Food Quality and Preference 131 (2025) 105572

Contents lists available at ScienceDirect

Food Quality and Preference

journal homepage: www.elsevier.com/locate/foodqual

Impact of five basic tastes perception on neurophysiological response: Results from brain activity

Diana Rico Pereira[a,*], Helena Rico Pereira[b,c], Maria Leonor Silva[a], Paula Pereira[a], Hugo Alexandre Ferreira[c,d]

[a] Egas Moniz Center for Interdisciplinary Research (CiiEM); Egas Moniz School of Health & Science, Caparica, Almada, Portugal
[b] CTS-UNINOVA, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
[c] Instituto de Biofísica e Engenharia Biomédica, Faculdade de Ciências da Universidade de Lisboa, Campo Grande, Lisboa, Portugal
[d] Instituto de Fisiologia, Faculdade de Medicina da Universidade de Lisboa,Portugal

ARTICLE INFO

Keywords:
Basic food tastes
Sensory stimuli
Electroencephalography
Brain activity
Brain waves
Self-assessment-manikin

ABSTRACT

The five basic tastes (sweet, salty, umami, sour, and bitter) perception plays a fundamental role in food choices. Nevertheless, how the perception of each basic tastes influence brain activity is still unknown. We investigated the effect of each taste on the brain activity of healthy adults using electroencephalography (EEG). For that, sucrose, sodium chloride, sodium glutamate, citric acid, and caffeine solutions were individually administered to 28 participants (18–25 years old). Self-reporting feedback was assessed using the 3-dimensional Self-Assessment-Manikin (SAM). The power density of the five frequency bands (delta, theta, alpha, beta and gamma) computed from the EEG signals was used to compare the five basic tastes. Significant differences ($p < 0.05$) were found for (1) beta waves: sweet vs umami, and salty vs umami; and for (2) gamma waves: sweet vs umami, and sweet vs bitter. The findings also indicate that sweet taste stimulated higher brain activity than umami in the gamma but not in the beta waves. Sweet, salty, umami and bitter tastes correlated with SAM responses. This study advances the understanding of brain response to taste stimuli, whilst improving the knowledge of these sensorial cognitive processes. Clinical trial Identifier: NCT06051175

1. Introduction

The sense of taste plays a crucial role in our evolutionary development and survival. It serves as a mechanism to identify potentially harmful or disagreeable substances, fulfil our nutritional needs (Chandrashekar et al., 2006), and discern the five basic tastes: sweet, salty, umami, sour, and bitter. Taste also has a role in appetite regulation, as it can influence feeding behaviour (Fu et al., 2021). Additionally, taste perception plays a fundamental role in food selection, food intake regulation and pleasure association with food (Boesveldt & de Graaf, 2017; Dotson et al., 2012; Li et al., 2020; Loper et al., 2015).

Understanding how the brain processes and responds to different taste stimuli will uncover the underlying mechanisms of eating behaviour and its relationship to health and well-being. The activation of emotions and hedonic responses depends upon the taste of food and whether it is palatable or disagreeable (Agovi et al., 2022; Lundy, 2008; Pool et al., 2014). Taste perception is also modulated by physiological changes associated with the individual's physiological state of hunger or satiety (Campos et al., 2016; Fu et al., 2021).

The gustatory cortex is the part of the brain responsible for processing taste information. Signals from taste buds of the tongue and other parts of the mouth are conveyed via the facial, glossopharyngeal, and vagus sensory nerves to the nucleus of the solitary tract in the medulla oblongata prior to reaching the thalamus, from which are then relayed to the gustatory cortex (De Araujo & Simon, 2009). The gustatory cortex is primarily located in two regions: the insular cortex and in the frontal operculum (Iannilli et al., 2014). The knowledge about the human gustatory cortex and how it influences our taste experience is not as advanced as understanding other sensory systems. For instance, researchers have extensively mapped cortical regions for other senses like vision and audition (Chikazoe et al., 2019). In taste, there is a lack of evidence of which cortical regions are involved in distinguishing between the different basic tastes, such as sweet, salty, umami, sour, and bitter.

* Corresponding author.
E-mail addresses: drpereira@egasmoniz.edu.pt (D.R. Pereira), hrpereira@fc.ul.pt (H.R. Pereira), lsilva@egasmoniz.edu.pt (M.L. Silva), pmpereira@egasmoniz.edu.pt (P. Pereira), hhferreira@fc.ul.pt (H.A. Ferreira).

https://doi.org/10.1016/j.foodqual.2025.105572
Received 19 January 2025; Received in revised form 6 April 2025; Accepted 30 April 2025
Available online 5 May 2025

Electroencephalography (EEG), a neurophysiological non-invasive technique for recording brain electrical activity, has been used to assess the physiological and emotional reactions to dietary items (Songsamoe et al., 2019). EEG is widely used in consumer neuroscience, offering advantages over functional magnetic resonance imaging (fMRI) due to its non-invasiveness, hight temporal resolution, cost-effectiveness, and greater practicality (Alvino et al., 2020).

EEG analysis includes extracting brainwave frequency power bands: delta; theta; alpha; beta; and gamma. The lowest frequency waves, delta and theta, are present during deep sleep and in drowsiness, respectively (Abhang et al., 2016a). Alpha waves, present in wakefulness, are associated with mental relaxation, and decrease with mental effort and with eye-opening (Abhang et al., 2016a). In contrast, beta waves, also present during wakefulness, are more evident during conscious thought and logical thinking (Abhang et al., 2016b). Gamma waves, the fastest frequency waves in brain, are increased during concentration, problem-solving and memory tasks (Abhang et al., 2016b).

In general, there is a scarcity of work on using EEG to study the sense of taste, particularly comparing all the five basic tastes (mainly missing umami). Prior research has focused on the power of brainwave frequency bands recorded in response to food cues (Okello et al., 2016; Songsamoe et al., 2019; Tashiro et al., 2019). Tashiro and colleagues showed a significant decrease in the beta band power over electrode position C3 (the left postcentral gyrus) when individuals were exposed to images of their favourite foods compared to foods they despised (Tashiro et al., 2019). Another study conducted by Okello et al. showed an increase in alpha, theta, and beta wave power one hour after the consumption of green and black tea (Okello et al., 2016). EEG was also used to discriminate flavour intensities, namely, similar sweet flavour intensities, different sensory intensities of umami flavour (Wu et al., 2022) and different sensory intensities between bitter, salty, sour and sweet (Yang et al., 2023). In pathologies such as obesity and food addiction (FA), EEG was also particularly useful (Imperatori et al., 2015; Schmidt et al., 2018). One study had found that children with overweight/obesity had increased delta and decreased alpha band activity when compared to normal children, during eyes-closed resting state (Schmidt et al., 2018). Additionally, participants with three or more FA symptoms, showed an increase of delta power, in five minutes resting state after a single taste of a chocolate milkshake (Imperatori et al., 2015).

