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RESEARCH ARTICLE

Anodal Electrical Stimulation Enhances the Perceived Piquancy Induced by Chili Peppers and Wasabi

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ABSTRACT Methods for enhancing perceived piquancy are expected to improve eating satisfaction and reduce health hazards such as reflux esophagitis caused by the excessive consumption of piquant ingredients. In this study, based on the differences in receptors, we classified the perceived piquancy into three types: HOT, MINTY, and SPICY. We particularly focused on the HOT sensation, which primarily contributes to the negative health effect of eating piquant foods. We proposed a novel method to enhance the intensity of piquancy by single-pole electrical stimulation. Our proposed method uses metal cutlery as an electrode to stimulate the part of the trigeminal nerve of the tongue related to piquancy. To evaluate whether the proposed method selectively enhances the HOT sensation, we conducted psychophysical experiments and demonstrated that 1.5 mA anodal single-pole electrical stimulation enhanced the HOT sensation and the SPICY sensation induced by chili peppers or wasabi. To our knowledge, this is the first study to establish a method for enhancing the perceived piquancy using only electrical stimulation.

INDEX TERMS Electric taste, galvanic taste stimulation, piquancy, spicy, taste display, the trigeminal nerve.

I. INTRODUCTION

Eating and drinking are essential life-sustaining activities that induce a feeling of satisfaction. The sense of taste is a principal component of food. Therefore, a substantial number of human-computer interaction (HCI) studies have focused on presenting, inducing, and modifying the basic tastes (sweet, sour, salty, bitter, and umami) [1], [2], [3], [4].

Although it is not one of the basic tastes, the sensation of piquancy can be an important aspect of the eating experience. The consumption of spicy food is rapidly increasing worldwide, and one in four people eat spicy foods daily worldwide [5], [6]. Consuming piquant food and drink has been reported to reduce fat and salt intake [7], [8]. These effects have the potential to reduce the incidence of obesity and hypertension. However, it has been revealed that excessive intake of spicy substances could have negative impacts on health by causing reflux esophagitis [9]. Thus, there is a trade-off between the positive and negative impacts of piquant foods on human health. In addition, some studies state that the high consumption of piquant foods and drinks is associated with the release of endorphins [10], [11], [12]. To solve this trade-off problem, we propose a novel method that makes people perceive strong piquancy even if the food contains only a few piquant substances. Using this method, people would perceive sufficient piquancy while eating and

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drinking, reducing the consumption of piquant food and drink.

A. RELATED WORKS

Systems for inducing and displaying the perception of piquancy have been studied in the HCI field. Yoshida and Ogawa [13] proposed a method for virtually simulating the perception of piquancy (like hotness) by applying a thermal grill illusion to the tongue. The thermal grill illusion is a perceptual phenomenon in which a thermal pain sensation is induced by touching a surface composed of alternating cold and warm bars. This method is applicable because piquancy and thermal pain are both perceived by the same receptors. Ranasinghe et al. [14], [15] proposed a piquancy-generation system with electrical, temperature, and olfactory stimulation. This system sandwiches the tongue between two silver electrodes and applies electrical and thermal stimulation to the tongue. Based on their experiment, they showed that, excluding umami, the system generated the basic tastes, spicy and minty sensations. Considering the health benefits of reducing the consumption of piquant substances, the interface for enhancing the perceived piquancy of food and drink during consumption gives people both health benefits and helps them regulate the intake of piquant substances. Although recent studies have focused on methods for inducing and displaying the perceived piquancy, no methods have yet been proposed for enhancing it while consuming food and drink. Moreover, existing methods require extensive coverage of the tongue surface with electrodes and heat sinks, which makes them impractical for everyday eating situations.

Our novel approach to overcoming these limitations is two-fold 1) stimulating the trigeminal nerve endings, and 2) applying single-pole electrical stimulation to the tongue. Regarding the first idea, it is known that chemical substances induce the trigeminal nerve's piquancy response [16]. It is also known that the receptors for piquant sensation are expressed on the tongue's trigeminal nerve endings [17], [18]. Several studies have revealed that electrical stimulation induces trigeminal activation and produces trigeminal sensations [19], [20], [21], [22]. Therefore, it is expected that electrical stimulation to the tongue could stimulate the nerves and receptors associated with the perception of piquancy.

