IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 9, 2021, accepted March 3, 2021, date of publication March 23, 2021, date of current version April 1, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3068263

Method of Modifying Spatial Taste Location Through Multielectrode Galvanic Taste Stimulation

HIROMI NAKAMURA[1], **MAKOTO MIZUKAMI**[2], **AND KAZUMA AOYAMA**[3,4]
[1]Interfaculty Initiative in Information Studies, The University of Tokyo, Bunkyo 113-0033, Japan
[2]Independent Researcher, Tokyo 180-0013, Japan
[3]Graduate School of Information Science and Technology, The University of Tokyo, Bunkyo 113-8656, Japan
[4]Virtual Reality Educational Research Center, The University of Tokyo, Bunkyo 113-8656, Japan

Corresponding author: Hiromi Nakamura (hiromi.nakamura@iii.u-tokyo.ac.jp)

This work was supported in part by the Japan Science and Technology Agency (JST) Promotion Individual Research to Nurture the Seeds of Future Innovation and Organizing Unique, Innovative Network (PRESTO) under Grant JPMJPR19J1, in part by the Japan Society for the Promotion of Science (JSPS) KAKENHI under Grant 20K19842, and in part by the Canon Foundation.

ABSTRACT Galvanic taste stimulation (GTS) is a technique of electrical stimulation that induces, inhibits, and enhances human taste sensations. This work focuses on a GTS method that induces taste sensation using electrodes attached to the chin and to the back of the neck. The authors aim to establish an advanced GTS method that induces taste sensations at specific locations inside the buccal cavity, without attaching electrodes inside the mouth. Conventionally, the location in the buccal cavity where the taste sensation has been perceived was uncontrollable, and it has been used to induce taste sensations for the whole buccal cavity or the throat. We hypothesized that the position of the taste induction can be affected by the electrical potential distribution inside the mouth. Then, we conducted simulations and experiments to verify the hypothesis with regard to control over spatial selectivity. Specifically, we developed a novel GTS configuration using electrodes attached around the head. We verified that the developed multielectrode GTS configuration can manipulate the electrical potential distribution in the tongue, and that it can manipulate the position where the sensation of taste is induced. To the best of our understanding, this is the first report that realized induction of spatially selective taste sensations at a specific position in the buccal cavity.

INDEX TERMS Buccal cavity, electrical taste, galvanic taste stimulation, human–computer interaction, taste display.

I. INTRODUCTION

Eating and drinking are fundamental human activities that provide vital nutrients and feelings of satisfaction. One of the most important elements of the eating experience is taste. Although multiple elements (e.g., appearance, texture, flavor, local weather, and accompaniment) affect the eating experience, humans continue to rely on taste for food selection and consumption. Humans have, therefore, developed many types of seasonings and flavorings unique to their regions and cultures.

There have been many human–computer interaction (HCI) studies focusing on human taste sensations, and galvanic taste stimulation (GTS) is one of the techniques explored by such studies. GTS is a technique that displays and manipulates tastes using electrical stimulation, and it acts as a virtual seasoning agent [1]–[4]. It generates complex taste sensations, i.e., the sensations known as electric or metallic tastes, arguably by stimulating gustatory sensory nerves. This phenomenon was discovered by Sulzer *et al.* in the 18th century and was applied in medical settings as a tool to help diagnose gustatory diseases [5], [6]. GTS has two variations: anodal, which attaches the anode in or around the buccal cavity with the cathode at an arbitrary location, and cathodal, which attaches only the cathode in or around the buccal cavity. The anodal GTS is known to yield electric tastes, whereas the cathodal GTS inhibits the taste of electrolytic solutions [7], [8].

Recently, Nakamura and Miyashita proposed an apparatus that imitates cutlery to apply GTS [9]. Furthermore, Ranashinghe *et al.* proposed a tongue-mounted interface to manipulate tastes using electrodes on the tongue by applying

The associate editor coordinating the review of this manuscript and approving it for publication was Tai-Hoon Kim.

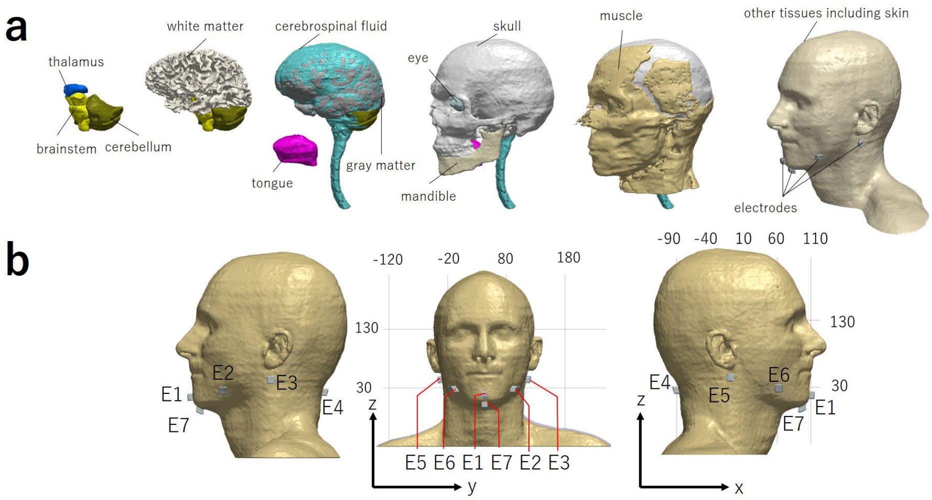

FIGURE 1. (a) Illustration of the head model and (b) position of electrodes.

electrical stimulations of various waveforms and by changing the temperature [10].

Conventional methods have a limitation in that the electric stimulation induces taste sensations only when electrodes are installed within the mouth or when electrodes come into contact with edible substances inside the mouth. This limitation has presented a huge barrier in terms of realistic applications, because it requires electrodes or substances to remain in the mouth, which generally degrades eating experiences. Considering this fact, Aoyama *et al.* developed a novel GTS method that induces and manipulates taste sensations using electrodes installed on the chin, jaw, and the back of the neck [11]. This method is able to reproduce taste sensations without hindering eating and drinking activities.

The GTS method proposed by Aoyama *et al.* induced taste sensations in the buccal cavity using an anode on the upper chin and a cathode on the back of the neck, while it induced taste sensations around the throat with the anode on the lower jaw and the cathode on the back of the neck. Based on this study, we considered that the taste locations varied because the electrical potential distribution yielded by the GTS inside the head varied depending on the electrode combination. These results provided the foundation for our hypothesis, which states that GTS can control the region in the mouth where the taste sensation is perceived by controlling the potential distribution.

