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New Thermal Taste Actuation Technology for Future Multisensory Virtual Reality and Internet

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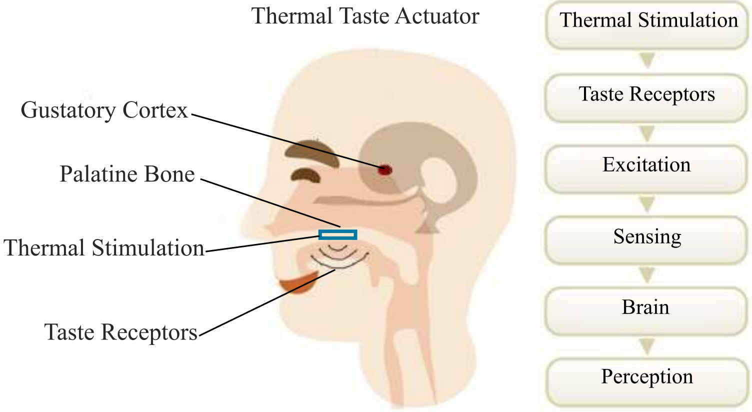

Fig. 1: The concept of producing thermal taste sensations.

Abstract—Today's virtual reality (VR) applications are mainly based on audio, visual, and haptic interactions between human and virtual world. Integrating the sense of taste into VR is difficult since we are dependent on chemical-based taste delivery systems. Therefore, developing a proper non-chemical digital taste actuation technology can unlock taste experiences in VR applications such as gaming, multisensory entertainment, remote dining, and online shopping. This paper presents the 'Thermal Taste Machine', a new digital taste actuation technology that can effectively produce and modify thermal taste sensations on the tongue. This device changes the temperature of the surface of the tongue within a short period of time (from 25°C to 40°C while heating and from 25°C to 10°C while cooling). We tested this device on human subjects and described the experience of thermal taste using 20 known (taste and non-taste) sensations. Our results suggested that rapidly heating the tongue produce sweetness, fatty/oiliness, electric taste, warmness, and reduced the sensibility for metallic taste. Similarly, participants reported that the cooling the tongue produced mint taste, pleasantness, and coldness. By conducting an another user study on the perceived sweetness of sucrose solutions after the thermal stimulation, we found that heating the tongue significantly enhanced the intensity of sweetness for both thermal tasters and non-thermal tasters. Also, we found that faster temperature rise on the tongue produce more intense sweet sensations for thermal tasters. We believe that this technology will be useful in two ways: First, it can produce taste sensations without using chemicals for the individuals who are sensitive to thermal taste. Second, the temperature rise of the device can be used as a way to enhance the intensity of sweetness. We believe that this technology can be used to digitally produce and enhance taste sensations in future virtual reality applications. The key novelties of this paper are as follows: 1. Development of a thermal taste actuation technology for stimulating the human taste receptors, 2. Characterization of the thermal taste produced by the device based on a set of taste related sensations and non-taste related sensations, 3. Research on enhancing the intensity for sucrose using thermal stimulation, 4. Research on how different speeds of heating affect the intensity of sweetness produced by thermal stimulation

Index Terms—Thermal Taste, Multisensory VR, Digitizing Taste, Characterization of Thermal Taste, TRPM5

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1 INTRODUCTION

In virtual reality (VR) applications, actuating the sense of taste is currently based on chemicals [11, 16, 17, 29], which is not an effective long-term solution, as the chemicals need to be refilled and maintained properly. Therefore, finding a digital taste actuation technology which can produce various taste sensations, and does not depend on chemicals, will be a useful future step for VR. Once we reach this goal, people will be able to experience taste sensations through VR and share these sensations across the internet, in the same way, as we experience audio, visual, and haptic sensations. One way of producing taste sensations without using chemicals is to apply thermal stimulation on the tongue and stimulate the TRPM5 (Transient receptor potential cation channel subfamily M member 5) taste channel. The TRPM5 taste channel is known to enhance the sensitivity for sweet, bitter, and umami tastes [14]. The deletion of TRPM5 in mice has reported to a specific loss of sensitivity for the sweet, bitter, and umami tastes [32].

Previous experiments from the medical field investigated the sensitivity of TRPM5 for different stimuli. These experiments found that raising the temperature on the tongue within a few seconds produced sweet sensations for a specific group of people [5] and increasing temperature or higher temperatures enhanced the sensitivity for sweetness [10, 30]. According to the previous experiments, only about half or fewer partic-

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ipants felt taste sensations for thermal stimulation [2,5,9]. This subset of the population is known as 'thermal tasters'(TT). However, these previous researchers have described thermal taste mainly using sweetness or other basic tastes. Therefore, the other sensations produced by the thermal stimulation which does not belong to five basic tastes have not been thoroughly investigated.

Regarding the VR, no one has made a controlled interactive system to induce different taste sensations using thermal stimulation. Having said that, some researchers including the authors, have proposed sweet taste actuation devices [4,21,22] using this technology. These previous works mainly focused on producing sweet taste (or other basic tastes) sensations, but, by improving this technology, we have identified that thermal taste is a complex taste sensation, and it can produce taste related sensations, as well as non-taste related sensations. To study these effects, we have developed a new computer controlled thermal taste device called 'Thermal Taste Machine' which is shown in Fig. 2. By placing the silver electrode of the device, on top of the tongue, the device can produce a modification of the temperature on the surface of the tongue from 25°C to 40°C while heating, and from 25°C to 10°C while cooling. This device is a computer-controlled device and can be easily integrated with software programs.

After building the device, we conducted a characterization study for thermal taste and described thermal taste using taste related and non-taste related sensations. We measured the induced sensations using a measurement index that can record intensities of 20 different sensations. The sensations were divided into two categories: The first category consisted of the five basic tastes (sour, sweet, salty, bitter, and umami) and seven other sensations that people often used to describe flavour experiences (carbonation, metallic, chemical, electric, fatty, minty, spicy). Another reason was that the sensations such as carbonation, fatty, and chemical are detected through their own receptors [3,7,8,18] and we decided to investigate whether the thermal stimulation is capable of exciting these secondary taste receptors as well. The second category consisted of eight non-taste related sensations, which include coldness, warmness, numbness, pain, pressure, lingering, pleasant, and unpleasantness. These are general terms that are used by the people to describe sensations related to temperature and touch. Further, we conducted two more experiments. The second experiment studied how thermal taste can modify the intensity of sweetness produced by sucrose solutions, and the third experiment studied how different rates of temperature rise affect the intensity of thermal sweetness (T-SW).

Experiments conducted on our thermal taste device revealed the following findings for the first time, for a virtual reality thermal taste technology: Our device produced different taste sensations other than sweetness including minty, fatty-oiliness, and electric taste, with some non-taste sensations including pleasantness on human subjects. Also, we observed positive effects towards umami, metallic, chemical, and spicy taste sensations. From the second experiment, we showed that using our device before tasting chemical sweet solutions enhanced the sweetness for both thermal and non-thermal tasters. Further, we found that different rates of stimulation produced different intensity for sweetness in thermal tasters. In addition, we described the thermal taste as a combination of different taste and non-taste sensations.

