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NEUROCOMPUTING AND INTERFACING DIGITAL TASTING SYSTEM: RESEARCH, DESIGN, AND EVALUATION

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1. INTRODUCTION

Taste is one of the five basic senses of the human being. The gustatory process, defined as "taste sensation", takes place when a substance inserted into the mouth reacts with the chemical substances in the oral cavity. The results of this process are interpreted as a specific taste, which is categorized into one of the five basic tastes: sour, bitter, salty, sweet and umami [1]. It is not only the mouth which is responsible for this identification. Many other organs and nerves play a role in this complex analysis to determine the state of the taste in hand, whether it's enjoyable, refreshing, unpleasant, or hazardous [2].

Taste is an important ability of perception in human life. However, some people may encounter the loss of taste partially or completely such as cancer patients undergoing chemotherapy. Meanwhile, others may not be able even to benefit from their sense of taste to introduce some enjoyable delight. This situation is mostly encountered with people suffering from diabetes or hypertension diseases, which prevents them from experiencing favorable tastes such as sweetness or saltiness respectively. In addition, the unpleasant taste of some medications can be a rough experience for some people, especially for children. These situations encourage searching for new techniques to solve or mask such problems.

Today, the importance of digital and electronic systems is very wide because it is as- sociated with the daily interactions of individuals [3, 4, 5, 6, 7, 8]. Hereby, it is able to exploit multiple senses together with expressions, gestures, and interactions with the arti- facts for communication. For instance, electronic media are now present in all hospitals, clinics, schools and even houses and are implemented in several ways. No wonder that this digital transformation may open the doors to finding new solutions for chronic problems that most humans around the world may suffer from.

The problems related to taste discussed previously cannot be solved while dealing with the taste as an abstract sense that cannot be altered. In the world of digitization, the taste should be approached as a digital system. This opens the gates of technology to the world of human sensation. Moreover, although taste sensation is linked to the brain, there is a lack of optimal neurocomputing digital taste sensation systems.

In this work, the aim is to build a system to generate taste sensations on human tongue, in order to overcome taste difficulties and solve its problems. Thus, to achieve such electronic simulation that triggers the brain, we introduce a digital taste interface which is based on electrical stimulation on the human tongue.

In the remaining sections, a biological background is presented in section 2, explaining the existing model in the literature, and relating the biological process that induce taste to an electrical stimulation that can produce a similar effect. In section 3, the new system approach is explained including the materials i.e. the components used based on the requirements and specifications, the utensils chosen and the methods followed. Moreover, safety ethics were provided as the new system involves human response for electrical stimulations. The description of the results of the new digital taste system is explained in details in section 4. The testing and evaluation results of the digital taste system is provided in section 5. The results are discussed in section 6 and the conclusion of the work done is provided in section 7. Finally, the future work to improve the system and other possibilities are provided in section 8.

2. LITERATURE REVIEW ON NATURAL BIOLOGICAL MODEL OF TASTE EXISTING

Taste receptor cells are distributed all over the tongue from the tip to the back and on the sides [1, 9]. Each taste cell has unique kind of protein receptor, targeted to identify one type of taste: sweet, salty, sour, umami or bitter [9, 10].

For instance, when a sweet molecule is ingested, only sweet receptors are activated. As shown in Fig. 1, after activation of receptors, a message is transmitted through nerves to the brain. The interpretation of this message results in distinguishing between different tastes [10].

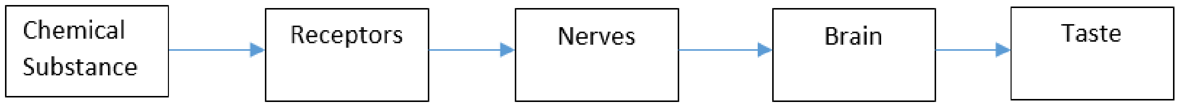

Fig.1: Taste chain [11].

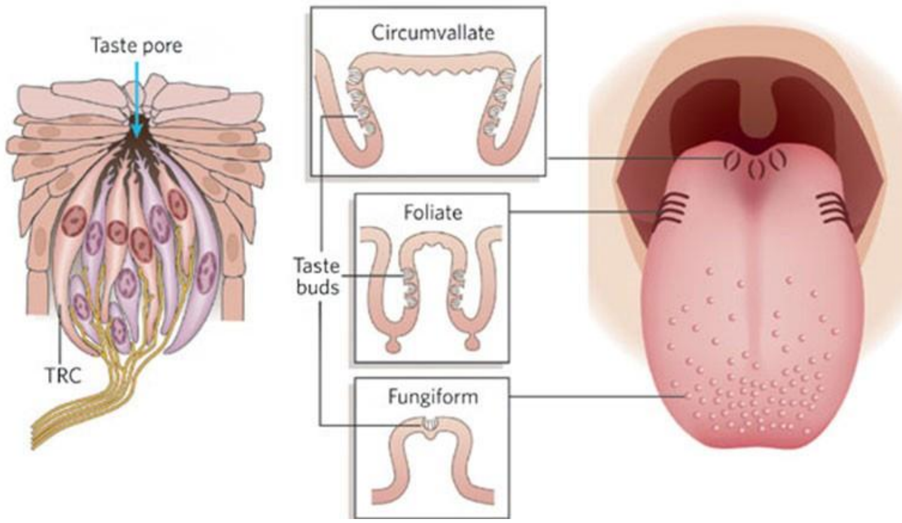

Fig.2: Taste Buds in Human Tongue [11].

2.1 Labeled Line Model (LLM)

According to the labeled line model [9], as shown in Fig. 2, the tongue has three types of papillae distributed over it. Each papillae contains 100 to 150 taste buds. The taste budsare found of the walls of the papillae. Hence, each taste bud contains 5 Taste Receptor Cells (TRC). Each taste cell detects only one of the basic tastes: sweet, bitter, sour, salt, and umami by its specific receptor [9]. Each taste cell is connected to a nerve at its end. These nerves are connected to specific regions in the gustatory cortex in the brain . Each taste has its own region in the brain and its own dedicated nerves. Hence, taste cells release neurotransmitters along the nerves to the brain in case of any taste stimuli. Each region in the brain will determine the taste corresponds to. So, the tastes are sent independently from each other, each in its own path or line [9]. This sums up the Labeled Line Theory and model (LLM). This theory is going to be considered for the rest of our work.

2.2 Generation of a Taste Signal

Regarding the generation of the Taste Signal, the activation mode begins when a substance binds to its receptor. Taste receptor cells sense certain compounds (salts, acids, etc.) due to activation of receptor molecules on the cell's surface [10]. Due to the release of some protein and the opening and closing of certain ion channel illustrated in Fig. 3 an action potential is fired and neurotransmitters are released through axons. After depolarization, the cell puts dozens of protein ions that cooperate and cause a tiny electrical current that cannot be felt. However, this current can be detected by nerves in the tongue. The scheme demonstrating the entire taste process is displayed in Fig. 4.

