Laterality of Human Primary Gustatory Cortex Studied by MEG

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Abstract

We examined the laterality of the human gustatory neural pathway by measuring gustatory-evoked magnetic fields (GEMfs) and demonstrating the activation of the human primary gustatory cortex (PGC). In patients whose chorda tympani nerve had been severed unilaterally on the right side, we stimulated the normal side (i.e., left side) of the chorda tympani nerve with NaCl solution using a device developed for measuring GEMfs. We used the whole-head magnetoencephalography system for recording GEMfs and analyzed the frequency and latency of PGC activation in each hemisphere. "The transitional cortex between the insula and the parietal operculum" was identified as PGC with the base of the central sulcus in this experiment. Significant difference was found in frequencies among bilateral, only-ipsilateral, and only-contralateral responses by the Friedman test ($P < 0.05$), and more frequent bilateral responses were observed than only-ipsilateral ($P < 0.05$) or only-contralateral responses ($P < 0.01$) by the multiple comparison tests. In the bilateral responses, the averaged activation latencies of the transitional cortex between the insula and the parietal operculum were not significantly different in both hemispheres. These results suggest that unilateral gustatory stimulation will activate the transitional cortex between the insula and the parietal operculum bilaterally in humans.

Key words: chorda tympani nerve, human gustatory pathway, laterality, magnetoencephalography, primary gustatory cortex, taste

Introduction

The human gustatory system has yet to be completely elucidated, especially the laterality of the human gustatory system, which is unlike that of the visual, auditory, and somatosensory systems. In rat, the gustatory pathway diverges and terminates in the bilateral gustatory cortex (Ganchrow and Erickson, 1972; Yamamoto and Kawamura, 1977). In squirrel monkey (i.e., a New World monkey) and macaque monkey (i.e., an Old World monkey), the gustatory pathway terminates in the ipsilateral gustatory cortex (Benjamin and Burton, 1968; Benjamin et al., 1968; Ogawa et al., 1985). In humans, by the investigation of patients with taste disorders caused by cerebral diseases, however, the laterality of the gustatory pathway remains unclear and is a matter of ongoing controversy, having been reported as being ipsilateral (Shikama et al., 1996), contralateral (Lee et al., 1998; Fujikane et al., 1999), and bilateral (Onoda and Ikeda, 2003).

Recent developments in imaging techniques have made possible various noninvasive methods, such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and magnetoencephalography (MEG), that allow us to measure the cerebral activity of human par-

ticipants. The human gustatory system has been studied using fMRI (Cerf et al., 1998; Faurion et al., 1998, 1999; Small et al., 1999, 2003; Cerf-Ducastel et al., 2001; O'Doherty et al., 2001; de Araujo et al., 2003; Frank et al., 2003), PET (Kinomura et al., 1994; Small et al., 1997; Zald et al., 1998; Frey and Petrides, 1999; Gautier et al., 1999; Zald and Pardo, 2000), electroencephalography (EEG) (Funakoshi and Kawamura, 1971; Kobal, 1985; Plattig, 1991), and MEG (Kobayakawa et al., 1996a,c, 1999; Murayama et al., 1996; Mizoguchi et al., 2002; Yamamoto et al., 2003). Analysis of brain function by fMRI and PET is based on the change of cerebral blood flow induced by neural activity and that of MEG and EEG on the electric potential and magnetic changes induced by neural activity. Therefore, both EEG and MEG feature higher temporal resolutions than PET and fMRI in measurements of brain activity. High temporal resolution is required to measure the latency of activity in the primary gustatory cortex (PGC), which is important in order to consider the laterality of the gustatory pathway. Only in a few reports, gustatory-evoked potentials were succeeded to

658 K. Onoda et al.

be recorded in a long history of EEG measurements. Kobal (1985) reported that three EEG components [i.e., P1 (180 ms), N1 (260 ms), and P2 (400 ms)] were recorded by gustatory stimulation with a gaseous taste stimulant. However, EEG is affected by the cerebrospinal fluid, skull, and skin, which tend to distort the summated dendritic exciting postsynaptic potentials (EPSP) and cause difficulty in identifying the active location. MEG is not affected by these factors and facilitates the identification of the activated cortices with their latencies. Therefore, MEG is thought to be a more powerful technique to identify the human PGC because of its high temporal and spatial resolutions.

