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Association of Oral Fat Sensitivity with Body Mass Index, Taste Preference, and Eating Habits in Healthy Japanese Young Adults

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Oral fat sensitivity (OFS, the ability to detect fat) may be related to overeating-induced obesity. However, it is largely unknown whether OFS affects taste preference and eating habits. Therefore, we aimed to evaluate (1) the association between body mass index (BMI) and OFS and (2) the relationship of OFS with four types of taste preference (sweet, sour, salty, and bitter) and eating habits using serial concentrations of oleic acid (OA) homogenized in non-fat milk and a self-reported questionnaire. Participants were 25 healthy Japanese individuals (mean age: 27.0 ± 5.6 years), among whom the OA detection threshold was significantly associated with BMI. Participants were divided into two subgroups based on oral sensitivity to 2.8 mM OA: hypersensitive (able to detect 2.8 mM OA, n = 16) and hyposensitive (unable to detect 2.8 mM OA, n = 9). The degree of sweet taste preference of the hypersensitive group was significantly higher than that of the hyposensitive group. Furthermore, there was significantly higher degree of preference for high-fat sweet foods than low-fat sweet foods in the hypersensitive group. There was also a significant inverse correlation between the OA detection threshold and the degree of both spare eating and postprandial satiety. Thus, OFS is associated not only with BMI, but also with the preference for high-fat sweet foods and eating habits. The present study provides novel insights that measuring OFS may be useful for assessing the risk of obesity associated with overeating in countries, including Japan, where BMI is increasing in the population.

Keywords: body mass index; eating habits; Japan; oral fat detection system; taste preference
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Introduction

Obesity is associated with a risk of obesity-related health complications, such as cancer, diabetes mellitus, hypertension, dyslipidemia, and cardiovascular disease (Hubert et al. 1983; Tokudome et al. 2000; Park and Kim 2012). In addition, dietary fat plays a role in weight maintenance and loss, while excessive dietary fat consumption is a potential contributor to weight gain (Bray et al. 2004; Astrup 2005; Shikany et al. 2010). Indeed, obese subjects prefer lipid when compared with lean subjects (Drewnowski 1985; Mela and Sacchetti 1991), suggesting that inappropriate fat perception may influence the risk of obesity by affecting eating behavior (Laugerette et al. 2005). Therefore, it is valuable to clarify the possible role of the oral fat detection system in terms of weight maintenance in individuals. In this context, signals elicited by dietary fat, especially free fatty acid, are suggested to be initiated in the oral cavity and transmitted to the brain through nerves and neuropeptides and neurotransmitters, such as beta-endorphin and dopamine, which are released just after fat intake as the mechanism of the brain's reward system (Fukuwatari et al. 1997; Hiraoka et al. 2003; Fushiki and Kawai 2005; Liang et al. 2006; Fushiki et al. 2006; Mizushige et al. 2007; Mattes 2009).

It is well accepted that human individuals can perceive five prototypical taste qualities (sweet, salty, bitter, sour, and umami). The process of sensing taste is first achieved at the level of taste receptor cells clustered in the taste buds, which are small structures on the tongue and soft palate that allow recognition of particular tastes of food and drink. Taste receptor cells are classified into four types depending on their morphological features. Type I cells transduce low salty taste. Type II cells express taste G-protein coupled

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receptors that sense sweet, umami, and bitter foods. Type III cells express channels to sense acids, whereas type IV cells appear to be taste stem/progenitor cells (Janssen and Depoortere 2013; Satoh-Kuriwada et al. 2014).

Sweet taste signals the presence of carbohydrates that act as a source of energy. Salty taste governs the consumption of salts required for maintaining water balance in the body. Bitter taste protects against the ingestion of poisons. Sour taste signals the presence of dietary acids that are present in decayed foods and unripe fruits. Umami taste helps to identify protein-rich foods (Niki et al. 2010; Janssen and Depoortere 2013).

In contrast, the response to oral fat stimulation was previously considered to rely mostly on textural, olfactory, and post-ingestive cues, but the taste of free fatty acids (FFA), such as oleic acid (OA), has recently been suggested as a new basic taste in addition to the five basic tastes (Laugerette et al. 2005; Janssen and Depoortere 2013). OA, $C_{18}H_{34}O_2$, is a monounsaturated fatty acid having 18 carbon atoms and one double bond and found in olive oil and many other vegetable and animal oils and fats. In fact, possible lipid receptors have been identified, such as free fatty acid receptor 1 (FFAR1, also known as G-protein coupled receptor 40) and G-protein coupled receptor 120 (GPR120), in some taste receptor cells (type I or type II cells) of the tongue's taste buds (Cartoni et al. 2010; DiPatrizio 2014). FFAR1, which is also expressed in many endocrine cells, is activated by medium-chain (6-12 carbons) and long-chain (13-21 carbons) fatty acids. In pancreatic beta cells, where FFAR1 is preferentially expressed, FFAR1 can directly mediate FFA-stimulated insulin secretion (Itoh et al. 2003; Edfalk et al. 2008; Janssen and Depoortere 2013). GPR120 is also a lipid receptor expressed in the taste buds, as well as in adipocytes and other cells (Gotoh et al. 2007; Oh et al. 2010; Janssen and Depoortere 2013). Recent studies have shown that GPR120 dysfunction leads to obesity, glucose intolerance, and fatty liver (Ichimura et al. 2012; Janssen and Depoortere 2013; DiPatrizio 2014). Moreover, several studies reported a difference in the OA detection threshold among human individuals and an inverse correlation between body mass index (BMI), a measure of body fat, and oral OA sensitivity (Stewart et al. 2010, 2011; Haryono et al. 2014). BMI is defined as the weight in kilograms divided by the square of the height in meters (kg/m^2).