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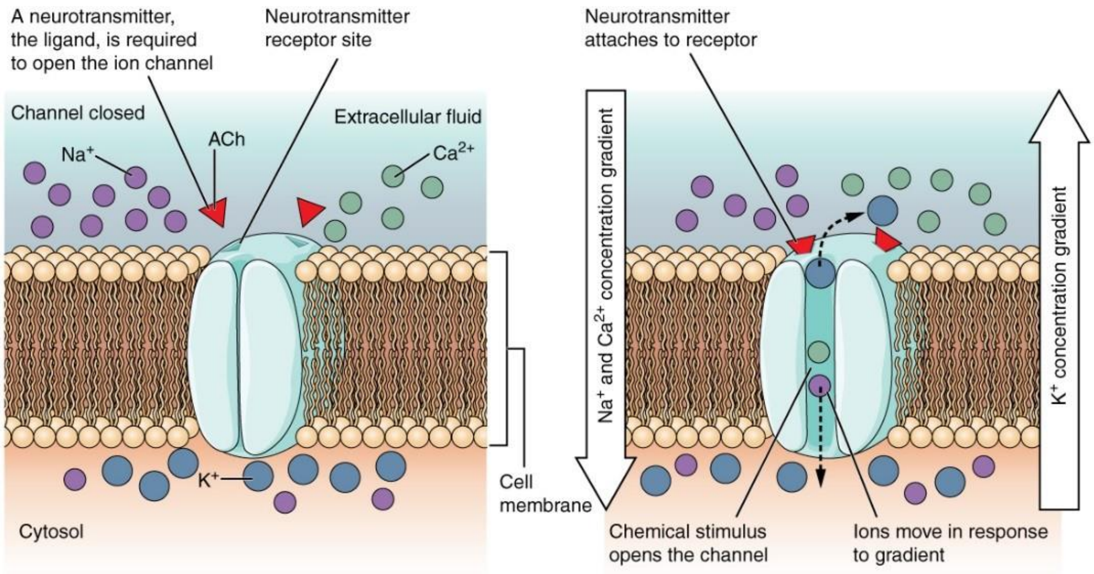
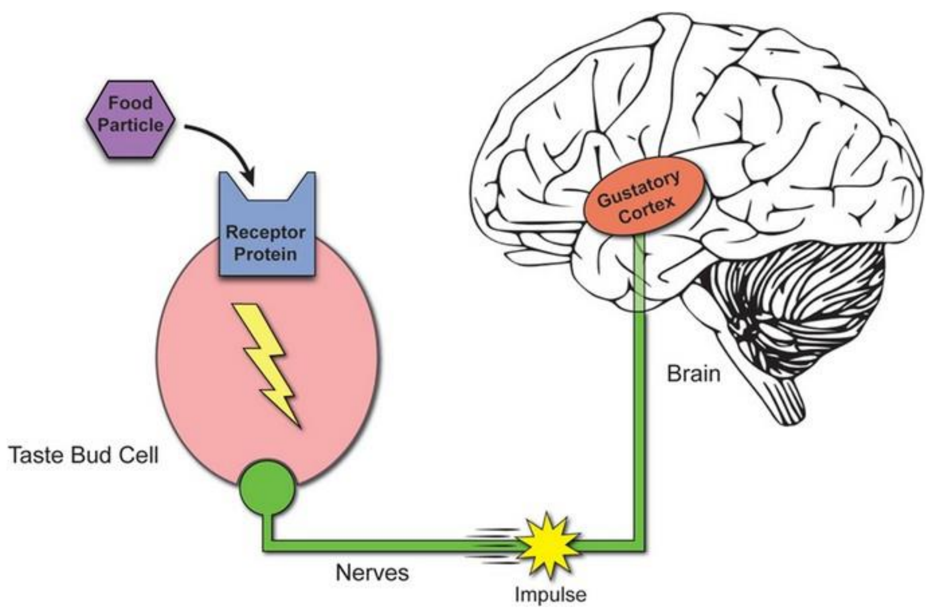


Fig.3: Opening of Ligand Gated Channel [12].

2.3 Electrical Stimulation of Taste

Regarding the electrical stimulation of taste, it has been found that a current source applied can initiate current flow through ionic channels in an axon membrane causing a voltage change across the membrane and initiation of an action potential [13].



Fi.4: Taste Map From Food to Brain.

To relate electrical to real chemical stimulation, electrical stimuli bypass the receptor molecules and directly depolarize the taste receptor cells. This is due to the fact that thecurrentis the flow of electrons, and the electrons cause a voltage change at the cell membrane level when reached. At first, the resting membrane potential at -70 mV, where the charge of inner membrane [14] is less than that of the outside membrane. When an electric current is applied to the tongue, the electrons reach the cell membrane level. This causes a decrease in the outer membrane potential since electrons are negatively charged, and leads to the increase of the overall membrane potential. Once the membrane potential reaches a threshold of - 55 mV as shown in Fig. 5, depolarization occurs and an action potential is fired [14].

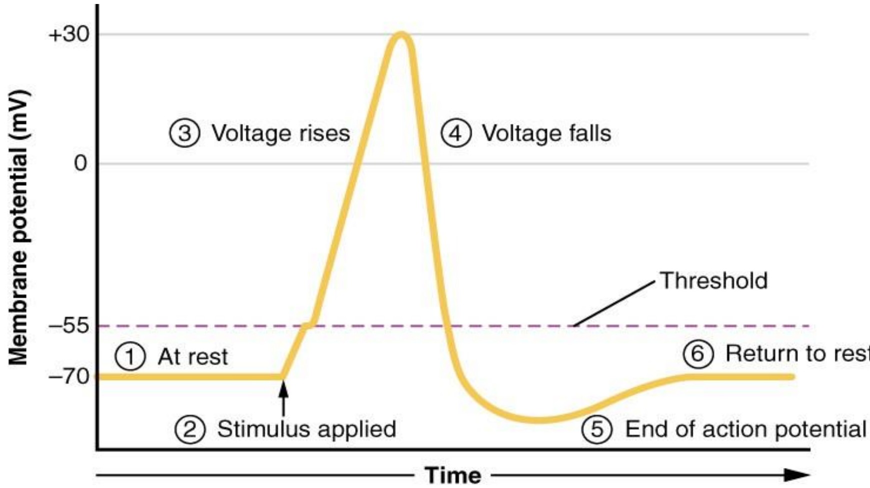


Fig.5: Membrane Voltage Alteration During Taste Process.

However, if the depolarization does not pass the threshold value, the action potential is not initiated.

3. MODEL AND DESIGN OF THE NEW DIGITAL TASTE SYSTEM

The new system's theoretical model was based on LLM as aforementioned, and the new general form of the design is provided in this section (shown in Fig. 6), the circuit is provided with more specific details and explanation, also the components are demonstrated based on specific requirements and conditions. In addition, the safety standards followed are provided.

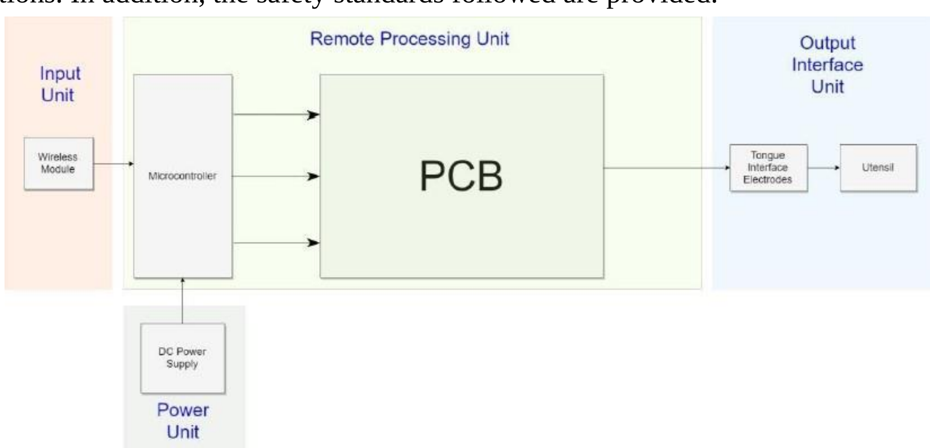


Fig.6: General Form of the System.

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3.1 Materials

The components used are demonstrated based on specific requirements and conditions, including the input unit, the power unit, microcontroller, the choice of the Arduino, Printed Circuit Board (PCB), Utensil, Electrodes Attached to the Utensil and the safety components.

3.1.1 Input Unit

The input unit is the interface with the user to choose the desired taste; this requires a wireless module to establish a connection with the microcontroller that can be achieved through Bluetooth, Wi-Fi, NFC modules. A comparison between the Bluetooth Module and the Wi-Fi Module [15, 16] is provided in Table 1.

For the input unit the data is exchanged over a short distance, the power consumption is required to be low and the dimensions of the module are preferred to be small for the implementation.