Murayama et al. (1996) tried to identify the human PGC and reported that it was in the boundary area of the opercular and insular cortex. However, tactile stimuli mixed with gustatory stimuli interfered with the measurement of tactile-free gustatory-evoked magnetic fields (GEMfs). Kobayakawa et al. (1996a) developed a gustatory stimulus presentation device characterized by a short rise time of the gustatory stimulus with negligible tactile stimulation and measured the GEMfs. They reported that the human PGC was located in "the transitional cortex between the insula and the parietal operculum" and the cortex in the base of the central sulcus (CS) (Kobayakawa et al., 1999) by analyzing GEMfs with the shortest latencies.

Studies by fMRI and PET also reported the location of the human PGC as the frontal operculum and the anterior insula. However, it was a putative PGC of humans by analogy to monkey PGC, which was located at the frontal operculum and the anterior insula (Small et al., 1999, 2003; O'Doherty et al., 2001; de Araujo et al., 2003). This putative human PGC was not coincident with that identified by MEG, which was located in the parietal cortex. Studies on hematomas in brain-injured patients (Börnstein, 1940b) and gustatory hallucination related to epilepsy (Hausser-Hauw and Bancaud, 1987) supported the idea that a taste-specific area is located in the parietal lobe. According to these researches and MEG studies, the transitional cortex between the insula and the parietal operculum and the base of the CS are the most likely candidates for the PGC in humans. The frontal operculum and the anterior insula, reported as the putative PGC by fMRI and PET studies, are more likely to be high-order gustatory regions.

Several studies have tried to reveal the laterality of the human gustatory pathway by measuring the GEMfs of healthy participants and demonstrating the activation of human PGC (Kobayakawa et al., 1996b; Murayama et al., 1996). To investigate the laterality of the human gustatory pathway, it is necessary to stimulate one side of the chorda tympani nerve. In relation to the laterality of the chorda tympani nerve, however, the lingual apex within about a 2-cm radius of the apex is doubly innervated since the bilateral chorda tympani innervates both sides of the lingual apex (Tomita et al., 1986). In previous studies on laterality of human gustation (Kobayakawa et al., 1996b; Murayama et al., 1996), a gustatory stimulus was given at a point 2 cm away from the

lingual apex in healthy participants. However, it is difficult to be confident about the fact that simultaneous stimulation of the contralateral chorda tympani nerve did not occur during the measuring of the GEMfs.

To achieve unequivocal unilateral gustatory stimulation, we used subjects whose right chorda tympani nerve had been severed during right middle ear cholesteatoma operations. In this experiment, only the left chorda tympani nerve innervating the lingual apex was exactly and unilaterally stimulated by the taste solutions in order to identify the PGC using MEG. We provided a tactile-free gustatory stimulus to the lingual apex of participants and measured GEMfs by MEG, with high temporal and spatial resolutions. We investigated the activation of cortical areas with the shortest latency, representative of the PGC, and compared the frequency and latency of PGC activation in both hemispheres.

Materials and methods

Participants

Six patients with unilaterally resected chorda tympani nerves participated in order to stimulate gustatory nerves unilaterally. They were all females from 30 to 50 years and had their right chorda tympani nerve transected during middle ear cholesteatoma operations. The average period between the middle ear cholesteatoma operations and the MEG experiments was 4 years, in which each participant's period was 1 month, 1 year and 1 month (two participants), 1 year and 7 months, 2 years and 3 months, and 17 years and 8 months. Before MEG experiments, electrogustometry and the filter paper disk method (Tomita et al., 1986) were used to evaluate the gustatory function of each participant. By electrogustometry, all participants could not detect the maximum gustatory stimulus (400 mA) on the right chorda tympani nerve area and could detect less than 8 mA on the left chorda tympani nerve area. By the filter paper disk method, all participants could not detect level 5 for all four kinds of tastes (maximum concentration: sucrose 2.34 M, sodium chloride 3.42 M, tartaric acid 0.53 M, quinine hydrochloride 0.1 M) on the right chorda tympani nerve area and could recognize all four kinds of tastes at level 3 (normal level: sucrose 0.29 M, sodium chloride 0.85 M, tartaric acid 0.13 M, quinine hydrochloride 0.003 M) on the left chorda tympani nerve area. These results confirmed that the right chorda tympani nerve was entirely damaged and the left one was normal. Therefore, the lingual apex of each participant was judged to be innervated unilaterally by the left chorda tympani nerve.

