Emotional modulation of cortical activity during gum-chewing: A functional near-infrared spectroscopy study

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Abstract

Evidence indicates that distinct brain regions are associated with various emotional states. Cortical activity may be modulated by emotional states that are triggered upon chewing with various flavors. We examined cortical activity during chewing with different tastes/odors using multi-channel near-infrared spectroscopy (NIRS). Thirty-six right-handed subjects participated in a crossover-design trial. Subjects chewed flavorful (palatable) or less flavorful (unpalatable) gum for 5 minutes. During gum-chewing these subjects experienced positive and negative emotions, respectively. Subjects rated the taste/odor/deliciousness of each gum with a visual analog scale. Bilateral hemodynamic responses in the frontal to parietal lobes, bilateral masseter muscle activation, and heart rate were measured during gum-chewing. Data changes during gum-chewing were evaluated. Subjects' ratings of the tastes and odors of each gum differed ($p<0.001$). Hemodynamic response changes were significantly elevated in the bilateral primary sensorimotor cortex during gum-chewing, in comparison to resting. The hemodynamic responses of wide brain regions showed little difference between the gum conditions; however, a difference was detected in the corresponding left frontopolar/dorsolateral prefrontal cortex. Muscle activation and heart rate were not significantly different between the gum conditions. Differential processing in the left prefrontal cortex might be responsible for emotional states caused by palatable and unpalatable foods.

Introduction

Chewing behavior is necessary for the digestion and absorption of various nutrients. In addition to these functions, chewing is tightly linked to emotional systems in the brain [1]. Food flavor, important in our self-perception of eating behavior, is a complicated sensation (e.g., taste, smell, temperature sensation, mechanoreceptive sense, and masticatory movement) formed by the synthesis of information from various sensory modalities. Sensory signals are individually processed in the gustatory and olfactory neural circuits in the brain, then integrated as a sensation of flavor in the insular and orbitofrontal cortical areas [2,3]. Cortical flavor information is further transmitted to the brain reward system, including the nucleus accumbens, midbrain dopamine areas, amygdala, and hypothalamus [3,4]. Hedonic (pleasure–displeasure) responses represent the first level of emotional experience [5]. Emotions related to eating affect the autonomous and motor functions of the whole body through the hypothalamus. Meals that seem delicious relieve muscle tension and relax the mind and body [6].

We previously revealed that cortisol release during palatable gum-chewing was significantly higher than that during unpalatable gum-chewing [7]. In addition, prefrontal cerebral blood flow during the chewing of gum with a palatable taste/odor showed higher values in comparison to cerebral blood flow during the chewing of gum without a palatable taste/odor [8]. Near-infrared spectroscopy (NIRS) can measure the hemoglobin (oxy-Hb) concentration as an indicator of the hemodynamic response [9]. We showed that food-related stimuli, including flavor and taste, cause consistent activation of the prefrontal cortex [8]. Our understanding of emotional influences, with respect to hemodynamic responses and the endocrine

system, depends on afferent sensory systems. Functional near-infrared spectroscopy (f-NIRS) is based on changes in spectral absorbance of both oxyhemoglobin (oxy-Hb) and deoxyhemoglobin (deoxy-Hb) detected by surface-mounted optodes [10-13]. These hemodynamic signals serve as a proxy for neural activity, similarly to hemodynamic signals acquired by functional magnetic resonance imaging (fMRI) [14-16]. f-NIRS is suitable for the measurement of brain activity during orofacial movement because of robust omission of head movement, and as in fMRI, signal sources are registered to standard brain coordinates.

It is known that appetite is enhanced by chronic stress, which causes the persistence of unpleasant emotions [17]; moreover, prefrontal cortex activity is reduced by negative emotions [18]. Hedonic memory is also strongly linked to appetite; previous studies have shown that the hedonic system is closely related to eating behavior. However, these studies did not include simple comparisons of cortical activation between pleasant and unpleasant emotions during chewing.

Thus, this crossover study aimed to clarify whether cortical activity is modulated by emotional states triggered by chewing items with different flavors. To investigate this, we clarified cortical activity during gum-chewing caused either pleasant or unpleasant emotions by means of f-NIRS, and changes in positive/negative emotions caused during chewing gum of different tastes and odors.

Material And Methods

The study protocols were approved by the Ethics Committee of Hyogo College of Medicine (approve num-2209). The study protocol was also registered in the UMIN CTR Japan Primary Registries Network (UMIN00025567). This study was conducted in compliance with the Declaration of Helsinki and according to the Ethical Guidelines for Medical and Health Research Involving Human Subjects established by the Ministry of Health, Labour, and Welfare in Japan. Written informed consent was obtained from all study participants.

Study protocol

Thirty-six right-handed volunteers (19 males and 17 females; mean age, 28.0 ± 4.0 years) who reported no history of medical/psychiatric disorder or medication use participated in this study; all subjects provided their written informed consent after receiving an explanation of the experimental protocol, as approved by the institutional ethics committee of Hyogo College of Medicine.

The experimental protocol is shown in Figure 1. All experiments were performed in a shielded room, with the room temperature set at 25°C. Chewing tests were undertaken at least 4 hours after meals. Subjects were instructed to sit on a chair with their necks supported by a head rest, and their eyes gently closed.