Noteworthy that a long range is not necessary, maintaining connection up to few meters is enough.

Table 1: Comparison Between Bluetooth Module and Wi-Fi Module [15, 16].

Specifications	Bluetooth module Hc-05	Wi-Fi module ESP8266EX
Operation voltage	4-6 V	3-3.6V
Average current	30 mA	80 mA
Dimensions	37.5 mm × 16 mm × 2.2 mm	24.75 mm × 14.5 mm

3.1.2 Power Unit

In our system we looked for the electrical characteristics of the power supply and the physical characteristics such as weight and the size of each component in order to improve the overall weight and size of the spoon that was used. Several options were considered for the power unit, the first option was to use a 9 V battery weighting about 42 *g* and of size 48 mm (Elevation) 24 mm (Length) 15 mm (Width) [17]. The second option was to use two or three Lithium batteries (CR 2016) in series, each $3V$ weighting 1.99 g and possessing a size of $20mm \times 1.6mm$, thereby a maximum weight of $3 \times 1.99\,g = 5.97\,g$ [18].

3.1.3 Microcontroller

The microcontroller is the link between the input, being the requested taste, and the circuit that was intended to generate the appropriate voltage.

When choosing the type of microcontroller, we targeted a set of requirements:

- Output voltage.
- Serial port.
- Number of output ports.
- Dimensions.
- Number of ground ports.
- TX and RX ports.
- Programming language.

The most commonly used micro-controllers nowadays are Arduinos because of its simple programming and implementation, and the availability of many types with different number of ports, voltages and sizes.

3.1.4 The Choice of the Arduino

Sever Arduinos are available and could be used for research and market purposes. The types are summarized in Table 2.

3.1.5 PCB

The PCB was used because of its clear interconnections made of copper between components in comparison with wires. Beside of the size advantage of the PCB, Surface Mounted Component (SMD) components may be placed on the surface of the PCB to reduce the size of the circuit. Then utensils were thought of.

Table 2: Arduino Types.

Name	Processor	Operating Input Voltage	CPU Speed	Analog In/Out	Digital IO/PWM	EEPROM [kB]	SRAM [kB]	Flash [kB]	USB	UART	Dimensions
Micro	ATmega32U4	5V/7-12V	16 MHz	12/0	23/7	1 kB	2.5 kB	32 kB	Micro Type B	yes	48x18 mm
Pro mini	ATmega328P	3.3V/ 3.35-12V	8 MHz 16 MHz	6/0	14/6	1 kB	1 kB	2 kB	-	yes	17.8x33 mm
UNO	ATmega328P	5V/ 7-12V	16 MHz	6/0	20/6	1 kB	2kB	32 kB	B	yes	68.6x53.4 mm
Nano	ATmega168 ATmega328P	5V/ 3.35-12V	16 MHz	8/0	14/6	1 kB	1/2 kB	16/32 kB	Mini-B	yes	43.18x18.54 mm
Pico	ATmega32U4	5V/ 3.35-12V	16 MHz	3/0	8/1	1 kB	2.5 kB	32 kB	Mini-B	no	15x15 mm
Beetle	ATmega32U4	5V	16 MHz	5/0	10/4	1 kB	2.5 kB	32 kB 4 kB used by bootloader	-	yes	20x22 mm

3.1.6 Utensil

Adopting a user-friendly tongue interface was one of the main objectives of the new system, the utensil has to have enough contact area with the tongue to generate the taste sensation. Set of utensils are available: Fork, Spoon, Spork and Chopsticks, however, based on the contact area, the most applicable and easy to implement the circuit within wasthe spoon so it was selected.

3.1.7 Electrodes Attached to the Utensil

Utensil attachments including electrodes can be made of gold, copper, zinc, silver or stainless steel all are good conductors and have non-toxic effect on human tissues. But zinc and copper cause a metallic taste, and in our case we aim to deliver the taste for the user without making him confused about what he tastes [19]. In addition, the spoon can be used while eating food zinc and copper can affect to a certain degree the taste of food by enhancing bitterness. However stainless steel and gold had no effect on the taste of the sample of food [19]. Silver also has no odor or taste that can change the actual taste. Then overall safety required safety components.

3.1.8 Safety Components

Safety and health issues of most of the regarded individuals were taken into consideration. The design was intended to be built carefully so that the magnitude of stimulating current falls in the range that ensures human safety. The ranges of safe stimulating current magni- tudes are stated, according to the IEC TS 60479-1 standard [20] and Human Responses to Electricity standard [21] as follows:

- The current magnitude range has to be 0.01 A or less; as this range produces a tingling to mild sensation, and does not expose the human health to any electric shocks [20, 22].
- For currents less than 0.5 mA which is our case, the time is not critical; the effect is "imperceptible" [20].
- The effect of frequency is related to the magnitude of current; for a current of 9 mA the range of frequency between 10 Hz and 1000 Hz are considered safe. Applying a frequency in this range with smaller magnitude of current is also considered safe [21].

The range of current magnitude and frequency used for stimulation fell in the safety ranges aforementioned, and do not exceed it in any case. Therefore, all safety ethics stated earlier are taken into account and this interface can be considered as safe for human interaction.

Based on the demands mentioned before and the options that were available, a clearer image of the system design and implementation is demonstrated in details in the next sub-section.

3.2 Design Method and Implementation

The design of a digital tasting system was introduced and shown in the block diagram in Fig. 7. This design was proposed based on previous designs and measurements to stimulate the sour and salt tastes. An electrical approach was introduced in this design to stimulate these taste sensations resulting from a set of user defined remote inputs.

Noteworthy that this prototype was designed to function in the safe range of operation, where all current values meet the standards.

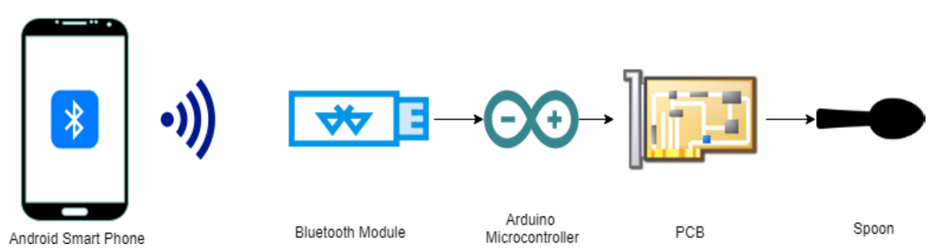


Fig.7: Block Diagram of the Proposed Design.

3.2.1 System Units

The digital tasting system was divided into four main units:

1. Power Unit: composed of two Lithium coin cell batteries which provide the design with the voltage required.
2. Bluetooth Input Unit: Bluetooth Input Unit: which consists of a Bluetooth module and an android application, which provide communication between the user and the remote input unit of the system.
3. Remote Processing Unit: which is composed of both an Arduino Pro MicroTM and a PCB. This is the main control and processing part of the design.
4. Output Interface Unit: which includes transmitting the generated signals to the tongue electrodes attached to a 3-D printed spoon. At this unit, the user can determine the taste sensation resulting from the stimulating system.

3.2.2 Power Unit

This unit is the basic power supply for the system to function. It consists of three Lithium coin cell batteries, where each cell provides 3 V. Thus the voltage provided to the system is 9 V. The coin cell batteries have been chosen for this design due to their compact size and light weight, which help the compatibility of the design. It has to be noted that this voltage was directed to a regulator built in the micro-controller, that produces a regulated 5 V. Hence, this 5 V was considered as the operating voltage in the system hereafter [18].

3.2.3 Bluetooth Input Unit

The input unit in this design can be split into two parts. The first part was an Android application on a smartphone and the second was a Bluetooth module connected to the system. The application used in this system was named "Bluetooth Terminal HC-05", where it is a free app on the Google Play Store. A preview of the app is provided in Fig. 8.