The remaining sections of this paper is organized as follows: In section 2, we will discuss the previous works of thermal stimulation on the tongue. We will provide a detailed description of the technology we developed in section 3. Then, we will discuss our user experiment procedures and results in section 4. Finally, section 5 will discuss our findings, future work, and potential applications.

2 RELATED WORKS

Some recent investigations have already studied the effects of thermal stimulation on the tongue. These investigations have been primarily from either the medical field or from the HCI field. One experiment [5] first showed that rapid heating the tip of the tongue from 15°C to 35°C (temperature was varied at approximately $\pm$ 1.5°Cs^{-1}) can evoked sweetness, and cooling of the tongue from 35°C resulted in either saltiness or sourness. Further, static cold temperatures (placing an ice cube on a side of the tongue) could produce salty taste sensations [1]. Another study [27] showed that increasing temperature on the tongue resulted in activation of the TRPM5 channel that generates a depolarizing potential in the taste receptor cells. They claimed that this effect caused the enhanced sweetness perception at high temperatures and 'thermal taste', the phenomenon whereby heating or cooling of the tongue evokes sensations of taste in the absence of chemical tastants. It was concluded that stimulating TRPM5 with temperature as an input results in different taste sensations as outputs. It has been further suggested that other tastes, such as salty and sour, may be linked to the temperature sensitivity associated with the channels involved in their chemical transduction [26]. Participants who perceived taste sensations while heating or cooling were referred as the 'thermal tasters' (TT) [31].

Even though the thermal effect with TRPM5 channel has been studied in medicine, a proper controlled interactive system that can reproduce thermal taste sensations has yet to be developed. Having said that, [22] has experimented with electrical and thermal stimulation in combination on the tongue, and showed that it is possible to generate four of the basic tastes: sour, bitter, and salty. During the experiments conducted in [23], stimulation of the tongue with heating and cooling the tongue, participants reported sensations of sweetness and sourness. The first sweet-specific device using thermal stimulation was proposed by the authors of this paper in 2015 [4]. Further, Ranasinghe et al. has also developed a sweet taste specific device in [21]. Meanwhile, in [25], the authors discussed an interface that influenced flavour observation, without changing the nourishment itself, by applying thermal sensations to the skin around the nose to cause skin temperature changes associated with charming or unpleasant feelings. However, findings of these studies were not extended towards the other taste sensations, except sour taste. Therefore, finding the optimum stimulation parameters to generate different taste sensations (like temperature levels, intensity, rates of temperature rising and falling, and frequency) are yet to be discovered, and integrating thermal taste interfaces with multisensory or VR applications remains largely unexplored.

Our approach is different from the works mentioned above in many ways. Our main objective was to develop a controllable interactive thermal taste technology to generate taste sensations for virtual reality. Our concept of stimulating taste receptors using thermal stimulation is shown in Fig. 1. This device is able to generate different rates of temperature rise for heating and cooling. Further, we decided that this technology should be a device that can be plugged into computers and it should be able to be programmed and controlled through the computer. Therefore, our work is different from the previous works from the medical field. Also, the works from HCI have mainly concentrated on inducing sweet taste sensations. In this study, we considered thermal taste as a combination of taste and non-taste related sensations. Therefore, one of our objectives was to describe thermal taste using known taste and non-taste sensations. Further, we studied how thermal stimulation can change the intensity of sweetness and also how different rates of temperature rise can affect sweetness. Our future objective is to integrate this thermal taste technology for VR and multisensory communication. According to our knowledge, no attempt has been made so far to achieve this.

3 SYSTEM DESCRIPTION

The thermal taste device developed by the authors is shown in Fig. 2. This device consisted of an Arduino microcontroller, a silver plate attached to a Peltier module, a liquid cooler system, an h-bridge motor driver, a current sensor, a temperature sensor, and a USB serial interface to communicate with the PC. The circuit diagram of the thermal taste device is shown in Fig. 3.

Changing the temperature on the tongue was achieved by using a Peltier module that was tightly attached with the silver plate as shown in Fig. 4. When current flows through the Peltier module, one side becomes cool and the other side becomes hot. By alternating the direction of the current flow, we were able to swap the heating and cooling sides. According to the specification of the Peltier module we selected, the surface temperature could be changed from -40°C to 80°C. This Peltier module was operated at 15.6V and it consumed up to 8.5A

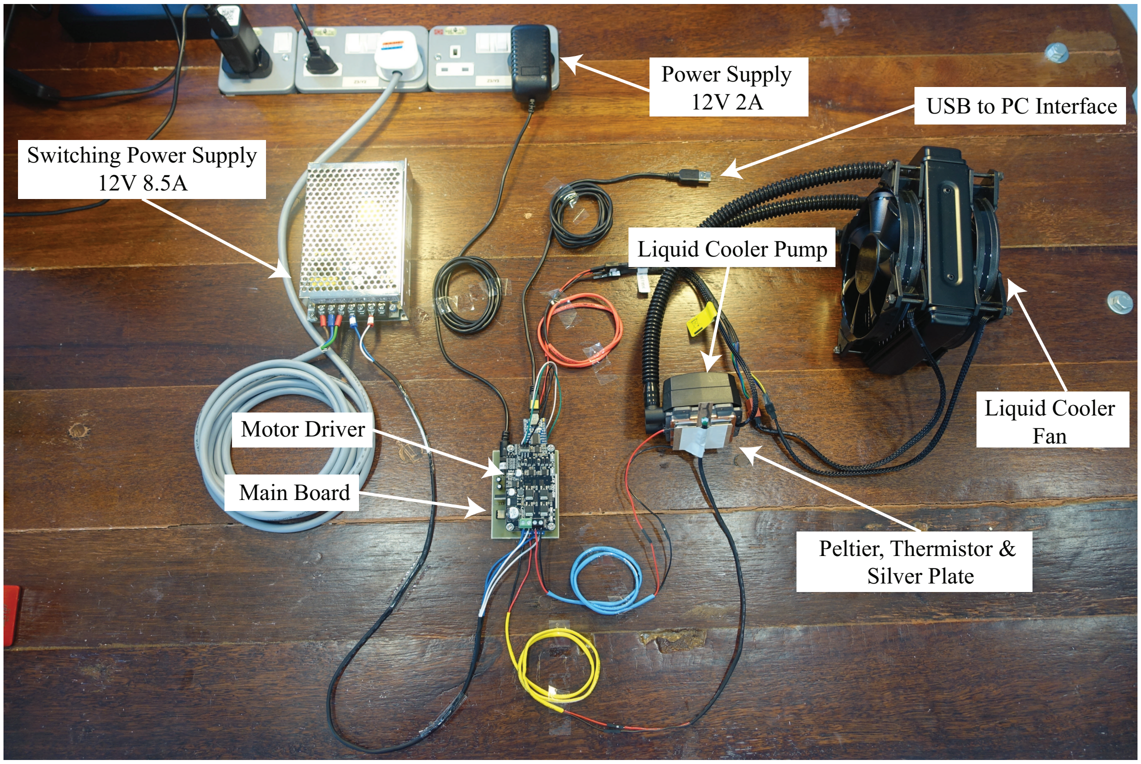

Fig. 2: The thermal taste device and its components. By placing the silver plate of the device on the tongue, users can feel the thermal taste sensations including sweet, minty, fatty, and electric.

for 100% duty cycle. Therefore, a high-power h-bridge motor driver was used to drive the Peltier module. Wires that are carrying power to the Peltier module were shielded to improve the safety. The motor driver received control signals from the Arduino microcontroller output pins.