We prepared two types of gum with different flavors: (1) a lemon-flavored sweet gum (Freezone; Lotte, Tokyo, Japan) that could induce a positive emotion (palatable gum), (2) a salty licorice-flavored sweet gum (Lotte, Tokyo, Japan) that could induce a negative emotion (unpalatable gum). We note that salty licorice is a displeasing and unfamiliar flavor for most Japanese people during their first experience. We

instructed the subjects to chew the tested gum at a comfortable rhythm at a constant speed of 70 chews per minute, using a metronome sound [19]. A piece of chewing gum was placed into the mouth of the subject by an examiner, immediately before the start of chewing; it was removed from the mouth by the examiner, immediately after the end of chewing. The subjects rated the taste/odor/deliciousness of each tested gum using a visual analog scale (VAS:0-100 = Very bad-Very good) after test chewing. They then rinsed their mouths with mineral water and rested for 10 minutes before chewing the other test gum. To evaluate the association between the change of the hemodynamic response and emotion, the relative value of the VAS was evaluated using the following formula.

Palatable gum =X/{(X+Y)/2}, Unpalatable gum=Y/{(X+Y)/2}

X: VAS of palatable gum

Y: VAS of unpalatable gum

NIRS monitoring

A 55-channel f-NIRS system was used to detect chewing-induced hemodynamic changes in the cerebral cortex (**Figure 2**). The f-NIRS system uses three wavelengths (780, 805, and 830 nm) of continuous near-infrared light (LABNIRS; Shimadzu Corp., Kyoto, Japan) with 19 light sources and 19 detectors; its sampling rate is 3.3 Hz. Each optode (light sources/detectors) was attached to the skull surface using a custom-made hard plastic cap, with an inter-optode distance of 3.0 cm. We defined the f-NIRS channel as the midpoint of the corresponding light source-detector pair.

The probe position was acquired by a 3D digitizer and projected on the standard brain coordinates, and the cerebral cortex area where the blood flow change occurred was identified. The transformation of the probe and channel positions into standard brain coordinates was performed using NIRS _SPM_v4 [20] running on MATLAB (MathWorks, Inc.). The position of 55 channels was calculated as the midpoint between the emitter probe and the detection probe. Since the probe positions were available from 6 subjects, we calculated the mean MNI coordinates for each channel and used them as the channel position coordinates of all subjects.

Cortical regions corresponding to each of the 55 channels were estimated using the Anatomy 1.8 toolbox for SPM[21] (**Table 1**).

Masseter muscle activity

Electromyograms of the bilateral masseter muscles were measured to monitor orofacial motor output during gum-chewing, in a manner similar to that of a previous report [22]. Surface electrodes were attached to the skin over the masseter. Analog signals were amplified by a bio-amplifier (BA-1008, TEAC, Tokyo, Japan) and stored in a personal computer for an offline analysis. The sensitivity, time constant, and high-pass filter values of the amplifier were set as 100 μV, 0.03 sec, and 3 kHz, respectively. Subjects were asked to clench their jaws with maximum power for 2 seconds to calculate the maximum voluntary

contraction (MVC). Masseter muscle activity during gum-chewing tests was calculated as the relative value of the MVC (%).

Heart rate and autonomic nervous response

Electrocardiography measurements were recorded using bipolar chest leads. Data were amplified with a biological signal telemeter (Polytele STS; TEAC, Tokyo, Japan) and were transferred to a personal computer at a sampling frequency of 1 kHz via an A/D conversion card (CBI-3133A; Interface, Hiroshima, Japan). Electrocardiography data were used to obtain heart rate values with a biomedical signal analysis software program (Fluclet®; Nagaoka & Co., Ltd., Nishinomiya, Japan). In addition, a fluctuation analysis was conducted to determine the RR-interval in electrocardiography by a wavelet analysis with a biomedical signal analysis software program. The high-frequency (0.04-0.15 Hz) component of the RR-interval (RR-HF) was calculated as the index of cardiac vagus nerve activity [23]. The ratio of low-frequency components to high-frequency (0.15-0.40 Hz) components (RR-LF/HF) was calculated as the index of cardiac sympathetic nerve activity [24].

Data analysis

The amplitude of the f-NIRS data was set to zero at the beginning of chewing for each gum-chewing trial. We regarded oxy-Hb as the hemodynamic responses of the original study. We calculated the standard deviation of oxy-Hb during 40-30 seconds just before the start of chewing (regarded as the baseline for rest before chewing), and data were normalized by dividing by this standard deviation. Next, the area under the curve (AUC) was calculated every 30 seconds in order to clarify the changes during chewing and compared to the values before the task. The mean oxy-Hb of 10 seconds (40 to 30 seconds, just before the task) which was a typical rest value, became zero and the AUC during the task (5 minutes) was calculated.

The channel-based AUC values were interpolated on the 3,753 2x2x2 mm voxels on the cortical surface (depth up to 1.8 cm) of the standard MNI brain [20,25,26] to generate an activity map for each condition of each individual [26,27]. A second level group analysis was performed using SPM8 with the voxel-wise datasets to compare differences in cortical activity between conditions.

Changes in each index before and during gum-chewing were evaluated using the AUC. Using the median values of each index 5 min before gum-chewing as the baseline, variations during and after gum-chewing were calculated for each index. Changes in each AUC due to tasks were evaluated using a one-sample Kolmogorov-Smirnov test. To evaluate temporal changes, representative values were calculated every 30 seconds. A repeated analysis of variance was performed to investigate changes in each index between baseline (median value for 5 minutes before chewing started) and each 30-second interval after the start of chewing. If a difference was significant, comparisons were made between values before gum-chewing and those in other intervals using the Dunnett test. To compare two samples (palatable gum vs. unpalatable gum, left vs. right for the same position channel), Paired *t*-tests or two-sample *t*-tests were

performed. Spearman's rank correlation was used to analyze the correlation between the AUC of oxy-Hb and the sensory evaluation.

All statistical analyses were performed using a commercially available software package (IBM SPSS Statistics, Version 22.0.0 for Windows; SPSS, Chicago, IL, USA). The level of significance was set at 5%.

