SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V12I3P115

Volume 12 Issue 3, 145-154, March 2025

Original Article

The Neural Logging of Taste: Studying Gustation Via Surface EEG & The Scope of Replicative Rendering

Angel Swastik Duggal[1]*, Praveen Kumar Malik[1], Rajesh Singh[2], Anita Gehlot[2]

[1]*School of Electronics and Electrical Engineering, Lovely Professional University, Punjab, India.*
[2]*Division of Research & Innovation, Uttaranchal University, Dehradun, India.*

**Corresponding Author : coffeeannon@gmail.com*

Received: 02 December 2024 Revised: 14 March 2025 Accepted: 24 March 2025 Published: 31 March 2025

Abstract *- The domain of taste electrophoresis has conventionally relied on physical sensory evaluation as the conventional logging technique for taste parameters. This paper presents a multi-perspective analysis of the neural aspect of taste-evoked potentials using custom-built low-cost hardware. Using biomedical means, the work proposes alternate means to bridge the gap between sensation and stimulation, bypassing subjective bias in testing by directly logging neural responses. There are various techniques with which the sensation of taste can be identified, surface EEG being a cheaper, non-invasive option among them. To study the neural response of taste, a 4-channel EEG kit was built using low-cost analog front ends. A gustatory galvanic stimulation circuit was also built to deliver taste-eliciting electrical impulses. The circuit was then fitted into a 3D-designed spoon for easy impulse delivery. The EEG response was then fed into an LSTM for further classification. The accuracy of the model was rounded off to 68%. The surface EEG data, although non-stationary in nature, can be plugged into AI-ML-based algorithms for analysis and event-window classification. For better results, using higher-spec hardware with more channels and higher sensitivity could significantly overturn the technique into a reliable means of logging accurate taste electro stimuli.*

Keywords *- Augmented reality, Biosignals, Electrogustometry, Galvanic taste, Nerve stimulation.*

1. Introduction

Electrical taste had been explored and logged even before the concept existed in 1752 by Sultzer, who attempted a taste test of lead and silver metals. Sulzer estimated the phenomenon as a vibrational event triggered by the metals reacting with the chemical compounds on the tongue. The record of the pungent sensation did not follow an explanation until Volta explored the phenomenon in depth and replicated it in 1801 [1]. Following almost a century, the topic remained on the sidelines with no substantial direct discoveries, although there were significant discoveries in the domain of electrolysis. In 1954, Beidlers' experiment on the theory of taste stimulation and receptors highlighted a relationship between the neural response and the number of receptor sites upon which the taste stimuli were adsorbed.

Based on the test results, an equation was derived, hypothesizing a dissociation reaction to be the underlying cause of taste stimuli. In 1962, Dzendolet's work supported the idea of a dissociation reaction being the cause with a slight variation, stating that the neural responses occurred upon the receptor sites getting vacated rather than filled [2]. Further investigations into this phenomenon were carried out by Von Humboldt (1797) and Fabbroni (1801). In addition, the early experiments of Nicholson, done alone and in collaboration with Carlisle (1801), had a bearing on the explanation advanced for the mechanism of "electric taste." The result of these early investigations pushed forth two main ideologies. The first was that the taste sensation was evoked by direct electrical stimulation of either the nerves or the receptors. The second hypothesis said that the stimulation was caused by the products passing the electric current through saliva, which is normally present on the tongue.

The reported qualities related to the polarity of electrical stimulation correlated well with the electrolysis products at the anode and the cathode under certain stimulation procedures. Starting with the initial efforts of prominent scholars like Volta, Sultzer, Beidler and Dzendolet, who set the foundation for the overall investigation of taste generated by electricity, modern technology gradually caught on to the topic and imbibed the current updated techniques and various upgrades from artificial intelligence machine learning and embedded systems were proposed in different publications. There have since been many developments in the galvanic taste domain, including electronic tongues and digital. Lollipops, AR headsets, odour-assisted taste machines, and Penta lipid membrane-assisted taste stimulators. Different approaches were taken to replicate tastes, most of them being experimental testing and recording the resulting taste profile.

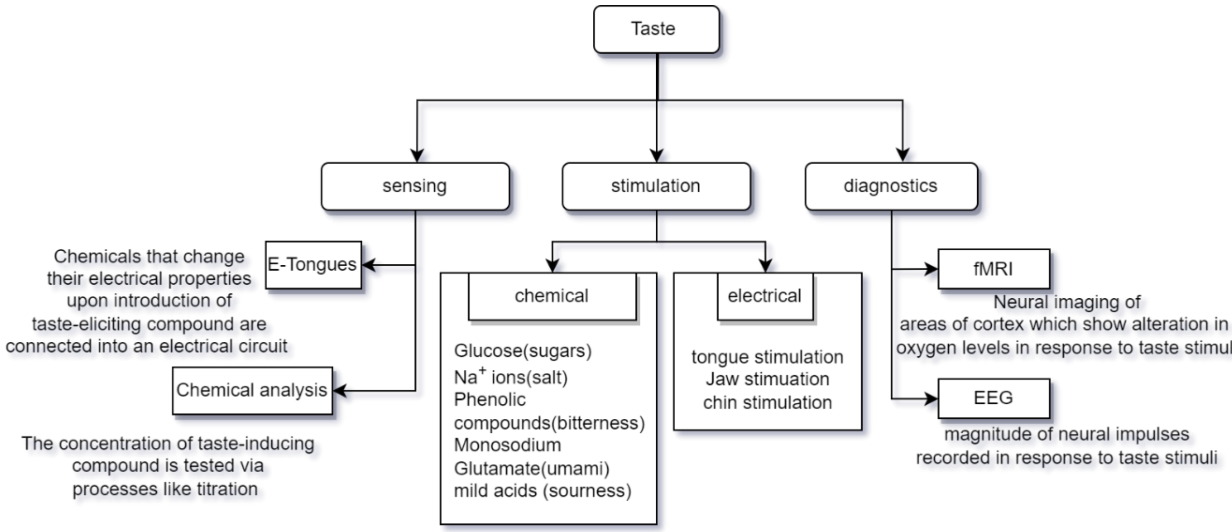

Fig. 1 A general block diagram of the taste subsystem in various domains

The study of overall cause and response in gustation has been thoroughly studied and analyzed from various branches of science (Figure 1). Thorough research has been conducted on the mechanism, response, and applied potential applications of gustatory stimuli in a bid to digitalize the sensation of taste. Experimentation has been done using sensory evaluation and double-blind taste testing of electrical stimuli for generating artificial taste summarized in the galvanostimulatory context [3]. This current work attempts to bridge the gap between taste sensing and actuation and explore the neural aspect of electrostimulated taste by logging and comparing EEG patterns elicited during the process with naturally generated taste signals using surface electroencephalography(sEEG).

