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Feasibility of modulating taste perception using subthreshold electrical stimulation

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Abstract

Subthreshold electrical noise can enhance sensory processing via stochastic resonance; however, its effect on taste remains unclear. This study investigated whether subthreshold white-noise electrical stimulation, applied to the skin surface along the mandibular margin, modulates taste perception. Young, healthy adults participated in psychophysical experiments using sodium chloride solutions for salty tastes and sucrose solutions for sweet tastes. For each taste, participants evaluated salty or sweet samples under randomized no-stimulation and stimulation conditions at 0.4, 0.6, and 0.8 times their sensory threshold using a nine-point taste intensity scale. The minimum perceptible concentrations were determined based on taste evaluation values. Additionally, stimulation to no-stimulation ratios were calculated as normalized minimum concentrations. For saltiness, the minimum concentration was significantly lower with stimulation under the 0.8 times condition than with no-stimulation (median, 0.15% vs. 0.20%; Holm-adjusted $p = 0.012$), and normalized minimum concentrations differed across stimulation intensities ($p = 0.004$). No significant effects were observed for sweetness at any stimulation intensity. Additionally, exploratory within-participant selection of the best-performing intensity was conducted separately for saltiness and sweetness, which yielded descriptively low minimum concentrations. These findings suggest feasibility of modulating taste perception with subthreshold electrical noise, particularly for saltiness, with no significant enhancement for sweetness.

Introduction

Taste plays crucial roles in enabling humans to consume the nutrients necessary for sustaining life and derive psychological satisfaction from eating and drinking. Therefore, a decline in taste due to aging, disease, or the effects of medication can significantly impair quality of life[1, 2]. Furthermore, chronic diseases, such as hypertension and obesity, are partly caused by an unbalanced diet, including excessive salt and sugar intake. The number of patients with such chronic diseases has been increasing worldwide, highlighting the growing importance of appropriate dietary guidance[3]. However, it is difficult to derive psychological satisfaction from meals that are low in salt and sugar, making it challenging to maintain healthy dietary habits in the long term. As such, enhancing taste through engineering techniques without altering the composition of food is a crucial technology for improving the quality of life of patients with diminished taste perception and healthy individuals who need to maintain or improve their health.

This study focused on the stochastic resonance (SR) phenomenon and engineering techniques to modulate taste perception. In SR, the response of a nonlinear system to a weak input signal is amplified by subthreshold noise[4]. In previous studies applying SR to humans, it was reported that subthreshold electrical stimulation with white noise below the perceptual threshold can enhance the tactile sensation in the fingers[5]. Since then, similar effects have been reported in the somatosensory[6, 7], vestibular[8, 9], and vision[10] sensations. That is, by applying subthreshold electrical noise, perception arises in response to weak inputs that are not perceived in the absence of noise. Various efforts have been made

to elucidate the mechanism by which SR is induced by subthreshold electrical stimulation; one leading hypothesis is that it affects the firing characteristics of neurons[11, 12]. Based on these findings, subthreshold electrical stimulation may have the potential to modulate taste perception when applied to taste-related neural systems. However, to the best of the authors' knowledge, although the effects of SR have been reported across various senses, no study has specifically targeted taste.

This study investigated the effects of white noise subthreshold electrical stimulation on taste perception. Taste experiments involving the salty taste of a low-concentration sodium chloride solution and the sweet taste of a low-concentration sucrose solution were conducted. Saltiness and sweetness were selected because reducing salt and sugar intake is important for preventing chronic diseases such as hypertension and diabetes. It was hypothesized that applying subthreshold electrical noise to the nervous system would modulate the salty and sweet tastes.

Methods

Participants

This study conducted experiments targeting young, healthy adults and focusing on salty and sweet tastes. The numbers of participants in the salty and sweet taste experiments were 17 (16 males, one female) and 15 (14 males, one female), respectively. The ages, heights, and weights of the participants are listed in Table 1. The selection criterion for the participants was that they were healthy adults affiliated with Ritsumeikan University. Participants were recruited through flyers and other means. Exclusion criteria included a self-reported history of taste disorders, history of smoking, and any physical ailments on the day of the experiment, such as cold, which could affect taste. Participants were free to choose which experiment to participate in and no monetary or other compensation was provided in any case. This study was conducted in accordance with the Declaration of Helsinki and approved by the Ritsumeikan University Ethics Review Committee for Medical Research involving Human Subjects (Approval No. BKC-LSMH-2022054-3). Written informed consent was obtained from all participants prior to the experiments.