The second idea is based on the existing study that revealed that single-pole electrical stimulation can enhance saltiness, sourness, and the metallic taste in food and drink by temporarily attaching an electrode to the tongue surface [23], [24]. In this study, we further expect that the single-pole electrical stimulation to the tongue can stimulate the nerves and receptors associated with the perception of piquancy. By using metal cutlery (e.g., a fork or a spoon) as an electrode, the tongue's trigeminal nerve can be stimulated without wide coverage.

B. THREE TYPES OF THE PERCEPTION OF PIQUANCY

Sensations of piquancy differ, such as the piquancy of chili peppers, wasabi, and mint. To verify the enhancement effect on the perception of piquancy, we first defined the perception of piquancy. Piquant substances are sensed by thermosensitive receptors in the trigeminal nerve endings, processed in the cortex and perceived as piquancy [26]. These thermosensitive receptors are called Transient Receptor Potential (TRP) channels. Three TRP channels, TRPV1, TRPM8, and TRPA1, are receptive to temperature stimuli and piquant substances [27], [28], [29], [30], [31], [32]. Each of these three receptors has a different ligand and triggers a different perception of piquancy. For example, TRPV1 is activated by capsaicin from chili peppers and induces pain and a burning sensation. TRPM8 is activated by menthol in mint leaves and induces a cool and minty sensation. TRPA1 is activated by isothiocyanates from wasabi and other mustard plants and induces a painful and spicy sensation. Based on these findings, we classified the perception of piquancy into three categories of sensations: HOT (TRPV1), MINTY (TRPM8), and SPICY (TRPA1).

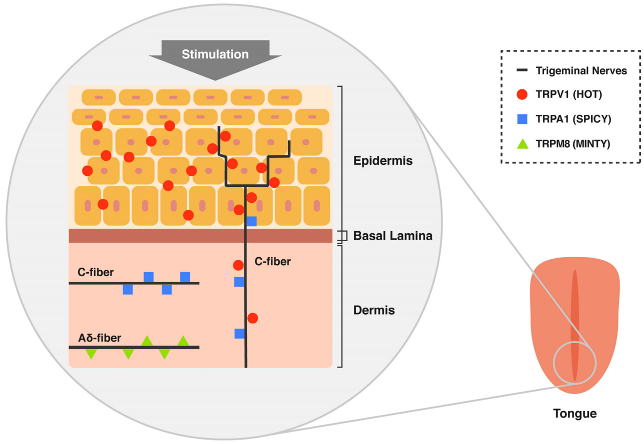

FIGURE 1. Cross section of the human oropharynx and the distribution of TRPV1, TRPA1, and TRPM8 (adapted from Alvarez-Berdugo et al. [18]). The endings of the C-fibers express TRPV1 on the epidermis. In comparison, TRPA1 and TRPM8 are expressed in nerve fibers below the basal lamina. It has been shown that TRPA1 is expressed on C-fibers and TRPM8 is expressed on both C-fibers and Aδ-fibers. In addition, TRPA1 and TRPM8 are not co-expressed in nerves [25].

TRP channels corresponding to the three piquancy sensations are expressed in different types of nerves on the tongue and drive the neural activity in different areas of the brain to induce each piquancy sensation(Fig. 1). TRPV1, which induces the HOT sensation, is activated by the TRPV1 agonist substance, and the activation signal is primarily transmitted by C-fiber in the trigeminal nerves. The activation signal of TRPV1 causes excitation in the gustatory insula and the autonomic insula [33], [34]. In the case of TRPM8, which induces the MINTY sensation, the TRPM8 agonist activates TRPM8, and the activation signal is transmitted by both C-fiber and Aδ-fiber in the trigeminal nerves [25]. Eventually, the activation of TRPM8 broadly drives the neural activity of the mouse brain, particularly in the posterior insula, primary somatosensory cortex, and secondary somatosensory cortex [35]. TRPA1, which induces the SPICY sensation, is activated by the agonist, and C-fiber in the trigeminal nerves transmits the activation signal [25]. Previous studies have suggested that the activation of TRPA1 produces neural activity like the activation of TRPV1 and TRPM8 [36], [37]. However, most of these previous studies were conducted in mice, and the relationship between each piquancy substance and the brain activity of humans is often unknown.