In addition to Aoyama's previous work, we examined the report by Bach-y-Rita *et al.* [12]. In the study, they examined the tactile sensation induced by electric current and investigated the spatial variances of sensations in the mouth. They reported that the perceived shape and the spatial position where the tactile sensation is perceived vary depending on the combinations of activated electrodes attached to the tongue. We focused on the reported precision of regional selectivity, which was considerably high, especially when compared to that of the conventional GTS method proposed by Aoyama. Then, we aimed to achieve similar spatial/regional selectivity with GTS, i.e., in the domain of taste sensations, and only with percutaneous electrical stimulation using externally attached electrodes. In other words, we hypothesized that we could achieve *current steering* inside the mouth and the manipulation of taste location in the buccal cavity using multiple electrodes attached outside of the mouth. Incidentally, there was no mention of taste sensations in [12], and they were using electrodes attached directly onto the tongue.

To control the potential distribution and the region in the mouth where the taste sensation is induced, we designed a multielectrode GTS that had seven electrodes (denoted as E1–E7). These were attached to the center of the chin (E1), approximately 4 cm below the external acoustic duct (E3 and E5), the midpoint of E1/E3 and E1/E5 (E2 and E6, respectively), the center of the back of the neck (E4), and the center of the lower part of the chin (E7), as illustrated in Fig. 1 (b). We will explain the reasons for these choices in Section 2 of this paper.

The objective of this study is, therefore, to verify that the multielectrode GTS using electrodes attached outside the mouth can manipulate the electrical potential distribution within the buccal cavity and can also manipulate the position where the sensation of taste is induced. In this study, we verified our hypothesis by conducting a simulation and a psychophysical experiment.

The novelty of this study is that it focuses on controlling the position in the mouth at which the sensation of taste is induced. Historically, control of the spatial position of taste sensation has not been discussed, because it has not been feasible, especially for noninvasive approaches. Consequently, no conventional method is capable of modifying the taste positions. However, our novel GTS configuration overcomes this challenge in feasibility by controlling the electrical potential distribution inside the mouth without interfering with the eating and drinking experience, i.e., by noninvasive galvanic electrical stimulation. Our novel GTS method expands the frontiers in the field of taste displays in that, once the technology is matured, a GTS employing our method will be able to provide a new dining experience. This has significant engineering value. It is also a notable breakthrough in the research field of HCI, as our novel GTS method establishes a completely new type of interface that can convey information by spatially varying the sensations of taste.

As discussed earlier, the previous study conducted by Bach-y-Rita *et al.* [12] achieved control of the location where the tactile sensation was perceived in the buccal cavity. However, their method had two limitations in our view. First, their method intended to induce only tactile sensations. Second, their method required electrodes to be placed inside the mouth. Our method instead focuses on taste sensations, and it does not require any electrodes to be placed inside the mouth. Our ultimate goal is to use the GTS to modify and design eating and drinking experiences, by manipulating taste sensations without disturbing the eating experience.

II. METHODS

In this study, we conducted an analytical simulation and a psychophysical experiment. In the simulation, we analyzed the electrical potential distribution on the tongue yielded by different configurations of electrical stimulations using multiple electrodes. Next, we conducted a psychophysical experiment to investigate the positions where taste sensations were induced by the multielectrode GTS with the electrode configuration used in the simulation. With the results from the simulation and the experiment, we herein demonstrate how our multielectrode GTS design works and controls the positions of taste sensations in the mouth.

A. ELECTRODE CONFIGURATION

Aoyama *et al.* reported that their novel GTS method induced taste sensations only when the anode was placed near the mouth on the chin [11]. Other studies have shown that electric taste sensations could be induced by attaching anodal electrodes inside the mouth [1], [4], [8]. Based on these results, we assumed that an electrical current from the GTS introduced by Aoyama passes through the mouth, in the front-to-back direction. This is highly anticipated, as the mouth is much wetter and has a much higher conductance than other parts, owing to saliva and other fluids. The electrical current passing through the mouth should stimulate the tongue as if the anode were installed inside the mouth.

With this assumption, we designed an electrode configuration for our novel method. As mentioned earlier, we developed a multielectrode GTS current steering method, which is illustrated in Fig. 1, to manipulate the potential distribution in the mouth to influence the taste position.

We designed our multielectrode configuration with the following considerations:

- E3, E2, E1, E6, and E5 align from left to right in the stated order. The position of the taste sensation and the electrical potential distribution can be manipulated laterally using these electrodes.
- E1, E2/E6, E3/E5, and E4 align from front to back. The position of the taste sensation and the electrical potential distributions can be manipulated in the antero-posterior direction using these electrodes.
- E1 and E7 have similar positions along the horizontal plane, but they have quite different positions along the inferior–superior direction. The position of the taste sensation and the electrical potential distributions can be manipulated in the inferior–superior direction using these electrodes.

TABLE 1. Electrical conductivity of tissues and body fluid.

	Electrical conductivity [S/m]
Eye	0.7
Tongue	0.3
Mandible	0.02
Brainstem	0.1
Skull	0.02
Cerebellum	0.1
Cerebrospinal fluid (CSF)	1.8
Gray matter	0.1
White matter	0.06
Thalamus	0.1
Muscle	0.35
Other tissues	0.1
Electrode	0.1

B. NUMERICAL ANATOMICAL MODEL

A Duke V2.0 volumetric conductor model of the human head (DOI: 10.13099/ViP-Duke-V2.0, IT'IS Foundation) was used. This model was created using magnetic resonance images of a 34-year-old male having a resolution of 0.5 mm × 0.5 mm × 0.5 mm. Although the model consists of 22 parts to represent the entire human body, we used only the parts above the shoulder for our simulation. The 13 parts used for our model are shown in Table 1. The Duke model represents the whole body using. *stl* file format. We cut out the parts below the shoulder using ScanIP (Simpleware, SYNOPSYS Inc.). Next, seven electrode parts were virtually attached by hand to the chin, in front of the gonions, below the mastoids, at the back of the neck, and the underpart of the chin of the model, as shown in Fig. 1. The coordinates of the positions where the electrodes were attached are shown in Table 2, where the coordinate system of the electrode positions was the same as that shown in Fig. 1 (b), and its origin point was at the back, right, and under the tongue. Note that this coordinate system is the same as that in Fig. 4. We defined the resulting model as the model for our multielectrode GTS configuration.

TABLE 2. Position of electrodes.