Table 1
Age, height, and weight (mean ± S.D.) of participants in each experiment

Experiment	Age (y.o.)	Height (cm)	Weight (kg)
Salty taste	23.4 ± 2.0	169.3 ± 6.7	65.7 ± 9.5
Sweet taste	23.3 ± 1.0	173.1 ± 7.7	62.4 ± 11.2

Experimental procedure

Prior to the experiments, participants were instructed to refrain from consuming any food or beverages other than water for 3 h to minimize the influence of food and beverage intake on taste perception. The experiments were conducted with one participant at a time in a laboratory maintained in a quiet

environment using the experimental procedure shown in Fig. 1. First, the researcher manually applied two disposable surface electrodes (Airlode, SMP-300, Mets, Japan) to the skin surface along the mandibular margin on the lower left side of the participant's face, near the marginal mandibular branch of the facial nerve. The facial nerve contributes to the neural pathway involved in taste perception through the chorda tympani. The proximal electrode along the mandibular margin was designated as the anode, and the distal electrode as the cathode, with 10 mm between the electrodes.

Next, as previously reported, the step method was used to determine the sensory threshold (ST) at which the participant could perceive electrical stimulation[13]. Specifically, the current applied to the participant was gradually increased from 0 mA and the current at which they perceived electrical stimulation was recorded. The current was then gradually decreased from a value slightly above this threshold and the current at which perception disappeared was recorded. This procedure was repeated three times, and the average value was taken as the ST. Furthermore, to examine whether the effect of stimulation varied with intensity in a manner consistent with the inverted U-shaped characteristic associated with SR, the stimulation currents were set to 0.4, 0.6, and 0.8 times the ST. This characteristic indicates that the effect of stimulation varies with stimulation intensity, with the greatest effect occurring at an optimal intensity.

After the ST was determined, participants took part in psychophysical experiments involving salty or sweet tastes and evaluated the taste of the samples listed in Table 2 for each experiment. The concentrations of the sodium chloride and sucrose solutions were selected based on previous findings and preliminary experiments. In a previous study involving 42 university students, 84% perceived saltiness at concentrations ranging from 0.02% to 0.20% in a sodium chloride solution[15]. In addition, our preliminary experiments confirmed that saltiness was perceived at concentrations of 0.50% or higher regardless of the presence or absence of SR electrical stimulation. For sweetness, a previous study involving 42 university students reported that 64% perceived sweetness at concentrations ranging from 0.10% to 0.80% in a sucrose solution[15]. Our preliminary experiments also confirmed that sweetness was perceived at concentrations of 0.60% or higher regardless of the presence or absence of SR electrical stimulation. These findings were used to define the concentration ranges examined in the present study.

Table 2
Mass and percentage concentration of samples used in the experiments

Experiment	**Samples**
Salty taste	Sodium chloride solution 0.00%, 0.05%, 0.10%, 0.15%, 0.20%, 0.30%, 0.40%, 0.50%
Sweet taste	Sucrose solution 0.00%, 0.05%, 0.10%, 0.15%, 0.20%, 0.30%, 0.40%, 0.50%

During the psychophysical experiments, the conditions in which subthreshold electrical stimulation was applied (current ON) or was not applied (current OFF) were presented in randomized order, with participants blinded to the stimulation condition. Under each condition, participants were provided with a randomly selected sample by the researcher, which they held in their mouth for 3 s, and then expectorated it into a designated container. Subsequently, participants rated the salty or sweet taste using a nine-point rating scale ranging from zero ("no taste detected") to eight ("the strongest imaginable salty/sweet taste"). A rating of two indicated a "a faint salty/sweet taste." The participants then rinsed their mouths with commercially available mineral water (I LOHAS, The Coca-Cola (Japan) Co., Ltd., Japan) for 1 min to remove any remaining sample. This procedure was repeated for each stimulation current level of 0.4, 0.6, and 0.8 times the ST. The stimulation current level was randomized for each participant, and a total of three sets were conducted, with each set consisting of stimulation and no-stimulation conditions at 0.4, 0.6, or 0.8 times. The order of "stimulation" and "no stimulation" and the stimulation intensity were randomized for each participant. Specifically, 48 trials were performed by each participant in the salty and sweet taste experiments (16 trials per set × three sets).