We explained the purpose and method of the present study to all participants beforehand and received their consent to participate. The study was conducted in accordance with the Helsinki Declaration. The ethical committees of Nihon University School of Medicine and the National Institute of Advanced Industrial Science and Technology also approved our study.

Recording of magnetic fields

The 64-channel whole-head Superconducting Quantum Interference Device (SQUID) system (CTF Systems Inc., Vancouver, Canada) was used to measure the GEMfs using a sampling rate of 250 Hz with a 40-Hz low-pass filter without a high-pass filter (Endo *et al.*, 2004). The location of the head with respect to the sensors was determined by measuring the magnetic fields produced by small currents delivered to three coils attached to the scalp, located at the nasion and the two preauricular points.

Gustatory stimulus presentation device

We used the taste presentation device developed by Kobayakawa *et al.* (1996c), which fulfilled the standards for the stimulus presentation method to evaluate the precise chemosensory event-related potential advocated by Evans *et al.* (1993). The standards applicable to the gustatory stimulus are as follows: (1) the taste solution is pulsatively introduced in deionized water separated by small air bubbles in order to stimulate only the gustatory nerve without stimulating the tactile sense, (2) this stimulator presents a rapid rise in the gustatory stimulus to 70% of the maximum concentration within 50 ms, the rise time to 80% of the gustatory stimulation in our device was 16.5 ± 1.49 ms (Kobayakawa *et al.*, 1996c), and (3) the temperatures of the taste solution and water are equal to body temperature.

The device had a computer-controlled electromagnetic valve to produce the air bubbles, which prevented the mixture of the taste solution and the deionized water. The taste solution and deionized water were carried in a polytetrafluoroethylene (Teflon) tube to each participant in a magnetically shielded room. A small hole (8.0×2.2 mm) in the tube was located precisely at the lingual apex of each participant, who put the tube between her lips. Only the lingual area that was in contact with the hole was stimulated by the taste solution. The hole in the tube was kept attached to the tongue by the negative pressure in the tube, and the taste solution and deionized water did not spill out into the oral cavity. The taste solution and the deionized water in the tube were eventually drained into a container at the end of the tube. The taste solution was pigmented red by food red (Allura Red AC, Aizen Hodogaya Co., Ltd., Yokohama, Japan). In this study, we employed two optical sensors positioned before and after the hole to monitor changes in the light transmission between the dyed taste solution and the transparent deionized water. We recorded the arrival time of the taste solution at the hole from the time lag between the two sensors.

Procedure

We used 1 M NaCl as the gustatory stimulus. The concentration of NaCl was almost equal to level 3 of the filter paper disk method (Tomita *et al.*, 1986), which was recognized as being within the range of normal gustation. In addition, this concentration is used in clinical gustatory examinations at the Taste and Smell Center and the Monell Chemical Senses Center (Philadelphia, PA) (Bartoshuk, 1989; Cowart, 1989). As mentioned earlier, gustatory stimulation was delivered at the center of the lingual apex. The stimulus was provided only to the left chorda tympani nerve of each patient whose right chorda tympani nerve had been resected. The temperature of both the 1 M NaCl and the control water stimulus was maintained at 36°C.

As illustrated in Figure 1, a computer set the stimulus period and interstimulus interval (ISI) to 400 ms and 30 s, respectively. The actual ISIs were slightly irregular (mean ± SD: 30 ± 0.136 s) because of a variable liquid flow rate from the electromagnetic valve to each participant in the shield room. Deionized water rinsed away the taste solution during the ISI. One session consisted of 40 trials over a period of approximately 20 min. Participants were instructed to indicate their perceived intensity of the stimulus a few seconds after each taste presentation using a visual analogue scale of 0 (not detectable) to 5 (very strong).

When the participants were asked to describe each stimulus after each session, they described the taste solution as "salty." We additionally asked if the participants perceived a temperature difference between the water and the NaCl solution, and they reported no detectable difference. Each participant took part in 6–10 sessions. During the measurements, participants wore earplugs, kept their eyes open, and concentrated on a fixed point.