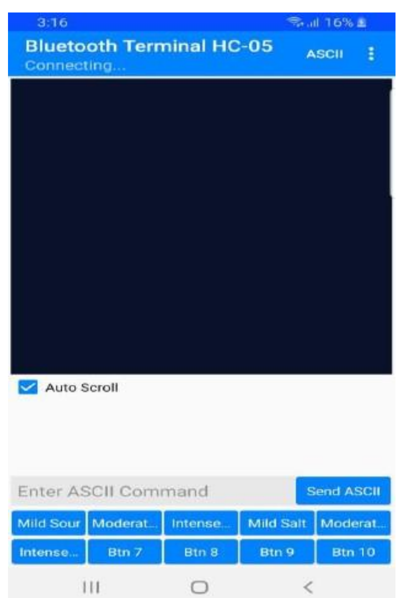


Fig.8: Bluetooth Terminal HC-05 App.

The main function of this unit was to connect the user to the system via a wireless connection. The user after pairing the smartphone with the module, was able to choose the desired taste that he/she preferred by pressing on the specific button previously configured as shown in Fig. 8. After pressing on the desired button, a message pops on the prompt stating the taste pressed along with its intensity.

On the other hand, the Bluetooth HC-05 module shown in Fig. 9 (a), was connected to the rest of the system. This module was able to maintain connection to approximately 10-15 meters with the paired phone [16].

3.2.4 Remote Processing Method

The remote processing method was considered as the most critical unit of the system. It contained the microcontroller alongside with the electric components of the system which were placed on a PCB. This combination was stated as the remote processing system.

(a) (b) (c)

Fig.9: Remote Processing Method. (a) Bluetooth HC-05 Module, (b) Arduino Pro Micro, (c) LM358N Pin Connections.

As for the microcontroller, it was chosen to be an Arduino Pro Micro [23] such as that shown in Fig. 9 (b) due to its dimensions that are highly compatible with the dimensions of the Bluetooth module. After receiving serial information from the Bluetooth module, the Arduino Pro Micro was able to identify which taste has been signaled. Thereby, triggering one of two available pins: the output pin for salt taste or the output pin for sour taste. After identifying which pin was active, the output signal, which was a Pulse Width Modulated (PWM) signal of amplitude 5 V, was directed to the PCB. The frequency of this PWM signal was chosen depending of the intensity of the taste identified. This technique was employed since the frequency of the signal and the intensity were directly proportional. This was due to the fact that the respiratory period of the taste receptors was the range of 3 ms [24], resulting in a maximum frequency of stimulation of 330 Hz. Hence, approaching a new technique in this research, three frequencies were set. The provided intensities were: mild, moderate, and strong with the frequencies 330/4, 330/2, and 330 Hz, respectively. Each pin was directed to a certain path on the circuit afterwards. The circuit consisted of different voltage dividers which decreased the signal to a desired amplitude. This modified signal was then fed to the second stage, where it was forwarded to a LM358N Operational Amplifier (Op-Amp), whose main purpose is to prevent the circuit loading and isolating the voltage across the path of the circuitry.

Two LM358N Op-Amp Integrated Circuit (ICs) were used in this design which provide four Op-Amp circuits. The first three Op-Amp circuits were used as buffers that provide unity gain and voltage isolation. The first LM358N IC was employed to prevent loading the Arduino output signal on the rest of the circuit, and to isolate the salt and sour pins, since they would follow the same circuit path afterwards.

Reaching the second LM358N, the first Op-Amp circuit was used as an isolator to prevent loading the system, since it required precise voltage values. The last OP-Amp was employed in a different technique. Due to the high input impedance of the Op-Amp, this led to the characteristic of the Op-Amp that stated that the voltage on the inverting and non-inverting pins were equal. Thus, using this characteristic, the voltage on the non-inverting pin could be transmitted to the emitter pin of the transistor [25]. In the last stage, the signal directed to the base of the 2N222 NPN Bipolar Junction Transistor (BJT) triggered it to turn on in the linear mode of operation. This mode was needed to make use of the relation that states that the collector current iC was equal to the emitter current iE. Thus, by proper designing, the system was able to provide a stable predicted value of current in the collector branch, through which the current circulates in the tongue interface.

4. RESULTS OF THE NEW DESIGNED DIGITAL TASTE SYSTEM

The different units of the new design are provided along with the different results for this stimulation. Software and real life simulations were recorded and reported. Starting with the circuit, the cascaded connections of the Op-Amp circuits and the subsequent transistor connections are shown in Fig. 10.

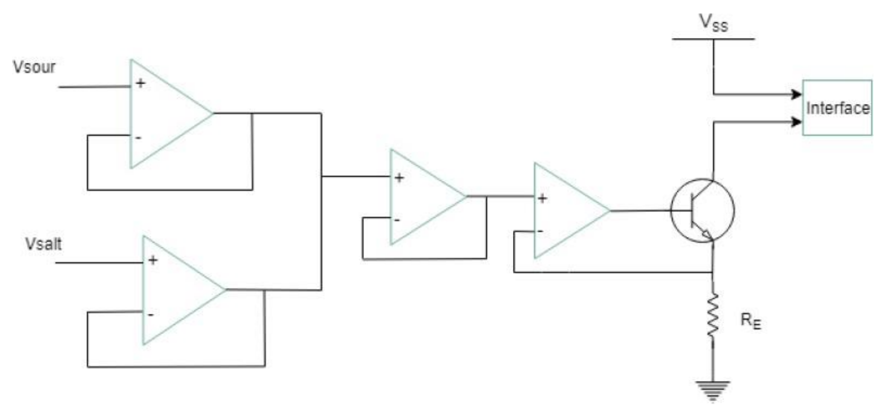


Fig.10: The Resulting Circuit Design.

In other terms, a value of current equal to 180 μA is needed for the sour taste to be stimulated. Then iC = 180 μA and iE = iC = 180 μA since the transistor is in the linear region of operation.

If the value of the emitter resistance RE is chosen to be 10 $k\Omega$, this will result in an emitter voltage of VE = RE iE = 10$k\Omega$ x 180 μA = 1.8 V. As stated earlier, through the

circuitry of the last Op-Amp, the voltage on the emitter pin is equal to the voltage at the non-inverting pin. Hence, the voltage divider designed, at the in- put of the first Op-Amp, should be able to decrease the value of the signal amplitude from 5 V to 1.8 V.

Similarly, a collector current iC =40 μA is required to stimulate the salt taste. Thus, requiring the value of the emitter current iE = iC = 40 μA. Hence, the emitter voltage should be VE = RE x iE = 10 kΩ 40 μA= 0.4 V. For that, the voltage divider on the input of the Op-Amp should be able to decrease the signal amplitude from 5 V to 0.4 V.

To prove that the NPN transistor was in the linear region of operation, it was chosen such that the resistance of the tongue on the interface was in the range of 10 kΩ. This proposal can be achieved in the case of having a moist wet tongue, thus drinking sufficient amount of water was needed before the start the experiment. The value of the current needed for sour stimulation was 180 μA more than that of the current needed to stimulate salt which was 40 μA. Taking the more tragic case, the sour stimulation, the value of the emitter voltage was equal to 1.8 V. The value of the base voltage in this case was then 1.8 + VBE (linear) = 1.8 + 0.6 = 2.4 V.

Thus, the collector voltage was then equal to V_{cc}-($R_{T\ ongue}$ × Ic) = 5-(10$k\Omega$ x 0.18) = 3.2 V.

The voltage at the base was smaller than the voltage at the collector. Moreover, the voltage at the base was greater than the voltage at the emitter. Therefore, the transistor was in the linear region of operation. This result also assured that in the salt stimulation case, the transistor was still in the linear region of operation. The different results of the remaining components are provided in the upcoming subsections.

4.1. Result of the Output Interface Unit

The resulting signal from the collector circulated in the tongue interface. The interface was a couple of silver electrodes that were equipped on the spoon. These silver electrodes, as stated earlier, are the most suitable type of conductor that can be used in contact with the human tongue [19]. The terminals of the silver electrode as directly soldered to the connections from the circuit in hand to ensure that the design was highly compact.