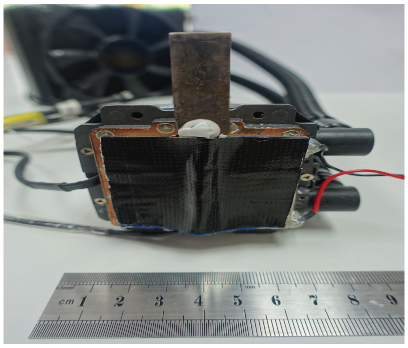

Fig. 4: Silver plate assembly with the Peltier module and the liquid cooler

To make the tongue stimulator plate, we used copper for our earlier prototypes and then used silver for the current prototype. The main reason for moving from copper to silver was to achieve faster temperature change. Compared with copper, silver provides faster temperature change, since silver has less specific heat. The specific heat of copper is 0.092 kCal(kg°C)$^{-1}$ while silver is 0.057 kcal(kg°C)$^{-1}$ [24]. Additionally, silver does not produce metallic sensations as in copper, which is a further advantage of silver over copper. The silver plate chosen for this device had a thickness of 0.5 mm, and we reduced the surface area of the metal plate to decrease the total weight, because a plate with less weight can heat and cool faster [12]. Further, the surface area and the shape of the silver plate affected heating and cooling. If the silver plate has more surface area than the surface area of the Peltier, heating and cooling of the silver plate becomes slower. Regarding the shape of the silver plate, the section that placed on the tongue needed to be closer to the Peltier module to ensure an efficient energy transmission. Therefore, we made the silver plate not much larger than the surface area of the Peltier, and made sure the section that touches the tip of the tongue situated closer to the Peltier module (Please refer to the Fig. 4). The silver plate was connected to the Peltier using a thermal epoxy that provided efficient heat transfer between the two surfaces.

Generally, Peltier modules have a cooling side and a heating side. By alternating the flow of the current, it is possible to change the heating side to be used for cooling and the cooling side to be used for heating, but it is not efficient. Therefore, during the development of this device, we had to make a choice: whether we should mount the silver plate on the cooling side or the heating side of the Peltier. Since most of the previous studies reported thermal taste sensations for heating rather than cooling, we decided to mount the silver plate on the heating side. This made our device is optimized for heating. As a result, we had to use the same heating side of the Peltier for cooling, which is not very efficient as using the original cooling side of the Peltier. To increase the efficiency while cooling, the excess energy (heat) produced on the cooling side needed to be drawn out continuously. Therefore, we used a liquid cooler instead of only using a heat sink and mounted on the cooling side of the Peltier. For reaching the correct set temperature while heating and cooling, the device controlled the current flow to the Peltier by modifying the PWM output, using a PID controller [20]. Further, this device was equipped with a current flow sensor and a temperature sensor to measure the amount of current flow to the Peltier module and the resulting temperature of the silver plate.

We used two different power levels in the circuit. The microcontroller and signalling channels were powered using the computer USB port power (5V, less than 500mA), and the rest of the components were powered from a switch-mode power supply that delivered 12V and 8.5A. To isolate the two power systems (logic and power), we used optocouplers that prevented flow of current to the logic circuit from the other circuit components.

The Arduino microcontroller performed three tasks: 1.) heating and

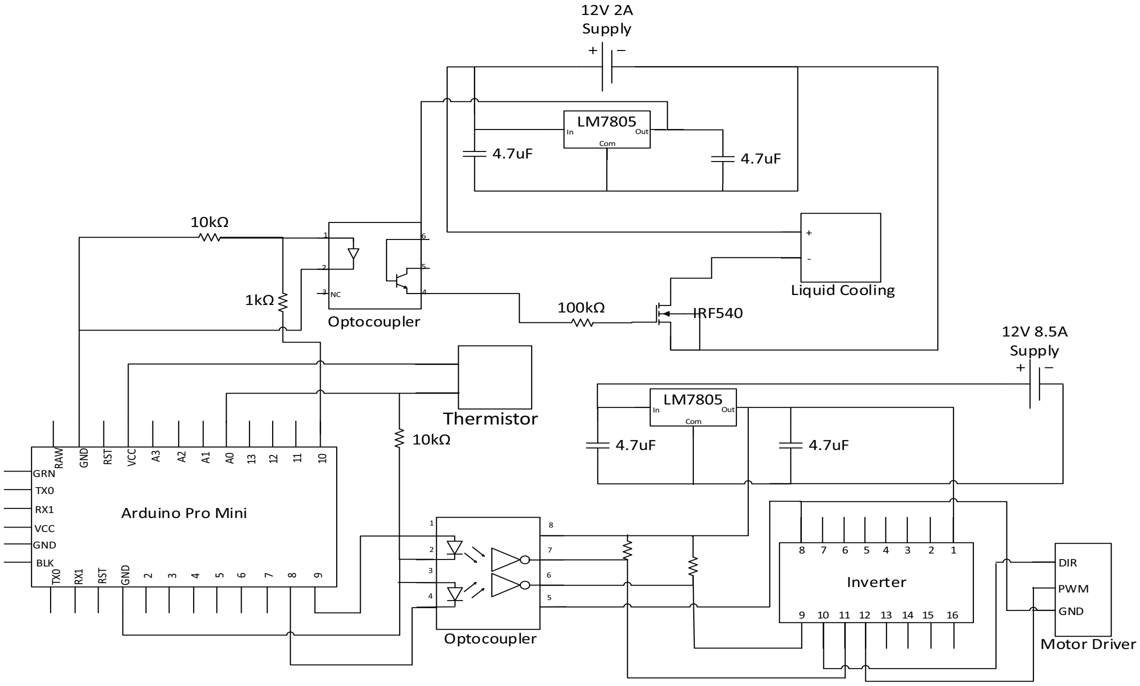

Fig. 3: The circuit diagram of the thermal taste device.

cooling of the copper electrodes according to the signals received from the PC, 2.) measuring the flow of current to the Peltier module, and 3.) monitoring the temperature of the electrode using the temperature sensor, and maintaining the proper stimulation temperature using PID control. To control the device using a computer we used a serial client software, such as Putty or hyperterminal. Users could easily use the serial interface to program this device and control its functionalities such as heating, cooling, temperature thresholds, and stimulation intervals.