Participants did not perceive any taste for the deionized water after it replaced the 1 M NaCl because they were adapted to the deionized water used for rinsing.

Analysis

Trials involving eye movements were rejected, and sessions with less than 32 available trials were not used for analysis.
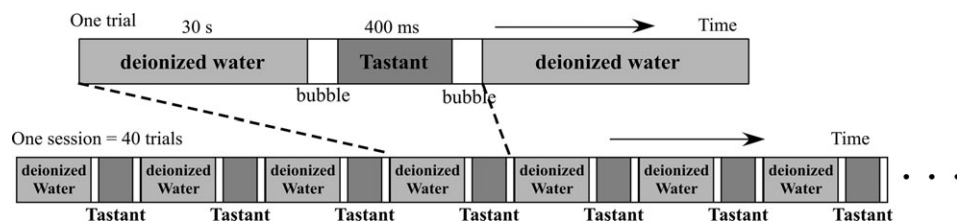
Figure 1 Procedure of gustatory stimulus application. The tastant flows for 400 ms. Before and after the tastant, an air bubble is inserted. Before the next gustatory stimulus, deionized water is introduced for about 30 s. This constitutes one trial. One session consists of 40 trials.

After selection of the acceptable trials, we averaged the data from each session. We first compared the magnetic responses for water and 1 M NaCl. For this comparison, we calculated the root mean square (RMS) for all 64 SQUID sensors (every sampling point) according to the following formula:

$$\text{RMS}(t) = \sqrt{\frac{\sum_{n=1}^{64} (X_n(t))^2}{64}},$$

where $X_n(t)$ is the magnitude of the neuromagnetic field at the nth sensor. RMS(t), therefore, represents the total magnitude of the field at all the sensors. Using t-tests, we investigated the differences between the RMS values of data collected 200 ms (50 points) before taste stimulus onset and 800 ms (200 points) after the onset. We found a significant difference ($P < 0.01$) between preonset and postonset RMS values for the presentation of NaCl but no significant difference ($P = 0.23$) for the presentation of water. These results show that there was no significant tactile stimulation and were consistent with the perception of the participants. These findings agreed with the results reported by Kobayakawa *et al.* (1996a). In that study, the authors measured the responses of healthy subjects to control stimuli using the same gustatory stimulus presentation device that we used here and reported that no significant response was found. We show averaged GEMfs from one participant for the presentation of water and the tastant in Figure 2a and b, respectively. In the lower row, we also show contour maps for three latencies; (1) is at the stimulus onset, whereas (2) and (3) are at 100 and 140 ms after the onset, respectively.

Three-dimensional MRI scans were obtained for all the participants (SIEMENS, Erlangen, Germany: 1.0 T). For source modeling, MRI head shape data were used to determine the fitting sphere for each participant. Before the acquisition of MRI data, oil-filled pellets were attached to the physical landmarks used in the MEG experiment. The positional information given by the images of the oil-filled pellets was used to align the MEG data with the participant's MRI. For estimates of the equivalent current dipoles (ECDs), we attempted to minimize the estimation error by using the equation of Grynszpan–Geselowitz (Grynszpan and Geselowitz, 1973). The error, E, was calculated according to the following formula:

$$E = \frac{\sum_{n=1}^{64} (\hat{X}_n - X_n)^2}{\sum_{n=1}^{64} X_n^2},$$

where X_n is the magnitude of the neuromagnetic field at the nth sensor and $\hat{X}_n$ is the calculated magnitude at the same sensor based on the theoretical model. The goodness of fit was calculated as $1 - E$. The locations and the magnitudes of the ECDs in each participant were estimated from the magnetic fields obtained at all 64 sensor positions. The coordinates of the dipole centers of gravity were overlaid on individual MRI slices to identify the corresponding locations in the brain. We evaluated the validity of an estimated ECD using three criteria: (1) the goodness of fit for the ECD should be more than 80%, (2) the ECD should not move more than 5 mm during a 30-ms period and should maintain a suitable power of less than 100 nA, and (3) the ECD should be located in the gray matter of the MRI images because simultaneous EPSPs should occur in the gray matter. We first found the point at which the magnetic fields exhibited a local maximum RMS value with the shortest latency. We estimated ECDs at every sampling point around this time point and chose the ECD with the greatest magnitude that fulfilled the three criteria mentioned earlier. We used the latency and magnitude data of this ECD to investigate the laterality of the gustatory neural pathway. In Figure 2b, the left ECD had a maximum magnitude 100 ms after the stimulus onset, whereas the right ECD had a maximum magnitude 140 ms after the onset. In this example, we observed activation in both sides of the brain. We therefore called the response in this session "bilateral activation."