The research pool is classified into three major sections: second, third, and fourth, each handling the different aspects of electrical taste. The first section deals with studies conducted using functional magnetic resonance imaging while experimenting with taste. The second section tackles studies using EEG to record and log changes in the brain's electrical activity while the detached experiment was performed. Lastly, the third section addresses the practice of applying low-amplitude Pulses over the buccal periphery to elicit the sensation of taste using electricity. The fifth section deals with the methodology of the procedure conducted, broken down into constituent modules. Section 6 deals with the 3 separate test results obtained from the methodology and is followed by sections 7 and 8, discussing the study's limitations and the conclusion drawn. This study was designed to partially assist in fulfilling targets 9.5, 9. b, and 9. c of the UN SDGs [4].

2. fMRI

fMRI, or functional Magnetic Resonance Imaging, is a non-invasive procedure wherein a patient is placed inside a giant electromagnet, and the brain is subjected to electromagnetic fields. The movement of oxygenated blood is detected by the change in magnetic fields with a brighter colouration than that of the flow of deoxygenated blood. This helps map the parts of the brain in activity at that time frame there have been numerous studies applying the fMRI method in various contexts to obtain data based on brain activity. The gustatory domain has had its own set of fMRI studies performed for several hypotheses. Some of the more recent tests have been explored and mentioned here forth.

In the earlier decade, it was assumed that the sensation of sweetness triggers the reward centre of the brain in response to the caloric boost provided, which conflicts with the neural taste response of calorific sweetness, owing to the small size owing to the small sample sizes. The study was performed to check the correlation between the reward centre and the calorific taste response to sweetness, which yielded a positive response in 30.8% of the past studies but did not exhibit the same in a sensitivity analysis. The study employed the activation likelihood estimation method to extract the required results [5].

Several distinctions have been found in the neuro-sensory response to taste based on gender classification. To explore the issue in depth, an fMRI of the insula, thalamus, and cortex was conducted, and the functional connectivity was compared for men and women. The taste profile yielded a difference in sensory response of middle-high and bitter concentration between male and female thalamus and insula. Men's fMRI displayed higher connectivity according to the outputs [6]. The taste sensation is often ascribed to be influenced by other environmental inputs, making it a function of gustatory, olfactory, optical, tactile and auditory sensory reception. According to earlier studies, peripheral influence is more pronounced in animals; nevertheless, it still plays a pivotal role in human gustation. A recent study conducted a double high-resolution fMRI on human participants to study the role of external factors by mapping the neural response of human subjects to low and highly concentrated taste stimuli. The resulting outputs indicated a randomized shift of taste responses from the conventional pattern mappings originally assumed to be taste-sensitive to specific gustatory stimuli. The high-concentration outputs did not match the low-concentration. The map that had been recorded and the taste responses varied vastly, indicating that taste had external factors affecting the outputs other than flavour concentration as well [7].

Other than sustenance, food intake is usually also influenced by the stimulation of the brain's endorphin release for consuming certain substances that taste good or serve as instant energy sources. However, earlier studies involving MRI and other neuro-analytic methods have had mixed results surrounding the topic. A study was performed to explore whether the reward value for foods other than the sweet stimuli increased or whether it was limited only to sweetness. Different fMRI studies were checked for solid proof of correlation between palatable food and the triggering of reward centres from the systematic review and in-depth analysis. It was surmised that the testing sample size was quantitatively small for most studies and that the primary taste areas, although not entirely taste-specific, are capable of sensing much more than a singular taste profile. A correlation between reward value increment and calorific sugar intake was also drawn [8].

3. EEG

The EEG or Electroencephalogram is a process involving sampling low-amplitude neural impulses, amplifying them, and logging the data into a storage peripheral in a numeric format wherein it can subsequently be plotted or analysed for various intents and purposes. It has been employed in various domains, with medical diagnostics being the primary sector, which uses the data to detect anomalies in neural function such as seizures, strokes, partial paralysis, Tourette's, and several other conditions. Observable within in the context of gustation, an EEG can be applied throughout the overall sequence of food intake. There are two different methods of application: invasive EEG using depth microwire electrodes and surface EEG (sEEG) using conductive strips applied directly on the scalp. A study even managed to distinguish between sweet and sour tastes using linear discriminant classification over 8-channel EEG data from 10 test subjects with multiple features from which wavelet entropy and the average energy resulted in 98% accuracy in output. The optimum time frame to log the EEG data post-stimulation was also tested. It was found that the best interval is a range between 20-30 seconds [9].

It had been experimentally proven that taste stimuli arising from different taste profiles are mutually distinguishable, but the status of perceptually similar tastes with varying magnitudes was still ambiguous. A test group of 22 random participants was subjected to a high-density 128-channel EEG neuro-response study to find out the answer. The participants were given sweet stimuli ranging from very mild to heavily concentrated sweet taste stimuli generated via acesulphame K, aspartame, and sucrose. After mixing the ingredients in varying ratios, the participants were also asked to distinguish between the three sweetness levels. As per the results, it was found that the sensory responses were quite identical and had only minor differences ranging between 0.08 and 0.18. The High-density EEG yielded better distinctions among different taste levels than the interactive survey. It was also found that the EEG responses of the individuals with higher taste sensitivities were sharper and displayed discernible distinctions at different taste levels. In a way, the high-res EEG answered several queries within a singular experiment, quantifying the distinction between several perceptually identical taste stimuli while establishing proof of the correlation between sensory analysis results and neural response over the same stimuli [10].