Results

Sensory test

Subjective estimates of the taste, odor and deliciousness of tested gums are shown in **Figure 3**. The subjects' ratings differed significantly with respect to the taste, odor and deliciousness of the gums. These data suggest that subjects could discriminate the type of gum tested without prior information. **Figure 4** shows representative oxy-Hb, heart rate, cardiac vagus nerve activity (RR-HF), cardiac sympathetic nerve activity (RR-LF/HF) and left/right masseter mass activities during pre- and post-chewing.

The change of hemodynamic responses induced by chewing

Figure 5 shows the temporal change of oxy-Hb for each of 55 channels. Regardless of the type of gum, oxy-Hb in both hemispheres increased in the area of primary sensorimotor cortex area during gum-chewing. For channels at the prefrontal area, oxy-Hb decreased immediately after the start of chewing; after 120 seconds, the oxy-Hb value nearly recovered to the baseline value, and remained at this level for the remaining time. Notably, the oxy-Hb in the bilateral sensory and motor cortexes showed remarkable and statistically significant increases due to chewing in comparison to the prefrontal cortex. There were no channels in the right frontal region that showed a significant increase in oxy-Hb during chewing of either type of gum.

Comparison of the hemodynamic responses changes between palatable and unpalatable gum

In the comparison of the AUCs of oxy-Hb changes between palatable and unpalatable gum, only channel 3 in the left frontopolar cortex showed a statistically significant difference during gum-chewing, specifically, the chewing of unpalatable gum increased the oxy-Hb value more in comparison to palatable gum (**Table 1**). Channels 1 ($P = 0.078$) and 8 ($P = 0.081$) showed the same tendency, wherein the oxy-Hb increased more with the chewing of unpalatable gum in comparison to palatable gum. **Supplemental file 1** shows the AUC of oxy-Hb that remained after subtraction of the AUC of oxy-Hb during palatable gum-chewing from the AUC of oxy-Hb during unpalatable gum-chewing for every 30 seconds. In the left frontal area (corresponding to frontopolar and dorsolateral prefrontal cortex), especially during the 30–90 seconds from the start of gum-chewing, the oxy-Hb value during the chewing unpalatable gum was higher than that during the chewing of palatable gum.

The comparison of the AUCs of oxy-Hb during gum-chewing in the hemispheres, revealed that the corresponding pre-motor and supplementary motor cortex/ supplementary eye fields including the frontal

eye fields cortex showed higher values in comparison to the right hemisphere during the chewing of both palatable and unpalatable gum (channel 13 and 16 in **Figure 5**).

The correlations between subjective evaluations and hemodynamic responses

There was a significant weak negative correlation between the AUC of oxy-Hb and the sensory evaluation by VAS for deliciousness in channel 3 (r=-0.267, P=0.023). There was no channel in which the AUC of oxy-Hb and sensory test showed a significant correlation with taste and odor. These data indicate that the relationships between emotional changes due to taste and odor and the hemodynamic responses were not represented by a simple correlation.

Heart rate, autonomic nerve activity and masseter muscle activity

Figure 6 shows that the heart rate was significantly increased during the chewing of both palatable and unpalatable gum. No significant difference between the types of gum was observed for changes in heart rate for each 300 seconds chewing. Because the types of gum were compared every 30 seconds, the heart rate during the chewing of unpalatable gum was revealed to be higher than that during the chewing of palatable gum for a brief period (60 to 90 seconds after the start of chewing). HF decreased significantly, while LF/HF increased significantly, during the chewing of both types of gum. In particular, these parameters showed significant changes immediately after the start of chewing. No significant differences between the types of gum were observed in the AUCs of either HF or LF/HF during the chewing of each type of gum. On the other hand, significant differences were observed between the gums in heart rate and autonomic nerve activity in certain 30-second periods. When masseter muscle activity was compared between the types of gum, no significant difference was observed. Thus, there were no differences between the two types of gum in cardiovascular or muscle activity, and the momentum for each type of gum was almost identical; differences in emotion caused no differences in momentum.

Discussion

The distinct brain regions are known to associate with various emotional states, and cortical activity may be modulated by emotional states that are triggered upon chewing with various flavors. This study was conducted to clarify the hemodynamic responses during chewing with different tastes/odors by f-NIRS. As a result, changes in hemodynamic responses were significantly elevated in the bilateral primary sensorimotor cortex during gum-chewing, in comparison to resting conditions. There were few differences in the hemodynamic responses of wide brain regions between the palatable and unpalatable gum conditions. Meanwhile the difference in hemodynamic response was detected in few channels, corresponding to the left frontopolar/dorsolateral prefrontal cortex. The muscle activity and autonomic nerve activities with the two gum conditions were almost the same.

Multi-channel f-NIRS, which was used in this study, can be used to monitor cortical activity changes and has various advantages: it can quantitatively evaluate neural activity with high temporal resolution on channel set-up, the device is compact, and it exhibits no restrictions with respect to measurement

location. Because the constraints during measurement are small, fNIRS enables experiments in a real-world setting with limited body movement ** (e.g., chewing [28-30]). This method can omit head movement during the analysis (e.g., chewing).

It is known that the anterior insula and adjoining frontal opercula cortex constitute the primary taste cortex; caudal parts of the orbitofrontal cortex constitute the secondary taste cortex [31,32]. These two cortical areas have been shown to be activated by taste in human neuroimaging studies using positron emission tomography (PET) and functional magnetic resonance imaging [33-38]. Our study aimed to clarify whether cortical activity is modulated by emotional states triggered by chewing items with different flavors. To investigate this, we examined cortical activity during the chewing of gums with different tastes and odors by means of multi-channel f-NIRS.