Therefore, this study aimed to investigate how sweet, salty, umami, sour, and bitter influence brain activity in healthy adults using EEG, hypothesizing that these tastes elicit distinct neural responses. Given that, this work contributes to advancing the field by being the first to integrate umami into a comprehensive analysis of the five basic tastes focusing on: 1) exploring their differential effects on brain waves (brain activity); 2) correlating emotional answers with such brain waves.

2. Materials and methods

2.1. Chemicals and preparations of solutions

For studying brain waves activation, solutions that represent the five basic tastes were prepared: a sucrose solution (0.0467 M) (sucrose, ⩾99 %, MP Biomedicals LLC, France) was used to elicit sweet taste; a sodium chloride solution (0.0856 M) (sodium chloride, ⩾99.8 %, Sigma-Aldrich, St. Louis, MO, USA) as salty taste; a sodium glutamate solution (0.0107 M) (L-glutamic acid monosodium salt monohydrate, >98 %, Alfa Aesar GmbH & Co KG, Karlsruhe, Germany) as umami taste; a citric acid solution (0.0052 M) (citric acid, 99.5 %, Sigma-Aldrich, St. Louis, USA) as sour taste; and a caffeine solution (0.0038 M) (caffeine, Sigma-Aldrich, St. Louis, MO, USA) as bitter taste. The solution concentrations were determined according to international standards (ISO 3972: 2011). The concentration values corresponding to medium to high intensity were used, according to Zhi et al. (2017). To prepare each one of the solutions, the pure reagents mentioned above (sucrose, sodium chloride, L-glutamic acid, monosodium salt monohydrate, caffeine, and citric acid) were dissolved in water at room temperature. The solutions were prepared on the day of the experiments immediately before the sensory test.

2.2. Participants and eligibility criteria

Twenty-eight healthy volunteers, 18 females and 10 males, aged between 18 and 25 years (mean and standard deviation of 20.4 ± 1.5 years old), were enrolled in the present study. All participants received information about the aims and procedures of the study and signed an informed consent. A code was attributed to all participants to guarantee the confidentiality of their data. Participants were excluded if they had neurological or psychiatric diseases, food allergies/intolerances related to the five basic tastes, or disabilities precluding the full use of the sense of taste, such as ageusia. The participants' general characteristics were collected using a self-reported questionnaire, including age, gender, lifestyle habits and clinical history. This study was approved by the Ethics Committee of Egas Moniz School of Health and Science (Process nr. 1226) and was carried out according to the Declaration of Helsinki. (Clinical trial.gov Identifier: NCT06051175).

2.3. Study design and experimental protocol

All the experiments occurred between 9 am and 7 pm in a safe, quiet, and odourless place. Each session lasted approximately 50 min for each participant. Participants were instructed to refrain from taking food and water at least one hour before the experiments. At the beginning of each session, participants were asked to remain calm. During the procedure, participants were seated in a chair, with the electrodes in place, and in front of a computer screen, with the experiment instructions being delivered using the Psychophy Platform (Peirce et al., 2019).

Due to the nature of the interventions, the taste solutions were blind to the trial participants but not to the data collectors. The sucrose, sodium chloride, sodium glutamate, citric acid, and caffeine solutions were administrated to each participant to elicit the sweet, salty, umami, sour, and bitter tastes, respectively. The order of the testing solutions was pseudo-randomized per participant, such that each taste solution would be presented a roughly equal number of times in the 1st, 2nd, 3rd, 4th, and 5th place in total, over all participants. Before testing the different solutions, participants rinsed their mouths with water. Each solution was delivered in a white cup (30 mL), allowing the participant to transfer the solution to their mouths without chewing or swallowing, keeping the liquid in the oral cavity. Each taste stimulus test lasted 2 s after which the contents were poured into a cup. The 2 s was the time interval selected to include only the first reaction to the sample and exclude brain stimulus related to taste guessing (Ohla et al., 2012). Immediately after the sensory stimulus tests, the participants rinsed their mouths with water again, followed by a 15-s pause to stabilize the EEG recording.

Each participant evaluated each stimulus twice, using the 3-dimensional Self-Assessment-Manikin (SAM), and was also asked to identify the taste.

2.4. Electroencephalography: Acquisition and processing

This study used a 32-channel EEG actiCHamp Plus device and the BrainVision recorder software (Brain Products, Germany) to collect and record each participant's brain activity during the experiment. The EEG data was acquired with a sampling frequency of 500 Hz, and the Cz channel was used as the reference electrode (Zhang et al., 2020).

The raw EEG data was filtered offline using a bandpass filter from 1 Hz to 45 Hz to remove noise and electromagnetic interference. Then, eye and movement artifacts were identified and removed from the raw data using the independent component analysis method (Comon, 1994). The channels FT9, FT10, T7, T8, TP9 and TP10 were rejected from the analysis because they were too noisy. After the preprocessing, the mean power spectral density (PSD) of each EEG channel was computed for a time interval of 2 s after the taste stimulus presentation, i.e., the immediate instant when the taste fell off into the participants' tongues. The PSD was obtained using the Welch's method (Welch, 1967) with the following parameters: a Hamming window (known to provide good PSD results (Verma & Dekar, 2018)) with 0.25 s (minimum time length to include at least one cycle of the delta waves); 50 % overlap (to increase frequency resolution); and 2 Hz resolution. All subjects had the cup in their hands during this time interval. By selecting the same moment for all participants, interferences in signal due to intersubject variability (e.g. movement due to picking the cup) were mitigated. The period of analysis did not include the spitting of the liquid. The following frequency bands PSD values were considered for further analysis: delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and gamma (30–45 Hz). The EEG raw data preprocessing and the PSD computation were performed using the MNE library Version 1.3.1 (Gramfort, 2013) in Python.