Results

Activation of PGC

We analyzed 46 sessions of the six participants and identified, in 36 sessions (78.3%), the response of the PGC in the transitional cortex between the insula and the parietal operculum and in the base of the CS. Figure 3 shows an example of the results estimated in the transitional cortex between the insula and the parietal operculum.

The average latencies (average ± SD) of the transitional cortex between the insula and the parietal operculum and the base of the CS were 129 ± 30 ms and 108 ± 16 ms, respectively.

Participants were asked about painful or irritating sensations following stimulations with taste solution, but nobody complained of those sensations. The average perceived intensity of taste was 2.5 ± 0.7 in 36 valid sessions.

Frequency of bilateral, only-ipsilateral, and only-contralateral responses

Table 1 shows the frequency of responses of PGC, classified into three types: the bilateral, only-ipsilateral, and only-contralateral responses of each participant. By the Friedman test, a significant difference was found among the only-contralateral, the only-ipsilateral, and the bilateral responses ($\chi^2 = 7.64$, $P < 0.05$). Furthermore, significant differences were found in the multiple comparison tests (the bilateral vs. the only ipsilateral, $P < 0.05$; the bilateral vs. the only contralateral, $P < 0.01$).

The difference between PGC activation latencies in both hemispheres

All participants showed the bilateral responses in the transitional cortex between the insula and the parietal operculum.
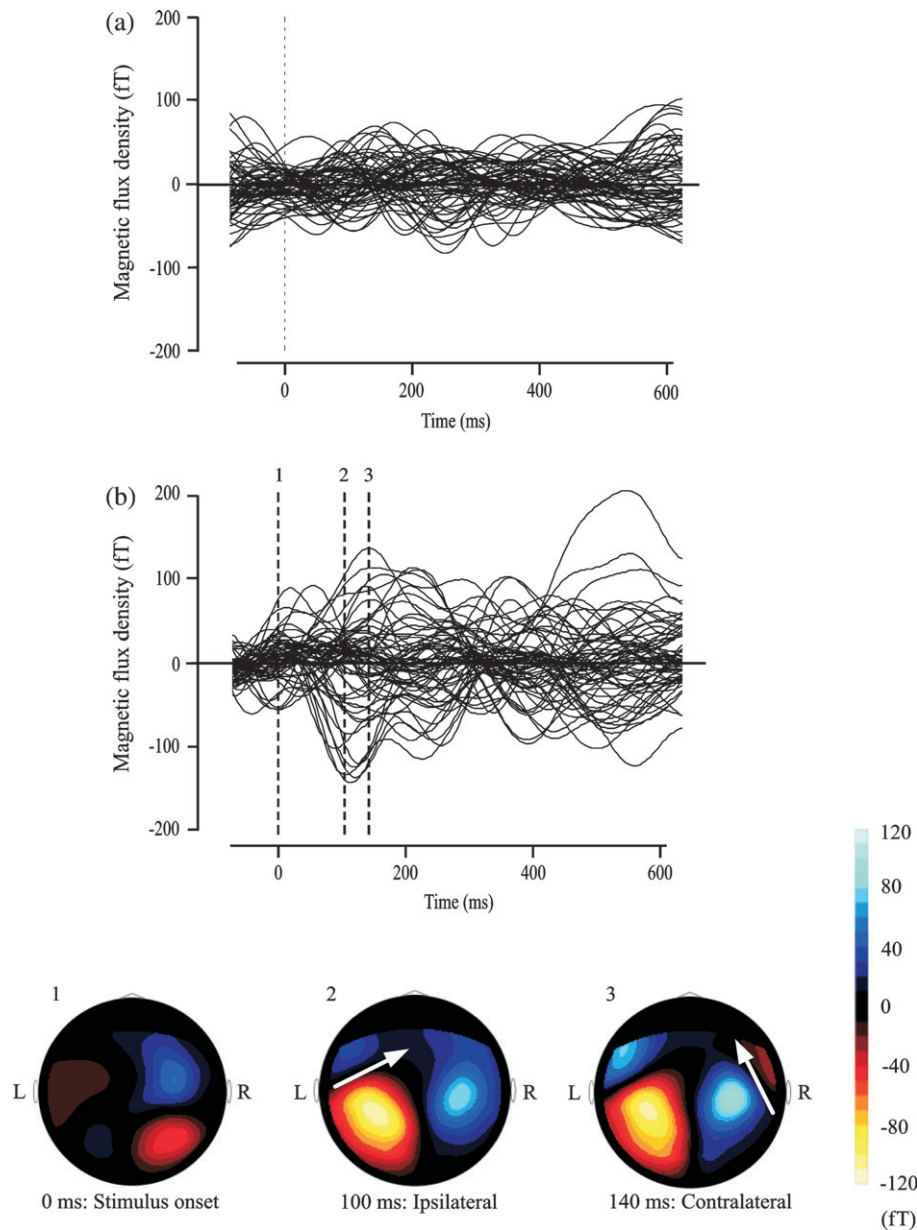
Figure 2   The magnetic responses from one participant to control conditions **(a)** and a taste stimulus **(b)**. (a) Averaged GEMfs for water presentation from 64 recording points were superimposed on the same graph. Instead of the tastant, 36°C deionized water was used as the control. The noise level of the response showed that any tactile stimulus was negligible. (b) In the graph, averaged GEMfs for tastant from 64 recording points were superimposed on the same graph. In the lower part, isocontour maps show the GEMfs. Blue regions demonstrate the source of the magnetic fields, and the red regions are sinks. The white arrows between the blue and red regions display directions of ECDs. The stimulus onset was at 0 ms (1). The left ipsilateral hemisphere responded at 100 ms (2) and the right contralateral hemisphere responded at 140 ms (3) in this experiment.