This study focused on enhancing the effect of the HOT sensation caused by piquant substances such as capsaicin, which primarily contributes to the negative health effects of eating piquant foods. In this study, we developed a prototype of a single-pole electrical stimulation system that can be controlled the current waveforms. This system stimulated the trigeminal nerve on the tongue and enhanced the perceived piquancy. To evaluate the enhancement effect of the perceived HOT piquancy by our proposed method, we conducted experiments focusing on the three types of piquancy that are received in different TRP channels; HOT, MINTY, and SPICY sensations.

II. METHOD

We conducted three psychophysical experiments to examine whether anodal single-pole electrical stimulation applied to the trigeminal nerve system on the tongue enhances a sensation of HOT, MINTY, or SPICY, respectively. We focused on enhancing the HOT sensation and examined whether only the HOT sensation could be selectively enhanced by anodal single-pole electrical stimulation.

A. STIMULATION DESIGN

Kajimoto et al. proposed a model of electrical stimulation that selectively stimulates the mechanoreceptors and nerves extending to different depths and the diameters of nerve fibers by varying the polarity of the electrical stimulation and by controlling the waveforms [38]. Although this model targets receptors and nerves on the fingertips, it can be applied to our method for perceived piquancy enhancement because the receptors and nerves related to piquancy sensations are present on the tongue. Three TRP channels related to piquancy sensations are distributed throughout the skin of the human tongue, as shown in Fig. 1.

The endings of the nerve fibers that express TRPV1, which induces hot sensations, reach the epidermis and extend perpendicularly to the skin surface. Conversely, TRPA1 and TRPM8 are expressed in nerve fibers below the basal lamina and can be assumed to extend parallel to the skin surface. Applying this distribution of TRP channels in the tongue to the model of Kajimoto et al. [38], each perception of piquancy can be enhanced by changing the conditions of electrical stimulation. In particular, TRPV1 and its nerve fibers can be stimulated by anodal single-pole electrical stimulation, which can therefore enhance the HOT piquancy sensation. In these experiments, we evaluated the intensity of the perceived piquancy when the participants received anodal single-pole electrical stimulation on the tongue.

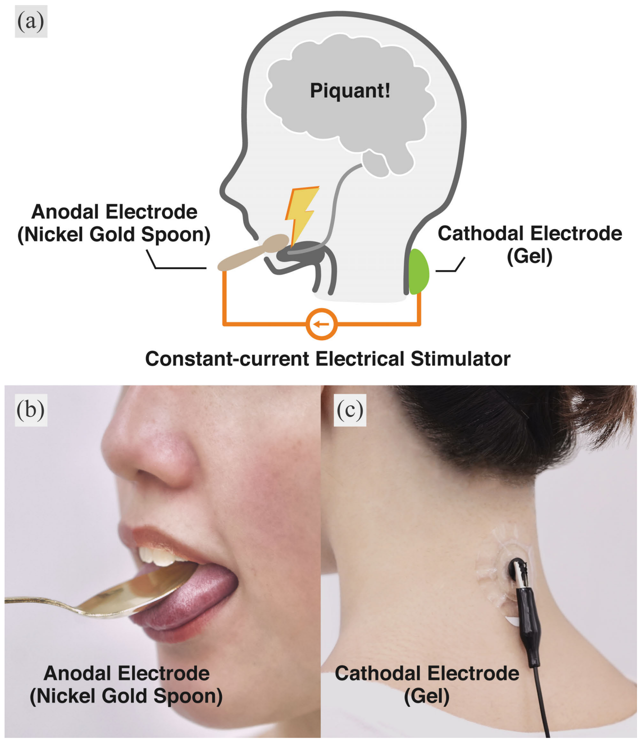

FIGURE 2. (a) Electrode configuration for single-pole electrical stimulation in this study. Both electrodes were connected to a custom-made constant-current electrical stimulator. We attached one electrode on the back of the neck and another on the tongue and stimulated the trigeminal nervous system of the tongue. (b) In our method, metal cutlery was used as the anodal electrode and placed on the tongue. (c) A gel electrode was used as the cathode electrode and attached to the back of the neck.