		E1	E2	E3	E4	E5	E6	E7
Electrodes Position	x [mm]	99.77	58.42	-7.58	-78.87	-7.52	58.29	90.39
	y [mm]	44.59	90.34	97.84	41.51	-22.75	-0.31	45.43
	z [mm]	22.50	31.60	46.55	29.60	46.50	31.60	8.60

TABLE 3. External surface dimensions and inward current density of each electrode.

	E1	E2	E3	E4	E5	E6	E7
Superficial measure [mm^2]	85.124	118.85	99.428	88.686	84.56	120.59	101.46
Inward current density [A/m^2]	11.74757	8.413967	10.05753	11.27574	11.82592	8.292562	9.856101

C. SIMULATION OF POTENTIAL DISTRIBUTION ON THE HEAD

Our multielectrode GTS model was exported to a NASTRAN format volumetric mesh file (2,710,722 tetrahedral elements in total), and the file was imported to COMSOL Multiphysics 5.5 (Comsol Inc.). Next, the electrical conductance was assigned as shown in Table 1. The parameters were determined based on a previous study conducted by Laakso and Hirata [13]. In their study, the parameters were determined based on previous studies conducted by Baumann *et al.* [14], Gabriel *et al.* [15], Gabriel *et al.* [16], and Lindenblatt and Silny [17]. The conductivity of the electrodes was defined to be equivalent to that of human skin.

The Laplace equation, $\nabla \cdot (\sigma \nabla V) = 0$, where V is the electrical potential, and σ is the conductivity, was solved by applying the following boundary conditions: (1) inward current = Jn (normal current density) was applied to the exposed surface of the anode, (2) ground was applied to the exposed surface of the cathode, and (3) all other external surfaces were insulated. The inward current density for each electrode was defined accordingly to adjust the current density distribution to 1.0 mA, considering the superficial size of each electrode (Table 3).

There were 42 simulation conditions to cover all possible selections of one anode and one cathode from the seven electrodes ($_7P_2$).

D. PSYCHOPHYSICAL EXPERIMENT

This experiment was conducted to show the relation between the electrical potential distribution and the spatial position of taste sensation and to establish a method for controlling the spatial position where taste sensations are induced. In the experiment, the subjects, who had electrodes attached to the same positions as in our simulation, indicated the positions where taste sensations were induced.

Six healthy participants (four males and two females, 27.17 years old on average) participated in the experiment. The experiment was conducted in accordance with the 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 a letter of consent. The study was performed in accordance with the ethical standards provided in the Declaration of Helsinki.

The experiment was conducted in a silent room. The subjects had their skin cleaned, and seven gel electrodes (Wizard gel, Yushiro Chemical Inc.) were attached manually to configure a multielectrode GTS (Fig. 1(b)). The subjects were instructed to sit on a chair and face the front with their mouths closed and their tongues fixed in a neutral position.

Direct current stimulation at 1.0 mA was applied to the subject after a cue from the experimenter, and the stimulation lasted until the subject signaled a cue to the experimenter. When stimulation was started and ended, the current was turned on and off abruptly. We employed this stimulation form because a 1.0 mA direct current was used in previous GTS studies, and it is known to be sufficiently strong to induce an electric taste. We continued applying the direct current until the subject signaled a cue, because it was difficult to estimate the current duration sufficient for all the subjects to localize the position of taste sensations. In order to address the concern regarding the adaptation of electrical stimulation, we preliminarily verified that the electric taste was strongly and continuously felt when 1.0 mA and 5 min chin anodal GTS was applied. The subject could experience the stimulation as often as desired during a trial. After a stimulation, each subject drew a mark on a picture to indicate the strongest point of taste perception, using an answer sheet shown in Fig. 2. The left side of the answer sheet illustrates the top view of the mouth, and the image on the right side of the sheet shows the left view of the mouth. In cases where the subjects

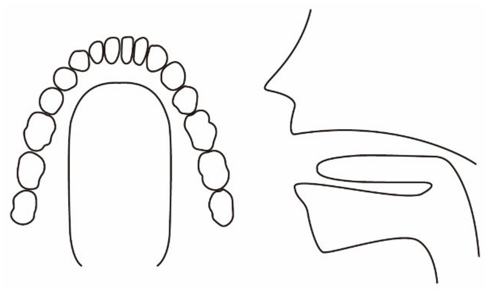

FIGURE 2. Schematic showing the top and side view of the mouth, which were shown in the answer sheet.

are to report two points with the strongest taste sensations, they were instructed to draw two marks to indicate which one was stronger (1 = stronger). Conversely, where the subjects did not perceive any taste sensation, they were instructed not to draw any points anywhere. There were 42 simulation conditions, which included all the possible selections of one anode and one cathode from seven electrodes ($_7P_2$). Each condition was conducted twice, and a total of 84 trials were conducted per subject.

After the experiment, the coordinates of the maximum potential points were measured using a ruler, and the taste occurrence rates were calculated based on reports from the subjects. We calculated the taste occurrence rates because taste induction might or might not happen, depending on the stimulation conditions. To calculate the taste occurrence rates, we treated the trials in which the subjects reported a taste-induced area as *taste-inducing* trials, and we treated those in which the subjects did not report taste-induced areas as *non-taste-eliciting* trials. Subsequently, we obtained the occurrence rate by dividing the number of taste-inducing trials by the sum of the taste-inducing trials and non-taste-eliciting trials.

Although this experiment was designed as a blinded experiment, the subjects could feel haptic sensations through the stimulation.

III. RESULTS

A. SIMULATION

Fig. 3 shows the electrical potential distribution on the tongue for each anode-cathode configuration. These figures indicate that the red area shifts according to the position of the anode, and the blue area shifts according to the position of the cathode. Fig. 4 displays the points having the maximum and minimum potentials under each condition. When E1 was the anode, the tip of the tongue had the maximum potential. When E2 and E3 were the anodes, the left side of the tongue had the maximum potential, and when E5 and E6 were the anodes, the right side of the tongue had the maximum potential. In addition, when one of E3, E4, or E5 was selected as the anode, the point having the maximum potential was observed at the back of the tongue. When E7 was the anode, the maximum potential point was at an inferior position, compared with that when E1 was the anode. Each point having the lowest potential was observed in a similar manner according to corresponding cathodal electrode position.

Figs. 5(a)–(f) show the coordinates of the averaged point having the maximum and minimum potentials under each anodal condition. Comparing these values with the values shown in Table 2 , we can observe that the coordinates of the averaged point having the maximum potential and the position of the anode are highly related. Using these values, we also computed the nearest electrode for each averaged point having the maximum potential and verified that all the conditions had the anode as the nearest electrode. Hence, these figures indicate that the point having the maximum potential is always close to the position of the anode. When they are grouped by the anodal positions, the error bars for the averaged positions of the points having the minimum potential are larger than those having the maximum potential points. This implies that the position of the point having the minimum potential is not determined by the position of the anode.