However, only three participants showed the bilateral responses in the base of the CS, these being too few for statistical analysis. Therefore, we calculated the average latency of each participant in both hemispheres on activation of the transitional cortex between the insula and the parietal operculum and compared the differences by the paired t-test. The average latency of the only-ipsilateral response in six participants was 130 ± 25 ms and that of the only-contralateral response was 133 ± 44 ms. The difference was not significant between the only-ipsilateral side and the only-contralateral side.

Discussion

Activation of PGC

All estimated ECDs with the shortest latencies observed in this study were located in the transitional cortex between the
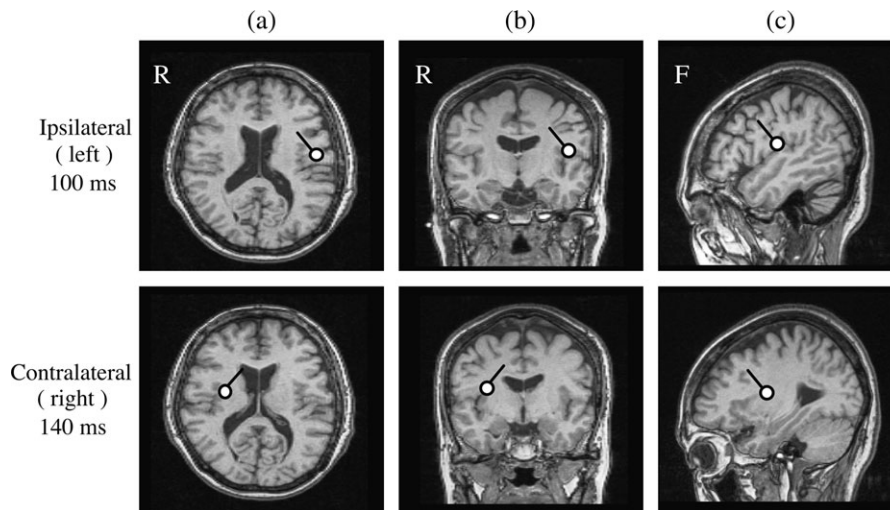
Figure 3 An example of the locations of ECDs plotted on an MRI from one participant. **(a)** An axial view, **(b)** a coronal view, and **(c)** a sagittal view. The white circles show the location of estimated ECDs, and the black line shows the direction of the electrical currents. R shows the right side, and F shows the front. White circles are located in the transition cortex between the insula and the parietal operculum.