However, because the previous studies on the relationship between BMI and oral fat sensitivity (OFS, the ability of individuals to detect fat in the oral cavity) were principally performed among non-Japanese individuals, it is not clear whether such associations exist in Japanese individuals. In addition, how the degree of OFS affects taste preference and eating behavior has not yet been clarified. To address this gap in the literature, we investigated the association of OFS with BMI as well as the relationship of OFS with the four types of taste preference (sweet, sour, salty, and bitter) and self-reported food behavior in healthy, young Japanese adults. Here, we report the results of these studies, discuss a possible role of the oral fat detection system in body weight maintenance, and characterize the relationship of OFS with taste preference and eating behavior in Japanese individuals.

Materials and Methods

Study outline

Subjects attended the laboratory at Tohoku University Graduate School of Dentistry and completed a self-reported questionnaire that obtained information regarding their health condition, eating habits, and taste preference towards the four prototypical tastants (sweet, salty, sour, and bitter). Then, the weight, height, BMI, and body fat percentage of each subject were measured using a bench-made stadiometer and a weighing scale (Inner Scan 50; Tanita, Tokyo, Japan). Blood pressure was determined using an electronic sphygmomanometer (CH-550; Citizen, Tokyo, Japan). After these procedures, the following tasks were performed: (1) a taste test for recognition thresholds and detection thresholds for the prototypical tastants using sucrose, quinine, salt (NaCl), acetic acid, and monosodium glutamate (MSG); and (2) a taste test for OA detection thresholds to divide subjects into two subgroups (oral OA hypersensitive and hyposensitive groups). Then, we evaluated (1) the association between OFS and BMI among Japanese individuals, (2) the relation between OFS and the four taste preferences (sweet, sour, salty, and bitter), and (3) the association between OFS and eating habits among Japanese individuals.

Participants

Twenty-five adults (mean age: 27.0 ± 5.6 years) were recruited through public advertisements (n = 16, male; n = 9, female). All the participants provided informed consent and completed the study. BMI ranged from 18.4 to 26.8 (underweight [< 18.5 kg/m^2]: n = 2; normal weight [18.5 to 24.9 kg/m^2]: n = 21; overweight [25 to 29.9 kg/m^2]: n = 2; obese [≥ 30 kg/m^2]: n = 0). Details regarding the participants' baseline characteristics are provided in Table 1. Participants were limited to Japanese young adults (20-39 years of age) who were healthy at the time of testing and were normotensive non-smokers based on the results from the examinations of the present study. A few participants, who did not meet the OA detection threshold of 12 mM, which was the maximum concentration that we prepared for the determination of OFS in the present study based on the data from previous studies, were also excluded. Ethics approval for the study was obtained from the Ethics Committee of Tohoku University Graduate School of Dentistry. All experiments were performed in compliance with the Declaration of Helsinki (http://www.wma.net) and institutional guidelines.

Determination of OA detection thresholds

The test stimuli for OA threshold sensitivity used in the study consisted of an emulsion of food grade OA (Sigma-Aldrich, MO, USA) in non-fat milk (Morinaga Milk Industry, Tokyo, Japan). OA, which is a fatty acid commonly found in food and is easy to use owing to its liquid nature at room temperature (Stewart et al. 2010; Haryono et al. 2014), was stored at –20°C before use. To prepare serial concentrations (0.02 to 12 mM, see Fig. 1 for detail) of OA samples, 12% (w/v) powdered non-fat milk and a varying amount of liquid-state OA was added to beakers to achieve the desired final concentrations. In addition, all preparations were mixed with 5% (w/v)

Table 1. Baseline characteristics of participants*.

	Men (n = 16)			Women (n = 9)			P-value**	All (n = 25)		
	n	Mean	SD	n	Mean	SD		n	Mean	SD
Age (years)		27.5	6.1		26.2	4.8	0.594		27.0	5.6
Height (cm)		171.8	8.0		159.0	4.0	< 0.001		167.2	9.2
Weight (kg)		63.1	9.0		54.5	6.0	0.018		60.0	9.0
BMI (kg/m^2)		21.3	2.2		21.6	2.4	0.806		21.4	2.2
BMI range (kg/m^2)		18.4-26.1			18.4-26.8				18.4-26.8	
Underweight (n)	1			1				2		
Normal weight (n)	14			7				21		
Overweight (n)	1			1				2		
Obese (n)	0			0				0		
Body fat (%)		16.0	3.8		29.3	4.3	< 0.001		20.8	7.6
SBP (mmHg)		117.1	9.0		109.4	4.6	0.028		114.3	8.5
DBP (mmHg)		71.9	6.9		68.1	10.5	0.283		70.6	8.4

BMI, body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure.
*BMI: Underweight, < 18.5 kg/m^2; normal weight, 18.5-24.9 kg/m^2; overweight, 25-29.9 kg/m^2; obese, ≥ 30 kg/m^2.
**Statistical difference between men and women by Student's t-test.
Data are presented as the means with standard deviation (SD).

gum arabic (acacia gum) (Wako Pure Chemical Industries, Osaka, Japan) and 5% (w/v) liquid paraffin (Wako Pure Chemical Industries) to produce perceptually identical textural attributes between the fatty acid and control samples. To prevent oxidation, each sample was mixed with 0.01% (w/v) EDTA (Dojindo Laboratories, Kumamoto, Japan). Then, after adding distilled water, all additives in each beaker were homogenized at room temperature with a homogenizer for 12 min at 7,000 rpm (HM-310; As One, Tokyo, Japan) to make the final mechanically emulsified OA sample in non-fat milk. The control vehicle was prepared in the same way without OA. The amount of each additive for making all preparations was precisely measured each time using a mass scale, a measuring cylinder, and pipettes. The participants were provided three samples at room temperature, two controls, and one containing OA, per set, in ascending order from the lowest (0.02 mM) to the highest (12 mM) concentration. Detection thresholds were defined as the concentration of OA required for a subject to correctly and repeatedly identify the OA sample as "odd" from the two control samples. All tests were conducted with the participants wearing blinders and nose clips. Participants were asked to refrain from eating 2 h before testing.