With these results, we confirmed that the position of the GTS electrodes around the mouth affects the electrical potential distribution within the mouth, and the points having the maximum and minimum potential on the tongue is controllable by the positions of the anode and the cathode, respectively.

B. PSYCHOPHYSICAL EXPERIMENT

Figs. 6 and 7 show the results of our psychophysical experiment. These figures indicate that the points having the maximum taste sensations were located at the center and tip of the tongue when the anode was placed at E1 and E7. The points were located at the left and right sides of the tongue when the anode was placed at E2 and E6, respectively. With the anode at E3 and E5, the points were relatively on the left and right halves of the tongue, respectively.

Fig. 8 shows the averaged position of the points having the maximum taste sensation under each anodal condition. These data support our understanding of Figs. 6 and 7, and these figures indicate that the points perceiving the maximum taste sensations were located at the center and anterior part of the tongue when the anode was placed at E1 and E7. They were located at the left and right sides of the tongue when the anode was placed at E2 and E6, respectively. With the anode at E3 and E5, the points were relatively on the left and right halves of the tongue, respectively.

Fig. 9 shows the heat map of the taste occurrence rate under each stimulation condition. It shows that the conditions in which the anodes were at E1, E2, or E6 induced taste sensations at higher occurrence rates (more than 88%). By contrast, the conditions in which the anodes were at E3, E4, and E5 showed lower occurrence rates (less than 53%).

IV. DISCUSSIONS

The results of our simulation and psychophysical experiment verified that our multielectrode GTS is able to manipulate

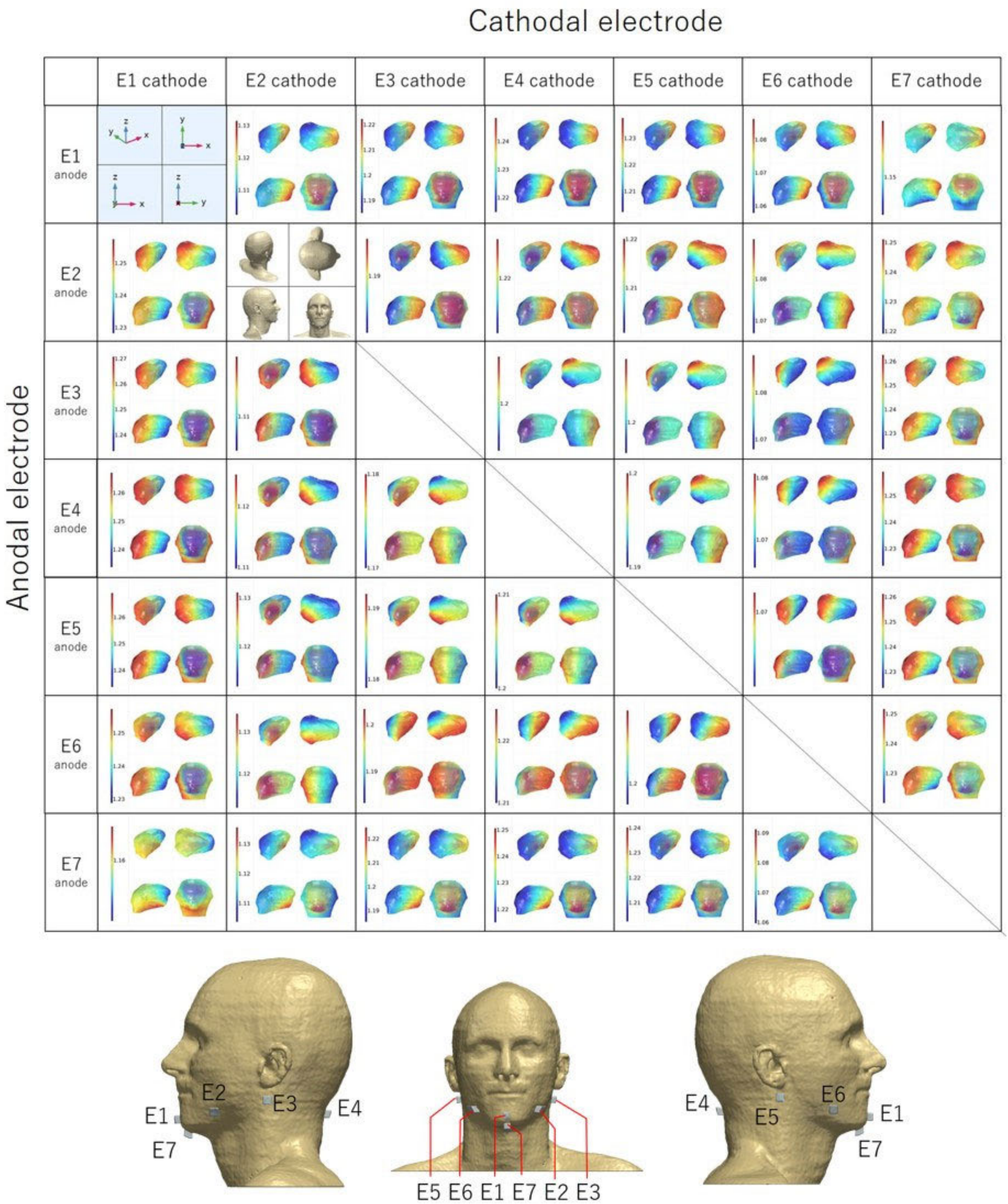

FIGURE 3. Simulation results for all anode–cathode combinations. Rows represent the position of the anode and columns represent the position of the cathode. Color shows voltage (V), adjusted for each cell: red signifies high, and blue signifies low potential. The angle of each figure in each cell is explained in E1–E1 and E2–E2: the upper-left figure of each cell shows the upper-right and back views of the tongue, and the upper-right, lower-left, and lower-right figures show the top, right, and front views, respectively. The color shows the potential (i.e., red means high, and blue means low potential).

the electrical potential distribution within the mouth and consequently, manipulate the spatial position where the taste sensation was perceived along the horizontal plane. Figs. 3, 4, and 5 indicate that the electrical potential distribution on the tongue shifted according to the position of the stimulation electrodes located outside of the mouth. Moreover, the distribution of high voltage points was strongly correlated with the position of the anodal electrodes.