EEG recordings are quite noisy owing both to the external factors and the subjects' response to them, creating a response event in the logs. Every stimulus plays out as an event in a neural EEG to the extent that a motor response like blinking creates a massive kink in the plot. The conventional solution is to temporarily block the noise-generating sensory inputs by shutting eyes and recording in a silent place, but newer methods have been discovered recently, requiring minimal interjection from the subjects. The subtractive method requires an infinite impulse filter to be applied at pre-processing. In addition to the preamplifier stages, a post-rec dual frequency feature extraction algorithm would serve as an added noise remover by filtering out only the relevant data for mathematical analysis. It was noted that the filtration method yielded a 95% accuracy upon the data being passed through an SVM classifier for distinguishing between tastes [11].

Human-interactive research tools involving data collection have too many random variables, making the data obtained quite unreliable due to unpredictable errors. Perhaps the participant could not express the stimuli, or the stimuli were too mild for the sensitivities of the subject. Such obscurities can be eliminated using EEG-aided metric evaluation. A study tested this method to ascertain product similarity based on consumer perception. In addition to the conventional survey tests, an EEG test recorded and processed the power of induced gamma oscillations of test participants after subjecting them to the test visual stimuli and subsequently measuring the evoked potentials of gustatory responses; the test resulted in a strong correlation between the two evoked responses, correlating the induced gamma signals and the generated potentials [12]. The high-density EEG method has successfully distinguished between different intensities of a particular taste, as was tested earlier regarding sweetness levels. An upgrade to the previous study was hypothesized, and a novel strategy using surface recording of neuromuscular responses was presented as an alternative solution to ascertain gustatory responses. Signals from sEMG recordings were obtained after subjecting participants to various chemical gustatory stimulants. Template EEG samples for the 5 main taste profiles (namely, sour, salty, sweet, bitter, and umami) were searched for within the recordings using a Support Vector Machine (SVM) approach followed by a Quadratic normalizer and a notch filter [13].

In a similar study, the taste profiles were classified using the random forest method, and the algorithm provided a 74.46% accuracy in a five-fold cross-validation test after sampling, filtering and noise removal. Diverse subjects and conditions were tested to make the model more inclusive and adaptive. The study reduced the required quad-channel features to four while maintaining the resultant efficiency of the model [14]. To study how taste is sensed using EEG signals, it is necessary to delve into the specifications of EEG recordings. It consists primarily of 4 main types of waveforms: alpha, beta, theta, and delta. Among the 5 fundamental tastes, the sensation of umami perceived primarily by Monosodium Glutamate (MSG) is also experienced by Disodium Inosine Monosulphate (IMP) and Disodium Succinate (WSA), although at different magnitudes. A study explored the feasibility of distinguishing between umami of different intensities from an EEG. Umami was observed to cause alpha waveforms to deflect positively from the baseline, partially providing differences in EEG of the same umami component consumed at different intensities and clearly differentiating between MSG, IMP, and WSA components consumed at the same levels [15].

As observed in the research pool, numerous studies have targeted the trend of taste classification using neural recordings. Various telltale indicators like wavelet features, spikes, spectral similarities and neural wave samples have been used in machine learning algorithms to differentiate between the five primary taste profiles; the study performed a comparative analysis of all the taste profiles at varying intensities and concluded that the sourness, bitterness and saltiness can be quantified way easier than sweetness and umami [16]. Gustatory stimuli are usually accompanied by motor events of related muscles assisting chewing or swallowing. A recent study embedded this phenomenon into the study of gustation of Chinese baijiu (rice-based liquor) by simultaneously logging EEG and EMG events upon consumption. It found that δ and β frequency bands had notable differences in the frontal and temporal cortical regions [17].

4. Galvanic Stimulation

Galvanic Tongue Stimulation (GTS) is the artificial elicitation of taste sensation by delivering low-amplitude current signals directly inside the buccal cavity. The current signals stimulate the taste papillae via a process called electrophoresis. The practice has various inversions, yielding different results based on the different studies conducted. Electrode position, polarity, signal frequency, electrolytic conductivity, etc, all contribute to the variation in the overall experienced taste profile. The same methodology can be used to inhibit certain taste sensations as well. A study explored this phenomenon in detail to find the internal/physiological working principle behind it. It was ascertained that the migration of electrolytic ions resulted in a reduction in taste intensities. The phenomenon was more pronounced with cathodal GTS [18].

Taste stimulation can be employed in a plethora of use cases, including deep dive mulsemedia, diet regulation, culinary experimentation, gustatory diagnostics, etc. The only drawback is the short term of sensory modulation, which rejects the feasibility of its integration into dietary regulation. The cumbersome and invasive form factor of the GTS apparatus not being capable of inducing throat feel adds to the difficulties in boosting the development of GTS as a viable technology. An update to previous studies introduced an alternative to the conventional invasive electrode positioning system with effective results. Instead of placing electrodes inside the buccal cavity, the study introduced the concept of Galvanic Chin Stimulation, wherein the electrodes were positioned with the cathode over the chin and the anode over the back of the neck. The experimentation resulted in a variation in the saltiness level of the consumed solution [19].

Taste intensity being subject to the sensitivity of the consumer's palette has led to varied results, demanding a taste display HMI for an explicable range of results. Research has been formerly conducted to develop a unified taste control system equipped with a display for denoting the levels of taste evoked on screen using graphical representations. As per the previously conducted testing, cathodal stimulation is an after-effect, while anodal stimulation works during the stimulation [20].