B. EXPERIMENTAL PARADIGM

Twenty healthy adults (thirteen males and seven females, 23.76 years old on average) participated in the first experiment, twenty (ten males and ten females, 24.75 years old on average) in the second, and twenty-one (fifteen males and six females, 24.84 years old on average) in the third. This study was performed in accordance with the ethical standards of the Declaration of Helsinki and with safety standards approved by the local ethics research committee at the University of Tokyo, Japan. The experiment was explained to the participants prior to their participation, and they signed letters of consent. All experiments were conducted in a quiet room. The participant's skin was cleaned, and electrodes were attached to the tongue and back of the neck (Fig. 2). The spoon on the tongue, used as the anode electrode, was made of nickel gold (Noritake, 12Y/71G). After the electrodes were attached, participants were instructed to sit on a chair.

All experiments consisted of two phases: Memorization and Evaluation (Fig. 3). Each experiment focused on a different type of piquancy perception (e.g., HOT, SPICY, or MINTY), using a different piquant substance in each case.

In the Memorization phase, all participants held approximately 25 mL of water including one of the piquant substances in their mouths and memorized the nature of the sensations they perceived (Fig. 3–(A)).

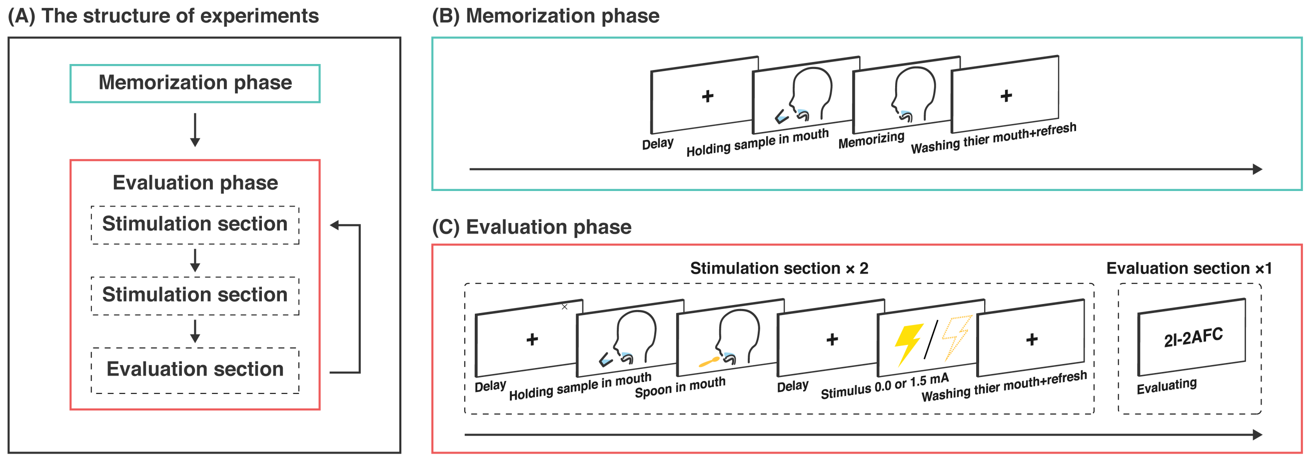

FIGURE 3. **Experimental paradigm for all experiments: (A) Memorization phase and (B) Evaluation phase. In the Memorization phase, participants memorized the nature of the sensation they perceived as piquancy. In the Evaluation phase, participants evaluated the intensity of the perceived piquancy, which is memorized in the Memorization phase, by the 2I-2AFC task.**

In the Evaluation phase, a single trial consisted of two intervals of a stimulation section and one evaluation section (Fig. 3–(B)). Each participant applied the electrical stimulation to the tongue while holding a sample containing a piquant substance in the mouth and evaluated the intensity of the perceived piquancy. Considering the safety aspect, less than 4.0 mA stimulation intensity should be used for electrical stimulation [39]. Iannilli et al.'s study [19] used the current intensity from 0.6 mA to 1.8 mA to stimulate the trigeminal nerve. From these findings, we chose two currents, 0.0 mA as the control condition and 1.5 mA as the stimulating condition, in a square wave with a duration of 10 s. At first, the participants held 20 mL of the sample including a piquant substance in their mouths. Either the 0.0 or 1.5 mA electrical stimulus was presented randomly in the first or the second intervals. After each interval in the two-interval, two-alternative forced-choice (2I-2AFC) task, the participant indicated which interval gave them a stronger perceived piquancy compared to that in the memorizing phase. Two intervals of stimulation section and one evaluation section were used as one trial, and a total of 10 trials were conducted per participant.