The position of taste perception, however, did not move in the inferior–superior direction by changing the inferior–superior position of the anode. In our simulation, Figs. 3, 4, and 5, which show the potential distribution, and the maximum and minimum potential positions, indicated that the electrical potential distribution for the E1 (chin) anodal GTS and that for the E7 (underpart of the chin) anodal GTS were different. For example, Fig. 5(c) shows that the

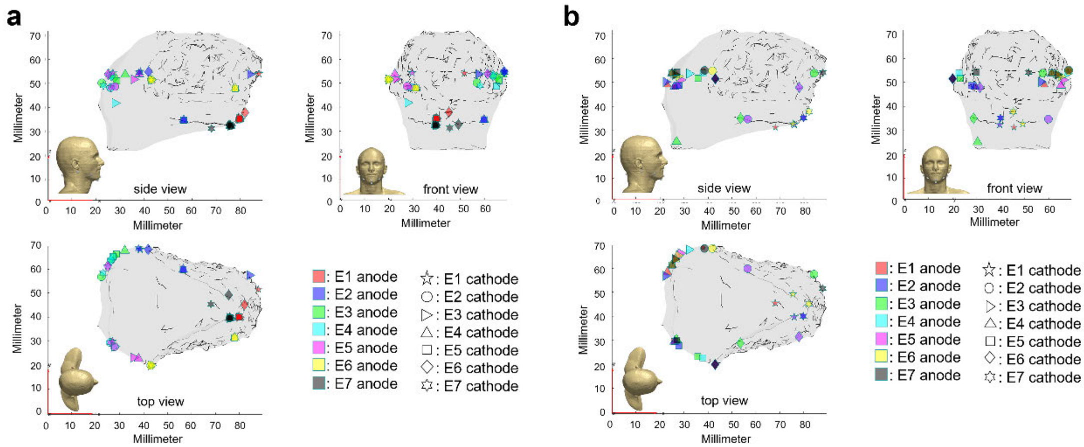

FIGURE 4. **Points having (a) the highest electrical potential and (b) the lowest electrical potential under each electrode condition. The human head in this figure indicates the orientation of the tongue. The grey area illustrates the tongue. The black line on the tongue shows its surface shape. For each marker, the color indicates the anodal electrode, and the shape indicates the cathodal electrode.**

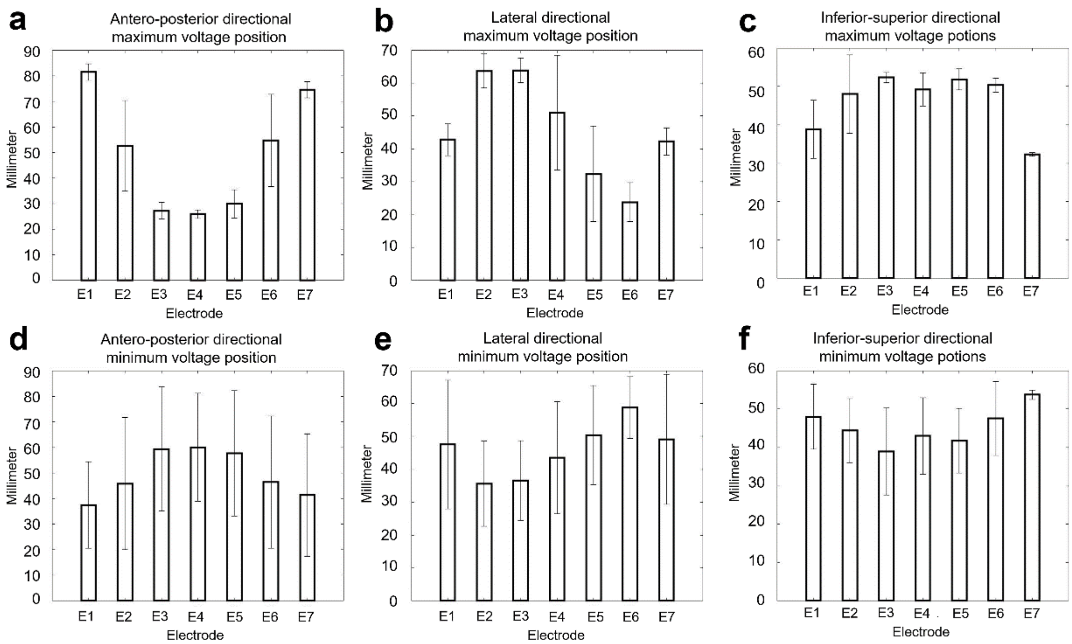

FIGURE 5. **Averaged position of points with the maximum (a, b, and c) and minimum (d, e, and f) electrical potential under each anode condition: (a) and (d) are for the antero-posterior direction, (b) and (e) are for the lateral direction, and (c) and (f) are for the inferior–superior direction. In each graph, the X-axis enumerates the position of the anode, and the Y-axis shows the distance along a specific axis between the origin and the averaged point. The same coordinate system in Table 2 was employed in these figures (the origin point is at the back, right, and under the tongue). The error bars show the standard deviations (SD).**

inferior–superior-directional positions of the averaged points having the maximum potentials were different in the E1 and E7 anodal conditions. By contrast, Figs. 6 and 7, which show the maximum taste positions, indicate that the points having the maximum taste sensation were distributed similarly in the two corresponding conditions. Furthermore, Fig. 8(c) shows that the inferior–superior-directional positions of the averaged points having the maximum taste sensations were almost the same for all the conditions. To better describe why the maximum taste position did not shift in the inferior–superior direction, we point out that the taste sensitivity of the top, side, and back parts of the tongue is high, and that of the inferior surface is low. Thus, it is highly possible that the electric taste induced by the GTS was perceived mainly on the surface of the tongue. Based on this understanding, it is a highly probable assumption that the subjects perceived electric tastes that occurred along the horizontal surface but not in the inferior–superior direction.