Table 1 Frequency of bilateral, only-ipsilateral, and only-contralateral responses of each participant

Participant	Bilateral	Ipsilateral only	Contralateral only
1	4	2	0
2	5	0	2
3	6	0	0
4	5	0	0
5	1	4	0
6	5	2	0
Total	26	8	2

Significant differences were found in a multiple comparison test (bilateral vs. only ipsilateral, $P < 0.05$; bilateral vs. only contralateral, $P < 0.01$).

insula and the parietal operculum or the base of the CS. Previous studies also reported these two areas as having the shortest ECD latencies (Kobayakawa *et al.*, 1999; Mizoguchi *et al.*, 2002). In addition, our finding that the base of the CS showed a shorter latency than the transitional cortex between the insula and the parietal operculum agrees well with the previous MEG studies using healthy participants (Kobayakawa *et al.*, 1999; Mizoguchi *et al.*, 2002).

The latency of the primary sensory response has been measured in other senses. The latency of the somatosensory-evoked field (SEF) by the median nerve stimulation was estimated to be 15–20 ms (Sutherling *et al.*, 1988; Aine *et al.*, 2000; Forss *et al.*, 2001) and that by the posterior tibial nerve was 38 ms (Fujita *et al.*, 1993). The latency of the visual-evoked field (VEF) was 70–100 ms (Aine *et al.*, 1995, 2000; Supek *et al.*, 1999; Moradi *et al.*, 2003) and that of the auditory-evoked field (AEF) was 50 ms (Farrell *et al.*, 1980;

Regan, 1982; Näätänen and Picton, 1987). The average latency of the primary response elicited by the gustatory stimuli in our study was therefore longer than the latencies of the SEF, VEF, and AEF. A possible underlying reason for this increased latency may be that the gustatory stimuli are chemical in nature and the receptors and transduction mechanisms are more complicated, whereas somatosensory, visual, and auditory stimuli are physical stimuli.

Laterality of PGC activation

Significant difference was found in the frequencies of the bilateral, the only-ipsilateral, and the only-contralateral responses by the Friedman test ($P < 0.05$), and more frequent bilateral responses were observed than the only-ipsilateral ($P < 0.05$) or the only-contralateral responses ($P < 0.01$) using the multiple comparison tests. Kobayakawa *et al.* (1996b) examined the laterality of the PGC by providing the gustatory stimuli to the lateral point 2 cm away from the lingual apex. They performed a total of eight sessions, using three healthy participants and reported that the bilateral responses were obtained in six sessions and the ipsilateral responses in two sessions. This result supports the findings of the present study, although the data pool was small. Murayama *et al.* (1996) also performed a total of five sessions, using four healthy participants, and reported that the bilateral responses were obtained in two sessions and the contralateral responses in three sessions. This result is in disagreement with the findings of the present study. However, the dropper method of the stimulus application used in the study would create an artifactual tactile component, so it would be difficult to prove their results to be tactile-free gustatory responses. From our data, we conclude that the gustatory stimulation will activate the PGC bilaterally in humans.

Laterality of the central gustatory pathway

In rats, the gustatory pathway ascends from the rostral region of the nuclei of the solitary tract to the pontine para-branchial nuclei (Norgren and Leonard, 1973). It then diverges and terminates, via the bilateral thalamic relay nucleus for taste (Ganchrow and Erickson, 1972), in the bilateral insula (Yamamoto and Kawamura, 1977).

In squirrel monkeys, a New World monkey, the gustatory pathway ascends from the rostral region of the nuclei of the solitary tract and terminates, via the ipsilateral ventral post-eromedial thalamic nucleus, parvicellular part (Beckstead et al., 1980), in the surface of the anterior opercular–insular cortex near the rostral end of the lateral sulcus in the ipsi-lateral hemisphere (Benjamin and Burton, 1968; Benjamin et al., 1968). In the macaque monkey, an Old World monkey, the gustatory pathway was similar to that of the squirrel monkey, and the gustatory cortex was located more dorsally than the New World monkey (Ogawa et al., 1985).