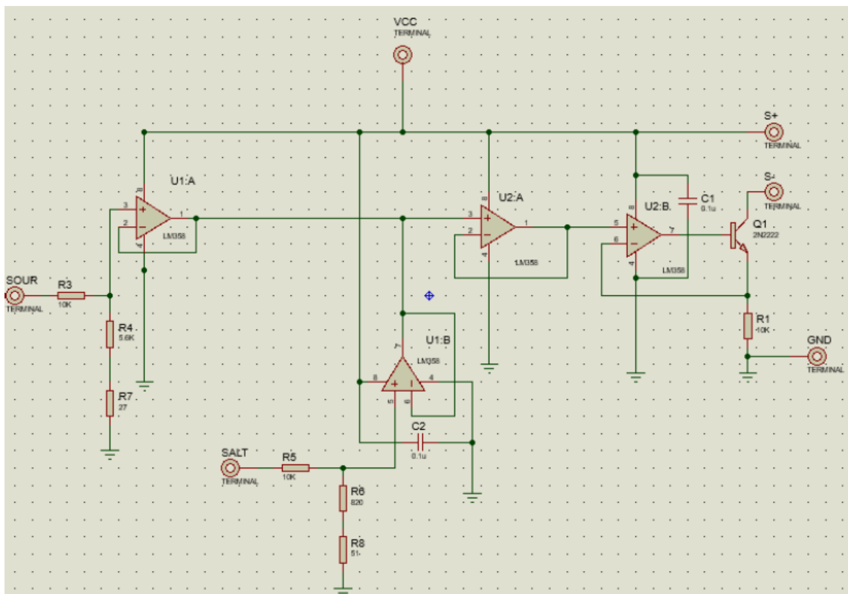


Fig.11: Schematic of the Design.

4.2. Results of the Software Simulation

The proposed design was simulated on the Proteus 8 software as shown in Fig. 11. The schematic of the design was implemented and then stimulated to check the results of the design.

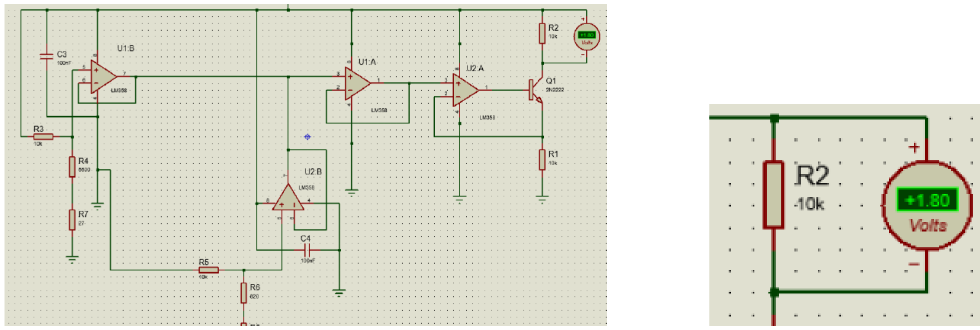
4.2.1. Proteus 8 Schematic Capture

It can be seen that a terminal for the sour pin was directed from the Arduino Pro Micro, as well as that for the salt pin as shown in the modified circuit design for sour stimulation in Fig. 12 (a).

The voltage divider for the sour taste was set to have R3 = 10 $k\Omega$, R4 = 5.6 $k\Omega$, and R7= 27 Ω. This voltage divider led to a signal amplitude of 1.8 V.

As for the salt terminal, its voltage divider is chosen to have R5 = 10 kΩ, R6 = 820 Ω, and R8 = 51 Ω. Similarly, this voltage divider led to a signal amplitude of 0.4 V.

The Op-Amp configuration required a 0.1 μF capacitor connected across the Vcc / GND connections.



(a) (b)

Fig.12: The Circuit Design: (a) Modification of the Circuit Design for Sour Stimulation. (b) Resulting Voltage Across R2 Representing the Tongue.

The resulting voltage across R2 representing the Tongue, resulted in a current of value i= $1.8/10k\Omega = 0.18$ mA = 180 μA. This was the value of the current through which the sour stimulation can take place at the tongue as shown in Fig. 12 (b).

After that, the DC source at R3 was changed into a pulse generator, and an oscilloscope was used in order to visualize how the PWM signal would appear after passing through the circuit.

For simplicity reasons, the frequency of the pulse generator was set at 1 Hz. The PWM signal was alternating between a high voltage of 1.8 V and a low voltage of 0.03 V as shown in Fig. 13.

4.3. Results of the Printed Circuit Board (PCB)

In this subsection, the various steps made to manufacture the PCB of the designed system are discussed. The steps, starts from the software implementation of the PCB to manufacturing it.

4.3.1. PCB Designing

The PCB was highly recommended, since the circuit need to be very compact in size. The natural size components of resistors and capacitors cause the design to be abnormally bulky and odd. Thus, the resistors and capacitors mentioned previously were replaced with their equivalents as SMDs. By the use of SMD components, the size was decreased approximately to its half in length and width.

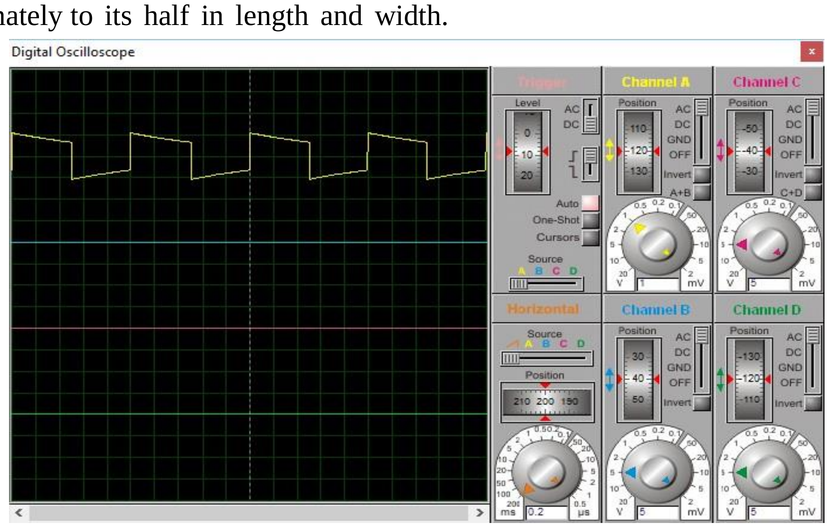
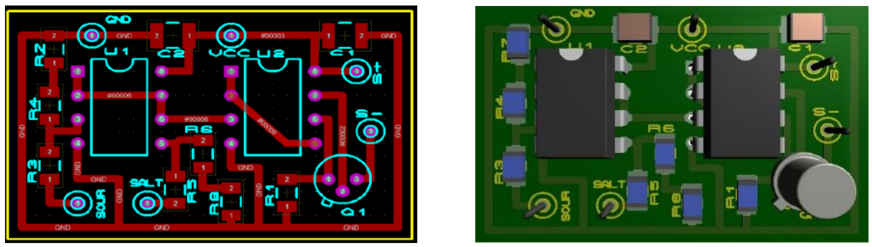


Fig.13: The Resulting PWM signal at R2 on the Oscilloscope.

In this case, the PCB designed was fit along with the Bluetooth module and Arduino Pro Micro inside the spoon being designed for this system. The schematic design provided in the previous subsection was exported to the PCB layout in the same software "Proteus 8". After placing the components on the PCB board, the components were manually routed together. A manual routing was done since the PCB in need has to be a single layered one. Hence, due to the multiple feedbacks in the circuit, the auto-router installed in Proteus 8 could not come in handy. The auto-router would establish multi-layer paths on the board, which was out of the scope of this research. The result of the PCB routing and dimensioning resulted in a board whose dimensions were 36 mm × 24 mm shown in Fig. 14 (a).