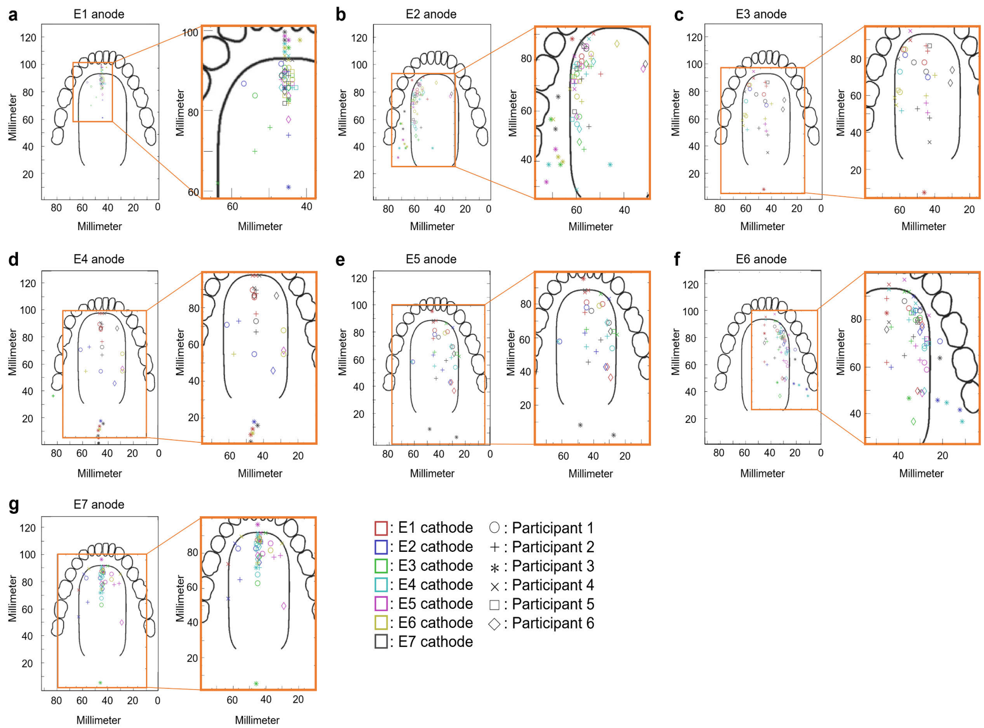

FIGURE 6. Points that perceived the maximum taste sensation from the side view, separately shown for each anodal electrode condition (a: E1 anodal, b: E2 anodal, c: E3 anodal, d: E4 anodal, e: E5 anodal, f: E6 anodal, g: E7 anodal.). The color of makers denotes the conditions of cathode positions, and the shape of markers distinguishes the participants. The electrode position is as follows: E1: center of the chin, E7: center of lower part of the chin, E3 and E5: 4 cm below of external acoustic duct, E2 and E6: midpoint of E1 and E3, and E1 and E5, E4: center of back of neck.

When we compare Figs. 5 and 8, we can observe that the shapes of Figs. 5(a) and (b), which present the positions of the averaged points with the maximum potentials in the antero-posterior and lateral directions, respectively, are similar to those of Figs. 8(a) and (b), which show the positions of the averaged points that have the maximum taste sensation in the antero-posterior and lateral directions, respectively. Both Figs. 5(a) and 8(a) have their lowest peaks under the E4 condition and the highest under the E1 and E7 conditions. Figs. 5(b) and 8(b) show their highest peaks under the E2 and E3 conditions, and their lowest peaks under the E6 condition. In contrast, the averaged positions with the minimum potentials, which are shown in Figs. 5 (d), (e), and (f), are not related to those in Figs. 8 (a), (b), and (c). These facts indicate that the position of the induced taste sensation was determined by the parts with higher electrical potential distribution. We computed the correlation between the average position of maximum potential points observed in the simulation, and the averaged positions of maximum taste points observed in the experiment, per each direction. The results showed that there was a high positive correlation between the two in the antero-posterior, and lateral directions (0.84 and 0.96, respectively). By contrast, there was a low correlation (−0.22) in the inferior–superior direction.

Fig. 9 shows the taste occurrence rate in each combination of electrodes. This figure indicates that the position of the anode strongly affected the induction of taste sensation. E1, E2 (midpoint of E1 and E3, left side), and E6 (midpoint of E1 and E5, right side) anodal conditions had a high taste reproduction rate (>88%). These electrodes were closer to the tongue than the others. Therefore, we can conclude that the tongue, which has most of the taste buds and related cells, was stimulated strongly under these conditions.

Interestingly, the E7 (underpart of the chin) cathodal condition had a high taste occurrence rate under all anodal conditions (>83%). To understand this better, we conducted an additional analysis. Fig. 10(a) shows the positions of the points having the maximum taste sensations under all E7 cathodal conditions from the top view. Fig 10(b) shows the average coordinate of the points having the maximum taste sensation, separately plotted for the antero-posterior, lateral, and inferior–superior directions. Fig. 10(a) and the graph at the center of Fig. 10(b) indicate that the E7 cathodal GTS was capable of changing the lateral directional position of taste perception quite solidly. Although statistical significance was not confirmed, we observed the same tendency in the antero-posterior direction, i.e., in Fig. 8(a). The points having the maximum taste sensation under the E1 anodal condition was more anterior than those under the E3 (4 cm below the left

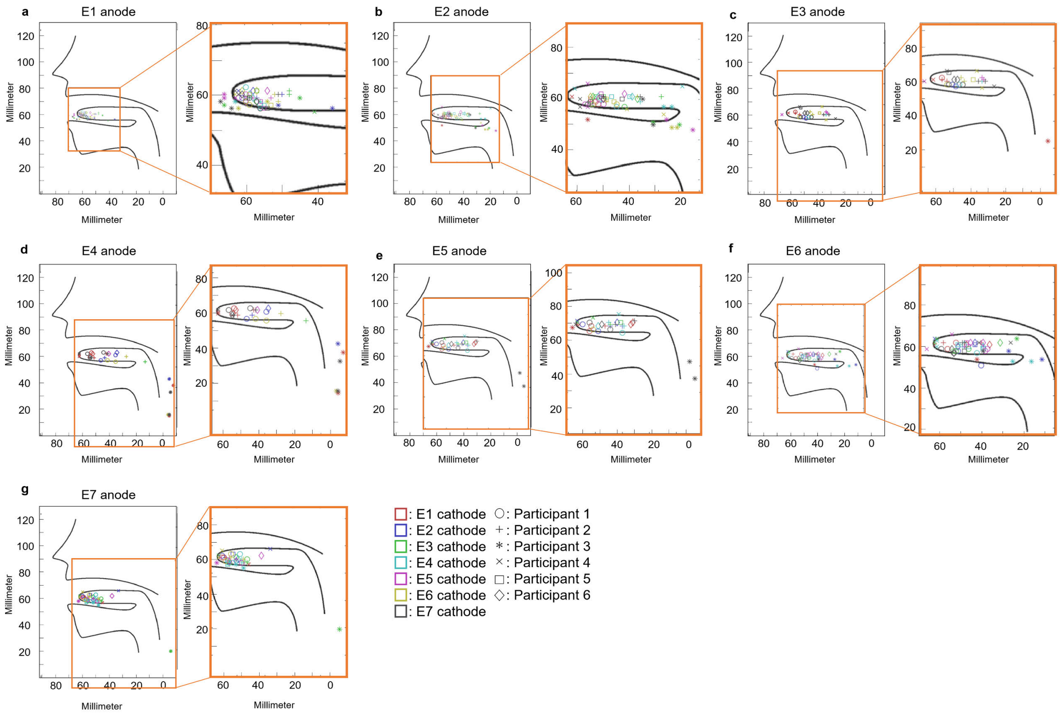

FIGURE 7. Points that perceived the maximum taste sensation from the top view, separately shown for each anodal electrode condition (a:E1 anodal, b:E2 anodal, c:E3 anodal, d:E4 anodal, e: E5 anodal, f: E6 anodal, and g: E7 anodal). The color of makers denotes the conditions of cathode positions, and the shape of markers distinguishes the participants. The electrode position is as follows: E1: center of the chin, E7: center of lower part of the chin, E3 and E5: 4 cm below of external acoustic duct, E2 and E6: midpoint of E1 and E3, and E1 and E5, E4: center of back of neck.