2.5. Measurement of emotional responses

The emotional responses to the tastes were also collected from the participants of this study. Using the three-dimension Self-Assessment-Manikin (SAM) questionnaire, participants ranked with a score on a 9-point Likert scale the level of valence (pleasant/unpleasant), arousal (exciting/calming) and dominance (overwhelming/subtle) they felt during the taste exposure (Bradley & Lang, 1994).

2.6. Statistical analysis

Pairwise comparisons between the PSD of pairs of the five tastes were performed using a cluster-level statistical permutation test considering all channels and each frequency band (delta, theta, alpha, beta or gamma) with 1000 permutations and a significance level of 5 % to handle the multiple comparisons problem (Maris & Oostenveld, 2007; Sassenhagen & Draschkow, 2019). The analysis was conducted with in-house Python scripts using the MNE library (Gramfort, 2013). The PSD differences between pairs of the five tastes were also assessed at the channel level, with the Wilcoxon-signed rank tests (in-house R scripts) with *p*-values corrected with the Benjamini-Hochberg procedure using false discovery rates of 0.05 and 0.1, considering the number of channels ($n = 25$) and pairs of tastes ($n = 10$). Regions reported by Koessler and colleagues (Koessler et al., 2009) were used as proxies to define the anatomical regions involved in taste discrimination.

For the SAM answers, the three dimensions were compared pairwise using the Wilcoxon-signed rank tests with the Bonferroni correction with in-house R scripts. Their effect size was also computed using the Wilcoxon Effect Size (R package) as described elsewhere (Tomczak & Tomczak, 2014). The boxplots of the PSD waves and SAM answers were created using GraphPad Prism 10. The mean PSD of each subject was also obtained to compute the correlation between the mean PSD of each subject and the SAM dimensions using the Spearman's rank correlation coefficient (at a 5 % significance level) for each frequency and taste.

3. Results

3.1. General characteristics of the participants

Twenty-eight healthy volunteers were included in this study. Table 1 shows the sample participants' demographic, clinical and lifestyle characteristics.

Table 1
General characteristics of the sample participants.

	Total ($n = 28$)	M ($n = 10$)	F ($n = 18$)
Age (mean, years)	20.4	21.5	19.8
Pathologies			
Rhinitis	1	0	1
Asthma	2	0	2
Dermatitis	1	0	1
Hypothyroidism	1	0	1
Anaemia	1	0	1
Sinusitis	1	0	1
Medication and supplementation			
Oral contraceptive	6	0	6
Iron	2	0	2
Creatine	1	1	0
Antihypertensives	1	1	0
Food allergies or intolerances			
Yes	7	1	6
No	21	9	12
Physical activity frequency			
No physical activity	12	3	9
< 2 h/week	3	0	3
2–4 h/week	6	3	3
> 4 h/week	7	4	3
Sleep habits (hours)			
<6H/day	0	0	0
6-8H/day	28	10	18
> 8H/day	0	0	0
Alcoholic beverages consumption			
Daily	0	0	0
Weekly	4	2	2
Monthly	10	4	6
Occasional	7	2	5
Never	7	2	5
Smoker habits			
Smoker	0	0	0
Non-smoker	28	10	18

3.2. Brain wave responses across the five basic tastes

The cluster permutation test indicated the presence of statistically significant differences between sweet vs umami in beta waves ($p = 0.025$, effect size = 0.29 – small, sweet < umami) and gamma waves power ($p = 0.039$, effect size = 0.12 – small, sweet > umami). Sweet vs bitter also showed significant differences in the gamma wave power ($p = 0.038$, effect size = 0.06 – small, sweet > bitter). Salty vs umami showed differences in the beta wave power (p = 0.04, effect size = 0.06 – small, salty < umami). The brain maps of these significant pairs of tastes are illustrated in Fig. 1 (For all brain maps please see the supplementary material Fig. S1.

The analysis of the pairwise comparison for each channel only showed statistically significant differences at False Discovery Rate (FDR), FDR = 0.1 (0.05 < p-value adjusted <0.1). These differences were found for all pairs of tastes in 63 comparisons, from which eight had *p*-value adjusted <0.07, as shown in Table 2.

3.3. Analysis of the emotional response and brain activity correlation

Fig. 2 shows the distribution of the responses given by the participants to the three dimensions of the SAM (valence, arousal and dominance) for each taste, namely, sweet, salty, umami, sour, and bitter.

The SAM's responses were compared using the Wilcoxon signed-rank test with Bonferroni correction. Statistically significant differences were found, considering a significance level of 5 %. In the dimension of valence, sweet was reported as having higher pleasantness than sour $p = 0.004$, effect size = 0.3 - moderate) and bitter (p < 0.001, effect size = 0.6 - large) tastes; salty had higher pleasantness than sour ($p = 0.002$, effect size = 0.4 - moderate) and bitter (p < 0.001, effect size = 0.6 - large); umami had higher pleasantness than bitter (p < 0.001, effect size = 0.5 - large); and sour had higher pleasant than bitter ($p = 0.033$, effect size = 0.3 - moderate). In the arousal dimension, the Wilcoxon test showed only that umami had higher excitement than bitter ($p = 0.036$, effect size = 0.3 - moderate) taste. Finally, in the dominance dimension, sweet had higher control than bitter (p < 0.001, effect size = 0.5 - large) taste, and salty had higher control than umami ($p = 0.023$, effect size =