In humans, the chorda tympani and glossopharyngeal nerves are known to terminate in the nuclei of the solitary tract (Nageotte, 1906). The pathway above the pons has merely been inferred from physiological studies and from patients with cerebral diseases (Börnstein, 1940a; Motta, 1959; Onoda and Ikeda, 2003), and its detailed course remains unclear. Patients with lesions from the lower to upper parts of the pons tend to display ipsilateral taste disorders (Goto et al., 1983; Nakajima et al., 1983; Pascual-Leone et al., 1991; Lee et al., 1998; Uesaka et al., 1998; Hoshino et al., 1999; Onoda and Ikeda, 1999, 2003; Combarros et al., 2000). The pathway is presumed to ascend ipsilaterally to the upper part of the pons. Other studies on this central pathway in monkeys and rats support this hypothesis.

In the present study, unilateral stimulation of the chorda tympani nerve caused significant bilateral responses in the PGC, and this result leads us to infer the existence of at least two pathways above the pons. One is the pathway in humans that diverges en route to and terminates at the PGC in both hemispheres, as in rats. The other is a gustatory pathway that terminates at the unilateral PGC and then leads to its counterpart in the other hemisphere via the corpus callosum, similar to the visual and auditory pathways that eventually terminate on both sides.

The callosal conduction time of vision is 14–20 ms (Andreassi et al., 1975; Ledlow et al., 1978; Rugg et al., 1984; Terasaki and Okazaki, 2002), which is the same as that of the auditory (Mononen and Seitz, 1977) and somatosensory (Gott et al., 1985) systems. In our study, the difference in average latencies of the responses of the transitional cortex between the insula and the parietal operculum between both hemispheres was 3 ms, which is considerably lower than the callosal conduction times of the visual, auditory, and somatosensory systems. Furthermore, the difference between the average latencies of PGC activation in both sides was not statistically significant. Our results, therefore, support the former hypothesis that the gustatory pathway above the pons diverges, ascends bilaterally, and terminates at the PGC in both hemispheres. This hypothesis coincides with the well-known fact that the optical nerve diverges in the chiasma opticum and the cochlear nerve diverges in the medulla oblongata and the pontine cochlear nuclei, and they terminate in both hemispheres. It is also compatible with our clinical experience that the cases with taste disorders caused by central vascular disorders are very rare comparing with its very high incidence.

There are several reports on patients with taste disorder in whom midbrain lesions caused an ipsilateral taste disorder (Johnson, 1996; Shikama et al., 1996) or a contralateral one (Lee et al., 1998). Thalamic lesions can also cause ipsilateral (Combarros et al., 1994) or contralateral taste disorders (Adler, 1933; Gänshirt, 1949; Stockert, 1951; Fujikane et al., 1999; Onoda and Ikeda, 1999). A lesion at the posterior limb of the internal capsule was found to cause a contralateral taste disorder (Onoda and Ikeda, 1999). A lesion in the corona radiata also caused a contralateral taste disorder (Fujikane et al., 1999). Insular lesions can cause ipsilateral (Pritchard et al., 1999; Kim and Choi, 2002) and bilateral taste disorders (Pritchard et al., 1999; Cereda et al., 2002; Kim and Choi, 2002; Mathy et al., 2003). Our hypothesis that the gustatory pathway diverges and ascends bilaterally and terminates at the PGC in both hemispheres could explain the relationship between these lesions and the laterality of taste disorders. Based on our findings, the bilateral response is considered unlikely to occur by way of the corpus callosum. We infer that a unilateral taste signal diverges en route to and terminates at the PGC, the transitional cortex between the insula and the parietal operculum, in both hemispheres. However, when we suppose that the gustatory pathway diverges en route to, ascends bilaterally, and terminates at the PGC, there is a possibility that taste disorders do not occur as a result of unilateral central lesions. However, there are actually some reports of taste disorders that occurred from unilateral central lesions above the pons. In rats, there is a report that approximately two-thirds of the fibers from the parabranchial nuclei lead to the ipsilateral thalamus, while the remainder of the fibers lead to the contralateral thalamus (Ogawa and Akagi, 1978). Therefore, we suppose that a dominant conducting pathway should also exist in humans. Further investigations are needed to clarify this.

Acknowledgements

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