Among the emotions associated with eating, we focused on simply “palatable” or “unpalatable,” or a comparison of pleasure and displeasure. In this study, cortical activities in the left prefrontal cortex, corresponding to the dorsolateral prefrontal cortex (DLPFC), increased during unpalatable gum-chewing in comparison to palatable gum-chewing. The prefrontal cortex is thought to be the center of cognitive functions, such as attention, learning, thought, memory, and action. In the prefrontal cortex, DLPFC is considered to control the execution function, which is deeply related to memory, attention, learning, and behavior [39-41]; PET studies have found that changes in DLPFC were related to reward value [34,36]. Kringelbach et al. showed activation in the left DLPFC region associated with taste or taste/odor combinations [37]. The prefrontal cortex, including DLPFC, is known to be responsive to exercise [42]. During low-intensity exercise, the left DLPFC activity is evoked [43]. In addition, young adults typically demonstrate left-lateralized frontal activation during light-intensity exercise [44]. Notably, chewing movement is a light-intensity exercise; thus, our results are consistent with prior studies.

Palatable gum has been marketed for many years in Japan, and is known to have a popular taste/odor; thus, the majority of subjects might be able to chew this gum with minimal attention, such as during semi-voluntary exercise (e.g., walking) for 300 seconds. Conversely, unpalatable gum has a displeasing flavor and is not delicious for most Japanese individuals. Moreover, the subjects were under stressful/negative-emotion conditions, in that they were asked to chew according to the rhythm of the metronome; thus, they had to expend greater effort with respect to the act of chewing in comparison to palatable gum. As a result, the chewing of unpalatable gum was a more voluntary exercise than the chewing of palatable gum. Cortical activities in the left frontal lobe, corresponding to the DLPFC, showed a higher value during the chewing of unpalatable gum than during the chewing of palatable gum.

For oxy-Hb changes in frontal lobe, the left hemisphere was significantly more increased by chewing in comparison to the right hemisphere; this may be because there is a language center in the left hemisphere [45]. Because all of the subjects in this study were right-handed, the language center was likely located in the left hemisphere. In this research condition, gum-chewing was performed in conjunction with a metronome, and the experimental room was always associated with the metronome sound. In this

study, afferent stimulation with the sound may have occurred in the language cortex, such that the left frontal lobe may have been activated.

The cortical activity changes in the primary sensorimotor cortex were increased, in comparison to the frontal lobe, likely because chewing is considered a semi-voluntary exercise. In the frontal association area, the more anterior portion is responsible for higher information processing. For example, the lateral frontal association cortex (frontal pole) is a unique cortex to humans, which plays an important role in complicated, abstract cognitive manipulation. Our previous study clarified that taste and odor can influence brain activation during chewing in sensory, cognitive, and motivational processes, but not in motor control [8]. In addition, cortical activity in bilateral hemispheres showed the highest value approximately 90 seconds after the start of chewing, and a tendency for high values to be maintained during chewing was also shown in our previous study [22]; notably, gum-chewing causes increased oxy-Hb because it is a low-intensity exercise [8,22].

Our results showed that body circulation and chewing muscle activity were comparable between the two types of gum. We found weak negative correlations between subjective evaluation and the cortical activity change in the left frontal cortex. It is known that cortical activity increases with brain activity, and right hemisphere superiority is likely related to the stimulation of the taste [46]and odor [47,48] pathways. Stimulation with palatable gum (familiar flavor for subjects) might cause reduced activation of the left hemisphere.

The present study was associated with some limitations. Importantly, there is no conclusive evidence to support that either emotion or preference is asymmetrically represented in the brain area. Because f-NIRS monitors changes in cortical activity on the surface of the cortex, the activity of the area deeply involved in taste/odor (i.e., gustatory and olfactory neural circuits) cannot be evaluated by our experiment. Multichannel f-NIRS has high spatial resolution, but accurate activation of the cortex area cannot be specified. Our study can only estimate the brain locations relative to the position where the channel is installed.

Conclusions

Regardless of the type of gum, oxy-Hb in both hemispheres increased in the primary sensorimotor cortex area during gum-chewing. Emotional changes due to taste and odor influence the left frontopolar/dorsolateral prefrontal cortex during gum-chewing; moreover, the relationships between emotional changes due to taste and odor and the activity of the cerebral cortex cannot be represented by a simple correlation. That is, the cortical activity induced by gum-chewing in this study changed according to taste and odor stimulation; however, the effect of emotional stimulation might be difficult to infer in the cerebral cortex.

Abbreviations

near-infrared spectrometer (NIRS), concentration of hemoglobin (oxy-Hb), gum-modulated positive motivation (palatable gum), gum-modulated negative motivation (unpalatable gum), high-frequency (0.04-0.15 Hz) component of RR interval (RR-HF), ratio of low-frequency components to high-frequency (0.15-0.40 Hz) components (RR-LF/HF), positron emission tomography (PET), dorsolateral prefrontal cortex (DLPFC)

Declarations

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Author responsibilities

Y.H., A.S., H.H., J.S., M.S., T.S., Y.O. and O.T. conceived and designed the research, reviewed data; Y.T. and H.K. made a critical revision of the manuscript; A.S., J.S., M.S. and T.S. collected data, performed the statistical analysis and drafted the manuscript. All authors had reviewed the manuscript.

Conflict of Interest

The authors declare no conflicts of interest in association with the present study.

Sponsor's Role

We have no sponsors to disclose.

Data availability

The datasets that were analyzed will be available from the corresponding author on reasonable request.

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Table

Table 1: Comparison of the hemodynamic responses during the chewing of palatable gum and npalatable gum, comparison of the AUCs during gum-chewing. P-value: Wilcoxon signed rank est. *: There was a significant difference between the palatable gum and unpalatable gum onditions.