Preparation of the taste samples

Salty taste samples were prepared by dissolving food-grade sodium chloride (100 g of table salt; Salt Industry Center, a public interest incorporated foundation, Japan) in commercially available mineral water (I LOHAS, The Coca-Cola (Japan) Co., Ltd., Japan). The same brand of mineral water was used for all the preparations. Prior to preparing the samples at each concentration, a 0.50% sodium chloride aqueous solution was prepared. Subsequently, the 0.50% sodium chloride aqueous solution was mixed with mineral water to prepare 100 g samples for each test. All concentrations are expressed as mass percentages.

Sweet taste samples were prepared by dissolving food-grade refined sucrose (white sugar, Mitsui DM Sugar Co., Ltd., Japan) in commercially available mineral water (I LOHAS, The Coca-Cola (Japan) Co., Ltd., Japan). Prior to preparing the samples at each concentration, a 0.50% sucrose solution was prepared. Subsequently, the 0.50% sucrose solution was mixed with mineral water to prepare 100 g of each experimental sample.

Each sample was prepared at room temperature with gentle stirring and freshly prepared before the start of each experiment. In addition, the samples were transported to the laboratory 2 h before the experiment and allowed to reach room temperature.

Electrical stimulation device

To deliver subthreshold electrical stimulation, an electrical stimulation device was used that was developed by modifying a portable noise stimulator developed in the authors' previous studies[16, 17] into a desktop-sized system (68 mm × 75 mm × 47 mm, 147 g). Briefly, the stimulator outputs a voltage waveform via a digital-to-analog converter based on white Gaussian noise data (from DC to 1000 Hz) following a standard normal distribution generated in the microcomputer using the Box–Müller method.

This voltage waveform is converted into current by a voltage-to-current conversion circuit, and arbitrary stimulation currents can be delivered to the human body through a current mirror circuit with a high impedance. The stimulation current applied to the human body was adjustable from 0.0 to 5.0 mA using a variable resistor.

Data analysis

In the salty and sweet taste experiments, participants assessed the minimum concentration at which they could perceive a salty or sweet taste, respectively. The minimum concentration for a given participant was defined as the lower of two consecutive concentration levels, in ascending order, at which a rating of two or higher, defined as the point at which a faint salty or sweet taste was detected, was recorded[15].

To evaluate the differences in the effects based on stimulus intensity, the minimum concentration in the stimulation condition was divided by the minimum concentration in the corresponding no-stimulation condition to calculate the normalized minimum concentration.

There are individual differences in the inverse U-shaped relationship between the stimulus intensity and sensory enhancement observed in the SR induced by subthreshold electrical stimulation[18]. Therefore, as an exploratory analysis, the intensity at which the normalized minimum concentration was the lowest among the three stimulus intensities for each participant was identified as the “optimal intensity.” Note that the study participants whose normalized minimum concentration was one or higher at all three stimulus intensities were treated as cases in which no stimulus intensity showing improvement was identified within the range of intensities examined.

Statistical analysis

To investigate whether there were differences in the minimum concentration between the stimulation and no-stimulation conditions for each intensity level of the subthreshold electrical stimulation, a Wilcoxon signed-rank test was performed and multiple comparisons were corrected for using the Holm method. Statistical significance was determined based on the Holm-adjusted p-values, with a significance level of 0.05.

Furthermore, to compare the differences in the effects of each stimulation intensity on taste perception, a Friedman test was performed on the normalized minimum concentration. When a significant difference was observed, followed by a post-hoc test using the Wilcoxon signed-rank test, and multiple comparisons were corrected for using the Holm method. For the Friedman test, an unadjusted p-value < 0.05 was considered statistically significant, whereas for the post-hoc comparisons, a Holm-adjusted p-value < 0.05 was considered statistically significant.

Furthermore, r was calculated as the effect size for the Wilcoxon signed-rank test, and Kendall's coefficient of concordance, W, was calculated as the effect size for the Friedman test. Values of r and W > 0.1 were classified as small effects, > 0.3 as moderate effects, and > 0.5 as large effects. MATLAB R2025b Update 2 (25.2.0.3055257) (MathWorks, Natick, MA, USA) was used for the statistical analyses.

As the minimum concentration corresponding to the optimal intensity obtained through exploratory analysis was selected based on the same data, no statistical analysis was performed and only descriptive statistics are presented.