Determination of sensitivity to five prototypical tastants

Sample solutions for sour, salty, sweet, bitter, and umami tastants were prepared using acetic acid, salt, sucrose, quinine, and MSG, respectively, at the concentrations detailed in Table 2. All of the tastants were purchased from Wako Pure Chemical Industries. Participants were presented with a series of seven or eight solutions for each prototypical tastant, which were arranged in ascending order of concentration. The participants drank 1 ml of each solution, expelled it shortly after, and then selected from the following options: (a) the solution tastes like water, (b) the solution tastes like something other than water, or (c) the solution has a specific taste (sour, salty, sweet, bitter, or umami). Detection thresholds were defined as the concentration of a compound required for it to elicit a taste sensation that was unknown to the assessor, and the recognition threshold was defined as the concentration of a certain compound required for the subject to accurately recognize and identify the specific tastant. The participants were requested to rinse their mouths with distilled water between each set of taste samples. Participants with missing values owing to the loss of taste were excluded from the subsequent correlational analysis.

Determination of taste preference degree

In the self-reported questionnaire for taste preference determination, which was employed in Omori's study on taste sensitivity (Omori 2013), the participants were asked to rate tastants (sweet, salty, sour, or bitter foods) on a scale of 1 to 5 based on the following (Table 3): 1, dislike it very much; 2, dislike it moderately; 3, neither like it nor dislike it; 4, like it moderately; or 5, like it very much. The participants were also asked to rate certain eating habits on a scale of 1 to 3 or 4 (Table 4). In the present study, six sweet foods listed in the questionnaire were subsequently classified into two subgroups according to the fat content contained in each: (i) high-fat sweet foods (ice cream, chocolate, and shortcake with fat contents of 13.4-16.4 g/100 g, 34.1-39.5 g/100 g, and 14.0 g/100 g, respectively, the Standard Tables of Food Composition in Japan 2010: http://fooddb.mext.go.jp/) and (ii) low-fat sweet foods (*yokan* [adzuki-bean jelly], *manju* [a Japanese cake, such as a steamed bean-jam bun], and candy with fat contents of 0.2 g/100 g, 0.2-2.0 g/100 g, and 0 g/100 g, respectively, the Standard Tables of Food Composition in Japan 2010: http://fooddb.mext.go.jp/).

Statistical analysis

The data are presented as the mean ± standard deviation except for correlation charts. Statistical differences were identified using appropriate tests as indicated. P-values < 0.05 were considered statistically significant. Statistical analyses were performed using SPSS statistics, version 22.0 (IBM, Armonk, NY, USA), and the statistical package JSTAT for Windows, version 6.8. (Sato, Japan).

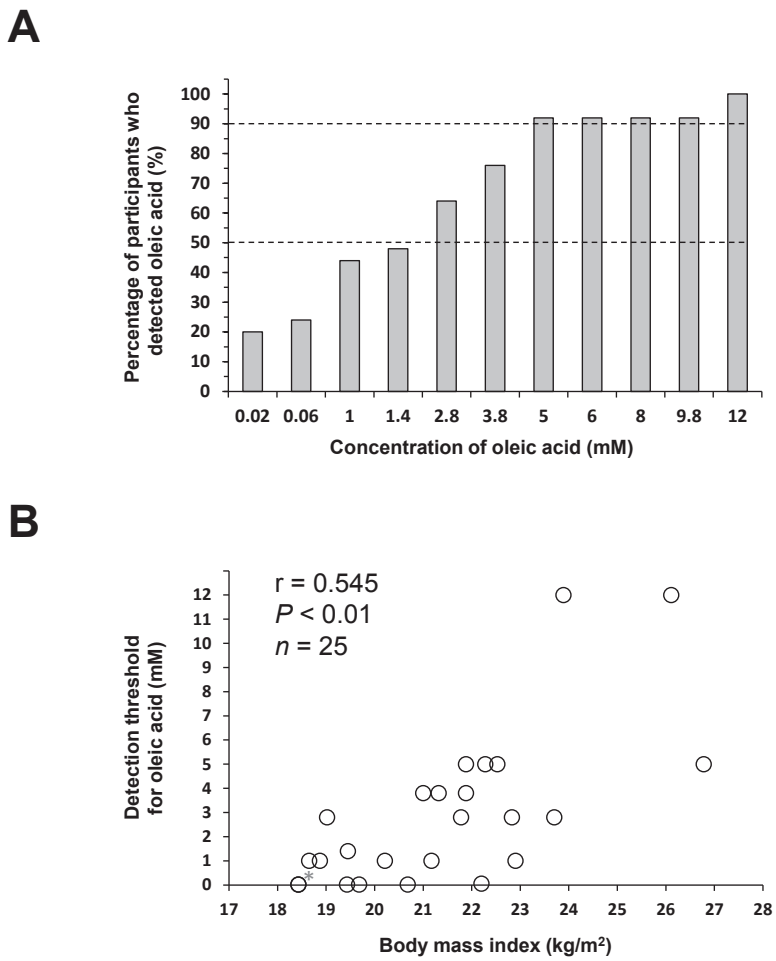

Fig. 1. Determination of fatty acid detection thresholds in young Japanese adults. Using indicated concentrations of oleic acid (OA) homogenized in non-fat milk, oral fat sensitivity of each participant was determined. (A) Cumulative distribution of minimum detection thresholds for OA, showing that more than half of the participants detected OA in non-fat milk at a concentration of 2.8 mM. (B) Association between detection threshold for OA and body mass index. A statistically significant association was observed between detection thresholds for OA and body mass index in participating healthy Japanese young adults. A statistical difference was identified using Kendall's rank correlation coefficient. r, coefficient of correlation between body mass index and detection threshold for OA. *P*-value for testing the hypothesis of no correlation. Note that two circles are perfectly overlapped (asterisk).

