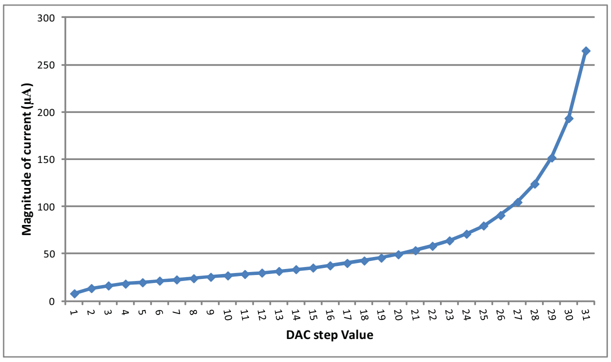

Figure 10. The change of output current according to DAC step value

The output signal from the tongue interface is monitored using a digital oscilloscope. As can be seen in Figure 11, waveform of the output signal is changing after the human tongue is connected to the constant current source. A possible explanation for this change is that the inductance and resistance of human tongue are affecting the waveform.

5.1 Experimental Evaluation

A preliminary experiment was conducted using the digital sour lollipop with sixteen participants aged between 21-28 (M=23, SD=2.54). All participants were in good health

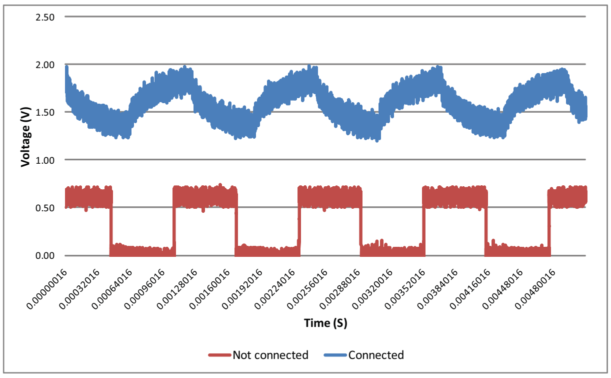

Figure 11. Output current waveforms with and without connecting to the tongue

conditions and no taste and smell problems were reported. All participates were asked not to smoke, eat strongly spiced meals nor consume alcoholic beverages prior to the experiment as it may affect their taste perceptions. After each experiment, participants were requested to describe their experiences and valuable information related to their experience with the system.

Since the sense of taste is a highly interrelated with other senses such as visual, auditory, and smell, the experiments were conducted in side a quiet, air conditioned (24°C) meeting room. As mentioned earlier, the main motivation of this study is to effectively shows the controllability of digital sour taste on human tongue. To use as the base level, three lime solutions were prepared with mild, medium, and strong sourness levels. Five participants volunteered to analyze these three solutions and adjusted the sourness based on their feedbacks.

5.1.1 Procedure

Each experiment was conducted in three steps based on three intensity levels of sour solutions. First, the participant was asked to taste 5ml of the mild sour solution, then he/she was instructed to hold the lollipop and use the tip of the tongue to touch the silver ball. During the first stage, the magnitude of current through the tongue was increased from 20μA until the participant responded that the intensity levels are matched. The corresponding magnitude of current was noted for the mild sensation. Second, they consumed the medium sour solution and the magnitude of current was increased from the previous value noted until a match found. Consequently, the same process continued in the third step with the strong solution. Participants rinsed their mouth with deionized water and rested two minutes between each stimulus for clearer distinction between each sensation. In addition, they were informed to relax and rinse their mouth if they feel tired or uncomfortable at any time during the experiments. After all three experimental rounds, participants were asked to describe their experiences during the experiments. The experimental setup of the digital sour lollipop is displayed in Figure 12.

Figure 12. The experimental setup of the digital sour lollipop

As Lackovic and Z. Stare. (2007) observed, the tongue impedance decreases with the increase in frequency [7], thus the frequency was configured at 800Hz in order to achieve optimal results from this experiment. We believe that, with the decrease in impedance, it might slightly increase the magnitude of current thus the susceptibility of taste perception on the tongue.

5.2 Results and Discussion

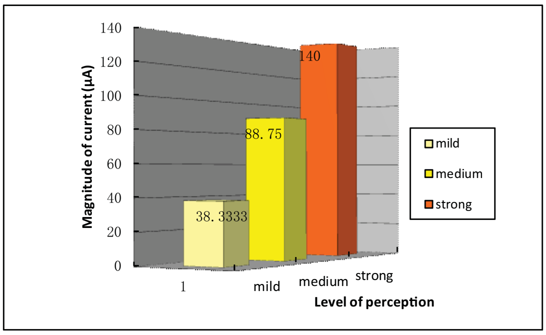

Figure 13. Mean threshold values for three intensity levels of digital sour taste - Mild: 20μA - 38.33μA, Medium: 38.33μA - 88.75μA, and Strong: 88.75μA - 140μA

As illustrated in Figure 13, we were able to identify corresponding three intensities (mild, medium, and strong) for digital sour taste. From the experiment, we found that most of the participants feel mild sour at around 40μA, medium at around 90μA, and strong at around 140μA. Few participants mentioned that although they felt the sour taste, the taste sensation is less similar to the natural (lime) taste. Many of the participants revealed that it felt uncomfortable when the current is around or over 180μA. Two participants indicated that they could feel the vibration of the tongue around 200μA. One of the most noteworthy comments we received was that several participants felt lower magnitude of currents resulted in more realistic sour taste sensations.

Additionally, further experiments need to be conducted to examine effects on different waveforms and both linear and nonlinear changes of current and frequency. For example, at present, we only conducted experiments on certain current and frequency levels (step by step). Next, we will experiment with different surface areas on the tongue and changing current - frequency over time to observe effects on taste sensations. Especially, the evidences of bitter sensation reported in several occasions from the bottom surface of the tongue, requires more controlled experiments in the future.

6. Conclusion and Future Work

In this paper, we described a novel methodology to digitally actuate the sensation of taste using electrical and thermal stimulation on human tongue. Two systems were developed to demonstrate the feasibility of actuating the sensation of taste digitally. The Tongue Mounted Digital Taste Interface is currently able to stimulate sour (strong), bitter (mild), and salty (mild) sensations although it requires further experiments and refinements. Based on initial experimental results, a more focused system, the Digital Sour Lollipop was developed for controlling the sour taste digitally. This system was tested and observed that it is capable of controlling the digital sour taste in three intensity levels. In the future, we believe that this technology will be further enhanced to develop new applications in remote multisensory interactions such as communicating taste sensations; for example, the possibility of tasting food remotely without physically consuming it.

7. Acknowledgement

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