Cortical areas corresponding to the channel

Cortical areas corresponding to each of the 55 channels were estimated using the Anatomy 1.8 toolbox for SPM [21]. The sable shows more than 5% area

FPC, Frontopolar; DLPFC, Dorsolateral prefrontal cortex; SEF, supplementary eye fields includes frontal eye fields; PM/SMA; Pre-Motor and Supplementary Motor Cortex; M1, Primary Motor Cortex; S1, Primary Somatosensory Cortex; STG, Superior Temporal Gyrus; SMAss, Somatosensory Association Cortex; SMGy, Supramarginal gyrus part of Wernicke's area; STGy, Primary and Auditory Association Cortex; T1, Subcentral area (primary taste cortex)

unpalatable gum		Palatable gum		palatable vs palatable			
Channel	mean	S.D.	mean	S.D.	P-value	Cortical region	Broadman area
CH1	-21.4	1224.6	-1344.9	918.4	0.078	FPC	10
CH2	-473.4	1493.4	-480.5	813.3	0.706	FPC	10
CH3*	**-69.8**	**564.4**	**-1160.1**	**492.5**	**0.037**	FPC	10
CH4	-641.6	627.1	-619.5	489.8	0.912	FPC	10
CH5	347.5	609.9	-420.1	481.5	0.167	FPC	10
CH6	-5.8	237.0	-573.3	310.9	0.136	FPC, DLPFC	9,10
CH7	-315.8	379.4	-705.8	597.2	0.765	FPC, DLPFC	9,10
CH8	503.0	185.4	13.4	153.0	0.081	DLPFC, SEF	8,9
CH9	82.8	532.5	-339.0	333.8	0.925	DLPFC, SEF	8,9
CH10	663.5	512.9	313.4	328.6	0.414	DLPFC, SEF	8,9
CH11	226.2	611.5	-317.2	329.9	0.660	DLPFC, SEF	8,9
CH12	270.8	303.7	179.8	122.4	0.765	DLPFC, SEF	8,9
CH13	241.7	110.4	455.0	151.7	0.271	SEF, PM/SMA	6,8
CH14	243.0	262.4	-153.1	173.4	0.148	SEF, PM/SMA	6,8
CH15	386.0	429.8	255.5	290.3	0.753	DLPFC, SEF	8,9
CH16	226.7	261.1	356.6	183.2	0.802	SEF, PM/SMA	6,8
CH17	427.1	313.7	-26.5	214.3	0.251	SEF, PM/SMA	6,8
CH18	212.1	68.4	194.3	85.8	0.777	PM/SMA	6
CH19	219.4	92.6	261.1	88.6	0.765	PM/SMA	6
CH20	388.0	151.0	236.6	74.1	0.582	PM/SMA	6
CH21	554.5	147.3	152.6	204.9	0.215	PM/SMA	6
CH22	1348.2	375.5	1472.0	375.0	0.802	PM/SMA, M1, Subcentral area	4,6,43
CH23	1838.6	1388.9	125.9	267.4	0.265	PM/SMA, M1, S1	3,4,6
CH24	796.1	556.8	181.5	117.9	0.671	PM/SMA, M1, S1	3,4,6
CH25	284.2	170.1	284.7	121.0	0.509	PM/SMA	6
CH26	561.8	181.5	442.8	168.1	0.912	PM/SMA, M1, S1	3,4,6
CH27	584.6	307.7	-132.1	600.5	0.489	PM/SMA,DLPFC	6,9
CH28	2048.3	863.1	2220.4	433.2	0.777	PM/SMA, M1, S1, Subcentral area	1,2,3,4,6,43
CH29	486.1	220.7	693.2	202.3	0.937	PM/SMA, M1, S1	1,2,3,4,6
CH30	92.2	94.7	124.1	72.6	0.925	S1	1,2,3

CH31	207.7	98.8	184.4	71.4	0.937	PM/SMA, M1, S1	3,4,6
CH32	186.4	113.1	98.2	100.3	0.551	PM/SMA, M1, S1	3,4,6
CH33	418.8	138.2	166.9	190.4	0.900	PM/SMA, M1, S1	1,3,4,6
CH34	1102.1	223.3	217.0	564.9	0.203	PM/SMA, M1, S1	1,3,4,6
CH35	2233.9	619.0	1750.2	775.1	0.671	PM/SMA, M1, S1, Subcentral area	3,4,6,43
CH36	505.8	351.3	865.1	189.8	0.925	S1, SMGy	1,2,3,40
CH37	162.0	306.5	266.3	117.6	0.423	S1, SMGy	1,2,40
CH38	58.7	384.5	103.1	197.2	0.706	M1, S1, SMAss	1,2,3,4,5
CH39	706.8	294.9	303.6	204.3	0.561	M1,S1	1,2,3,4
CH40	627.4	196.2	170.1	277.4	0.912	S1, SMGy	1,2,3,40
CH41	757.0	215.3	341.7	551.4	0.615	PM/SMA, M1, S1, SMGy	1,2,3,4,6,40
CH42	841.9	483.5	880.0	319.4	0.850	STG, SMGy, STGy	22,40,42
CH43	448.5	331.8	704.7	182.8	0.789	SMGy	40
CH44	103.0	412.6	309.3	189.0	0.814	S1, SMAss, SMGy	2,5,40
CH45	583.4	439.2	92.1	361.9	0.182	SMAss	5,7
CH46	559.6	399.3	275.4	357.8	0.405	S1, SMAss	2,3,5,7
CH47	1591.0	443.9	155.3	690.2	0.338	S1, SMAss, SMGy	2,5,40
CH48	663.2	226.8	542.7	273.8	0.561	S1, SMGy	1,2,40
CH49	1252.6	602.2	1435.6	694.7	0.683	S1, SMAss, SMGy	2,40,42
CH50	52.0	486.5	394.3	368.1	0.888	SMGy	40
CH51	583.5	427.2	772.0	236.6	0.900	SMGy	40
CH52	336.5	386.7	164.5	238.4	0.441	SMAss, SMGy	5,7,40
CH53	596.7	297.8	200.3	231.4	0.307	SMAss	5,7
CH54	902.9	404.6	338.2	548.7	0.423	SMGy	40
CH55	654.6	320.0	415.0	294.6	0.753	SMGy	40