Table 2. Concentration of tastants used for the determination of taste thresholds for the prototypical stimuli*#.

Dilution	Acetic acid (mM)	MSG (mM)	NaCl (mM)	Sucrose (mM)	Quinine (μM)
1	10.00	50.0	100.0	100.0	100.0
2	5.00	30.0	50.0	50.0	50.0
3	3.00	10.0	30.0	30.0	30.0
4	1.00	5.0	10.0	10.0	10.0
5	0.50	3.0	5.0	5.0	5.0
6	0.10	1.0	3.0	3.0	3.0
7	0.05	0.5	1.0	1.0	1.0
8	–	–	–	–	0.5

MSG, monosodium glutamate.
*Prototypical stimuli are acetic acid, sour; MSG, umami; NaCl, salty; sucrose, sweet; quinine, bitter.
#Participants were presented with each series of dilutions in ascending order, from the lowest (dilution 7 or 8) to highest (dilution 1) concentration.

Table 3. Food preference among hypersensitive and hyposensitive participants.

		Hypersensitive* (n = 16)		Hyposensitive* (n = 9)		P-value**
		Mean	SD	Mean	SD	
Sweet food	Adzuki-bean jelly (Yokan)	3.38	1.20	3.33	0.71	0.926
	Steamed bean-jam bun (Manju)	3.63	1.02	3.44	0.53	0.629
	Candy	3.44	0.73	3.00	0.50	0.124
	Ice cream	4.75	0.45	4.33	0.71	0.083
	Chocolate	4.56	0.73	3.78	0.83	0.022
	Shortcake	4.38	0.81	3.44	1.24	0.032
Salty food	Potato chips	4.31	0.95	3.89	0.78	0.266
	Salted squids (Ika shiokara)	3.06	1.57	2.67	1.22	0.521
	Salted kelp (Shio Kombu)	3.06	1.00	3.11	0.93	0.906
	Pickled vegetables (Tsukemono)	3.31	0.95	3.00	0.71	0.398
	Salted cod roe (Tarako)	3.69	1.49	3.11	1.05	0.319
	Salted salmon	4.13	0.81	3.56	0.88	0.115
	Miso soup (Misoshiru)	4.13	0.81	3.89	1.27	0.573
Sour food	Japanese orange (Mikan)	4.56	0.63	4.44	0.73	0.674
	Hassaku orange	3.69	1.08	3.11	1.17	0.225
	Pickled Japanese plum (Umeboshi)	3.06	1.44	2.78	0.83	0.593
	Yogurt	4.25	0.86	4.11	0.78	0.692
	Lemon	3.06	1.18	2.67	0.50	0.256
	Grapefruit	3.38	1.09	3.78	0.83	0.347
Bitter food	Celery	2.00	0.97	1.78	0.97	0.587
	Tea	4.38	0.62	4.44	0.73	0.802
	Green pepper	3.44	0.89	3.22	0.97	0.580
	Parsley	2.81	0.83	2.00	0.87	0.030
	Coffee	3.26	1.01	3.56	1.01	0.758

*Hypersensitive, detection threshold for oleic acid ≤ 2.8 mM; hyposensitive, detection threshold for oleicacid > 2.8 mM.
**Statistical difference between hypersensitive and hyposensitive participants using Student's t-test or Welch's t-test.
Data are presented as the means with standard deviation (SD). Means are statistically significantly different at $P < 0.05$.

Table 4. Questions on food behavior excerpted from the self-reported questionnaire.

Question 1. What do you think about the amount of your food intake?
Scale 1. It is extreme (overeating).
Scale 2. It is adequate.
Scale 3. It is not enough.

Question 2. If you do not eat until the stomach is full, do you fail to feel a sense of satiety?
Scale 1. I experience this frequently.
Scale 2. I have such a tendency.
Scale 3. I occasionally feel this way.
Scale 4. I feel a sense of satiety before a full stomach.

Question 3. Do you like greasy foods?
Scale 1. I like them very much.
Scale 2. I like them moderately.
Scale 3. I dislike them moderately.
Scale 4. I dislike them very much.

Question 4. How often do you consume sweet foods?
Scale 1. I do not consume sweet foods at all.
Scale 2. I do not consume sweet foods very often.
Scale 3. I sometimes consume sweet foods.
Scale 4. I frequently consume sweet foods.

Results

To assess the effect of BMI on the detection threshold for OA in Japanese young adults, we first determined the correlation between the detection threshold for OA and BMI among the 25 healthy participants. As shown in Fig. 1A, B, the cumulative distribution of the minimum detection threshold for OA indicated that more than half of the participants detected OA in the non-fat milk at a concentration of 2.8 mM. In addition, more than 90% of the participants detected OA in non-fat milk at a concentration of 5 mM. However, only approximately 20% of participants detected OA at a concentration of 0.06 mM. A statistically significant association was observed between the detection thresholds for OA and BMI (r = 0.545, $P < 0.01$). These results suggest that OFS is inversely associated with BMI in accordance with previous reports (Stewart et al. 2010, 2011; Haryono et al. 2014).

As a control experiment, we next evaluated the correlation between the detection or recognition of the taste threshold for five prototypical tastants (acetic acid for sour, salt for salty, sucrose for sweet, and MSG for umami) and BMI among the same participants. No statistically significant association was identified between BMI and the detection or recognition threshold for each prototypical tastant. These results support the idea that OFS is independent of sensitivity for these tastants (Figs. 2 and 3).