We conducted an experiment to identify the higher and lower temperature limits of this device. We used the maximum PWM value, kept the device running on full power, and recorded the temperature output from the sensor attached to the silver plate. Fig. 5 shows the experimental results. According to the results, the device reached a maximum of 100°C and a minimum of 4°C. We did not manage to lower the temperature below 4°C, even though the Peltier specification claimed a minimum temperature of -40°C. This is mainly because we mounted the silver plate on the original heating side of the Peltier, so the cooling will not be as efficient compared with using the original cooling side of the Peltier. Further, limitations of the heat sink, liquid cooler design, and efficiency of the thermal epoxy could be the other reasons for this.

We used a PID controller for this device to achieve, faster responses and good stability. By experimentally testing for different PID combinations, we concluded that the most suitable PID parameters for heating as Kp=20,Ki=10,Kd=30 with a 6.0s rise time (set temprature 40°C), and the most suitable PID parameters for setting back the temperature to 25°C after heating was: Kp=60,Ki=0,Kd=50 (set temperature 25°C). Further, we found that the most suitable PID parameters for cooling as Kp=1000,Ki=300,Kd=8000 (set temprature 10°C), and for setting back the temperature back to 25°C after cooling as: Kp=20,Ki=10,Kd=30 (set temperature 25°C). Fig. 6 shows how temperature changes with the time for each set of PID parameters while reaching the desired temperatures (40°, 25°C, and 10°C). During our experiments we used the rising and falling sections of the temperature curves (referring to the blue and red color curves in Fig. 6) for stimulating the subjects. We used the orange and cyan color curves to set the device back to the 25°C. These selected PID parameter sets resulted in 5% steady state error of the setpoint, less overshoot, and a very quick settling time.

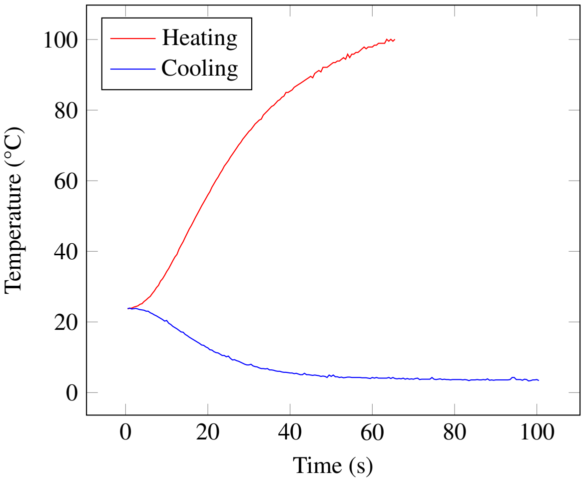

Fig. 5: This figure shows the highest and lowest temperatures obtained by the device when it operates on full PWM.

4 USER EVALUATION

We conducted three different user evaluations for the thermal taste device. First, we did a characterization of thermal taste sensations. Second, we studied whether the thermal taste device can alter the intensity of sweet taste sensations produced by the sucrose. Third, we tested whether the different rates of temperature rise modifies thermal sweet sensations. For all three experiments, participants filled out and signed a consent form before the experiment and all three experiments were conducted according to the ethics guidelines approved by the institutional review board (IRB). Participants were paid for their time according to the standard hourly rate defined by the institute. All participants had normal or corrected-to-normal vision, and reported no taste or smell related sensory dysfunctions. All participants were asked not to use perfume, nor to smoke, eat, or drink (except water) one hour prior to the testing. A questionnaire was first completed by each individual relating to his/her health status and allergies. Participants were

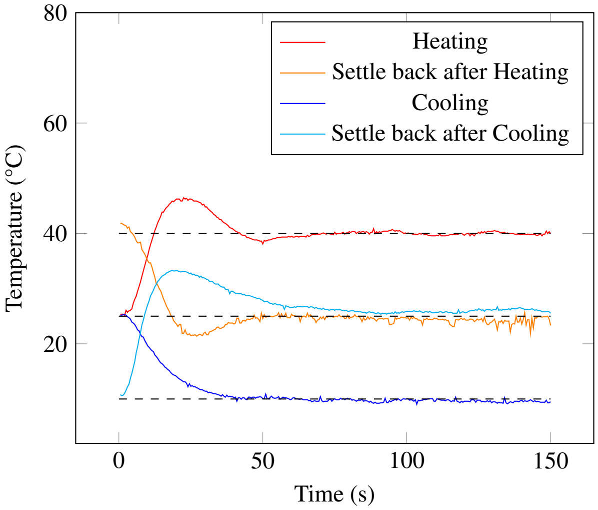

Fig. 6: The most suitable PID control curves obtained for this device for heating, cooling, and settling back the device to 25°C after heating and cooling

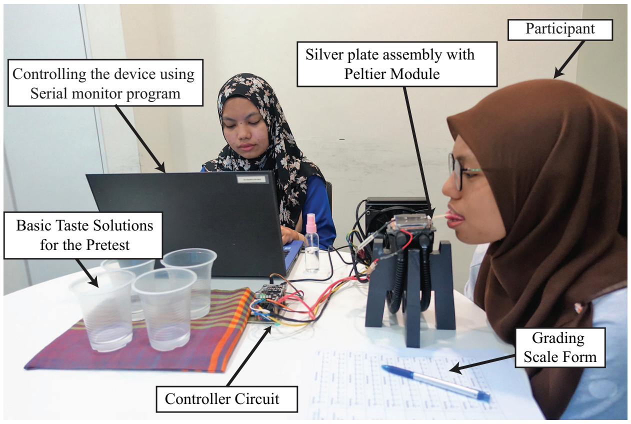

Fig. 7: This figure shows the user study setup of the thermal taste characterization experiment

physically screened by answering some general well-being questions.

4.1 Characterization of Thermal Taste

In this study, we stimulated the surface of the tongue using heating (from 25°C to 40°C) and cooling (from 25°C to 10°C). A 'device off' state was added as the control experiment. The order of stimulations was randomized and each subject went through 12 trials in total (3 different types of stimulations × 4 trials per stimulation). Before conducting this study, we conducted a pilot study with 10 naive subjects. The goal of the pilot study was to familiarize ourselves with the user study protocol. A total of 39 healthy naive subjects (23 females) participated in the main study. A majority of the participants were university students who were between the ages of 20 to 23 years old, and a few adults also participated in the experiment (mean age 24 ± 6.9).