Figures

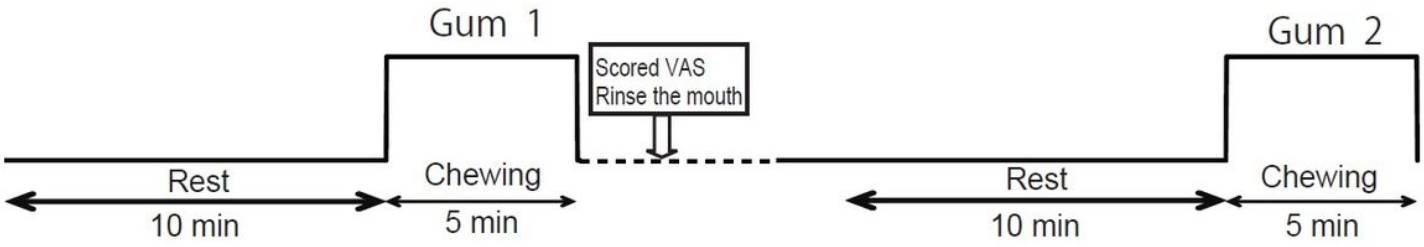

Figure 1

Experimental protocol. The order of palatable gum and unpalatable gum was random.

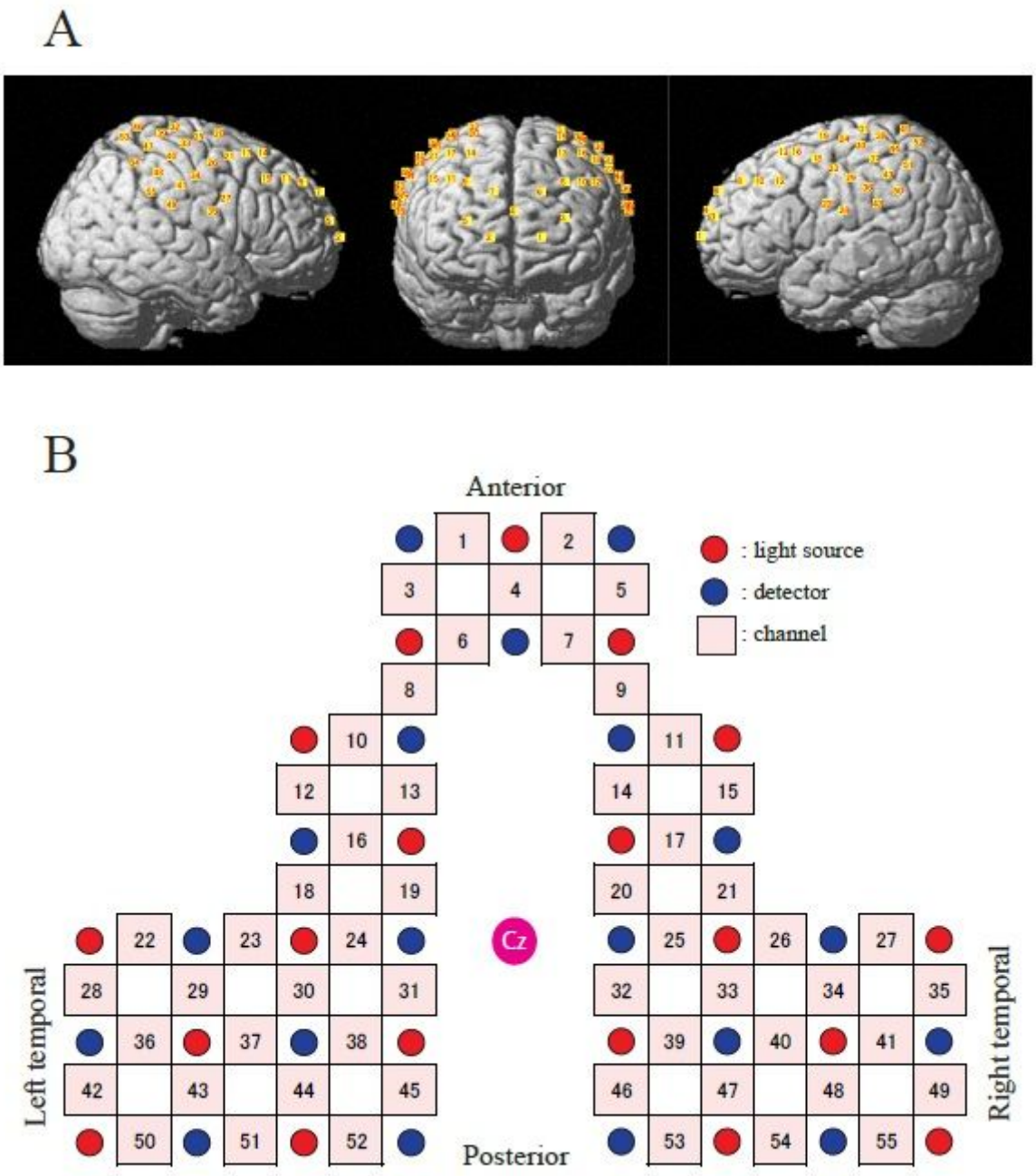

Figure 2

Channel location on the cortical surface A: The predicted location of each channel on the cortical surface. Front, Right and left hemispheres of a single rendered brain illustrate average locations for the 55 channels identified by number. B: A schematic illustration of the location of each optode and channel. Cz represents the vertex.