Results

Table 3 lists the ST values and their corresponding stimulation current intensities. None of the participants perceived electrical stimulation during subthreshold electrical stimulation.

Table 3
ST and stimulation current in each experiment (means ± S.D.)

Experiment	ST (mA)	Stimulation current (mA)		
		ST×0.4	ST×0.6	ST×0.8
Salty taste	0.115 ± 0.048	0.046 ± 0.019	0.069 ± 0.029	0.092 ± 0.039
Sweet taste	0.083 ± 0.086	0.033 ± 0.034	0.050 ± 0.051	0.067 ± 0.069

Saltiness experiment

Figure 2 shows the effect of subthreshold electrical stimulation on the minimum concentration of saltiness. Under the 0.8 times condition, the minimum concentration in the stimulation condition (median 0.15%, interquartile range (IQR) 0.10–0.20%) was significantly lower than that in the no stimulation condition (median 0.20%, IQR 0.15–0.30%), indicating a significant effect (Holm-adjusted p = 0.012, r = 0.893). Under this condition, noise caused a decrease in the minimum concentration in nine of the 17 participants, while no change was observed in the remaining eight participants. In contrast, under the 0.4 times condition, the minimum concentration in the stimulation condition (median 0.15%, IQR 0.15–0.20%) compared to that in the no stimulation condition (median 0.15%, IQR 0.15–0.20%) showed no significant difference (Holm-adjusted p = 0.375, r = 0.514). Similarly, under the 0.6 times condition, the minimum concentration in the stimulation condition (median 0.20%, IQR 0.15–0.20%) was comparable to that in the no stimulation condition (median 0.20%, IQR 0.15–0.20%), and no significant difference was observed (Holm-adjusted p = 0.957, r = 0.040). Furthermore, the numbers of participants for whom the minimum concentration decreased, remained unchanged, or increased due to noise were four, 10, and three, respectively, under the 0.4 times condition, and four, eight, and five, respectively, under the 0.6 times condition.

A Friedman test comparing the normalized minimum concentrations at each stimulus intensity revealed a significant difference and a moderate effect between the stimulus intensities (p = 0.004, W = 0.320).

Post-hoc comparisons revealed significant differences between the 0.4 and 0.8 times conditions (Holm-adjusted p = 0.006, r = 0.887) and between the 0.6 and 0.8 times conditions (Holm-adjusted p = 0.009, r = 0.750), indicating a large effect. In contrast, no significant difference was observed between the 0.4 and 0.6 times conditions (Holm-adjusted p = 0.908, r = 0.046).

In an exploratory analysis of the optimal intensity for each participant, the minimum concentration in the stimulation condition (median 0.15%, IQR 0.10–0.20%) was lower than that in the no-stimulation condition (median 0.2%, IQR 0.15–0.30%).

Sweetness experiment

Figure 3 shows the effect of subthreshold electrical stimulation on the minimum concentration of sweetness. Under the 0.4 times condition, the minimum concentration in the stimulation condition (median 0.30%, IQR 0.17–0.50%) compared to that in the no-stimulation condition (median 0.30%, IQR 0.1–0.30%) showed no significant difference (Holm-adjusted p = 0.615, r = 0.403). Under the 0.6 times condition, the minimum concentration in the stimulation condition (median 0.20%, IQR 0.15–0.40%) was compared to that in the no-stimulation condition (median 0.30%, IQR 0.10–0.40%), and no significant difference was observed (Holm-adjusted p = 0.910, r = 0.242). Under the 0.8 times condition, the minimum concentration in the stimulation condition (median 0.30%, IQR 0.10–0.50%) was compared to that in the no-stimulation condition (median 0.30%, IQR 0.10–0.40%), and no significant difference was observed (Holm-adjusted p = 0.910, r = 0.178). The numbers of participants for whom the threshold concentration decreased, remained unchanged, or increased at each stimulus intensity were seven, four, and four, respectively, under the 0.4 times condition; seven, four, and four under the 0.6 times condition; and six, six, and three under the 0.8 times condition.

The Friedman test was used to compare the normalized minimum concentrations at each stimulus intensity and no significant differences were found (p = 0.634, W = 0.030).

In an exploratory analysis of the optimal intensity for each study participant, the minimum concentration in the stimulation condition (median 0.10%, IQR 0.00–0.19%) was lower than that in no-stimulation condition (median 0.4%, IQR 0.25–0.50%).