Taste transduction works by placing electrodes over the chin and the back of the neck and delivering galvanic signals through them to trigger neurotransmitters via electrophoresis. Generally, there has been no standardized location for electrode placement inside the buccal cavity. The electrodes were merely placed in randomized locations, which stimulated the whole buccal cavity.

This phenomenon was dealt with by another study that aimed to localize the sensations at certain locations sans direct electrode placement. Spatial selectivity was attempted by bypassing insular stimulation and placing the electrodes around the head in a novel configuration, followed by testing the spatial control hypothesis. The study concluded that by arranging the electrodes in that configuration, the spatial dispersion of gustatory stimulation could be localized by regulating the electrode potential distribution [21].

Although cathodal stimulation has been explored extensively for its ability to boost a post-stimulatory response, anodal stimulation still has had lesser traction despite the immediate taste induction owing to the disagreeable metallic taste ensuing from the stimulation. In pursuit of the gap in findings, the taste-enhancing quality of anodal stimulation and its response to the taste invocation of salt solution was tested. Chin stimulation was preferred in a bid to conduct the whole gustatory process unperturbed and as close to natural conditions as possible. The participants were asked to rank the level of saltiness as per their perception. It was noted that a higher current intensity evoked a higher magnitude of saltiness perceived [22].

Upon conducting the general literary review of the distinct techniques to analyse neural gustatory response to taste stimuli, it was discerned that despite fMRI being more accurate, sEEG would comparatively be a more affordable option to perform in-house testing of the gustatory stimuli.

5. Methodology

The prime goal of the study is to study signal shapes while validating the phenomenon of taste electrophoresis. In a bid to study whether the delivered galvanic signals' shapes and simultaneous multichannel frequencies can influence the taste profile, the study uses the custom 4-channel sEEG kit developed using 4 bioamp sEEG pills as a recording interface while using the galvanic signal module as the stimulus delivery mechanism. A typical EEG reading consists of four spectral divisions, namely delta (0.5-4Hz), theta(4-7Hz), alpha(8-14Hz), and beta (14-30Hz), out of which the beta and the alpha range depicting a relaxed awake state and active conscious state data were subjected to testing. The study uses two modules in the testing process: the recording module and the stimulation module. Both modules work in tandem to test the feasibility of replicating the naturally generated gustatory signals. The modules are described in detail individually for more clarity:

5.1. Recording Module

The recording module comprises a custom EEG kit using 4 BioAmp EXG Pills (Figure 2).

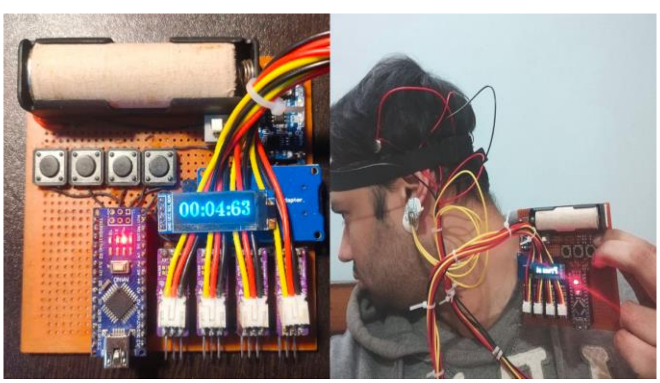

Fig. 1 The recording module consists of four channels

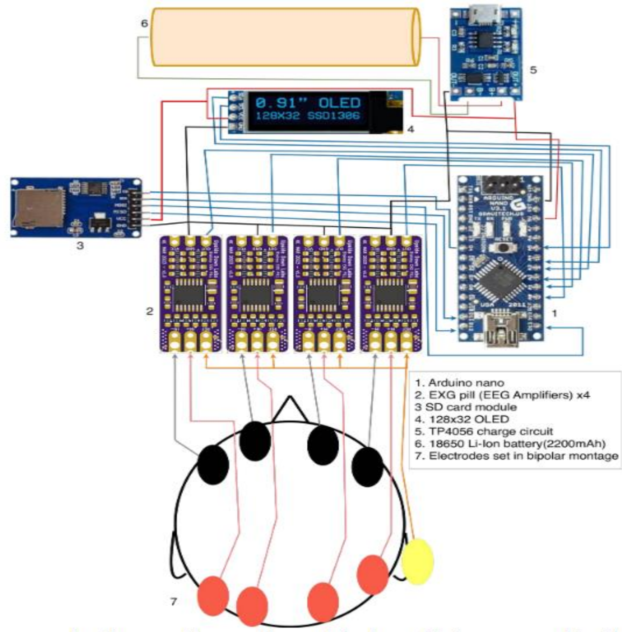

Fig. 3 The connection diagram of the recording module with electrodes

These are bipolar biopotential-amplifying Analog FrontEnds (AFEs) capable of cleanly amplifying very low amplitude signals using TL074H JFETs, which boast a slew rate of 20 V/µs and a temporal voltage offset drift of 2 µV/°C. The entire circuit contained an SD card module, a 32x128 OLED display, and a 2200mAh Li-Ion battery to allow for a wireless circuit. The kit features 4 bipolar EEG channels, each with V+, V-, and reference electrodes.

With the input signals fed into the Arduino nano running a software-based fourth-order band-pass filter ranging from 0.5Hz - 29.5Hz, the data could either be fed into an SD card module or an Android phone with serial USB OTG feature.

The custom kit was programmed to yield a fourth-order Butterworth filter output with its cut-off frequency set to 25Hz. Based on the width of spectral bands required. The electrodes were connected in a bipolar montage around the somatosensory cortical region and the motor-sensory region after being sanitized and hydrated for better signal retention. The circuit was wired according to the connection diagram (Figure 3).

5.2. Stimulation Module

The stimulation module constitutes a Digispark ATTiny85 programmed to receive analogue input over ports P2, P4, and P5 and, subsequently, output two individual tones with their frequencies matching the ADC input value. Trimpots were installed in connection with 0-5 Volt lines, and their variable outputs were fed to P2, P4, and P5 as ADC inputs. The output of P2 controlled the duty cycle of the tones, ensuring that the overall current could be regulated easily.