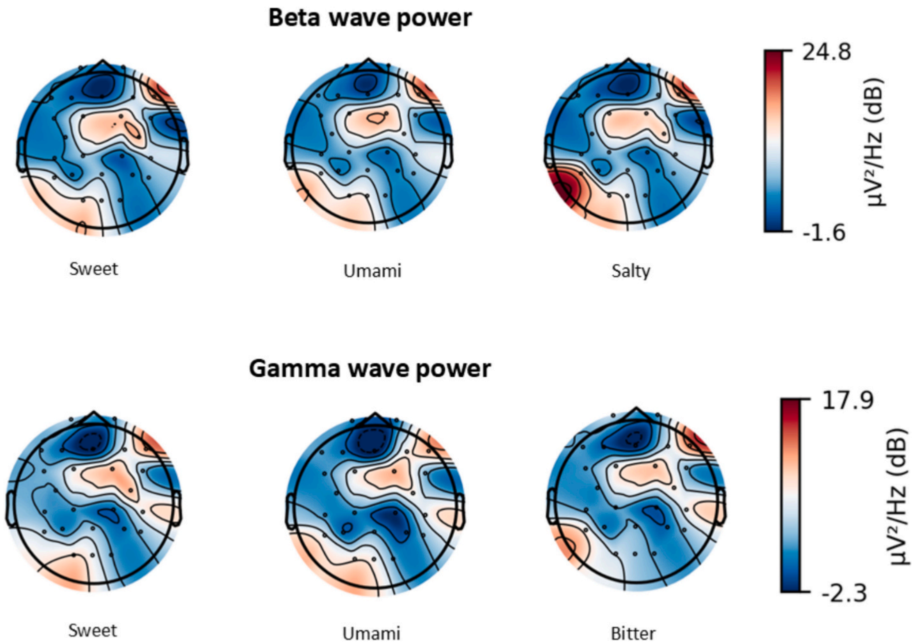

Fig. 1. Brain maps of the average (all subjects) power spectrum density of the tastes with statistically significant differences in cluster-level statistical permutation test.

Table 2
Wilcoxon signed-rank test results from the pair comparisons with adjusted *p*-values between 0.05 and 0.07 of the channel-level analysis.

Pair	*p*-value	Channel	Frequency Band	*p*-value adjusted
sweet vs salty	0.0041	Pz - superior parietal lobe	beta	0.0634
sweet vs umami	0.0032	C4 - postcentral gyrus	theta	0.0608
sweet vs umami	0.0041	O2 - middle occipital gyrus	beta	0.0677
salty vs umami	0.0048	Fz - bilateral medial	theta	0.0664
salty vs bitter	0.0034	P7 - inferior temporal gyrus	beta	0.0614
salty vs bitter	0.0027	CP5 - supramarginal gyrus	gamma	0.0665
salty vs bitter	0.0024	CP1 - postcentral gyrus	gamma	0.0678
sour vs umami	0.0032	CP6 - supramarginal gyrus	gamma	0.0658

0.3 - moderate) and bitter ($p = 0.001$, effect size = 0.5 - large) tastes.

All tastes, except salty, showed statistically significant correlations between the SAM answers and the PSD but in different domains. The sweet taste showed a statistically significant negative correlation with arousal in delta ($r = -0.50$, $p = 0.008$), theta ($r = -0.48$, $p = 0.010$), and beta waves ($r = -0.37$, $p = 0.048$). In valence, sour showed only statistically significant positive correlations: theta ($r = 0.48$, p = 0.01), alpha ($r = 0.43$, p = 0.02), beta ($r = 0.50$, $p = 0.007$) and gamma ($r = 0.41$, $p = 0.027$); and bitter only in gamma waves (r = 0.41, $p = 0.028$). For dominance, both sweet and umami showed statistically significant positive correlations in theta (umami: $r = 0.37$, $p = 0.049$), beta (sweet: $r = 0.44$, $p = 0.018$; umami: r = 0.43, $p = 0.021$), and gamma waves (sweet: $r = 0.40$, $p = 0.035$, umami: r = 0.50, p = 0.007). For all plots of statistically significant correlations between the 3 domains of the SAM and PSD (in delta, theta, alpha, beta and gamma waves) please see the supplementary material S2.

Table 3 describes the participants' responses when asked to identify the stimulus. Some participants attributed more than one word to the stimulus, and others did not know what to say. Most people correctly identified the sweet (51 answers) and salty (50 answers) tastes. For the umami taste, answers like "I don't know" and "strange taste" were recorded. Regarding sour, six answers referred "bitter", while for bitter, nine answers referred "sour".

4. Discussion

This study found significant differences in PSD of: (i) beta waves: sweet vs umami and salty vs umami and (ii) gamma waves between sweet vs umami and sweet vs bitter. The pairwise comparison at the individual channel level only showed statistically significant differences at FDR = 0.1, indicating that these results are exploratory and require further confirmation. Additionally, all tastes, except salty, showed a correlation between the emotional response and the respective PSD of beta and gamma brain waves.

4.1. Brain wave responses across the five basic tastes – Whole brain channels

To our knowledge, only three studies have compared the effects of different basic tastes (Crouzet et al., 2015; Gao et al., 2023; Hashida et al., 2005). One study measured the global field power and showed that this value increased earlier for the bitter taste (150 ms) than for the sweet taste (270 ms) (Crouzet et al., 2015), which may support our differences between sweet and bitter. That study also observed that salty and sour tastes caused similar brain changes (Crouzet et al., 2015), corroborating the significant difference found between those two tastes in the present study. Other work observed that sweet and salty tastes also differ, which contradicts our findings (Hashida et al., 2005). Nonetheless, in contrast to our methods where we analysed the PSD immediately after the stimuli, they only studied the EEG signal after 2 s of the stimuli. The third study, using a machine-learning approach, verified that discriminating all the five basic tastes was very demanding, mainly due to the variability of the emotional experience between participants (Gao et al., 2023).

Differences between bitter (caffeine) and sweet tastes were also observed in this study. Understanding how the bitter taste influences brain function is relevant. For instance, one study found that bitter and