To examine the relationship between OFS and the four taste preferences (sweet, sour, salty, and bitter), we next divided the participants into two subgroups: a hypersensitive group (sensitive to 2.8 mM OA) and a hyposensitive group (insensitive to 2.8 mM OA). In addition, we used the acquired self-reported questionnaires from the participants. As shown in Table 4, the analysis of the preference degree

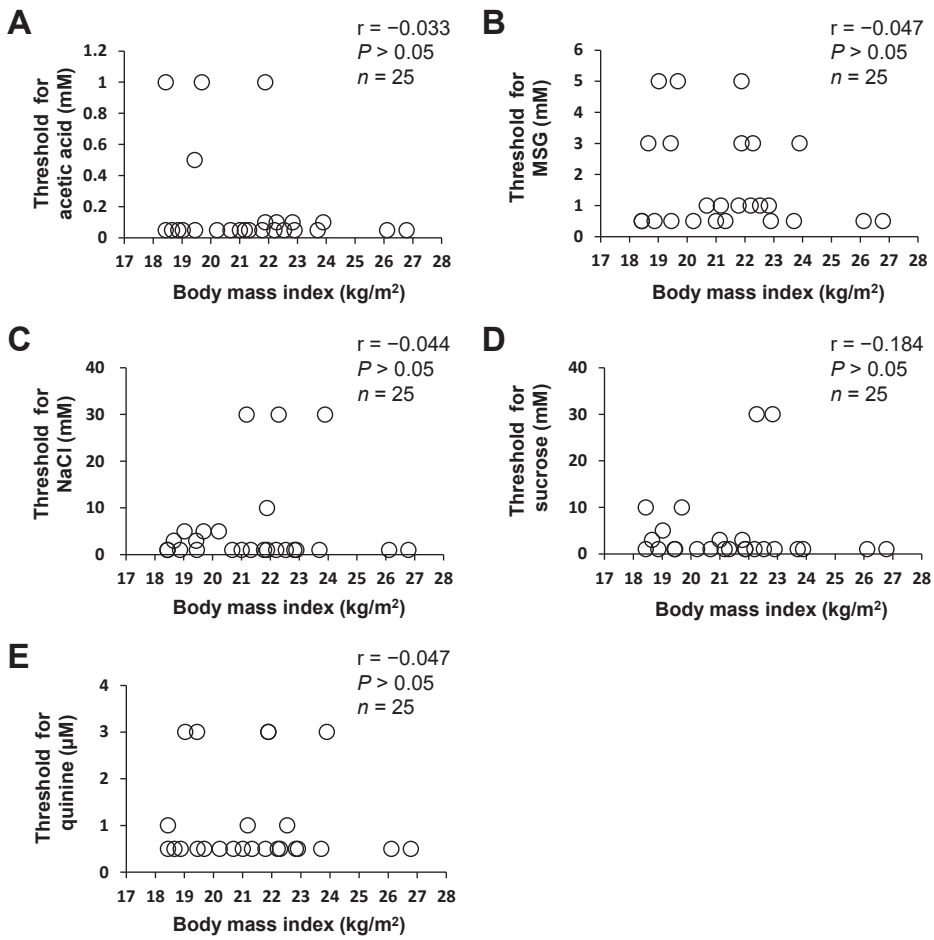

Fig. 2. Association between detection taste thresholds for the prototypical tastants and body mass index. Detection taste thresholds for the five prototypical tastants (acetic acid for sour, monosodium glutamate for umami, NaCl for salty, sucrose for sweet, and quinine for bitter) were determined with a series of seven or eight solutions for each prototypical tastant detailed in Table 2. No significant association between detection taste thresholds and body mass index was observed for all of the tastants tested in the participants. Statistical differences were identified using Kendall's rank correlation coefficient. r, coefficient of correlation between body mass index and the detection taste threshold for each prototypical tastant. *P*-values for testing the hypothesis of no correlation. All participants reached the detection threshold for each tastant.
MSG, monosodium glutamate.
Some plotted circles are closely or perfectly overlapped.