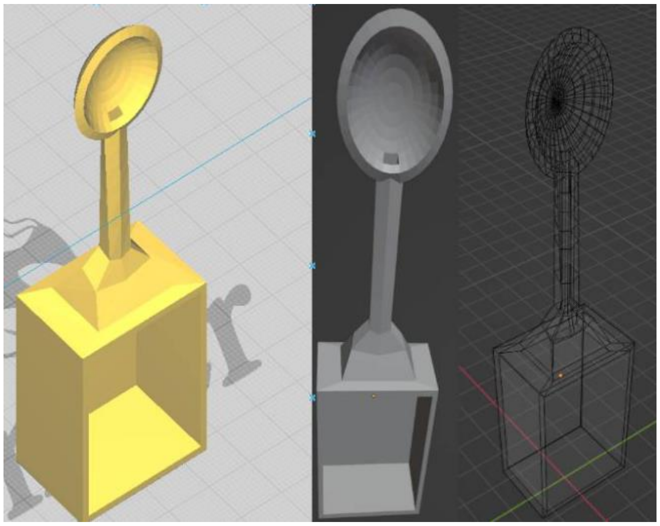

Fig. 4 The design of the simulation module's impulse delivery mechanism. The spoon-like structure has a hollow opening for wires carrying electronic stimuli

The overall system was isolated from the mains supply using a pair of 3.7 Volt Li-ion batteries connected to a TP4056 charging circuit, which regulated the output to 5 volts. The electrodes were placed with the cathode inside the buccal cavity and the anode at the back of the neck. The circuit was designed to be miniscule enough to be housed in a designated enclosure attached to the handle of a conductive metal spoon. The other electrode of the system was designed to be connected via tactile contact while holding the utensil. This connection sits atop the enclosed in the form of a metal plate isolated from direct contact with the metal spoon.

Once the structure was designed in a blender (Figure 4), it was printed using standard PLA for rigidity and safety since PLA is non-toxic in nature. The neck of the spoon was designed to be thin and hollow to allow the passage of the conducting wires through the inside (Figure 5). Each wire carries a different tone signal, providing multichannel galvanic feedback for taste electrostimulation. The circuit, upon completion, could be housed inside the box of the design (Figure 6).

An experiment was designed wherein sEEG data from 4 individuals from different age groups was recorded. The data was classified into the following three baskets: normal sEEG, sEEG during natural salt intake, and sEEG during galvanic stimulation. The output of the sEEG device was recorded and fed into a PC for further processing. EEG records were then transformed into the frequency domain to find dominant frequencies during various experiment stages for observation. The Blackman-Harris windowing method was applied to the FFT calculation. After calculating the FFT, the output was plotted to find the dominant frequency bands while the activity occurred during the stimulus delivery. The power spectral density was also sought to determine the power of the peak signal frequencies in various stages. The LSTM data cleaning and optimization algorithm used the MinMax function due to its sensitivity to feature values and negate the effect of any potentially extreme noise values. To obtain a normalized value, It simply uses the ratio of the difference between the lowest value of a feature and the difference between the max and min value of that feature. Considering the EEG LSTM purpose, it was the ideal choice compared to standard, robust or logarithmic scaling. Also, considering the LSTM was ReLU-based, the MinMax scaler worked best considering that it prevented values from going below zero. After scaling, the dataset was split into training and testing sets reshaped into 3D to be fed into the sequential LSTM with 100 neurons. The Adaptive Moment optimizer was used as it was relatively faster to train and displayed lesser variation in altering the learning rate, making its outputs more reliable.

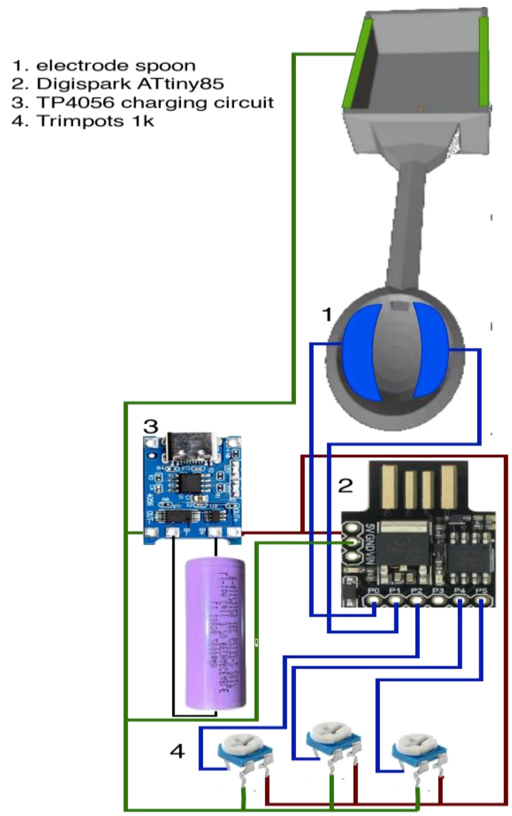

Fig. 2 The circuit diagram of the simulation module

Fig. 3 The prototype stimulation module with circuit parts exposed

Upon recording, taking into account the time-sequence nature of the EEG data, an LSTM classification algorithm was used to train a predictor that could distinguish between 3 conditions: no salt consumed, natural salt consumed, and artificial stimulus at 200Hz. The 4 spectrally filtered waves denote the response of the somatosensory cortex. After testing the conventional response to normal salt, the e-stimulation module was tested with the same sample rate and time interval. A mixed portion was extracted from the overall results and plugged into an LSTM training dataset to predict the class of signals containing an amplified frequency waveform that would depict the sensation of saltiness and those without. The recording duration was of 50 seconds with a sample rate of 33sps. The data was collected in CSV formats before classification, and noise components, such as surges and incomplete readings, were filtered out beforehand. The data was then provided headers to identify the columns programmed into the EEG kit. The four points were named T5, T3, T6, and T4, annotating the location of electrode placement based on the 10-20 montage in the sEEG electrode placement system. The starting and ending two seconds were shaved off to remove myo-artefacts. The LSTM model was checked and retrained to obtain the optimum Root Mean Square Error (RMSE).