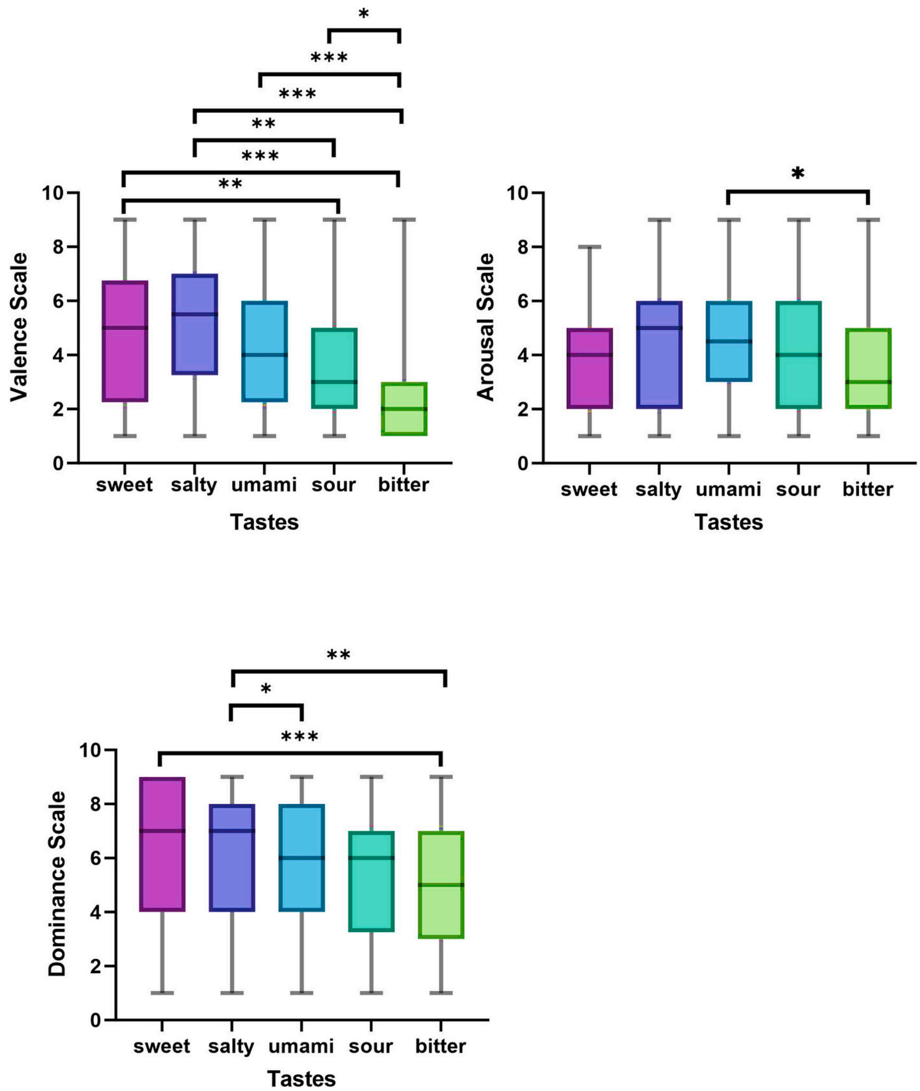

Fig. 2. Boxplot with the distribution of the 3-dimensional Self-Assessment-Manikin answers given by all participants. (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$).

Table 3
Answers given by the participants in the interviews for each taste.

Taste	Answers
Sweet	"sweet" (51), "neutral" (5)
Salty	"salty" (50), "others" (6)
Umami	"I don't know" (12), "salty" (5), "I don't like it" (7), "strange taste" (8), "others" (8)
Sour	"sour" (56), "bitter" (6), "I don't like it" (1)
Bitter	"bitter" (18), "sour" (9), "strange taste" (6), "I don't like it" (10), "tastes like poison" (2)

sweet differ in anorexia nervosa (Tóth et al., 2004). Nonetheless, a direct comparison with previous studies that have also assessed the effect of caffeine (Ajjimaporn et al., 2022; Okello et al., 2016) on the brain can not be performed. The present study did not explore caffeine consumption or its effect after 30 min to one hour of administration, as the previous studies have done. The results presented here showed that during the 2 s of tasting, the bitter taste had the same effect on the delta, theta and alpha waves as the salty, umami, and sour tastes, suggesting that caffeine tasting did not immediately change the brain's attention/relaxation levels. Nevertheless, it is important to note that such stimulating effects of caffeine for motivation and energy are usually associated with moderate doses of caffeine (20–400 mg/day), which are higher than those used in this study (Ajjimaporn et al., 2022).

4.2. *Brain wave responses across the five basic tastes – Individual brain channels*

At the individual channel level, the results indicated that several brain regions were involved in taste discrimination, namely, the postcentral gyrus, supramarginal gyrus and the inferior temporal gyrus. Although whole-brain electrodes were previously found to provide better results, the temporal and central electrodes seem to play a critical role in taste discrimination (Gao et al., 2023).

These regions identified in the present study have been previously linked to taste and tongue processing and thus support the results obtained in this study. Imaging studies have found that the tongue sensory response lies at the base of the postcentral gyrus (Boling et al., 2002), while the supramarginal gyrus was also shown to be involved in the process of perceiving different tastes (Hwang et al., 2019). There is also evidence that the inferior temporal gyrus may respond to different taste stimuli, i.e., sweetness and bitterness (Hwang et al., 2019).

4.3. *Emotional response*

The challenge of identifying specific taste responses in humans may be related to the complexity of our taste experiences being associated with these multiple levels of objective chemistry and subjective valence. Regarding SAM, in valence, sweet was considered the most pleasant and bitter the most unpleasant. This can be explained by tasting perception being biologically inherited and affected culturally. Biologically, since birth, humans can recognize tastes. Studies have found that newborns and fetuses tend to consider sweet as pleasant and bitter as unpleasant by analyzing their facial expressions (Steiner et al., 2001; Ustun et al., 2022). Besides this, individual food preferences are also influenced throughout life by factors such as culture, religion, environment and personal experiences (Galindo et al., 2012).

In the dimension of arousal, there were fewer differences (only between umami and bitter), suggesting that the participants found the umami taste more exciting because they could not identify it, as referred to in the interview as a "strange taste". In fact, this taste is commonly used to intensify food. It has been reported that the umami taste requires training on the part of the European participants to be recognized, as it is "strange" on first contact (Bellisle, 2008).

Concerning the dimension of dominance, sweet showed significant differences compared to the bitter taste and salty with umami and bitter tastes, which is also to be expected as sweet and salty are the best-known tastes, giving the participant greater dominance or control over those tastes.

4.4. Correlation between emotional response and brain activity

The SAM results align with the statistically significant cases found with the cluster permutation test (sweet/salty vs umami, sweet vs bitter). In fact, the statistically significant correlation between SAM responses and PSD were found for all tastes except salty. High arousal, in sweet, was correlated with lower PSD in delta and theta (reduced relaxation), and beta waves (decreased cognition). High valence was correlated with high PSD in theta, alpha (increased relaxation) and beta waves for sour; and gamma (increased cognition) for both sour and bitter. High dominance was correlated with higher theta in sweet and umami (increased relaxation), higher beta in sweet and umami (increased cognition), and higher gamma in umami (increased cognition).