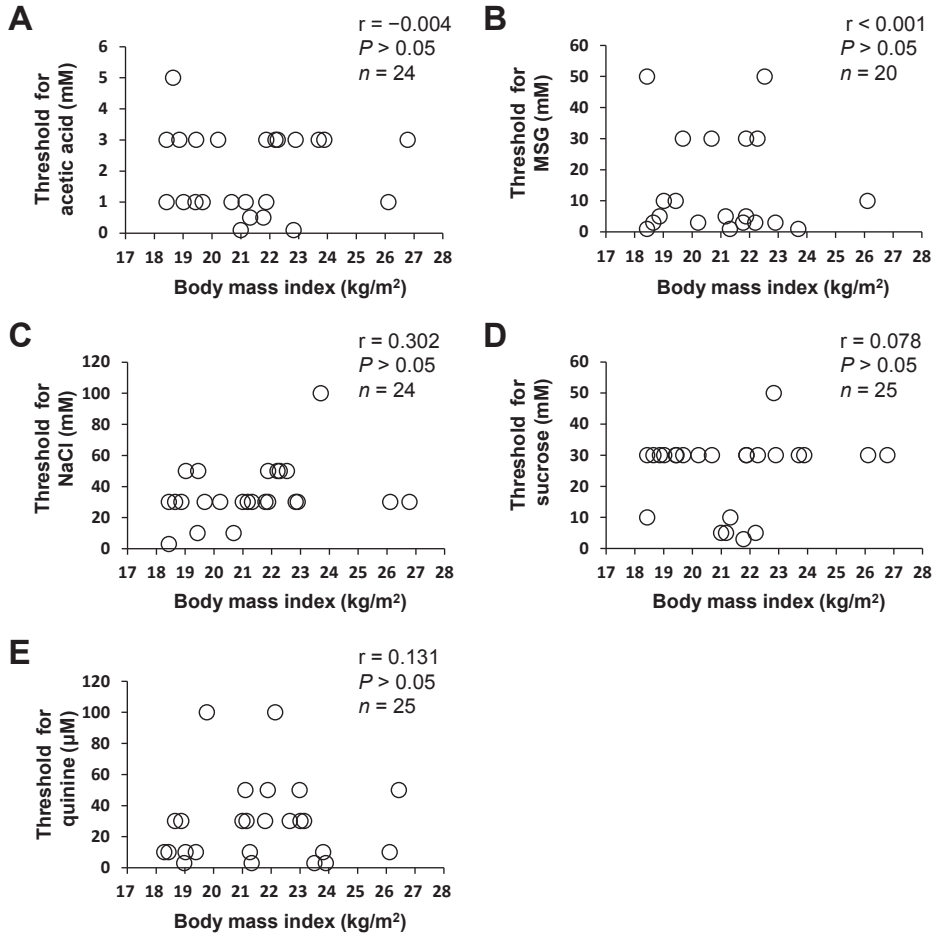

Fig. 3. Association between recognition taste thresholds for the prototypical tastants and body mass index. Recognition taste thresholds for the five prototypical tastants (acetic acid for sour, monosodium glutamate for umami, NaCl for salty, sucrose for sweet, and quinine for bitter) were determined with a series of seven or eight solutions for each prototypical tastant detailed in Table 2. No significant association between recognition taste thresholds and body mass index was observed for all of the tastants tested in the participants. Statistical differences were identified using Kendall's rank correlation coefficient. r, coefficient of correlation between body mass index and the recognition taste threshold for each prototypical tastant. *P*-values for testing the hypothesis of no correlation. On the loss of taste, one participant did not reach a recognition threshold for acetic acid, and three participants did not reach a recognition threshold for monosodium glutamate. In addition, one participant did not reach a recognition threshold for NaCl. The missing values by the loss of taste were excluded from the above correlational analysis.
MSG, monosodium glutamate.
Some plotted circles are closely or perfectly overlapped.

for each tastant (such as candy, lemon, and celery) in the two OA sensitivity groups (OA hypersensitivity group and OA hyposensitivity group) showed a significant difference in preference degree only for chocolate, shortcake, and parsley between the two OA sensitivity groups. In addition, the summarized average extent of preference for each prototypical tastant showed that the two OA sensitivity groups differed significantly only in terms of sweet preference (Fig. 4A). Interestingly, among the six sweet foods listed in the questionnaire, the summarized average degree of preference for the three high-fat sweet foods (see Materials and Methods for detail), but not the three low-fat sweet foods (see Materials and Methods for detail), showed similar statistical difference between the two OA sensitivity groups (Fig. 4A). Moreover, there were significant differences in the taste preference degree between low-fat sweet foods and high-fat sweet foods in the OA hypersensitive group, but not the OA hyposensitive group (Fig. 4B). However, there were significant differences in the taste preference degree between bitter foods and sweet foods in both groups (Fig. 4C), suggesting that OFS also has a specific association with the degree of preference for high-fat sweet foods.

Finally, we investigated the relationship of OFS and lifestyle habits with food intake using four questions in the self-reported questionnaires in the present study as detailed in the Materials and Methods and Table 4. OFS was statistically and negatively associated with degree of spare eating ($r = -0.466$, $P < 0.01$) and degree of satiety after food intake ($r = -0.440$, $P < 0.01$), respectively (Fig. 5). However, no statistical association was observed between