C. HOT SENSATION EXPERIMENT

This experiment aimed to demonstrate the enhancement of the HOT sensation by anodal single-pole electrical stimulation. We hypothesized that anodal electrical stimulation of the tongue would stimulate the nerve fibers related to the HOT sensation, causing an enhancement of the sensation similar to that experienced when eating chili peppers. In this experiment, we used capsaicin as the HOT substance because capsaicin is a specific ligand of TRPV1, which evokes the HOT sensation [27]. Because capsaicin is fat-soluble, capsaicin-extract oil was emulsified with soy lecithin and water to a 0.1 wt% capsaicin-water concentration.

D. MINTY SENSATION EXPERIMENT

This experiment aimed to demonstrate no enhancement of the MINTY sensation by anodal single-pole electrical stimulation. Because the nerve fibers that express TRPM8 extend parallel to the skin surface, it is assumed that those related to the MINTY sensation are not stimulated by anodal electrical stimulation to the tongue. In this experiment, we used menthol as the MINTY piquant substance because menthol is a specific ligand of TRPM8, which evokes the MINTY sensation [29], [30]. Because of menthol being fat-soluble, a 0.3 wt% menthol-water concentration was prepared by emulsifying peppermint oil and water with soy lecithin. The reason for this low menthol concentration is that Macpherson et al. [40] reported TRPA1 (mTRPA1) activity at high menthol concentrations.

E. SPICY SENSATION EXPERIMENT

The experiment aimed to demonstrate that there was no enhancement of the SPICY sensation by anodal single-pole electrical stimulation. The nerve fibers that express TRPA1 extend parallel to the skin surface, so it is assumed that the nerve fibers related to the SPICY sensation are not stimulated by anodal electrical stimulation. However, Kobayashi et al. [25] reported that TRPA1 is co-expressed with TRPV1. Therefore, if the anodal electrical stimulation can stimulate the TRPV1 receptors, it may stimulate the co-expression of TRPV1 and TRPA1 and enhance the SPICY sensation. In this experiment, we used allyl isothiocyanate (AITC) from wasabi as the SPICY substance because TRPA1 which evokes the SPICY sensation is activated by AITC [41]. The sample used in this experiment contained 2.0 wt% wasabi (S&B Foods, Wasabi powder).

III. RESULTS

For static analysis, we set the score of the 2I-2AFC evaluation phases to be the number of times the condition with 1.5 mA