After completing the questionnaire, a pre-screening procedure was conducted to ascertain the capability of the subject to identify different tastes, and to rule out any taste dysfunction before proceeding to the main experiment. Subjects were randomly presented with four different known taste solutions (sour, salty, bitter, and sweet solutions prepared using citric acid, sodium chloride, caffeine, and sucrose). Participants were asked to taste each taste solution one at a time and identify the type of taste. After the trial, participants were asked to rinse their mouths with distilled water. The idea behind this step was to reset the taste receptors to their original state. Then, this same procedures was repeated for next three taste solutions. In our case, all the participants were able to correctly identify the four tastes. Therefore, all 39 participants were selected for the main experiment

During the main experiment, participants were made to seat comfortably on a chair in a closed room. After the participant was settled we asked the participant to rinse his/her mouth with distilled water and place the silver plate of the thermal taste device on his/her tongue. Then, the experimenter activated the thermal taste device with one of the randomized stimulations (either OFF, heating, or cooling). After the stimulation finished we asked the participant to rate the sensations he/she felt on the tongue using the intensity recording sheet we prepared with 20 sensations. Our user study setup is shown in Fig. 7. After the trial, the participant was asked to rinse his/her mouth and continue to the next trial. The procedure for each participant lasted for about one hour.

4.1.1 Results

The percentages of the participants who reported the taste related sensations and non-taste related sensations for thermal stimulation is shown in Fig. 8 and Fig. 9. The means for the intensities of taste sensations and non-taste related sensations produced by thermal stimulation is shown in Fig. 10 and Fig. 13. One way ANOVA method was used to compare the means between three different stimulations; device switched off, heating, and cooling. Results showed that the effects were significant, for sweetness (p=0.003), fatty-oiliness ($p<0.001$), minty (p=0.005), electric (p=0.04), heating ($p<0.001$), cooling ($p<0.001$), and pleasantness (p=0.005). These results indicate that heating of the tongue induced sweet, fatty (or oily), electric, and warm sensations, while cooling of the tongue resulted in minty, cooling, and pleasant sensations. A previous experiment with mice suggested that the long-chain unsaturatedfreefatty acid and linoleic acid (LA) could depolarize the TRPM5 channel [15]. Also it showed that mice lacking TRPM5 exhibits less sensitivity for LA. Therefore, we can argue that the similar fatty taste sensations were produced in the human subjects by thermal stimulation. Further, for heating the tongue showed positive results for producing spicy, numbing, and unpleasant sensations. In addition to that, heating the tongue has reduced sensibility for metallic taste with compared to cooling or off states. A similar result was discussed earlier for the thermal tasters in [2]. By using different types of heating, these effects can be further explored and enhanced in future.

4.2 Enhancement of Sweet Taste using Thermal Stimulation

Previous experiments from the medical field reported that the thermal stimulation can enhance the taste sensations [27, 30]. The reason for this is that the TRPM5 cation channel shifts the midpoint for votage-dependent activate to negative voltages while it stimulating with the temperature [13]. Therefore, temperature rise can promote the activation of the channel. Similarly, we hypothesized that stimulating the tongue using thermal taste machine should also increase the sensitivity for sweet taste sensations. Therefore, we decided to conduct an experiment to test this hypothesis using thermal taste machine and sucrose solutions. Twenty volunteers (5 females, Mage = 25.30, SD = 5.43, age range = 20-44) were recruited as participants for this study from a near by university. The experiments were conducted in a quiet meeting room at the university.

Two solutions of sucrose with the concentration of (3.1 gL^{-1}) and (24 gL^{-1}) were used. Six different scenarios were tested with the factors on/off and solution (water, sweet lower, sweet higher). Participants sampled three different liquid solutions (water, 3 gL^{-1}, 24 $\mathrm{g/L}^{-1}$ sucrose) after one of two thermal interface conditions, on or off. The trials were randomized across the participants. In each trial, participants were asked to place the tip of the tongue on the thermal interface for 14s. After the on or off stimulation, the participants were asked to remove the interface, taste one of the three solutions, and evaluate this solution on three visual analogue scales (intensity, valence, sweetness), ranging from 1 to 10. Participants rated each liquid one time in both conditions. At the beginning of each trial, the surface temperature of the digital

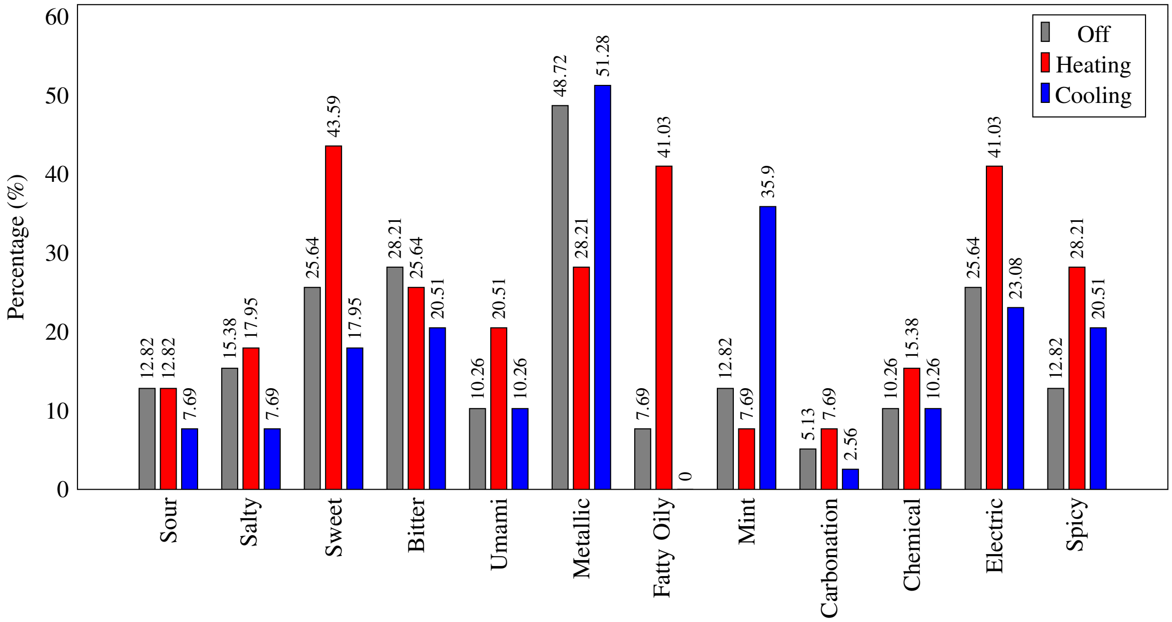

Fig. 8: Percentage of participants who reported taste related sensations for three different stimulations; off, heating, and cooling.