Discussion

This study investigated the effects of white noise subthreshold electrical stimulation on taste perception. Psychophysical experiments were conducted on salty and sweet tastes. The results showed that for saltiness, the minimum concentration in the stimulation condition was significantly lower than that in the no-stimulation condition under the 0.8 times stimulation intensity, and significant differences were observed in the normalized minimum concentrations among the 0.4, 0.6, and 0.8 times stimulation intensities. In contrast, no significant differences were observed for sweetness at any stimulation intensity. In the exploratory optimal intensity test, the minimum concentrations of saltiness and sweetness under the stimulation condition were lower than those under the no-stimulation condition.

These results support the possibility that subthreshold electrical stimulation can modulate taste perception, with enhanced sensitivity observed for saltiness under the 0.8 times condition.

In the salty taste experiment, it was found that applying subthreshold electrical stimulation under the 0.8 times condition significantly reduced the minimum concentration. Under the stimulated condition, the minimum concentration decreased in nine out of the 17 participants under the 0.8 times condition, while the remaining eight participants showed no change. Furthermore, the normalized minimum concentration at each stimulation intensity was lower under the 0.8 times condition than under the 0.4 and 0.6 times conditions. Based on these findings, it is possible that subthreshold electrical stimulation under the 0.8 times condition enhances the perception of saltiness within the range of stimulation intensities examined. Furthermore, the variation in the stimulation effect across intensities is consistent with the intensity-dependent characteristics reported for SR [14, 18]. Additionally, the minimum concentration was lower when the optimal intensity, that is, the intensity deemed appropriate by each participant, was used. As this finding was based on an exploratory analysis, it should be interpreted with caution and requires further validation. Nevertheless, this exploratory finding is consistent with the possibility of an optimal stimulation intensity, as expected from SR.

In the sweet taste experiments, no significant differences were observed in the minimum concentration between the stimulation and no-stimulation conditions under any of the intensity conditions, and no significant differences were observed in the normalized minimum concentration among the different stimulus intensities. Furthermore, a wide IQR and high variability were observed in each condition. Regarding these results, given the wide interindividual variability in sweet taste perception threshold[15], it is possible that the results were largely influenced by the characteristics of the participants in this study. In contrast, for the optimal intensity identified for each participant, the minimum concentration in the stimulation condition was lower than that in the no-stimulation condition. However, as this finding was obtained from an exploratory analysis, it should be interpreted with caution and requires further validation. Nevertheless, this exploratory finding should be regarded as hypothesis-generating, raising the possibility that an optimal intensity may also exist for sweetness. These findings raise the possibility that optimizing the stimulation intensity according to the taste function is important.

The major contribution of this method, which applies subthreshold electrical stimulation based on the concept of SR to taste perception, is its potential to modulate taste perception without causing pain or discomfort to participants through the application of weak electrical currents to the skin surface. This is because, when attempting to modulate taste perception through subthreshold electrical stimulation of the nervous system related to taste, the detection of taste substances that elicit taste depends on an individual's taste receptors. As there are significant individual differences in the number, distribution, and responsiveness of taste receptors to taste substances[19, 20], adjusting the optimal intensity is essential. However, it is conceivable that once information transmission occurs along neural pathways, it can be modulated.

Existing methods for enhancing taste involve placing electrodes inside the mouth to electrically stimulate taste receptors[21] or delivering electrical stimulation to the mouth via tableware[22, 23]. However, these methods have two major limitations. First, there is a burden on the user, such as the risk of electric taste, numbness, or pain caused by the flow of electricity in the mouth. Second, the range of taste substances that can be enhanced is limited. Although the presentation and enhancement of tastes involving electrolyte taste substances has been widely reported, it is difficult to present or enhance the taste of non-electrolyte substances using electrical stimulation alone[24, 25]. Although the significant effect observed in this study was limited to saltiness, the exploratory findings for sweetness were hypothesis-generating. Future studies are needed to determine whether our approach is effective for other tastes. Nevertheless, subthreshold electrical stimulation based on the concept of SR could provide a novel approach to modulating taste perception while potentially addressing some of the limitations of existing approaches.

In the present study, the stimulation electrodes were placed near the marginal mandibular branch of the facial nerve. Although this branch is primarily motor and is not directly involved in the transmission of taste information, changes in taste perception were observed with the present electrode configuration. However, the present study does not establish which neural structures or pathways were responsible for the observed effect. Further studies characterizing the neural structures affected by the stimulation and their responses will be necessary to elucidate the mechanisms underlying the observed effects.