The answers given by the participants regarding the identification of tastes show that they identify sour and bitter as if they were synonyms. However, this is probably a question of language and not of confusing the two tastes. It is also interesting to note the reference of one participant associating the bitter taste with poison because that's the function of bitter, to alert humans to potentially noxious and/or poisonous chemicals (Chandrashekar et al., 2006). This finding is also consistent with SAM results for the dimensions of dominance, where the lower values for bitter indicate an automatic avoidance behaviour.

Overall, these findings demonstrate that different basic tastes evoke distinct patterns of brain activity, with significant differences in beta and gamma waves, particularly between sweet, umami, salty, and bitter stimuli. Beta and gamma activity are associated with conscious thought, memory, and cognitive processing, suggesting that specific tastes may modulate these functions. These neural differences are relevant for sensory science and consumer research, as they provide objective insights into how taste perception influences both cognitive and emotional responses. Such findings can enhance sensory evaluation methods by integrating EEG as a tool to complement self-reported assessments.

Additionally, the correlation between taste perception and self-reported emotions (SAM responses) highlights the potential applications of EEG in product development and marketing strategies aimed at optimizing consumer experience. By leveraging the link between taste-induced neural responses and cognitive-emotional processes, this research offers valuable insights for the formulation of food products designed to evoke specific mental and emotional states. Ultimately, a deeper understanding of taste-related brain activity contributes to guiding healthier food choices and refining product development to align with consumer preferences.

4.5. Limitations

This study had some limitations. The first one is that the EEG only provides information about cortical regions. Nevertheless, fMRI studies have shown that deeper brain regions, like the insula, the amygdala and the operculum, are involved in gustatory systems (Chikazoe et al., 2019; Jiang et al., 2014). Therefore, an extension of this study using fMRI will provide more information to understand how the brain reacts to different tastes and set up a pathway for building a brain map for taste and food products. Another limitation of this study is that the exact moment the participant tasted the sample was manually and visually assessed, which is prone to human error. Using a gustometer, which we plan to use in future studies, will control the administration of taste stimuli and mitigate this drawback.

Lastly, this study only had 28 participants, and the sample is not balanced for sex. There were also only two trials per tastes. Previous studies focused on power analysis have analysed the brain response in low number participants (ranging from 8 to 46) and trials (ranging from 1 to 3) (Gao et al., 2023; Hashida et al., 2005; Imperatori et al., 2015; Kotini et al., 2016; Okello et al., 2016; Ustun et al., 2022; Wu et al., 2022). Although we extended the number of subjects compared to the literature, the conclusions reported in this study would benefit from an additional external sample. We found that the perception of each of the five basic tastes originates from different brain responses at the cortical level. This difference is more evident when comparing beta and gamma waves produced by the umami and sweet tasting, which suggests that cognitive, emotional and alertness processes are involved in the perception of these tastes.

The present study extends the previous works by correlating brain activity in different brain waves with emotional responses, and also by including the umami taste in the analysis, as previous research was mainly focused on the four other tastes (Crouzet et al., 2015; Kotini et al., 2016), different types of umami (Wu et al., 2022) or sweetness (Andersen et al., 2019). Therefore, the present study's findings can be a starting point for further understanding the role of gamma waves in the cognitive processing of food, namely in sweet vs umami and salty vs umami. In this context, further studies are needed to confirm the results of the present study.

5. Conclusion

We added to the field an analysis of the neural responses to the five basic tastes—sweet, salty, umami, sour, and bitter—using EEG power spectrum analysis and emotional self-assessments. Significant differences in beta and gamma wave activity were identified, particularly between sweet and umami and sweet and bitter, highlighting distinct neural processing patterns associated with these tastes. By including umami, often underrepresented in previous studies, this work broadens the understanding of taste perception and its neurophysiological underpinnings. Additionally, the integration of subjective emotional evaluations provides an often-overlooked nuanced view of the relationship between sensory stimuli and cognitive-emotional responses.

The findings contribute to advancing knowledge in nutrition-related neuroscience and sensory science, with potential applications in food product development and health interventions. However, this pilot study acknowledges limitations, such as reliance on cortical data from EEG, manual timing of stimuli, and a relatively small sample size. Future research incorporating fMRI, automated stimulus delivery, and larger, more diverse samples is essential to validate and extend these findings. This work represents a step toward a more comprehensive mapping of the neural correlates of taste perception, informing both theoretical and applied advancements in the field.

CRediT authorship contribution statement

Diana Rico Pereira: Writing – original draft, Methodology, Investigation, Formal analysis. **Helena Rico Pereira:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Maria Leonor Silva:** Writing – review & editing, Conceptualization. **Paula Pereira:** Writing – review & editing, Conceptualization. **Hugo Alexandre Ferreira:** Writing – review & editing, Methodology, Conceptualization.

Ethical statement

All participants voluntarily participated and submitted informed consent forms before study engagement. Ethical approval for the involvement of human subjects in this study was approved by the Ethics Committee of Egas Moniz School of Health and Science (Process nr. 1226) and was carried out according to the Declaration of Helsinki.

Funding

This research received no external funding.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was financed by national funds through the FCT—Foundation for Science and Technology, IP, under projects UIDB/04585/2020, UIDB/00645/2020 and PhD grant 2021.08306.BD.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodqual.2025.105572.

Data availability

Data will be made available on request.

References

Abhang, P. A., Gawali, B. W., & Mehrotra, S. C. (2016a). Technical aspects of brain rhythms and speech parameters. In *Introduction to EEG- and speech-based emotion recognition* (pp. 51–79). Elsevier. https://doi.org/10.1016/B978-0-12-804490-2.00003-8.

Abhang, P. A., Gawali, B. W., & Mehrotra, S. C. (2016b). Technological basics of EEG recording and operation of apparatus. In *Introduction to EEG- and speech-based emotion recognition* (pp. 19–50). Elsevier. https://doi.org/10.1016/B978-0-12-804490-2.00002-6.