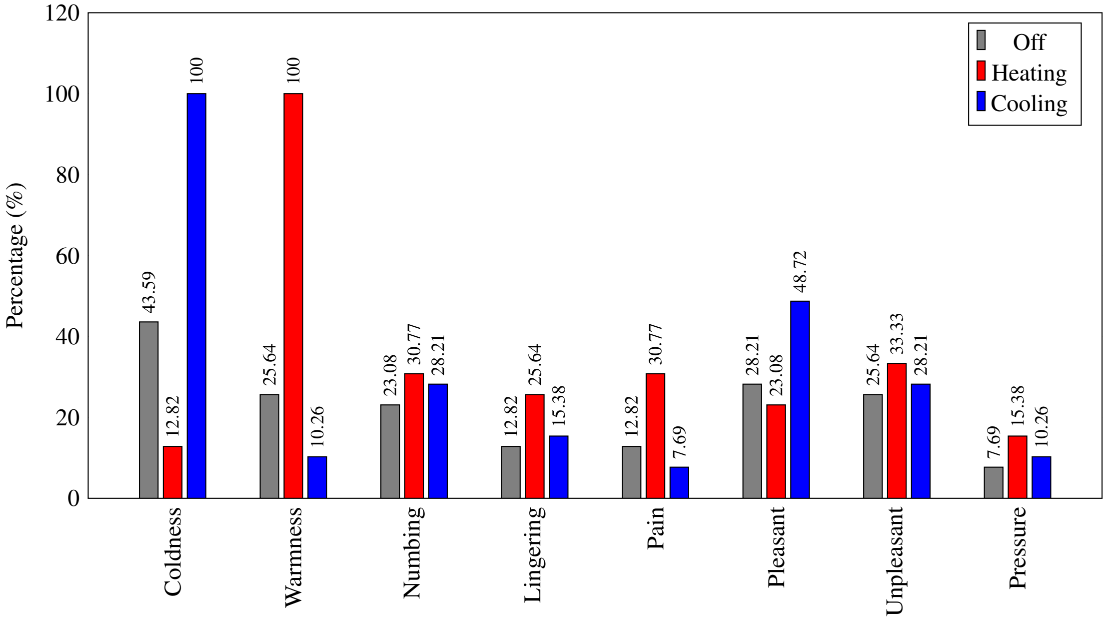

Fig. 9: Percentage of participants who reported non-taste related sensations for the three stimulations; off, heating, and cooling.

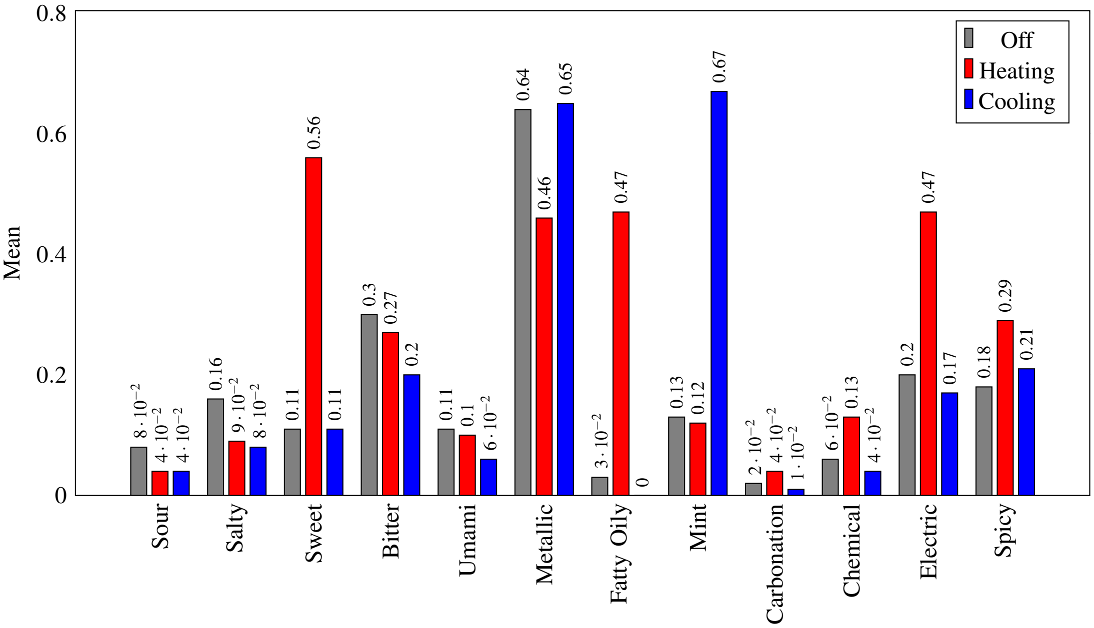

Fig. 10: Means of the taste related sensations reported for three different stimulations. We obtained stastically significant results for sweet, minty, fatty, and electric tastes

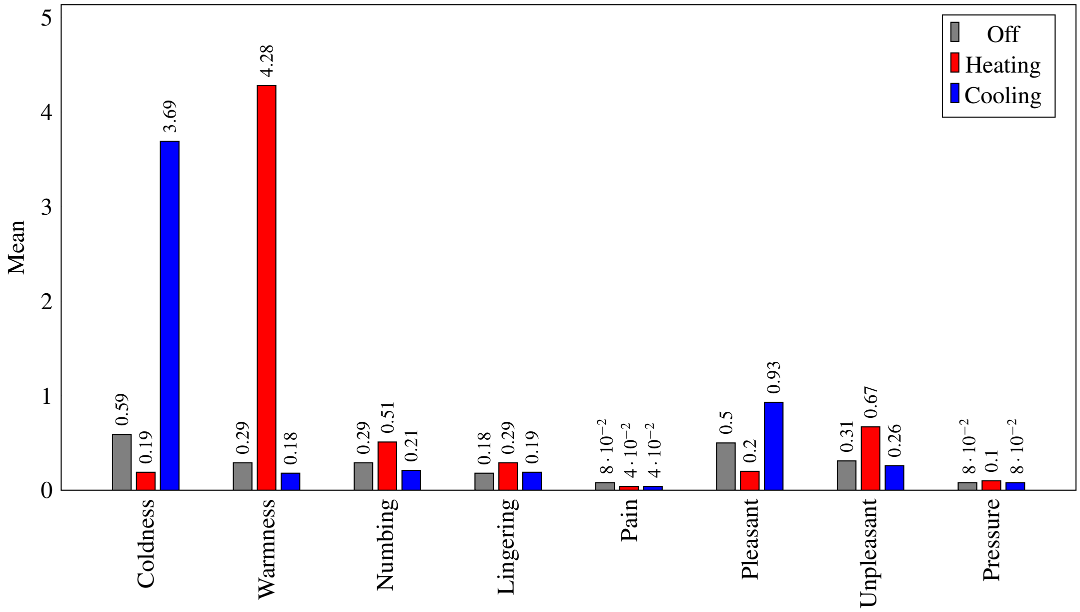

Fig. 11: Means of the non-taste related sensations reported for three different stimulations. We obtained stastically significant results for pleasantness, coolness, and warmness