Limitations

This study had several limitations. First, because the sample size was small and consisted primarily of young, healthy males, the findings cannot be generalized to females, older adults, or patients with impaired taste function. Furthermore, the optimal intensity for each participant was identified exploratively from the same dataset, and its reproducibility using independent data was not confirmed. Additionally, the study did not identify the stimulated neural pathways or neurophysiological mechanisms underlying changes in taste perception.

Conclusion

This study suggests that subthreshold electrical stimulation based on the concept of SR has the potential to modulate taste perception. These findings provide new insights into the use of SR-inspired approaches for modulating human taste perception. By further examining its effects on different taste qualities and elucidating the underlying mechanisms, novel methods for modulating taste perception may be established.

Declarations

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Data availability

The dataset for this study is available from the authors upon reasonable request.

Additional information

Competing interests statement

The authors declare no competing interests.

Author Contribution

Conceptualization: Y.S., K.T., Y.F., M.M., S.O. and N.S.; Data curation, Formal analysis and Investigation: Y.S., K.T. and Y.F.; Methodology: Y.S., K.T., Y.F., M.M., S.O. and N.S.; Funding acquisition: S.O. and N.S.; Project administration: Y.S., S.O. and N.S.; Resources: Y.S., H.F., S.O. and N.S.; Software: Y.S. and H.F.; Supervision: Y.S., S.O. and N.S.; Visualization: Y.S.; Writing—original draft: Y.S.; Writing—review and editing: Y.S., M.M., S.O. and N.S. All authors reviewed and approved the final manuscript.

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Data Availability

The dataset for this study is available from the authors upon reasonable request.

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Figures

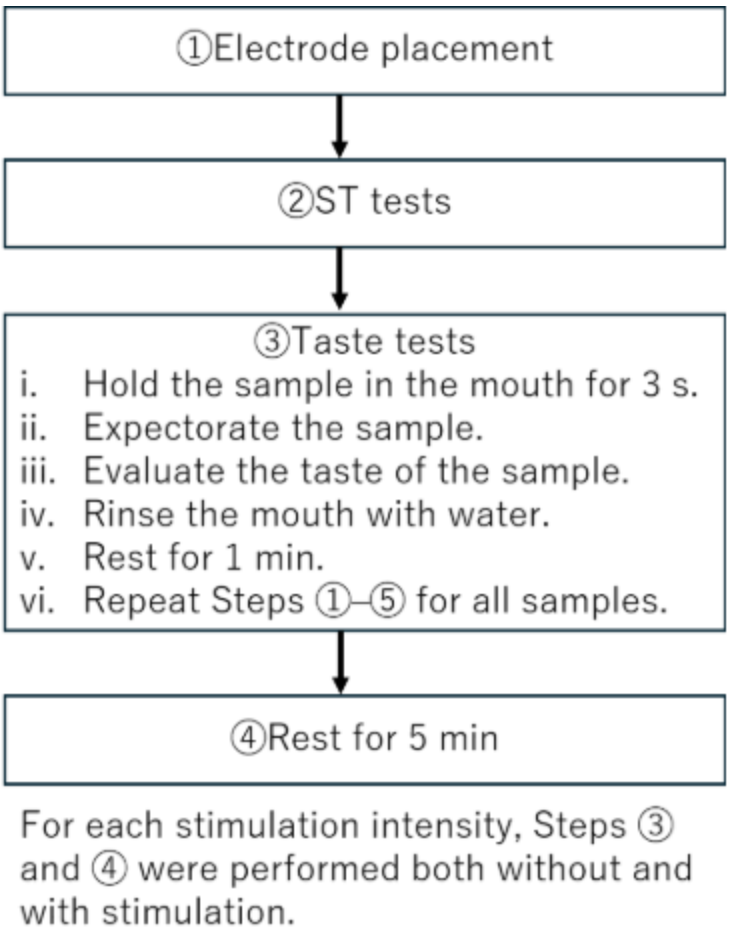


Figure 1

Flow chart of the experimental procedure.