Agovi, H., Pierguidi, L., Dinnella, C., Viggiano, M. P., Monteleone, E., & Spinelli, S. (2022). Attentional bias for vegetables is negatively associated with acceptability and is related to sensory properties. *Food Quality and Preference, 96*(September 2021), Article 104429. https://doi.org/10.1016/j.foodqual.2021.104429

Ajjimaporn, A., Noppongsakit, P., Ramyarangsi, P., Siripornpanich, V., & Chaunchaiyakul, R. (2022). A low- dose of caffeine suppresses EEG alpha power and improves working memory in healthy university males. *Physiology & Behavior, 256* (August), Article 113955. https://doi.org/10.1016/j.physbeh.2022.113955

Alvino, L., Pavone, L., Abhishta, A., & Robben, H. (2020). Picking your brains: Where and how neuroscience tools can enhance marketing research. *Frontiers in Neuroscience, 14* (December). https://doi.org/10.3389/fnins.2020.577666

Andersen, C. A., Kring, M. L., Andersen, R. H., Larsen, O. N., Kjær, T. W., Kidmose, U., … Kidmose, P. (2019). EEG discrimination of perceptually similar tastes. *Journal of Neuroscience Research, 97*(3), 241–252. https://doi.org/10.1002/jnr.24281

Bellisle, F. (2008). Experimental studies of food choices and palatability responses in European subjects exposed to the umami taste. *Asia Pacific Journal of Clinical Nutrition, 17*(Suppl 1(1)), 376–379. http://www.ncbi.nlm.nih.gov/pubmed/18296383.

Boesveldt, S., & de Graaf, K. (2017). The differential role of smell and taste for eating behavior. *Perception, 46*(3–4), 307–319. https://doi.org/10.1177/0301006616685576

Boling, W., Reutens, D. C., & Olivier, A. (2002). Functional topography of the low postcentral area. *Journal of Neurosurgery, 97*(2), 388–395. https://doi.org/10.3171/jns.2002.97.2.0388

Bradley, M. M., & Lang, P. J. (1994). Measuring emotion: The self-assessment manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry, 25*(1), 49–59. https://doi.org/10.1016/0005-7916(94)90063-9

Campos, C. A., Bowen, A. J., Schwartz, M. W., & Palmiter, R. D. (2016). Parabrachial CGRP neurons control meal termination. *Cell Metabolism, 23*(5), 811–820. https://doi.org/10.1016/j.cmet.2016.04.006

Chandrashekar, J., Hoon, M. A., Ryba, N. J. P., & Zuker, C. S. (2006). The receptors and cells for mammalian taste. *Nature, 444*(7117), 288–294. https://doi.org/10.1038/nature05401

Chikazoe, J., Lee, D. H., Kriegeskorte, N., & Anderson, A. K. (2019). Distinct representations of basic taste qualities in human gustatory cortex. *Nature Communications, 10*(1), 1–8. https://doi.org/10.1038/s41467-019-08857-z

Comon, P. (1994). Independent component analysis, a new concept? *Signal Processing, 36* (3), 287–314. https://doi.org/10.1016/0165-1684(94)90029-9

Crouzet, S. M., Busch, N. A., & Ohla, K. (2015). Taste quality decoding parallels taste sensations. *Current Biology, 25*(7), 890–896. https://doi.org/10.1016/j.cub.2015.01.057

De Araujo, I. E., & Simon, S. A. (2009). The gustatory cortex and multisensory integration. *International Journal of Obesity, 33*(Suppl. 2), S34–S43. https://doi.org/10.1038/ijo.2009.70

Dotson, C. D., Babich, J., & Steinle, N. I. (2012). Genetic predisposition and taste preference: Impact on food intake and risk of chronic disease. *Current Nutrition Reports, 1*(3), 175–183. https://doi.org/10.1007/s13668-012-0021-3

Fu, O., Minokoshi, Y., & Nakajima, K. (2021). Recent advances in neural circuits for taste perception in hunger. *Frontiers in Neural Circuits, 15*(February), 1–8. https://doi.org/10.3389/fncir.2021.609824

Galindo, M. M., Schneider, N. Y., Stähler, F., Töle, J., & Meyerhof, W. (2012). Taste preferences. In *, 108. Progress in molecular biology and translational science* (pp. 383–426). https://doi.org/10.1016/B978-0-12-398397-8.00015-0

Gao, H., Zhao, S., Li, H., Liu, L., Wang, H., Wang, Y., Luo, Z., Zhang, J., & Li, G. (2023). Basic taste sensation recognition from EEG based on multiscale convolutional neural network with residual learning. *IEEE Transactions on Instrumentation and Measurement, 72*, 1–10. https://doi.org/10.1109/TIM.2023.3280529

Gramfort, A. (2013). MEG and EEG data analysis with MNE-Python. *Frontiers in Neuroscience, 7*. https://doi.org/10.3389/fnins.2013.00267

Hashida, J. C., de Sousa Silva, A. C., Souto, S., & Costa, E. J. X. (2005). EEG pattern discrimination between salty and sweet taste using adaptive Gabor transform. *Neurocomputing, 68*(1–4), 251–257. https://doi.org/10.1016/j.neucom.2005.04.004

Hwang, L. D., Strike, L. T., Couvy-Duchesne, B., de Zubicaray, G. I., McMahon, K., Breslin, P. A. S., … Wright, M. J. (2019). Associations between brain structure and perceived intensity of sweet and bitter tastes. *Behavioural Brain Research, 363*, 103–108. https://doi.org/10.1016/j.bbr.2019.01.046

Iannilli, E., Noennig, N., Hummel, T., & Schoenfeld, A. M. (2014). Spatio-temporal correlates of taste processing in the human primary gustatory cortex. *Neuroscience, 273*, 92–99. https://doi.org/10.1016/j.neuroscience.2014.05.017

Imperatori, C., Fabbricatore, M., Innamorati, M., Farina, B., Quintiliani, M. I., Lamis, D. A., … Della Marca, G. (2015). Modification of EEG functional connectivity and EEG power spectra in overweight and obese patients with food addiction: An eLORETA study. *Brain Imaging and Behavior, 9*(4), 703–716. https://doi.org/10.1007/s11682-014-9324-x

Jiang, Y., King, J. M., & Prinyawiwatkul, W. (2014). A review of measurement and relationships between food, eating behavior and emotion. *Trends in Food Science and Technology, 36*(1), 15–28. https://doi.org/10.1016/j.tifs.2013.12.005

Koessler, L., Maillard, L., Benhadid, A., Vignal, J. P., Felblinger, J., Vespignani, H., & Braun, M. (2009). Automated cortical projection of EEG sensors: Anatomical correlation via the international 10-10 system. *NeuroImage, 46*(1), 64–72. https://doi.org/10.1016/j.neuroimage.2009.02.006

Kotini, A., Anninos, P., Gemousakakis, T., Adamopoulos, A., & Professor, A. (2016). Maedica-a journal of clinical medicine the effects of sweet, bitter, salty and sour stimuli on alpha rhythm. A Meg Study. *Maedica A Journal of Clinical Medicine, 11*(3), 208–213.