(a) (b)

Fig.14: The Printed Circuit Board (PCB). (a) PCB Layout in Proteus. (b) PCB 3-D Top View.

To make a more realistic model of the PCB, and predict how the components would look like when mounted on it, a 3-D model was also demonstrated by the use of Proteus 8. The top view of the 3-D model was presented in Fig. 14 (b).

4.3.2. PCB Manufacturing Simulation, Real and Pre-Testing Results

After the design of the PCB has been done, the execution phase was reached. To manufacture the PCB, the Beirut Arab University (BAU) Computerized Numerical Control (CNC) machine was employed. The CNC's task is to implement the design on a copper board. The software used for the CNC was not the same as the software used in the design of the PCB layout. Thereby, the design file needed to be exported as a Gerber file, which is a global format for PCB designing. Some design configurations would change, but the overall design would resemble that of Proteus 8.

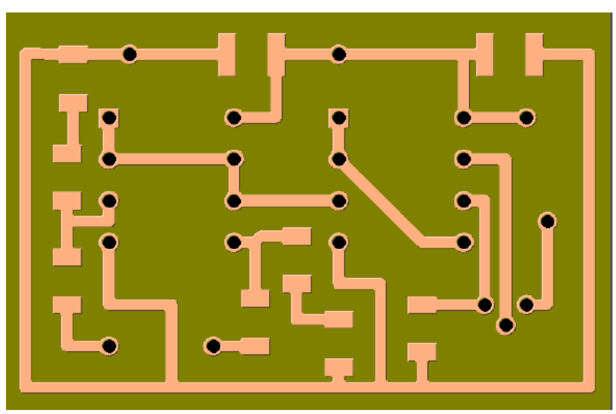
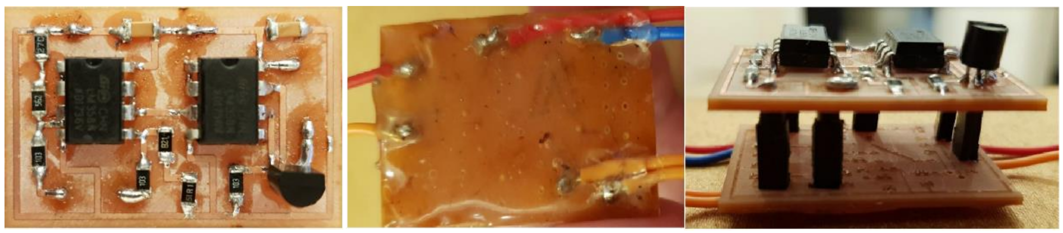


Fig.15: Simulation Result of the Copper CAM layout of the Printed Circuit Board.

After that, the Gerber file containing the design was imported to the software used for the CNC which was "Percival Copper CAM". The PCB simulated layout is shown in Fig.

15. The PCB layout was hatched, drilled with 0.8 mm drills and milled. At the end of this stage, the CNC was ready to begin execution. After manufacturing the PCB and checking the proper connections for any faults such as short circuits, the different components from resistors, capacitors, Op-Amp and transistors were soldered onto the PCB as shown in Fig. 16 (a). To take more precautions when connecting the PCB to the rest of the system, a lower layer was introduced beneath the PCB to solder the connecting wires on. Afterwards, a light layer of wax was introduced in order to tighten up these connections. The bottom and side views of the modified PCB are shown in Figs. 16 (b) and (c), respectively.

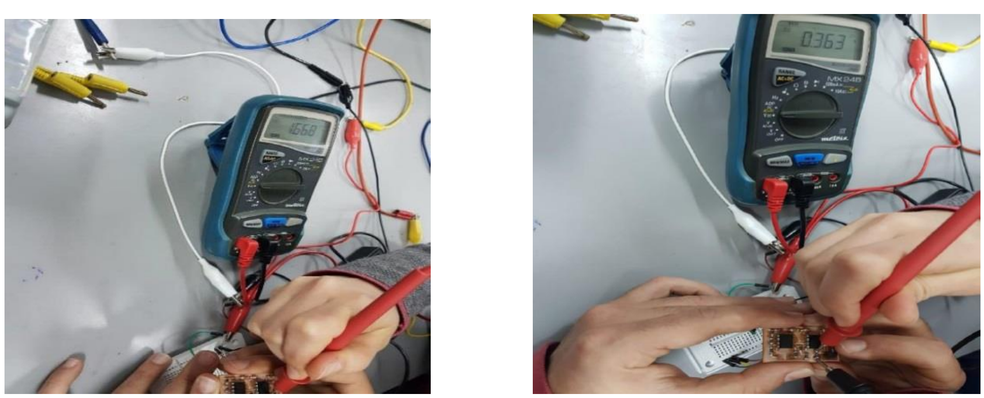


(a) (b) (c)

Fig.16: Real Results of the Neurocomputing Taste System Design: (a) Real Result of the PCB Manufactured with Soldered Components. (b) Bottom View of the Lower Layer of PCB. (c) Side View of the PCB.

To assure the functionality of the PCB in hand, it was tested in the Biomedical Engineering Laboratory at BAU, with a DC input value, assuming that the sour and salt stimulations were provoked by the easier DC method. This was considered as a pre-testing to the PWM alternating case.

A 5 V was introduced by a DC source generator at the sour terminal, while the salt pin was grounded. This resembled the reaction of the Arduino when a sour taste command was sent by the user. The tongue, in this case, was replaced by an equivalent 10 kΩ resistor. The output voltage on the resistor was measured to be around 1.7 V as shown in Fig. 17(a). Furthermore, to measure the output when salt was chosen by the user, we interchanged the connections of the 5 V and ground. The voltage value measured was around 0.36 V as shown in Fig. 17 (b).



(a) (b)

Fig.17: Pre-Testing Results of DC Voltage Measurement. (a) At the Output Resistor (Sour). (b) At the Output Resistor (Salt).

4.4. Results of Tongue Interface Design

A utensil was designed in order to equip the digital system on. The utensil design compromised most of the modern techniques in a friendly manner, to assure the functionality of the system and to achieve user satisfaction. The utensil chosen to be implemented in the new design was a spoon, due to its large surface area in comparison with other utensils such as forks, cups, etc. This large area helps in designing a genuine tongue interaction method. In addition, it provides an ease of design due to its mostly flat and regular structure. Thus, the user can feel the "digital taste" noticeably. In addition, larger variety of food can be physically eaten with a spoon rather than with a fork.

The proposed utensil was composed of four main parts as shown in Fig. 18. First, the silver-coated copper patch, through which the user can feel the taste when the tongue is in contact with it. Second, the curvature area, which is composed of 2 attached parts. The first part encapsulated the silver-coated patch as a bottom layer, while the second part was used to hold food as an upper layer of the spoon. Between these two components, wires were connected from the circuit to the silver-coated patch. The last part was the handle of the spoon where the digital components and circuit were placed. This handle was designed to be opened by the use of hinges that are placed on its sideways. This assured that the components were reachable and subjected to replacement at any time, in case of any failure subjecting to troubleshooting.

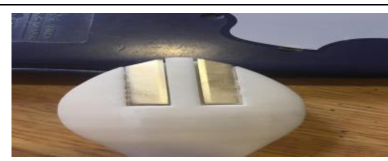
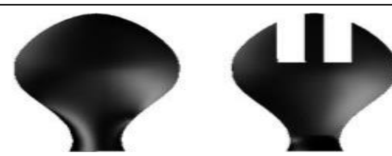
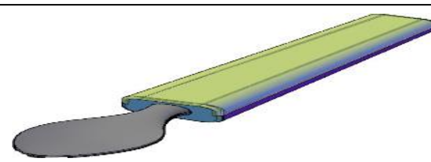
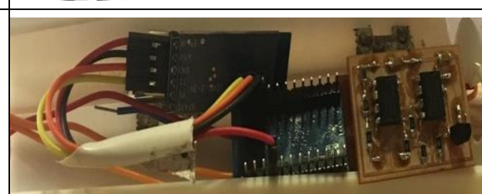
Components	Figure
The silver-coated patch	
The curvature area	
The handle	
The circuit	

Fig.18: The main aspects of the spoon and the design components, respectively.