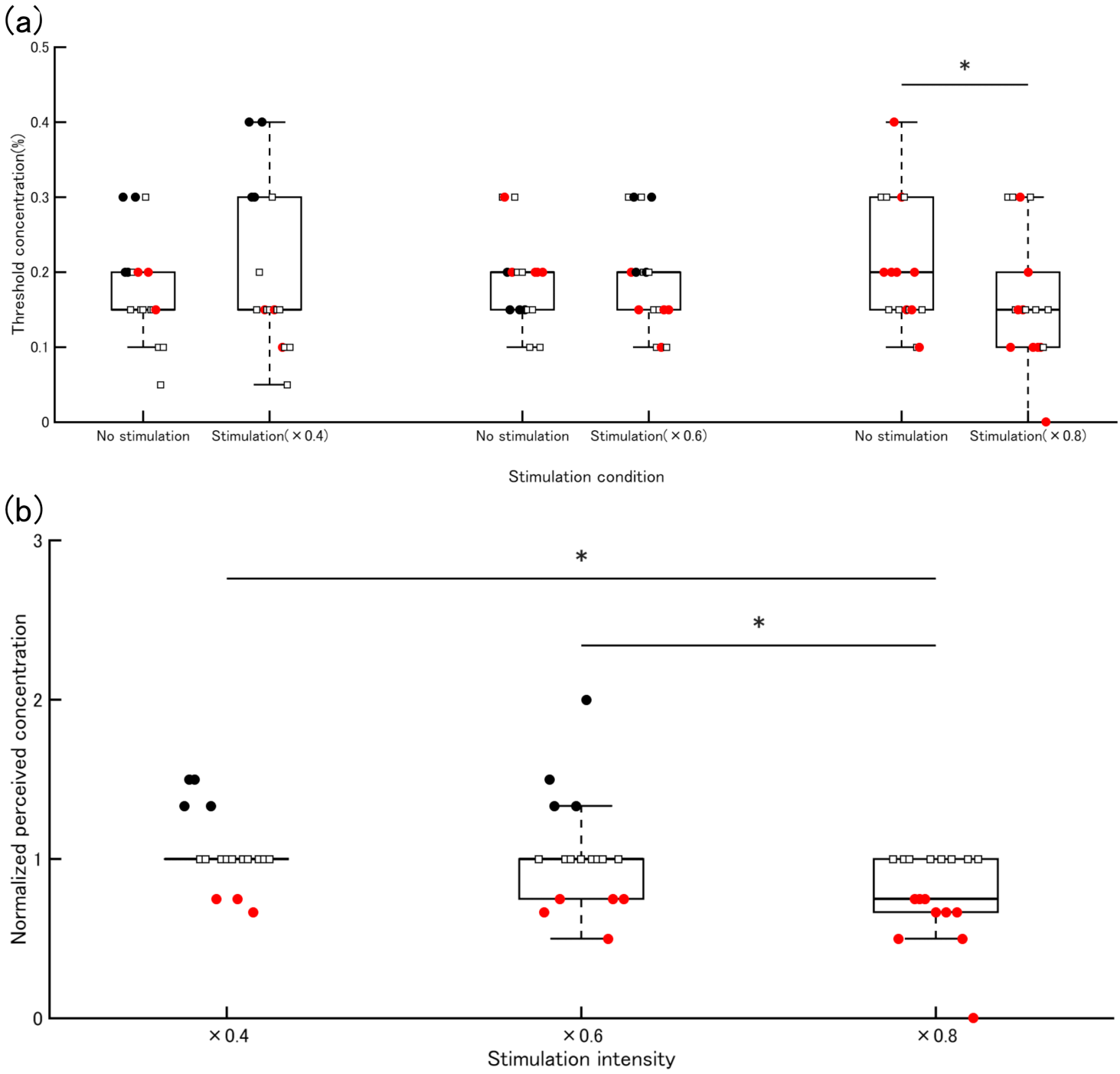


Figure 2

Effects of subthreshold electrical stimulation on saltiness. (a) Minimum concentration at each stimulation intensity. (b) Normalized minimum concentration as a function of the stimulation intensity. The red, black, and white markers represent participants for whom the minimum concentration decreased, remained unchanged, or increased, respectively, in response to subthreshold electrical stimulation. The horizontal lines, bottoms of the boxes, tops of the boxes, and bottom whiskers, and top whiskers represent the median, 25th percentile, 75th percentile, minimum, and maximum, respectively. Asterisks indicate statistical significance (Holm adjusted $p < 0.05$).