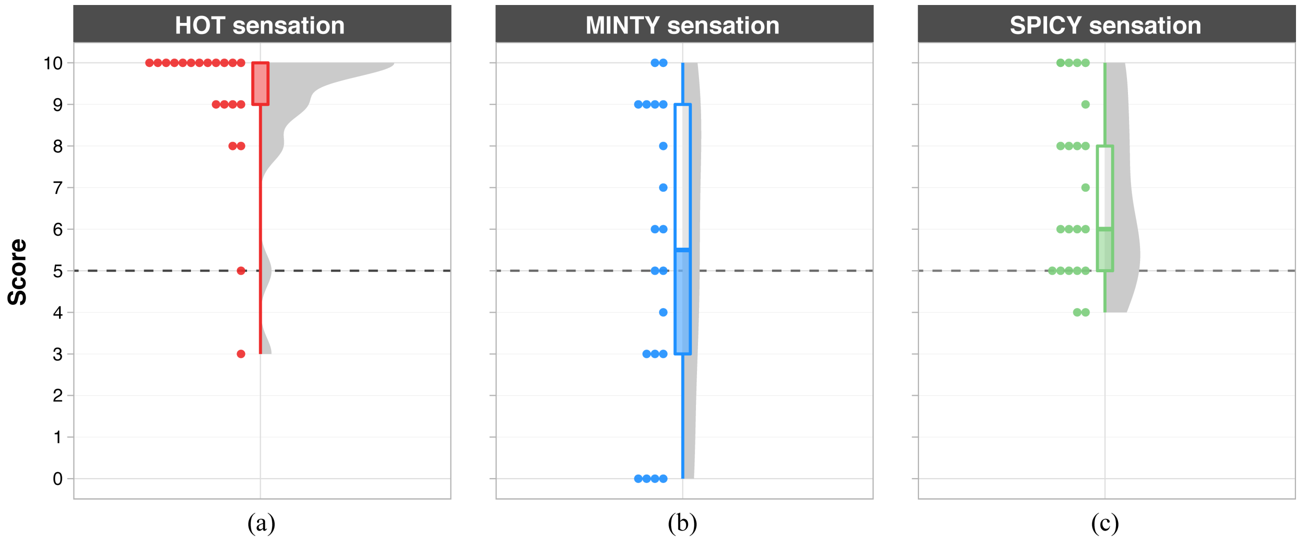

FIGURE 4. Score distributions for each experiment: (a) HOT sensation experiment, (b) MINTY sensation experiment, and (c) SPICY sensation experiment. The raincloud plot (right) depicts the distribution of score, which was the number of times the condition with 1.5 mA electrical stimulation was selected as the stronger piquancy, per participant (left, single dots). The dashed lines indicate the chance level (i.e., five), which the users select randomly. The overlaid boxplot diagram illustrates the upper and lower scores (box) and median (line within the box).

electrical stimulation was selected as affording the stronger piquancy sensation. For example, a score of five indicates that the 1.5 mA condition was chosen as the more intense piquancy sensation in five of ten trials. The distribution of the score values of each experiment was checked using histograms and the Shapiro-Wilk test, and the non-parametric Wilcoxon's signed-rank test was used to test the difference between the median of the score data and the chance level (5 points).

A. HOT SENSATION EXPERIMENT

Figure. 4–(a) shows the distribution of the scores of the HOT sensation experiment. The results reveal a significant difference between the median of the score data and the chance level ($V = 189$, $p < 0.05$).

B. MINTY SENSATION EXPERIMENT

Figure. 4–(b) shows the distribution of the scores of the MINTY sensation experiment. The results reveal no significant difference between the median of the score data and the chance level ($V = 90.5$, $p > 0.05$).

C. SPICY SENSATION EXPERIMENT

Figure. 4–(c) shows the distribution of the scores of the SPICY sensation experiment. The results reveal a significant difference between the median of the score data and the chance level ($V = 129$, $p < 0.05$).

IV. DISCUSSION

The results showed that there was a significant difference between the 1.5 mA stimulation and no-stimulation conditions in both the HOT and SPICY sensations experiments. This suggests that 1.5 mA anodal electrical stimulation enhances the perceived strength of the HOT and SPICY sensations. According to the model of electrical stimulation on the skin [38], the anodal direct current stimulates nerves that extend vertically to the skin surface such as the TRPV1-expressing nerves. However, in this study, the anodal single-pole electrical stimulation enhances both the HOT sensation evoked by TRPV1 and the SPICY sensation evoked by TRPA1. There are three possible reasons for this finding.

1) The first possible cause is an interaction between the TRPA1 and TRPV1 receptors. Lee et al. [42] showed that the peak fiber activity evoked by injecting allyl isothiocyanate (a selective agonist of TRPA1) and capsaicin (a selective agonist of TRPV1) in combination was approximately 400% greater than the mathematical sum of the responses to allyl isothiocyanate and capsaicin when they were administered individually, thus revealing the synergy between TRPA1 and TRPV1. When the TRPV1 receptors in the tongue undergo anodal electrical stimulation, despite the TRPA receptors not being stimulated directly, synergy could occur and enhance the SPICY sensation.
2) The second possible cause is that the anodal electrical stimulation stimulates C-fibers which co-express both TRPV1 and TRPA1. Kobayashi et al. [25] reported that TRPA1 is co-expressed with TRPV1 in C-fibers, which are related to sensations of pain. If anodal electrical stimulation can stimulate the TRPV1 nerve fibers and enhance the HOT sensation, it may stimulate the co-expression of TRPV1 and TRPA1 by the nerve fibers and enhance the SPICY sensation.
3) The third possible cause is that the anodal electrical stimulation stimulates parts of the trigeminal nerve that include receptors for all three of TRPV1, TRPA1,

and TRPM8. If so all piquancy sensations would be affected, but only the HOT and SPICY sensations, which are perceived by the same receptors as pain, are enhanced, and the MINTY sensation may be masked by the enhanced HOT and SPICY sensations. In addition, the density of cold spots where TRPM8 is concentrated in the oral mucosa is less than that of pain spots where TRPV1 and TRPA1 are concentrated [43]. Thus, we have concluded that the enhanced MINTY sensation might have been masked by the HOT and SPICY sensation when the big, single, and large electrode was placed on the tongue.