Due to some design constraints, it was not recommended to use the utensil for liquids. Since the liquid could invade the void between the curvature parts, even though they were separated in fraction of millimeters, thus reaching the digital components afterwards. This leakage could possibly lead to a short circuit between the components, resulting in the malfunctioning of the spoon. As an improvement producing a single curvature part, rather than two attached parts could be taken into account preventing any liquid leakage to the components departure. Moreover, there would be an alternative way of connection between the silver-coated patches, in order to assure that no short circuit would result in case of liquid usage between them. As for our work, it was preferred to use dry or moist food when dealing with the spoon.

5. TESTING AND EVALUATION RESULTS OF THE DESIGNED SYSTEM

The schematic of the design was implemented and then the stimulus was tested to check the performance of the design. Results were divided into the contribution results, the software and manufacturing of the Tongue Interface results, the circuit testing and evaluation results, stimulation results and the system cost result.

5.1. Evaluation of Contributions Results

The system developed was based on a PWM signal; the idea behind this form of stimulation was that when an action potential is fired, within its period another stimulation cannot take place. So if we supposed a DC current has fired an action potential, during a specific period called refractory period, the user was subjected to an unnecessary amount of current. While in our design we were estimating the refractory period based on proper references, thus instead of using a DC current, a pulse was generated only when it can fire an action potential, this was defined by the frequency value set for the stimulation.

Moreover, the frequency controlled the intensity of taste; in the system three intensities were considered: mild, medium and strong with three different values, where the strong one was the maximum number of stimulations depending on the refractory period (1/3 ms) [24]. The medium was the maximum frequency divided by 2 meaning that the number of fired action potential was reduced and the time between two stimulations was greater than the refractory period. Besides, the mild was the maximum frequency over 4, thereby the number of action potential fired was smaller than the medium case.

5.2. Evaluation of Results of Software and Manufacturing of the Tongue Interface

The spoon described in the method of the Tongue interface design was sketched on AutoCAD software. The aim of the design was to be as practical as possible for users, without being disturbed by the circuit components. The user has to have the same feeling as that when using an ordinary spoon. Thus, this was achieved by non-visualizing the components, that may tangle to bother the comfort ability of the user. Hence, as a target for the design, the digital components were consolidated in one area and covered safely. The real image of the improved design is illustrated in Fig. 18.

5.2.1. Results of the Spoon Dimensions

The dimensions of the illustrated design were inspired by an actual spoon and configured empirically. Exact dimensions such as the width and the thickness of the handle were difficult to implement due to the presence of the circuit components, but the length was close to the actual spoon (12 cm), knowing that the standard length of a meal spoon is 6.5 to 7.5 inches, that is 16.5 cm to 19 cm [26]. In addition to the curvature piece, with a width of 4 cm alike the actual utensil as shown in Fig. 19.

5.3. Testing and Evaluation of the Circuit and System

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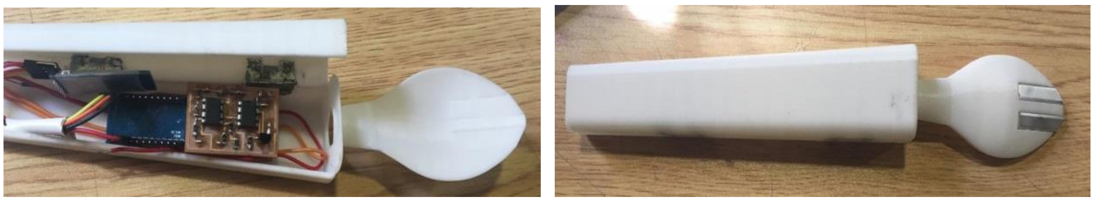
The PCB along with the rest of the system was checked, in order to make sure that the system was functioning properly. The results and their interpretation were provided then discussed. The testing of the circuit at the final stage was to ensure that the current across the output was in the desired range of each taste. However, it was simpler to test the voltage value since the predicted current was in micro-Ampere, which makes it difficult to trace through using an ordinary multi-meter.

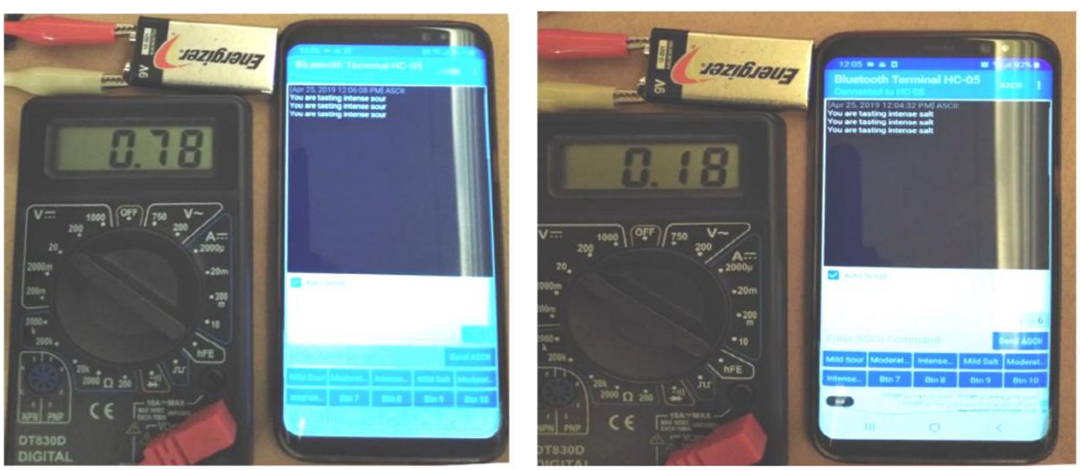


(a) (b)

Fig.19: The 3-Dimensional Printed Spoon: (a) Top View. (b) Back View.

However, as we were measuring a PWM signal, which is an alternating signal, we had two options in terms of measuring. The first option w√as to measure the Root Mean Squared(RMS) value of the voltage, and then multiply by 2 in order to calculate the maximum amplitude value of the signal. The second option was to measure the DC value, which was actually the DC component of the alternating signal. Hence, the DC component was the average between the maximum and the minimum of the signal. Thus, multiplying by the DC value measured by '2' would result in the maximum amplitude. Being simpler for calculation, the second technique was used.

A 10 kΩ resistor was placed instead of the tongue while measuring.



(a) (b)

Fig.20: Testing the Output Voltage. (a) Of the PCB (Sour). (b) Of the PCB (Salt).

As stated earlier, the values shown in Fig. 20 represented the DC values of the (a) Sour taste and (b) Salt taste, respectively. Hence, to get the maximum amplitude value, these values were multiplied by 2. Then, the voltage value for the sour and salt tastes were as follows:

- $V_{Sour} = 2 \times 0.78 = 1.56$ V

- $V_{Salt} = 2 \times 0.18 = 0.36$ V

The current generated was in the requested range of the selected taste, which was clarified by using Ohm's Law I= V/R. Thereby, the resulting currents after applying Ohm's Law were:

- ISour = 1.56 / 10kΩ = 0.156 mA = 156 μA
- ISalt = 0.36 / 10kΩ = 0.036 mA = 36 μA

Both values fell in the accepted range of values, taking into consideration the error occurring when dealing with the parameter *a* which relates the emitter current the collector current. The resulting tastes were as summarized in Table 3.

Table 3: The Different Tastes and Their Attributes.