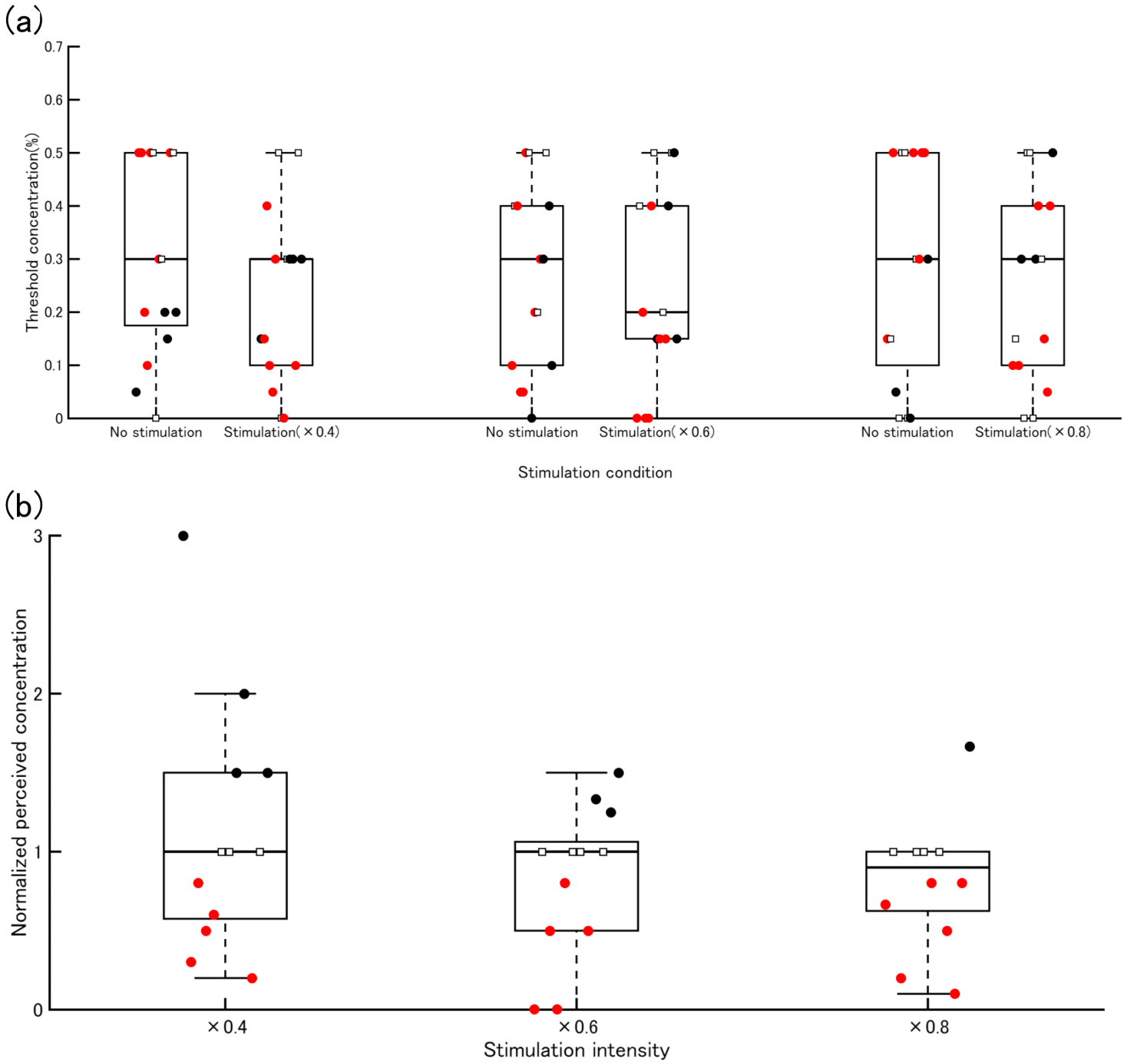


Figure 3

Effects of subthreshold electrical stimulation on sweetness. (a) Minimum concentration at each stimulation intensity. (b) Normalized minimum concentration as a function of the stimulation intensity. The red, white, and black markers represent participants for whom the minimum concentration decreased, remained unchanged, or increased, respectively, in response to subthreshold electrical stimulation. The horizontal lines, bottoms of the boxes, tops of the boxes, bottom whiskers, and top whiskers represent the median, 25th percentile, 75th percentile, minimum, and maximum, respectively.