6. Results and Discussion

The study results were classified into three phases of the experiment: normal EEG, Salt EEG, and electrostimulation EEG.

6.1. Normal Taste EEG

The FFT of the normal yielded four waveforms, each representing the frequency of amplitudes at various locations of the bipolar EEG montage. As described in the plots, (Figure7) the spectral maxima of the event appear to occur at 14.21 Hz according to the data at T4, T5, and T6, while T3 shows the maxima at 14.18Hz showing that the normal closed-eye EEG data produced a spectral waveform depicting alert wakefulness. Since the PSD is directly correlated to the FFT values squared and divided by twice the frequency value, a similar plot was obtained for the PSD (Figure 8). This was the data obtained from a normal EEG performed as a control medium for the experimental study.

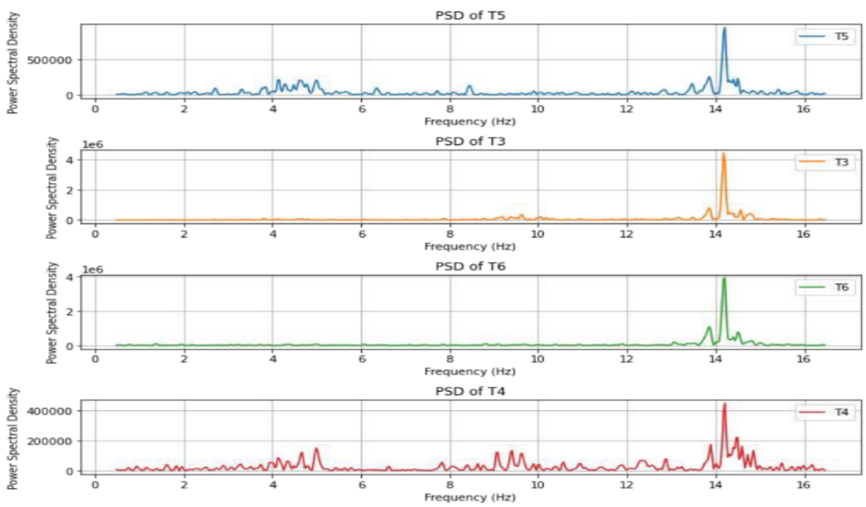

Fig. 4 The FFT of the raw data of normal state EEG yields the frequency maxima of all 4 channels at ~14.2Hz

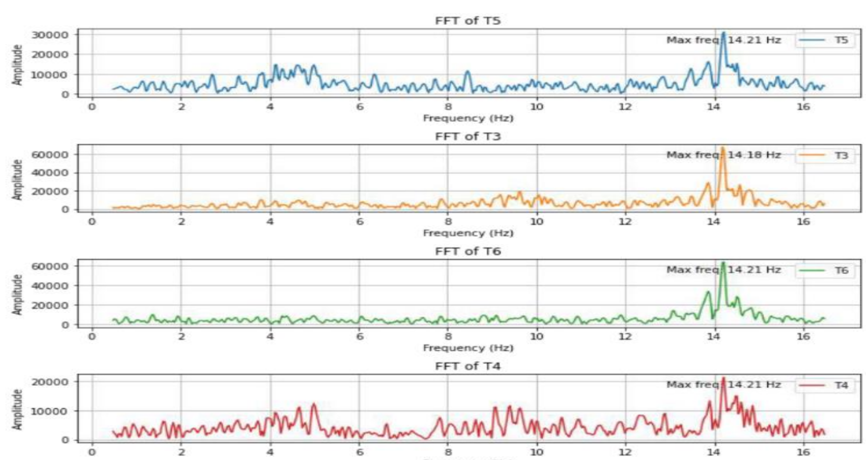

Fig. 5 The PSD of the raw data of a normal state EEG yields the spectral power at nearly the same frequency component

6.2. Natural Salt EEG

The EEG results upon consumption of natural salt yield a slight shift in the dominant frequencies in the FFT (Figure 9). Considering the non-linearity of EEG patterns, the same experiment was applied to 6 different isolated events of salt consumption concatenated into a dataset. The PSD of the data also depicted a similar trend in the salt EEG.Upon confirming the overall shift in spectral dominance, the final step was to analyse the electrostimulation components at 200 Hz. (Figure 10).

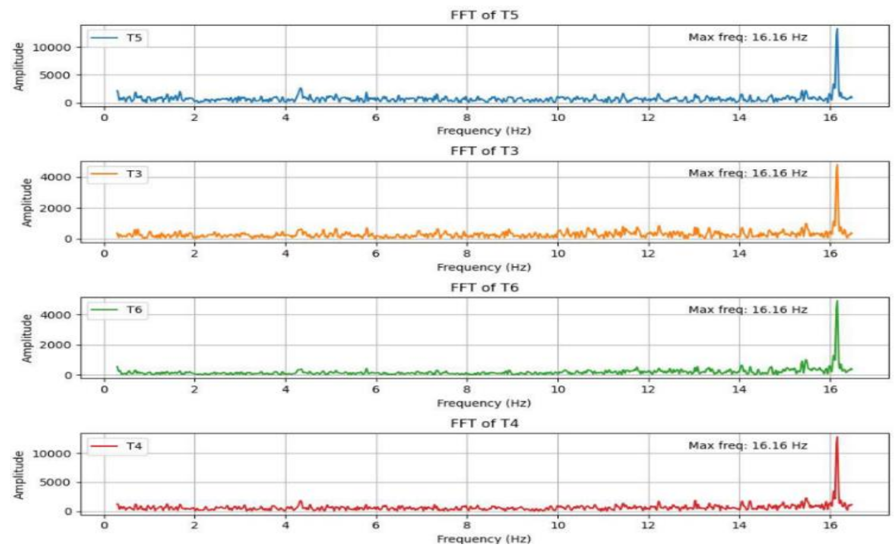

Fig. 6 The FFT of the raw data samples of an EEG upon consuming salt yields a frequency maxima of all 4 channels at 16.1Hz