	F = 82 Hz	**F = 165 Hz**	**F = 333 Hz**
I= 36 μA	Mild Salt	Medium Salt	Strong Salt
I =156 μA	Mild Sour	Medium Sour	Strong Sour

5.4. Evaluation of Stimulation Results

After making sure that the system was completely functional and met the requirements needed, the system was tested by a variety of people. The different people undergoing the test were forced to drink a sufficient amount of water, in order to assure that the tongue was wet for the experiment to function properly. Some of the experiments were recorded and shown in Fig. 21.

First of all, we started the testing trials by a group of 4 members as shown in Figs. 21 (a) and (b). Of all the 4 members of the tested group, 3 members could feel the tastes and the change in intensity when pressing the different buttons on the Bluetooth App i.e. 75%, then as the number of members increases the percentage of feeling the taste increases to 90% for 10 members.

After that, the testing was taken to another level. The experiments were done on people with no knowledge about how and what the output taste should be like.

A member from the Department of Electrical and Computer Engineering (ECE), Faculty of Engineering at BAU proposed to be the tester for this experiment in the Biomedical Engineering Laboratory. After drinking the sufficient amount of water, she was stimulated by an intense taste of sour. The reactions, before and after the stimulation, can be seen clearly in Figs. 21 (c) and (d), respectively.

It was obvious that different people felt different intensities of the taste according to their reaction to the taste itself. However, on average 83% of the people who tested the system felt the taste and they were capable of identifying it directly.

(a)

(b)

(c)

(d)

Fig.21: Testing Experimental Results: (a) A Member Trying the Sour Taste. (b) A Member Trying The Salt Taste. (c) A Member Before The Stimulation. (d) A Member After The Stimulation.

5.5. Evaluation of the System Cost

Among all the challenges encountered during the implementation of the new Neurocomputing and interfacing digital tasting system, the target was to have a cost-effective system, this was achieved according to the total cost of the new system as shown in Table 4.

6. DISCUSSION

Regarding the results of the tongue interface design, Fig. 18 illustrates the main aspects of the spoon, respectively. The design shown in Fig. 18 met the technical requirements perfectly, it had a width of 3.5 cm and a height of 14 cm, but it was very edgy to the end user. Thus it would not be a comfortable utensil to use all the time, and since a friendly design implementation was one of the project's aim, it was improved to the third design which was used as the final one.

Table 4: Table of The Digital Taste Cost.

Components	Cost U.S. Dollars
Arduino Micro	10
Bluetooth module	5
PCB fabrication	30
Female jumpers	1
Transistors, resistors and amplifiers	1.7
SMD components	3
Solder	3.8
3D printing	40
Total	**94.5**

The final design shown in Fig. 19 was made of curved edges, in addition to shrinking the top level of the handle, thus placing the circuit in an exact void and not having useless area. Moreover, the handle could be opened and flipped easily by the use of hinges. The spoon was later manufactured by 3-D printing technology, using Polyl-actic Acid (PLA) material. PLA is one of the two common plastics used on FDM machines (3-D printing) and is commonly available as a 3-D printable filament. It is classified as a "thermoplastic" polyester, where the name has to do with the way the plastic responds to heat. PLA has high melting point enough not to be disturbed by the circuit blocks (150-160°C). In addition, PLA is not toxic, i.e. can be used for such aim [27]. The overall structure of the 3-D printed spoon with the implemented circuit showing its dimensions can be shown clearly in Fig. 18 (a) and (b).

In our research, the results of the stimulation on the tongue revealed the sensation of sourness and saltiness by two different magnitudes of current and for different intensities of the taste, this was in accordance to the result of Auvray et al. [28].

Regarding the technical and non-technical constraints as compared to existing research, in this project many constraints are imposed regarding the components used, the circuit and the design of the spoon. The constraints may be related to the safety of the user in terms of the magnitude and the frequency of the current that can be applied to the tongue of humans. And other constraints like the design and the fabrication of the utensil are imposed to guarantee a certain level of comfortability for the user. These constraints are divided into two categories: Technical and Non-Technical and discussed in Table 5.

7. CONCLUSION

Despite technical and non-technical constraints, Taste sensation is generated by electrical stimulation using tongue interface implemented in the form of a spoon. Our study provides a new method to digitally stimulate the sense of taste by electrical stimulation on the human tongue. A link between the chemical stimulation and electrical stimulation was successfully ensured through the new design and electronic interface for inducing taste digitally.

Table 5: Technical and Non-technical Constraints.

Technical constraints	Non-Technical constraints
The stimulating current magnitudes is preferred to not exceed 200 micro-amperes because an uncomfortable feeling was accompanied on the tongue with such magnitude of stimulation	Wearable interfaces in the mouth or nose are not comfortable, and are hard to use by most individuals. One of the objectives in this system is to adopt a more user friendly interface.
The intensity is controlled by the frequency related to the refractory period known equal to 3 ms so the maximum frequency is set to 1/3ms = 333 Hz [21, 24]	The size of the utensil should be taken into consideration, thus the design of the tongue interface is limited in its dimensions and we seek it to be as close as possible to the regular utensil used in our everyday life.
The range of current magnitude used for the stimulation must fall in the safety range for humans [20, 22].	The material of the utensil should go with the condition of attaching the circuit to the utensil and that ensures the requested conductivity on the part in con- tact with the tip of the tongue [27].
It is preferable for the tongue to be in the range of 10 k so that the circuit works in the linear region of operation [25].	The material of electrodes used for the tongue interface must be safe to interact with human tissues and does not produce any metallic taste sensation [19].

The proposed design was based on a module that is responsible for electric and stimulation to produce different taste sensations. In addition, the taste was delivered through the tongue interface by silver electrodes, coupled with a control system responsible for generating specific stimulation parameters based on user inputs selected on his mobile. A spoon for implementing the taste interface was issued and 3-D printed in order to provide a user friendly tool as a solution for various problems.

The results of the stimulation on the tongue reveal the sensation of sourness and saltiness by two different magnitudes of current and for different intensities of the taste. Experimental results showed that the new model and design of the digital taste system works well and testing results showed clearly that 90% of the tested members were able to distinguish the taste.

The understanding of taste mechanism is very complex and includes many variables from tongue all the way to the brain. The taste sensation is linked to the brain, our study provided a new neurocomputing method and it was successful in digitally stimulating areas of the brain and the sense of taste by electrical signals at specific frequencies on the human tongue. Thus the studied population was able to distinguish the sour and salt tastes feasibly.

Moreover, the new neurocomputing and interfacing Digital Taste system could pave the way for helping patients suffering from loss of taste due to neurological diseases, however further specific research is needed.

8. FUTURE WORK

More studies are needed on the sweetness receptors because this taste is not electrically stimulated and the thermal stimulation is limited and needs much more improvement to be recognized clearly. By thermally stimulating sweet receptors, a very weak sense is determined so if we can find another way to trigger sweet receptors on the tongue without a chemical compound and at the same time activate olfactory receptors, sweet compounds can be replaced in order to help people with diabetes or to mask unpleasant tastes produced by medications.

Another way is to go more deeply to the gustatory cortex in the brain and find how the region responsible for sweetness can be triggered directly without including the tongue or by the intermediate of another organ or different type of receptors belonging to another sense. Design wise, an improvement can be done on the size of the included circuit, in which the components can be replaced by SMDs, this results in decreasing the size of the circuit blocks, minimizing the dimensions of the utensil's handle, thus producing a much friendlier spoon for the end user. In addition, a USB port to charge the power supply of the system can be used, where it is considered as a necessity for most digital equipment nowadays. Using the charging procedure, most of the problems faced due to low battery life can be tolerated.

Besides of the biomedical importance of our system for the people suffering from taste problems, no sense of taste, bad taste in the mouth, diminished sense of taste, distorted sense of taste etc. and for people having diabetes and hypertension, this technology shows the possibility for sharing tastes in social networking and adapting it in virtual reality, gaming and other domains.

Acknowledgment

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Data Availability

The data used to support the findings of this study are included within the article.

Conflict of Interest

The authors declare no conflict of interest.

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