The results of our experiments indicate that our method may stimulate the trigeminal nerve in the tongue related to the perception of piquancy, but the underlying mechanism of enhancing the perceived piquancy by electrical stimulation and the impact of endorphins on food satisfaction are still unclear. In our future work, we will reveal the underlying mechanism by evaluating the perceived sensation felt when a specific TRP channel is knocked out and anodal electrical stimulation is applied for simulating the current density distribution in the tongue. In addition, we plan to evaluate the health implications of our methods such as their effect on eating satisfaction, reducing the intake of fat and salt, and metabolism.

In this study, we demonstrated that our anodal single-pole electrical stimulation method could enhance the HOT sensation induced by chili peppers and the SPICY sensation induced by wasabi. However, the proposed method has several limitations.

First, our proposed method was not shown to be capable of enhancing the MINTY sensation. As a reason for this, we assumed that anodal electrical stimulation was unable to stimulate the Aδ-fibers which extend parallel to the skin surface. Saito et al. [44] found that the cold sensation was generated by cathodal electrical stimulation on the forehead and that there were individual differences in the point at which the cold sensation was generated. As both cold and MINTY sensations are related to Aδ-fibers and TRPM8, the cathodal electrical stimulation may be able to enhance the MINTY sensation at the location of the cold point for each participant.

Second, our proposed method is difficult to use while chewing food, because it requires an electrode to be placed on the surface of the tongue. Using metal cutlery as an electrode has the advantage of being easily applied to everyday eating and drinking experiences; however, the effect of enhancing the intensity of piquancy occurs only while an electrode is in contact with the tongue. Aoyama et al. [45] proposed a method for controlling the oral current density from the electrodes attached to the chin and modifying taste perception. Our study indicated that perceived piquancy can be enhanced by controlling the distribution of current density in the oral cavity and stimulating the trigeminal nerves of the tongue. In our experiments, we attached the electrode to the anterior of the tongue and did not detect the subject's specific anatomical location of the trigeminal nerves. Therefore, if an electrode placed on the chin could change the current intensity in the mouth, it would be possible to stimulate the nervous system related to the perception of the piquancy of the tongue and enhance the sensation of piquancy without disturbing natural eating and drinking behaviors. Conversely, as the chin and tongue are physically distant, there are technical challenges in ensuring the current density distribution to sufficiently stimulate the human tongue from the chin.

V. CONCLUSION

The three main contributions of our study are:

1) We proposed a novel method for enhancing the perceived piquancy and developed a single-pole electrical stimulation system that can stimulate the trigeminal nerve of the tongue.
2) We classified the perceived piquancy into three types of sensations that are received by different receptors: HOT, SPICY, and MINTY.
3) We demonstrated that 1.5 mA anodal electrical stimulation enhances the piquancy of the HOT sensation induced by chili peppers and the SPICY sensation induced by wasabi.

Collectively, this is the first report establishing a method for enhancing the perceived piquancy using electrical stimulation. Our proposed method can enhance the perceived piquancy of food and drink by using metal cutlery as an electrode. However, it remains limited in that our proposed method does not enhance the MINTY sensation felt on the tongue. Our future work will include finding a method of enhancing the MINTY sensation and stimulating the nerves of the tongue from outside the mouth. In addition, to establish an interface that enhances all of the piquancy sensations to improve eating satisfaction, we will measure the intensity of the perceived piquancy for each current intensity by using the brain activity measurement method like functional near-infrared spectroscopy.In the future, we will construct an enhanced interface of piquancy perception using our method, which would enable people to perceive strong piquancy even if the food contains only a few piquant substances, thereby reducing the health hazards caused by the excessive consumption of piquant foods.

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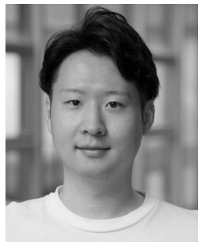

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