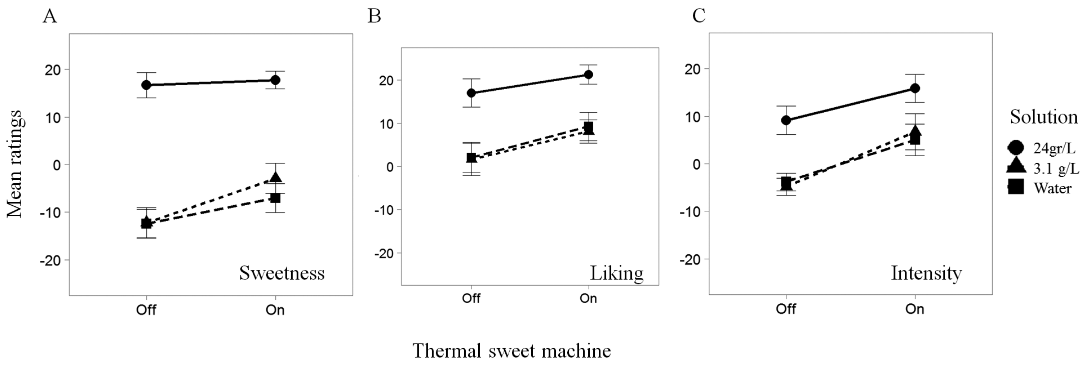

Fig. 12: This graph shows that thermal taste device significantly improved the sweetness of the two sweet taste solutions

interface was registered, as well as the time to reach 40°C. Furthermore, participants rinsed their mouth with water between each stimulus.

However, this experiment was conducted with two limitations. The first limitation was as soon as the silver plate removed, tongue started to cool. The second limitation was that the sweet taste receptors which are located in the other areas such as sides and back of the tongue, and the soft palate were not heated. Therefore, the effect of the thermal stimulation was only limited to the sweet taste receptors located in the anterior of the tongue.

4.2.1 Results

The sweetness, liking, and intensity ratings were analysed by means of a 2 x 3 analysis of variance-type statistic (ATS), with factors on/off and solution (water, sweet lower, sweet higher). The plotted means of different conditions are showed in Fig. 12. ATS is a non-parametric analysis of variance that is robust to outliers and the violation of assumptions of the parametric analysis of variance [6]. The significant main effects were further analysed by means of pairwise Wilcoxon signed rank tests. The analyses were performed in R statistics [28]. The ATS was used as implemented in R package nparLD [19].

Significant effects of on/off, $F_{ATS}(1,\infty) = 9.31$, p = .002, and solution, $F_{ATS}(1.59,\infty) = 79.21$, $p < .001$, were found for the sweetness ratings. The interaction between on/off and solution was not significant, $F_{ATS}(1, \infty) = 2.56$, p = .079. Pairwise comparisons revealed that the sweet ratings were higher after thermal stimulation of the tongue than when no stimulation took place (p = .014). The ratings were also higher for the solution with a higher sucrose concentration than the other two solutions ($p < .001$, for both comparisons).

A significant main effect of solution, $F_{ATS}(1.22, \infty) = 23.27$, $p < .001$, was found for the liking ratings. Neither on/off, $F_{ATS}(1,\infty) = 3.08$, p = .079, nor the interaction between on/off and solution, $F_{ATS}(1.56, \infty) = 0.52$, p = .549, were statistically significant. Pairwise comparisons revealed that the participants liked the higher sucrose concentration more than the lower concentration and water ($p < .001$, for both comparisons). For the intensity ratings, significant main effects of on/off, $F_{ATS}(1, \infty) = 14.52$, $p < .001$, and solution, $F_{ATS}(1.22, \infty) = 16.44$, $p < .001$, were found for the intensity ratings. The interaction between on/off and Solution, $F_{ATS}(1.90, \infty) = 1.32$, p = .268, was not significant. Pairwise comparisons revealed higher intensity ratings for the higher concentration than both the lower concentration and water ($p < .001$, for both comparisons). Moreover, the participants rated the solutions as more intense after thermal stimulation than after no stimulation ($p < .001$).

In summary, the thermal sweet taste device, appeared to influence both the sweetness and intensity ratings of the solutions. Moreover, and as expected, the participants liked the higher sucrose concentration more, and also found it sweeter and more intense, than the lower sucrose concentration and water [31]. This is the first occurrence that a thermal taste device developed in VR or HCI fields reported enhancement of sweetness. Therefore, our device can be used in VR applications for enhancing the sensation of sweetness in combination with chemical sweeteners. Our results showed that this effect can be applied on both thermal tasters and non-thermal tasters.

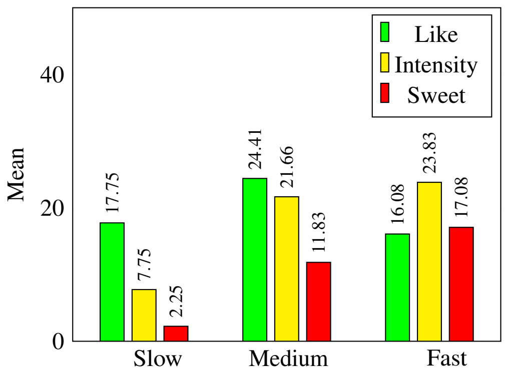

Fig. 13: Means of likeness, intensity, and sweetness reported for slow, medium, and fast rates of thermal taste device

4.3 How Different Rates of Temperature Rise Affect Sweetness

This experiment was designed as two sub-experiments. During the first part of the study we identified people who could receive thermal sweet sensations from the thermal taste device. Then, in the second part of the experiment, we asked those thermal sweet tasters to try three different rates of temperature rise (keep the temperature on 20°C as the control experiment, change from 20°C to 40°C within 20s, 20°C to 40°C within 30s) and rate the sweetness they felt for different rates of temperature change.

For this experiment, we recruited 36 naive participants (12 females, Mage = 25.88, SD = 5.75, age range = 20-44) from a nearby university. The experiments were conducted in a quiet meeting room at the university.

During the study, we asked the participants to rate how strong they feel five basic taste sensations (sour, sweet, bitter, salty, and umami) during the thermal taste stimulation. We purposely asked the participants to report their responses for five basic tastes to avoid developing any bias towards sweet taste. The intensities were marked in a scale from -50 to +50 (where +50 is the the extreme sweet, 0= no sweet, -50 is extremely not sweet). the we found six participants who reported thermal sweet taste sensations (M = 13.33, SD = 12.11). Our idea was to study how different stimulation speeds affect sweet taste. Since our participant size for the experiment was only six subjects we treat this experiment as a pretest.