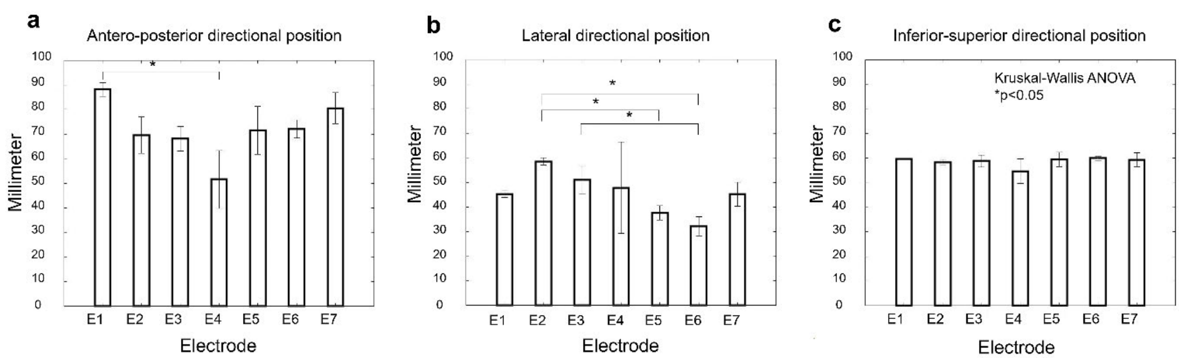

FIGURE 8. Averaged position of the points having the maximum taste sensation under each anodal electrode condition: (a) antero-posterior direction, (b) lateral direction, and (c) inferior–superior direction. The error bars in this figure show the SD. Asterisks indicate significant differences calculated by the Kruskal–Wallis analysis of variance (ANOVA) and multiple comparisons (Scheffe method, $p < 0.05$). The units of the Y-axes in these figures equals the actual measurement of 1 mm on the answer sheet, and we set an origin point at the back-right-under the tongue. The averaged positions were computed by averaging the coordinates of all points with the maximum taste sensation reported by all participants. Note that we used the top-view sketch data for the analysis of antero-posterior directional position in this figure.

acoustic duct), E4 (back of the neck), and E5 (4 cm below the right acoustic duct) anodal conditions. These observations indicate that the position of the maximum taste sensation can be changed solidly in the horizontal direction, especially laterally, by changing the position of the anode and using the cathode at E7. Because the E7 (underpart of the chin) cathodal GTS induced taste sensations at the highest occurrence rate and changed the taste position solidly according to the position of the anode, we can conclude that the cathode at E7 was the best configuration for the current multielectrode GTS for taste display. Our future work will investigate mechanisms of this nature. Currently, we assume that it relates to the direction of the electric current, the current density, and the sensitivity distribution on the surface of the tongue. It will also be our future work to find the best position for the cathode under the chin. The present results show that the

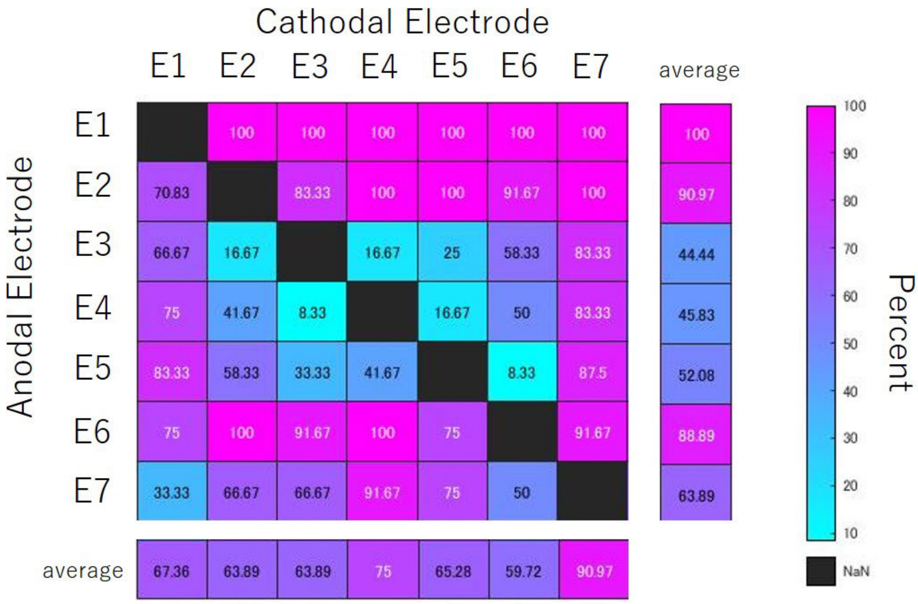

FIGURE 9. Heat map of taste occurrence rate under each stimulation condition. Rows represent the position of the anode, and columns represent that of the cathode. The magenta shows higher rate, cyan shows lower rate, and black shows no data [%]. The number in each cell shows rate of taste occurrence.