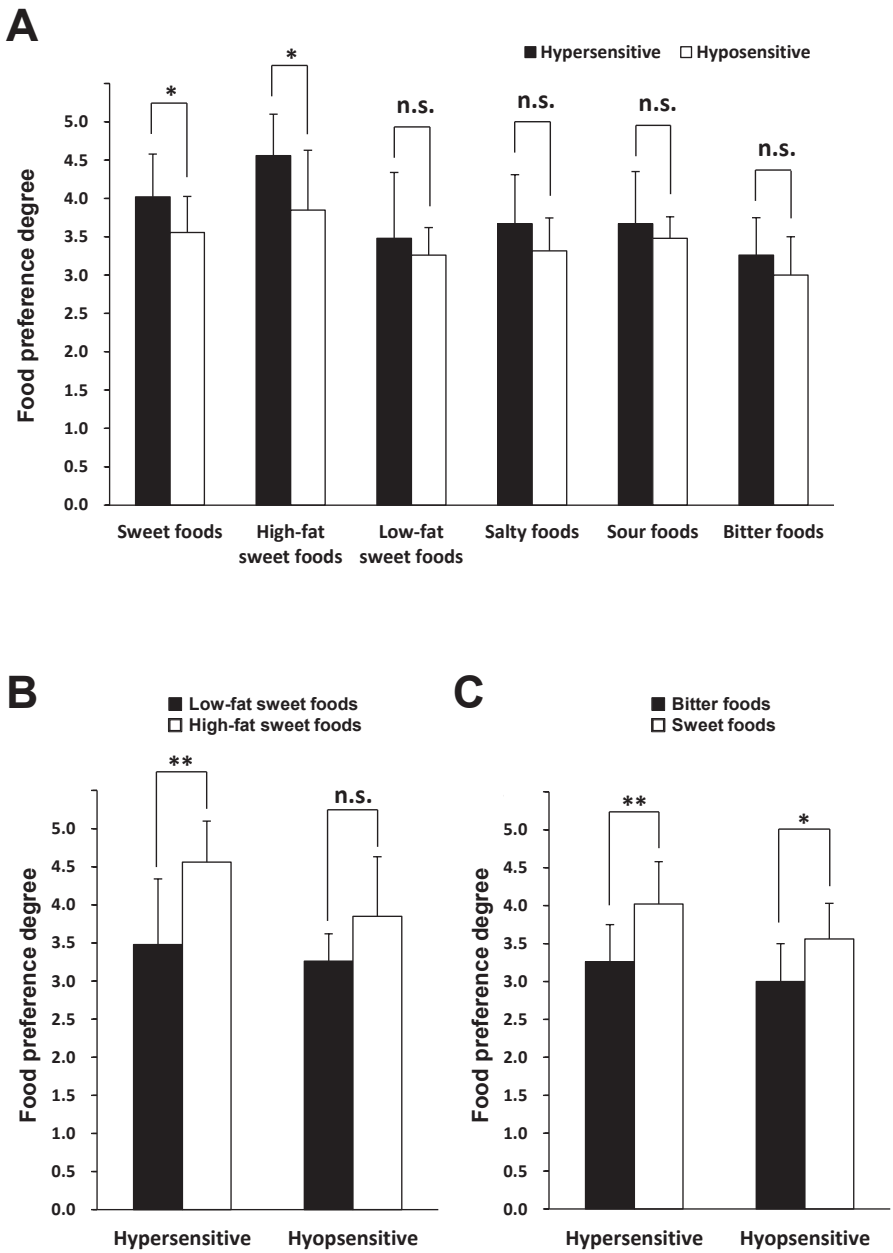

Fig. 4. Comparison of taste preference degrees. In the self-reported questionnaire for taste preference determination, participants rated taste preference degree of various tastants for four prototypical tastes (sweet, sour, salty, and bitter) on a scale of 1 to 5 as detailed in Table 3 as follows: 1, dislike it very much; 2, dislike it moderately; 3, neither like it nor dislike it; 4, like it moderately; or 5, like it very much. The summarized average degrees of the preference of each prototypical taste foods were then compared between each indicated subgroups of participants. (A) Comparison of average taste preference degree between two oral oleic acid (OA) sensitivity subgroups of the participants ($n = 25$). Significant differences in average taste preference degrees between the OA hypersensitive group (able to orally detect 2.8 mM OA, $n = 16$) and the OA hyposensitive group (unable to orally detect 2.8 mM OA, $n = 9$) were identified using Student's t-test or Welch's t-test. (B) Comparison of average taste preference degree between low-fat sweet food and high-fat sweet food in each oral OA sensitivity subgroup. The six sweet foods used in self-reported questionnaires were divided into two subgroups (low-fat sweet foods [*yokan*, *manju*, and candy] and high-fat sweet foods [ice cream, chocolate, and shortcake]) according to the general fat content level. Significant differences were observed between average taste preference degrees for low-fat sweet food and high-fat sweet food in the hypersensitive group but not in the hyposensitive group. Statistical differences between low-fat sweet food and high-fat sweet food groups were determined using Student's t-test or Welch's t-test. (C) Comparison of average taste preference degree between bitter foods and sweet foods in each oral OA sensitivity subgroup. Significant differences were observed between average taste preferences for bitter and sweet foods in both the hypersensitive and hyposensitive groups. Statistical differences between bitter and sweet foods were determined using Student's t-test.
For (A) to (C), $*P < 0.05$, $**P < 0.01$.
n.s., not significant.

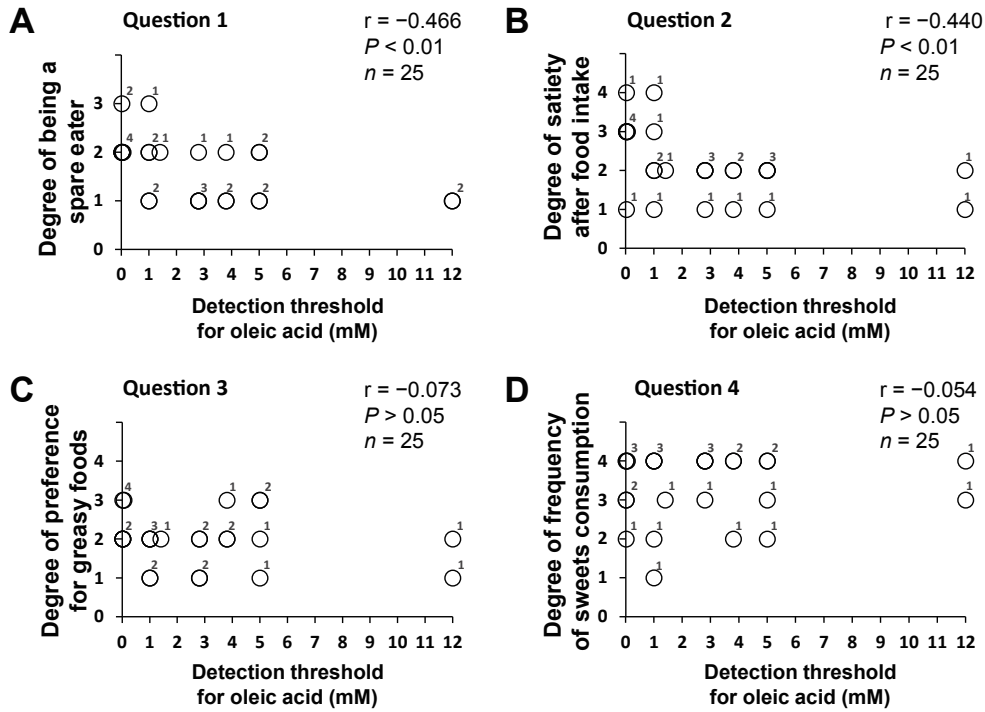

Fig. 5. Association between detection thresholds for oleic acid (OA) and eating habits. In the self-reported questionnaire, the participants rated four indicated eating habits on a scale of 1 to 3 or 4 as detailed in Table 4. A significant association between detection threshold for OA and the scores for each eating behaviors was observed among the participants for questions 1 and 2, but not questions 3 and 4 (Table 4). Statistical differences were identified using Kendall's rank correlation coefficient. r, coefficient of correlation between detection threshold for OA and the score for each lifestyle habit on food intake. *P*-values for testing the hypothesis of no correlation. All participants ($n = 25$) answered questions regarding eating habits. Some plotted circles are closely or perfectly overlapped. Indicated numbers (#1 to #4) at the upper right of the plotted circles make supplementary statements on the number of circles plotted at (almost) the same position.