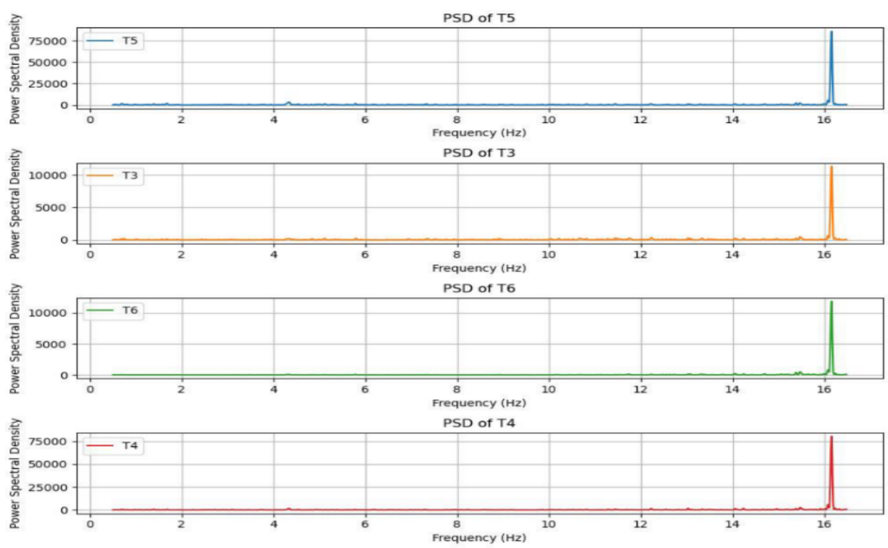

Fig. 7 The PSD of the raw data samples of an EEG upon consuming salt yields a power density at 16 Hz, similar to the FFT

6.3. EEG of Taste Electrostimulus

The EEG response of the event with electrostimulus was recorded with some noise components faced due to the introduction of an external electrical pulse of 10% duty cycle and 200Hz frequency (Figure 11). The PSD shows a noisier but closer response to the salt stimulus (Figure 12). Upon obtaining the required confirmation, an LSTM model was trained with 500 units in 50 epochs.

The specifications of the LSTM applied are provided in Table 1. The Root Mean Square Error (RMSE) obtained with the configuration turns out to be 0.476, as the test loss was 0.2265. The LSTM model can predict among the classes of the three EEG patterns with an accuracy percentage of 68% considering the low number of channels of EEG and the non-linear nature of the EEG patterns, the low percentage of accuracy was an expected outcome.

The parameters in the LSTM were selected upon attempting various iterations in epochs wherein the model either displayed overfit or would show less than 26% accuracy as calculated from the RMSE.

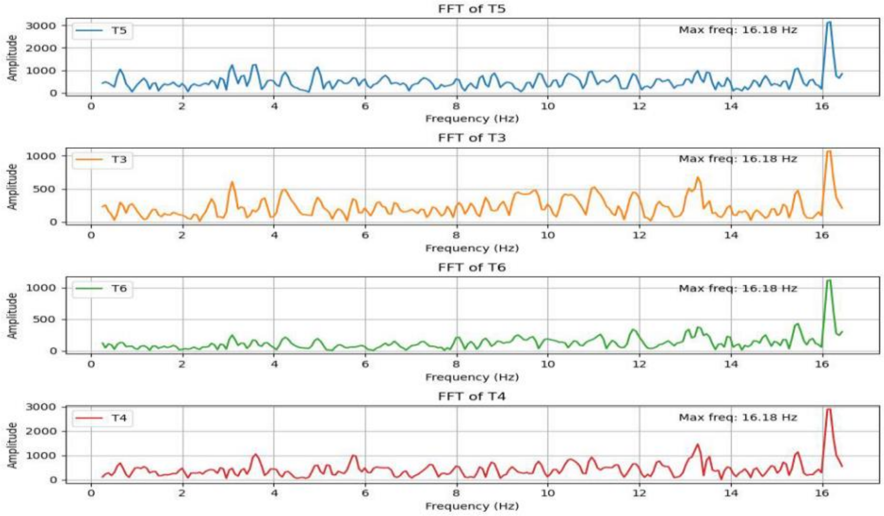

Fig. 8 The FFT of the raw data samples of an EEG upon an electro stimulus of 200Hzyields a noisy maximum at ~ 16 Hz

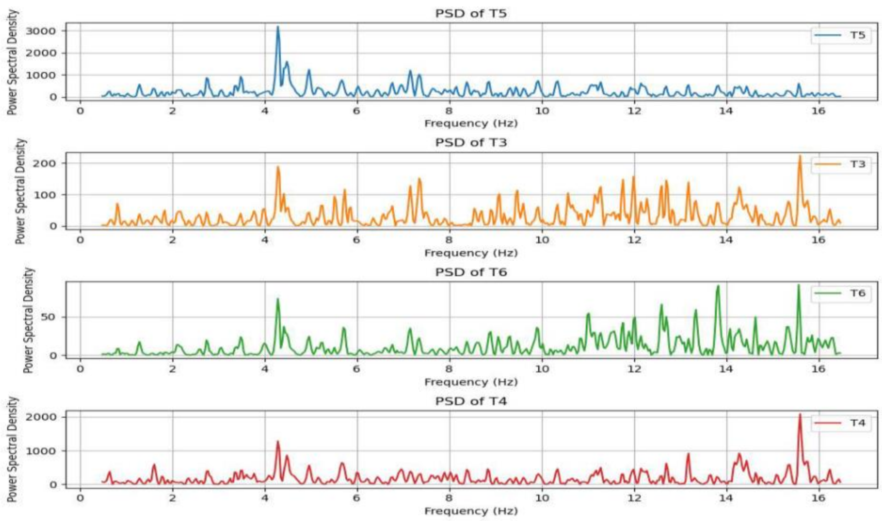

Fig. 9 The PSD of the raw data samples of an EEG upon electrostimulation yields a noisy spectral density distribution