After identifying six thermal tasters, we stimulated these six participants using the three different stimulation rates slow, medium, and fast (rates were approximately 0.66°Cs^{-1}, 1°Cs^{-1}, and 1.5°Cs^{-1}). Each participant went through 12 trials (three stimulations × 4 times). After

Table 1: A comparison between the related works and 'Thermal Taste Machine'

Title	Sensations Produced	Modified Sensations	Stimulation Parameters
Thermal stimulation of taste [5]	• Warming the anterior edge of tongue produced sweetness •Cooling produced sourness and/or saltiness	nil	• Heating (20°C to 35°C) • Cooling ($\leq$ 20°) • Rate ± 1.5°Cs^{-1}
Heat activation of TRPM5 underlies thermal sensitivity of sweet taste [27]	nil	• Enhanced the gustatory nerve response to sweet compounds	• 15°C to 35°C
Influence of temperature on taste perception (A review paper) [26]	• Warming produced sweetness • Cooling produced sourness and/or saltiness	• Bitterness decreased by cooling	nil
Digital Taste and Smell Communication [22]	• Cooling produced sourness	nil	• Cooling (35°C to 20°C)
Digitally stimulating the sensation of taste through electrical and thermal stimulation [23]	• Produced sweetness and sourness while increasing the temperature	nil	• 25°C to 40°C in 80s
Virtual Sweet: Simulating Sweet Sensation Using Thermal Stimulation on the Tip of the Tongue [21]	• Produced sweetness for heating first and cooling as well as cooling first and then cooling	nil	• Heating to Cooling (20°C - 35°C - 20°C) • Cooling to Heating (35°C - 20°C - 35°C)
Affecting Tumbler: Affecting our flavor perception with thermal feedback [25]	nil	• Enhanced the sweetness, saltiness and sourness for apple juice and orange juice	Applied heating and cooling the skin around nose
Thermal Taste Machine (this paper)	• Produced significant effects for sweetness, fatty-oiliness, electric, and warmness while heating • Produced significant effects for minty, pleasantness, coldness while cooling • Showed positive effects towards umami, chemical, spicy and reduction of metallic taste while heating • Produced sweet sensations of different intensities using different rates of temperature rise	• Produced significant effects on enhancing sweetness of sweet solutions	• Heating (25°C - 40°C) • Cooling (25°C - 10°C) • Different rates of temperature rise for heating (1.5°Cs^{-1}, 1°Cs^{-1}, 0.66°Cs^{-1}) and cooling (0.5°Cs^{-1})

each stimulation, the participants were asked to remove the interface and evaluate the sensation on three visual analogue scales (intensity, valence, and sweetness). Participants felt sweeter sensations during the faster temperature rise than the slower temperature rise and the control stimulation. They also felt more intense sensations for the faster temperature rising. However, these pairwise comparisons were not significantly different after using Bonferroni corrections. Note that, given the sample size, it was expected that many of these analyses would not yield significant differences, nevertheless, the descriptive statistics show some patterns that may be further explored.

5 DISCUSSION AND FUTURE WORKS

'Thermal Taste Machine' showed positive results towards producing and modifying taste sensations for sweet, chemical, minty, fatty, pleasantness, heating, and cooling. Except for the sensations of sweetness, heating, and cooling, this is the first time that any other sensation has been reported for thermal taste stimulation. Therefore, the first experiment successfully showed that thermal taste is a combination of more than one sensation. This study also demonstrated that heating of the tongue produced sweet sensations, which was reported by all the previous works mentioned in the literature review section.

Further, our second experiment proved that sweet taste produce by sucrose can be easily enhanced by the 'Thermal Taste Machine'. This is the first time it was found in a thermal taste device developed for VR or HCI. This effect can be used in VR applications to enhance sweetness for both thermal tasters and non-thermal tasters. Finally, our third study suggested that faster temperature rise can produce more intense sweet sensations. This can be directly applied on producing the sweetness of virtual food and beverages in VR applications for thermal tasters. Table 1 shows a comparison of the related works and the 'Thermal Taste Machine'. Thermal taste machine produced more taste sensations and also enhanced sweet taste sensations, which has not been reported in previous works.

Our future objectives include finding sets of thermal stimulations that can produce more taste sensations. Further, we are interested to conduct cross model studies with mixing the thermal taste with other stimuli such as different kind of visual, auditory, touch, and smell stimuli. able to fine-tune our parameters with different speeds and ranges by further improving the heat sink design, silver plate assembly, and Peltier device. We are also aiming to stimulate human subjects with lower temperatures than 0°C and study the effects. So far, 10°C is the lower bound that researchers have studied [4, 5, 23, 27].

In order to make this device readily available for VR and for everyday life, we still need to address some limitations related to it. One of the key limitation of this device is the lack of user friendliness for frequent use. Some users are hesitant to place the silver plate of the device on top of the tongue due to inconvenience of placing a metal plate on the tongue, fear of burning the tongue, and concerns about the hygiene. Therefore, it would be useful to find more innovative ways of delivering the thermal stimulation to the tongue. The slow onset of the thermal taste compared to the chemical taste is an another limitation. Users should wait for about 10s to 20s to feel the taste sensations. Further, these thermal taste sensations are generally rated weaker compared to taste sensations produced by the chemicals. Therefore, finding methods to produce rapid and more intense thermal taste sensations would be useful future contributions in this research. As suggested in the experiment 3, we believe that the limitation about intensity of thermal taste can be overcame with improving the rate of temperature change. Probably, by testing with different temperature range may produce different sensations as well. Currently our stimulation range is limited to 10°C to 40°C. Improvements of this technology also would benefit from a collaboration of experts from different fields such as food and flavours, nutrition, and medicine. Then we would be able to carefully select the most crucial type of taste stimulations that would benefit for people and produce them using thermal taste technology.

After addressing the above mentioned limitations, we expect that thermal taste technology will be useful in future. In VR and multisensory communication, sensory experiences that involve visual, audio, and touch are, broadly speaking, implemented in different contexts successfully. However, sensing and reproducing taste and smell ex-

Fig. 14: In future, we will be able to communicate and share taste experiences digitally and remotely using thermal taste devices

periences is still a challenge. We believe that after conducting more experiments and improving our device, we will be able to propose stimulation parameter sets for different taste sensations. It would be also possible to combine thermal taste technology with other digital taste and smell actuation technologies and produce meaningful and complex flavour experiences. This digital generation of taste and smell will be useful for several applications of VR, such as gaming, entertainment, online marketing, and remote dining, where people can create content, new information of food that can be shared (as shown in Fig. 14), learned, and experienced. We also hope that this research will be useful for certain clinical populations such as, for example, patients with diabetes.

6 CONCLUSION

This paper made the following significant research contributions; 1. This paper presented the first thermal taste device that can produce sweet, chemical, minty, fatty, and pleasant sensations. 2. We recorded 20 types of thermally induced (taste related and non-taste) sensations and presented how they were modified by heating and cooling. 3. Our device was the first thermal taste device that can enhance the sweet sensations. 4. It has also suggested that faster rates of temperature rise may produce more intense sweet sensations. The final objective of this research is to develop a successful thermal taste technology that can be easily integrated into VR and digital communication. We believe that this will creates a quantum leap in the field of virtual reality. Today virtual reality applications are mainly based on audio, visual, and touch sensations. With the digitization of taste and smell, we will be able to experience all five basic senses in virtual reality, and the virtual experience will become closer to real life. This will create more applications and opportunities in fields such as human computer interaction, gaming, medicine, and internet shopping.

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