OFS and either the preference degree for greasy foods or the degree of frequency of sweets intake.

Discussion

The modification of lifestyles can reduce obesity, which leads to the development of obesity-related health complications including diabetes mellitus (Vetter et al. 2010; Wadden et al. 2012). However, the risks of obesity-related health complications have already reached an unprecedented global high, because of the substantially increased prevalence of obesity for decades (Finucane et al. 2011; Stevens et al. 2012). Although the prevalence of obesity in Japan is still lower than that of the global average at present, that the prevalence of overweight and obesity has been increasing over the last several decades in Japan, especially among men, should not be overlooked (Nagai et al. 2015; Ri et al. 2015).

The brain governs nutrient intake behavior by integrating many different internal and external state and trait-related signals (Smeets et al. 2012). After consuming foods, taste receptors relay sensory signals to the brain, which evaluates and distinguishes the stimuli. It is well known that such a taste perception then influences food intake as a food-induced brain response (Smeets et al. 2012; Loper et al. 2015). Therefore, understanding the role of each taste quality in relation to taste preference and eating habits is crucial for expanding our knowledge of the factors associated with body weight maintenance and the risk of obesity-related health complications. However, the relationship of OFS with taste preference and the effect on eating habits is still largely unknown, especially in Japanese individuals.

In the present study, we clearly report that the detection threshold for OA, but not the five prototypical tastes detected in the oral cavity, was associated with BMI among the participants that consisted of young, healthy Japanese adult men and women (Figs. 1, 2 and 3). Moreover, more than 50% of the participants were able to detect 2.8 mM of OA in the non-fat milk (Fig. 1A). Therefore, we divided participants into two subgroups, an oral fat hypersensitive group (sensitive to 2.8 mM OA in non-fat milk) and an oral fat hyposensitive group (insensitive to 2.8 mM OA in non-fat milk), to further investigate the data acquired from the participants. In addition, we showed that more than 20% of participants could detect OA in non-fat milk at a concentration of only 0.06 mM that was about 40- and 200-fold dilute compared to the 2.8 mM and 12 mM (maximum OA concentration used for the present study) solutions, respectively (Fig. 1A), suggesting that the detection threshold for oral OA varies greatly among Japanese individuals, similar to a

study conducted in Australia (Stewart et al. 2010). This is an important feature of the fat detection system in the oral cavity from the perspective of oral medicine.

Regarding the examination of the preference degree towards the four tastes (sour, sweet, bitter, and salty) in the participants that were divided into two oral OA sensitivity subgroups (hypersensitive and hyposensitive), we report the novel finding of a statistically significant difference in the preference degree of high-fat sweet foods, but not low-fat sweet foods, between the hypersensitive and hyposensitive groups, despite the absence of an association between the sweet taste detection or recognition thresholds and BMI (Figs. 2, 3 and 4). Moreover, the oral OA hypersensitive participants preferred high-fat sweet foods to low-fat sweet foods to a significant degree, in contrast to the hyposensitive participants who showed similar preference for high-fat sweet foods and low-fat sweet foods (Fig. 4B). These results suggest that oral OA hyposensitive individuals may have failed to efficiently detect and receive prolonged fat signals in their brain; thus, they were obliged to evaluate the preference degree for high-fat sweet foods in the self-reported questionnaire by depending mainly on the other palatable sensation, the taste of sweetness. Further studies should elucidate the mechanism of the different preference degrees for high-fat sweet foods between the oral OA hypersensitive and hyposensitive groups. This is because the failure of efficient oral fat detection from sweet foods or other food products may have some relation with the reported tendency of observed higher food consumption in oral OA hyposensitive participants compared to oral OA hypersensitive participants (Stewart et al. 2011).

In this context, it is noteworthy that the oral fat detection threshold was inversely associated with the degree of self-awareness of both (i) spare eating and (ii) satiety after food intake (Fig. 5), because these results support the idea that oral OA hypersensitive individuals have a greater ability to detect fat in sweets or other food products than oral OA hyposensitive individuals; therefore, they can sense satiety after food intake more easily with the brain's reward system for fat signals and stop their food intake earlier, eventually leading to the inhibition of excessive food consumption. However, a multidisciplinary approach may be required for the confirmation of these findings and clarification of its underlying mechanism in humans. The above results regarding the self-recognition of eating habits acquired from the present study may also contribute to resolving the mechanism of the modulation of OFS by recent fat intake as reported in studies conducted in Australia (Stewart and Keast 2012; Newman et al. 2013; Keast et al. 2014).

In summary, we characterized the mode of association of OFS with BMI and the taste preference degree and lifestyle behavior and its effects on food intake in healthy Japanese young adults. Specifically, the OA detection threshold, but not the five prototypical tastants, was associated with BMI. Moreover, we found that oral fat hyposensitive participants, but not hypersensitive participants, failed to show a significantly higher preference for high-fat sweet foods compared to low-fat sweet foods on average. In addition, oral OA sensitivity had a statistical correlation with self-recognition of eating habits in terms of food intake and satiety after food intake. Therefore, in the future, it would be important to consider oral fat hyposensitive individuals as possible patients with dysfunctional oral fat detection systems and latent excessive food eaters, in countries with increasing obesity rates, especially in Japan. Concurrently, because the reason for such large individual variability in OFS is unknown, it would be highly valuable to clarify the underlying mechanism and establish a novel medical treatment or healthcare system including lifestyle-modification for improving OFS. This could lead to the prevention of or recovery from excessive increases in BMI that are mainly caused by a dysfunctional oral fat detection system.

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Conflict of Interest

The authors declare no conflict of interest.

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