Li, T., Zhao, M., Raza, A., Guo, J., He, T., Zou, T., & Song, H. (2020). The effect of taste and taste perception on satiation/satiety: A review. *Food & Function, 11*(4), 2838–2847. https://doi.org/10.1039/C9FO02519G

Loper, H. B., La Sala, M., Dotson, C., & Steinle, N. (2015). Taste perception, associated hormonal modulation, and nutrient intake. *Nutrition Reviews, 73*(2), 83–91. https://doi.org/10.1093/nutrit/nuu009

Lundy, R. F. (2008). Gustatory hedonic value: Potential function for forebrain control of brainstem taste processing. *Neuroscience and Biobehavioral Reviews, 32*(8), 1601–1606. https://doi.org/10.1016/j.neubiorev.2008.07.002

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods, 164*(1), 177–190. https://doi.org/10.1016/j.jneumeth.2007.03.024

Ohla, K., Busch, N. A., & Lundström, J. N. (2012). Time for taste—A review of the early cerebral processing of gustatory perception. *Chemosensory Perception, 5*(1), 87–99. https://doi.org/10.1007/s12078-011-9106-4

Okello, E. J., Abadi, A. M., & Abadi, S. A. (2016). Effects of green and black tea consumption on brain wave activities in healthy volunteers as measured by a simplified electroencephalogram (EEG): A feasibility study. *Nutritional Neuroscience, 19*(5), 196–205. https://doi.org/10.1179/1476830515Y.0000000008

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., … Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods, 51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Pool, E., Delplanque, S., Porcherot, C., Jenkins, T., Cayeux, I., & Sander, D. (2014). Sweet reward increases implicit discrimination of similar odors. *Frontiers in Behavioral Neuroscience, 8*(MAY), 1–8. https://doi.org/10.3389/fnbeh.2014.00158

Sassenhagen, J., & Draschkow, D. (2019). Cluster-based permutation tests of MEG/EEG data do not establish significance of effect latency or location. *Psychophysiology, 56*(6), 1–8. https://doi.org/10.1111/psyp.13335
Schmidt, R., Sebert, C., Kösling, C., Grunwald, M., Hilbert, A., Hübner, C., & Schäfer, L. (2018). Neuropsychological and neurophysiological indicators of general and food-specific impulsivity in children with overweight and obesity: A pilot study. *Nutrients, 10*(12), 1983. https://doi.org/10.3390/nu10121983
Songsamoe, S., Saengwong-ngam, R., Koomhin, P., & Matan, N. (2019). Understanding consumer physiological and emotional responses to food products using electroencephalography (EEG). *Trends in Food Science & Technology, 93*(October 2018), 167–173. https://doi.org/10.1016/j.tifs.2019.09.018
Steiner, J. E., Glaser, D., Hawilo, M. E., & Berridge, K. C. (2001). Comparative expression of hedonic impact: Affective reactions to taste by human infants and other primates. *Neuroscience and Biobehavioral Reviews, 25*(1), 53–74. https://doi.org/10.1016/S0149-7634(00)00051-8
Tashiro, N., Sugata, H., Ikeda, T., Matsushita, K., Hara, M., Kawakami, K., Kawakami, K., & Fujiki, M. (2019). Effect of individual food preferences on oscillatory brain activity. *Brain and Behavior: A Cognitive Neuroscience Perspective, 9*(5). https://doi.org/10.1002/brb3.1262
Tomczak, M., & Tomczak, E. (2014). The need to report effect size estimates revisited. An overview of some recommended measures of effect size. *Trends in Sport Sciences, 1*(21), 19–25.
Tóth, E., Túry, F., Gáti, Á., Weisz, J., Kondákor, I., & Molnár, M. (2004). Effects of sweet and bitter gustatory stimuli in anorexia nervosa on EEG frequency spectra. *International Journal of Psychophysiology, 52*(3), 285–290. https://doi.org/10.1016/j.ijpsycho.2003.11.001
Ustun, B., Reissland, N., Covey, J., Schaal, B., & Blissett, J. (2022). Flavor sensing in utero and emerging discriminative behaviors in the human fetus. *Psychological Science, 33*(10), 1651–1663. https://doi.org/10.1177/09567976221105460
Verma, R., & Dekar, R. (2018). Sleep disorder detection by Welch algorithm based PSD analysis on EEG signals. *International Research Journal of Engineering and Technology, June*, 858–865. www.irjet.net.
Welch, P. (1967). The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms. *IEEE Transactions on Audio and Electroacoustics, 15*(2), 70–73. https://doi.org/10.1109/TAU.1967.1161901
Wu, B., Blank, I., Zhang, Y., & Liu, Y. (2022). Investigating the influence of different umami Tastants on brain perception via scalp electroencephalogram. *Journal of Agricultural and Food Chemistry, 70*(36), 11344–11352. https://doi.org/10.1021/acs.jafc.2c01938
Yang, T., Zhang, P., Xing, L., Hu, J., Feng, R., Zhong, J., Li, W., Zhang, Y., Zhu, Q., Yang, Y., Gao, F., & Qian, Z. (2023). Insights into brain perceptions of the different taste qualities and hedonic valence of food via scalp electroencephalogram. *Food Research International, 173*(P1), Article 113311. https://doi.org/10.1016/j.foodres.2023.113311
Zhang, L., Wang, P., Zhang, R., Chen, M., Shi, L., Gao, J., & Hu, Y. (2020). The influence of different EEG references on scalp EEG functional network analysis during hand movement tasks. *Frontiers in Human Neuroscience, 14*. https://doi.org/10.3389/fnhum.2020.00367
Zhi, R., Cao, L., & Cao, G. (2017). Asians' facial responsiveness to basic tastes by automated facial expression analysis system. *Journal of Food Science, 82*(3), 794–806. https://doi.org/10.1111/1750-3841.13611