Table 1. Specifications of the sequential LSTM applied

Layer type	Output Shape	Parameters
(LSTM)	None,500	1010000
dense_1 (Dense)	None, 1	501
No. of epochs	50	
LSTM units	500	
Test size	0.2	
Trainable params	1,010,50	
Optimizer	adam	

7. Limitations

The non-linearity of EEG tends to sway the results of neural models, thereby reducing the accuracy of predictions. A huge data set is required to fine-tune the model to be more concrete with suitable results. Moreover, numerous inversions of signals need to be studied via EEG for taste electrostimulation to be identified as a viable commercial option. Future research can focus on recording EEGs and strengthening the model's accuracy while adding more classes to the identification process.

8. Conclusion

The paper described an approach to building a gustatory taste electrostimulation and delivery mechanism and a neural model that could recognize the difference between 3 data classes with 68% accuracy: normal EEG, Salt intake, and EEG during galvanic Electro-stimulation. The model was developed using data from 4 individuals. The domain of taste electrostimulation has tremendous potential to influence the future of augmented reality. Galvanic taste can not only be used as a component in mulsemedia applications but also medically to reduce salt intake by providing external stimuli. Its utility as an extension to the area of taste modification can be recognized as an effective means to broaden the general gustatory experience.

References

[1] Johann Georg Sulzer, *New Theory of Pleasures*, 1767. [Google Scholar]

[2] Ernest Dzendole, "Electrical Stimulation of Single Human Taste Papillae," *Perceptual and Motor Skills*, vol. 14, no. 2, pp. 303-317, 1962. [CrossRef] [Google Scholar] [Publisher Link]

[3] Letao Wang et al., "Artificial Taste: Advances and Innovative Applications in Healthcare," *Applied Sciences*, vol. 15, no. 2, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[4] Goal 9 | Department of Economic and Social Affairs, 2023. [Online]. Available: https://sdgs.un.org/goals/goal9

[5] Antonietta Canna et al., "Intensity-Related Distribution of Sweet and Bitter Taste Fmri Responses in the Insular Cortex," *Human Brain Mapping*, vol. 40, no. 12, pp. 3631-3646, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[6] Sara Ponticorvo et al., "Sex Differences in the Taste-Evoked Functional Connectivity Network," *Chemical Senses*, vol. 47, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[7] E Porcu et al., "Information-Based Taste Maps in Insular Cortex are Shaped by Stimulus Concentration," *bioRxiv*, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[8] Roberts Carl A et al., "A Systematic Review and Activation Likelihood Estimation Meta-Analysis of fMRI Studies on Sweet Taste in Humans," *The Journal of Nutrition*, vol. 150, no. 6, pp. 1619-1630, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[9] Ismi Abidi, Omar Farooq, and M M S Beg, "Sweet and Sour Taste Classification Using EEG Based Brain Computer Interface," *2015 Annual IEEE India Conference*, New Delhi, India, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[10] Camilla Arndal Andersen et al., "EEG Discrimination of Perceptually Similar Tastes," *Journal of Neuroscience Research*, vol. 97, no. 3, pp. 241-252, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[11] Kalyana Sundaram Chandran, and Marichamy Perumalsamy, "EEG-Taste Classification through Sensitivity Analysis," *International Journal of Electrical Engineering & Education*, vol. 60, no. 1, pp. 1649-1661, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[12] Marina Domracheva, and Sofya Kulikova, "EEG Correlates of Perceived Food Product Similarity in a Cross-Modal Taste-Visual Task," *Food Quality and Preference*, vol. 85, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[13] Hengyang Wang et al., "Quantitatively Recognizing Stimuli Intensity of Primary Taste Based on Surface Electromyography," *Sensors*, vol. 21, no. 21, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[14] You Wang et al., "Qualitative Recognition of Primary Taste Sensation Based on Surface Electromyography," *Sensors*, vol. 21, no. 15, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[15] Ben Wu et al., "Investigating the Influence of Different Umami Tastants on Brain Perception Via Scalp Electroencephalogram," *Journal of Agricultural and Food Chemistry*, vol. 70, no. 36, pp. 11344-11352, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[16] Shuo Zhao et al., "Basic Taste Intensity Recognition based on sEMG and EEG Signals," *2022 China Automation Congress*, Xiamen, China, pp. 5437-5441, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[17] Aliya et al., "Evaluation of Flavor Perception of Strong-Aroma Baijiu Based on Electroencephalography (EEG) and Surface Electromyography (EMG) Techniques," *Food Chemistry*, vol. 472, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[18] Kazuma Aoyama et al., "Galvanic Tongue Stimulation Inhibits Five Basic Tastes Induced by Aqueous Electrolyte Solutions," *Frontiers in Psychology*, vol. 8, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[19] Kazuma Aoyama et al., "Taste Controller: Galvanic Chin Stimulation Enhances, Inhibits, and Creates Tastes," *Acm Siggraph 2018 Emerging Technologies*, pp. 1-2, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[20] Kazuma Aoyama, "Galvanic Taste Stimulation Method for Virtual Reality and Augmented Reality," *Human Interface and the Management of Information. Designing Information*, pp. 341-349, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[21] Hiromi Nakamura, Makoto Mizukami, and Kazuma Aoyama, "Method of Modifying Spatial Taste Location through Multielectrode Galvanic Taste Stimulation," *IEEE Access*, vol. 9, pp. 47603-47614, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[22] Hiromi Nakamura et al., "Anodal Galvanic Taste Stimulation to the Chin Enhances Salty Taste of Nacl Water Solution," *Journal of Robotics and Mechatronics*, vol. 33, no. 5, pp. 1128-1134, 2021. [CrossRef] [Google Scholar] [Publisher Link]