Figure 3

Results of sensory testing The Y-axis scale shows the sensory testing results. The data for each gum were calculated using the following formula. Palatable gum =X/{(X+Y)/2}, Unpalatable gum=Y/{(X+Y)/2} X: VAS of palatable gum, Y: VAS of unpalatable gum □: indicates a significant difference between unpalatable gum and palatable gum (paired t-test, p< 0.001)

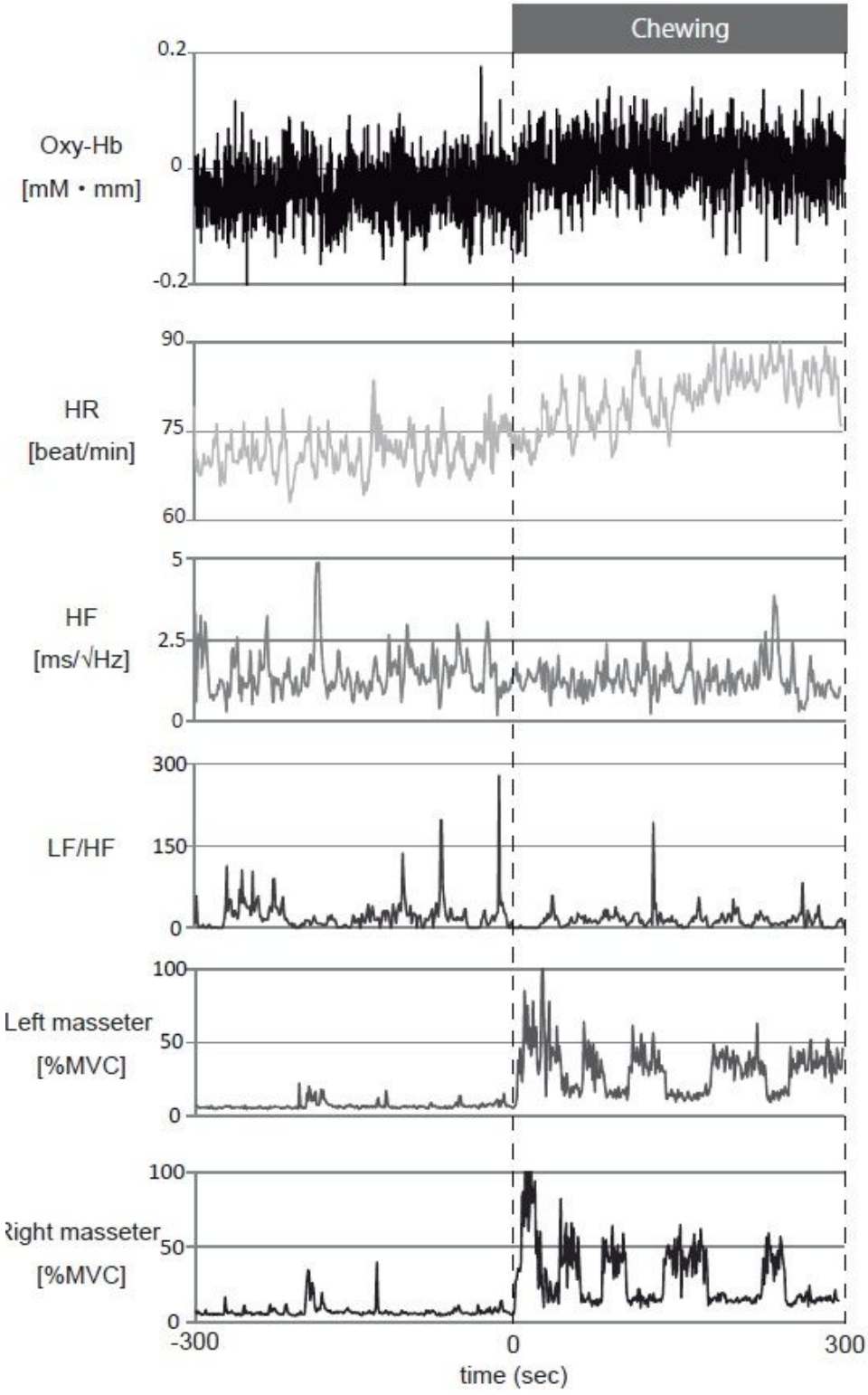

Figure 4

Representative temporal changes in oxyhemoglobin (oxy-Hb), heart rate (HR), cardiac vagus nerve activity (RR-HF), cardiac sympathetic nerve activity (RR-LF/HF) and left/right masseter mass activity (l-%MVC, r-%MVC) during gum-chewing. -300 to 0 seconds: before chewing, 0 to 300 seconds: during chewing. Calculations represent values per second for data.