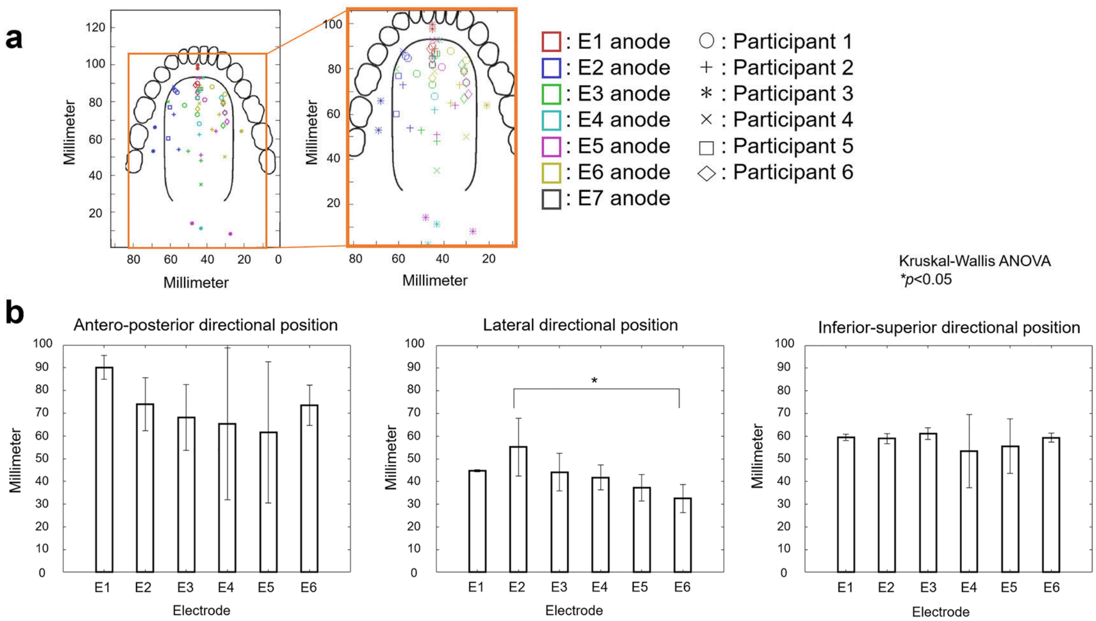

FIGURE 10. Results of our psychophysical experiment under the E7 cathodal condition: (a) the position of the maximum taste sensation from the top view. The colors of the markers show the corresponding anodal electrodes, and their shapes show the subject number. (b) shows the position of the averaged points having the maximum taste sensation in the antero-posterior, lateral, and inferior–superior directions. The error bars in this figure show the SD. The asterisks indicate the significant differences calculated by Kruskal–Wallis ANOVA and multiple comparisons (Scheffe method, $p < 0.05$).

cathodal electrode should be attached to the inferior part of the head for the best performance of the spatial taste control. However, this does not mean that E7 is the best position for this purpose. Considering that E7 is at the inferior position, compared with the other electrodes, those at lower positions (e.g., lower jaw, neck, or shoulder) might be better at controlling the taste position more precisely with higher taste occurrence.

We emphasize that we did not discuss the resolution of the position of taste sensations and its control in this paper. This will be investigated in our future work, along with a method to modify the location of taste sensations more precisely.

Our psychophysical experiment employed a blind study design. Nevertheless, the subjects may have perceived haptic sensations induced by electrical stimulation. However, we confidently believe that the taste positions indicated in this paper correctly denote the position where the subjects actually perceived the sensations. This is because haptic sensations are known to be induced near both anodal and cathodal electrodes, whereas, in this present work, most of all the subjects reported taste sensations near the anodal electrodes, and no bias towards cathodal electrodes was observed.

In our simulation, we assumed that the electrodes have the same electrical conductivity as the skin. This assumption is based on our preliminary measurement of electrodes in our stock. Obviously, the conductivity can vary depending on manufacturers and types/models; for example, metallic electrodes have extremely high conductivity. However, this variance in conductivity will not affect our conclusion on the simulations. The conductivity of electrodes affect two factors of electrical characteristics: the voltage between the anode and the cathode (higher conductivity results in lower voltage between the two), and the potential distribution on the electrodes and on the parts of the skin contacting the electrodes (higher conductivity results in higher uniformity). The voltage between the two electrodes will not affect the distribution of potential; when the voltage between the two electrodes is increasing, the point with the highest potential will just have a higher absolute value of voltage. Conversely, the uniformity of potential distribution on the electrodes would have an impact on the potential distribution within the head, as it affects the amount and the direction of the electrical current flowing into the skin. However, the impact should be negligible because the dimension of each electrode ($\sim$120 mm^2) is insignificant compared to the entire skin. Note that the models for body and the electrodes are designed as a simple resistance in which each tissue has uniform conductivity.

In this paper, we demonstrated that our multielectrode GTS method could modify taste positions in the buccal cavity. Although the current multielectrode GTS induced only an electric taste, it may be possible to modify taste qualities in the future. For example, Ranashinghe *et al.* reported that taste quality could be modified by changing the stimulation waveform and temperature [10]. While this must be verified, we believe that, by employing the technique introduced by Ranashinghe, it will be possible to control the spatial distribution of all the five basic taste sensations with which we can design five spatially varying taste sensations. Moreover, the GTS technology provides two additional taste effects: inhibition and enhancement. We presume that these two effects can also gain spatial freedom by applying the technique discussed in this study.

V. CONCLUSION

In this study, we verified that multielectrode GTS can manipulate the position in the mouth where taste sensation is perceived. To the best of our knowledge, this is the first report that aims to control the position inside the mouth where taste sensations are induced. Our GTS method can induce taste sensations and manipulate their positions using electrodes placed outside the mouth. Thus, it can provide the effects of stimulation without hindering the eating and drinking experience. There are limitations in the current multielectrode GTS. First, it only manipulates the position of taste sensations along the horizontal plane. Second, it is the topic for future works to apply the same technique for taste enhancement and suppression. The resolution of these limitations remains a challenge, and we intend to conduct further research on this.

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HIROMI NAKAMURA was born in Kyoto, Japan, in 1986. She received the Ph.D. degree in engineering from Meiji University, in 2014. From 2014 to 2017, she was a Postdoctoral Researcher (Research Fellowship for Young Scientists (PD)) with The University of Tokyo, and with the National Institute of Advanced Industrial Science and Technology, from 2017 to 2019. From 2019 to 2020, she was a Project Research Associate with The University of Tokyo. Since 2020, she has been a Project Associate Professor with The University of Tokyo. Her research interests include virtual reality, human–computer interaction, and augmented human.

MAKOTO MIZUKAMI was born in Kobe, Hyogo, Japan, in 1990. He received the B.Eng. degree in wireless communications and the M.Eng. degree in human information engineering from Osaka University, in 2014 and 2017, respectively. Since 2017, he has been working as an Engineer with software companies, while he also has been actively coworking with multiple researchers, as an Independent Researcher. His current interests include human information engineering, human information science, wellbeing, software quality assurance, and virtual reality. He was awarded the Best Poster Award at the 8th Augmented Human International Conference, in 2017.

KAZUMA AOYAMA was born in Shimane, Japan, in 1989. He received the Ph.D. degree in information science from Osaka University, in 2016. Since 2018, he has been working with the Virtual Reality Education and Research Center, The University of Tokyo, Japan, as an Assistant Professor. Since 2019, he has also been working as a Researcher of PRESTO at the Japan Science and Technology Agency. His research interests include virtual reality, brain science, and neuro engineering.