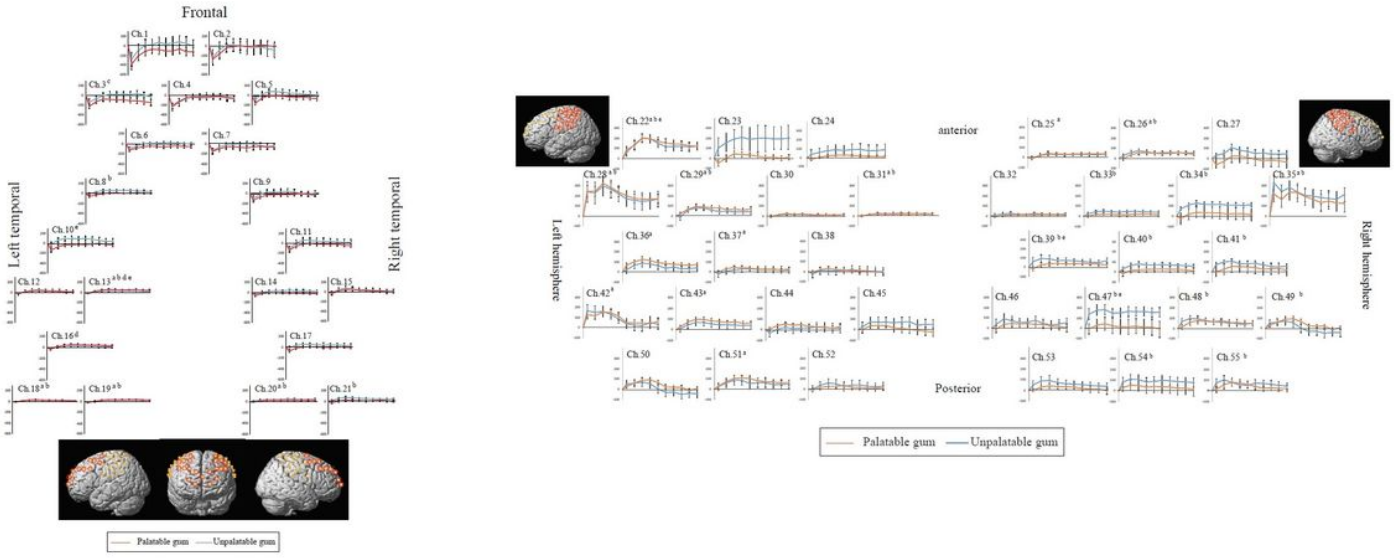

Figure 5

Temporal profiles of changes of the hemodynamic response during the chewing of palatable/unpalatable gums. A: Channels of the frontal area, B: Channels of the temporal and parietal area 3D figure images show the channel positions (red circle). Blue line: unpalatable gum. Red line: palatable gum. Data are represented as the mean ± SEM every 30 sec. Each plot and error bar shows the mean and S.E. for the area under curve (AUC) of the hemodynamic response before and during chewing. a: A significant increase in AUC was observed by chewing of palatable gum. b: A significant increase in AUC was observed by chewing of unpalatable gum. c: S significant decrease in AUC was observed by chewing of palatable gum. d: Significantly higher than the contralateral side during the chewing of palatable gum e: Significantly higher than the contralateral side during the chewing of unpalatable gum

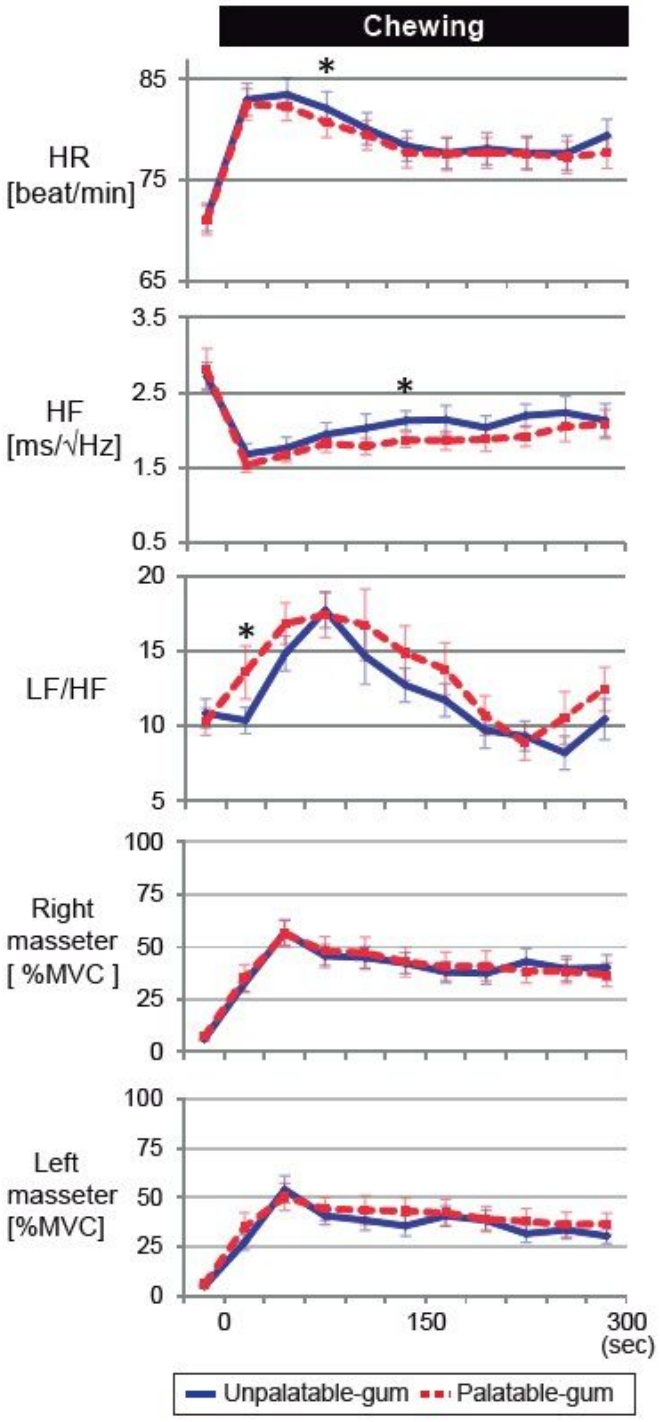

Figure 6

Temporal changes in heart rate, autonomic nerve activity, and bilateral masseter muscle activity : indicates a significant difference for these 30 seconds between palatable gum and unpalatable gum. Blue line: unpalatable gum. Red line: palatable gum.

Supplementary Files

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