Structural Equation Modeling of Associations Among Taste-Related Risk Factors, Taste Functioning, and Adiposity

Shristi Rawal1,2, Tania B. Huedo-Medina1, Howard J. Hoffman3, Helen Swede4, and Valerie B. Duffy1

Objective: Variation in taste perception and exposure to risk factors of taste alterations have been independently linked with elevated adiposity. Using a laboratory database, taste-adiposity associations were modeled and examined for whether taste functioning mediates the association between taste-related risk factors and adiposity.

Methods: Healthy women (n = 407, 35.5 ± 16.9 y) self-reported histories of risk factors of altered taste functioning (tonsillectomy, multiple ear infections, head trauma) and were assessed for taste functioning (tongue-tip and whole-mouth intensities of quinine and salt) and density of taste papillae. Twenty-four percent had elevated waist circumferences; thirty-nine percent had overweight or obesity. Using structural equation modeling, direct and indirect associations between taste-related risk factors, taste functioning, and adiposity were tested.

Results: In models with good fit, elevated central adiposity was explained directly by history of risk factors (tonsillectomy, multiple ear infections) and directly by lower taste functioning (lower tongue-tip taste function, lower papillae density). Risk factors of taste alterations were significantly associated with lower taste functioning, with taste mediating the association between head trauma and reduced adiposity.

Conclusions: This large laboratory-based study supports associations between taste-related risk factors, taste functioning, and adiposity. These findings need to be confirmed with other population-based studies, including the National Health and Nutrition Examination Survey 2013-2014 taste data.

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Introduction

Variation in taste perception, from normal genetic variation to taste alterations, is associated with differences in dietary behaviors and adiposity status (1-3). Taste variation has been linked with differences in preferences for dietary sources that can influence total energy consumption, including sweets, high-fat foods, vegetables, and alcoholic beverages (1-3). Growing evidence suggests that taste receptors expressed along the gut regulate neurotransmitters and metabolic hormones involved in appetite, energy intake, and metabolism, further supporting taste-adiposity linkages (4). Some variation in taste perception has been explained by polymorphisms in taste receptor genes (5,6) and density of taste receptors on the tongue (1,2). Environmental insults to taste-related cranial nerves also may cause taste alterations, including diminished, intensified, or phantom (i.e., dysgeusia) sensations (2). Exposures to these environmental insults have been directly associated with adiposity (1-3,7-10). Here, we employed structural equation modeling (SEM) to simultaneously examine direct and indirect associations between reported risk factors of taste alterations, taste functioning, and adiposity in an existing database of laboratory-based studies. Secondly, we aimed to develop a framework for analyzing taste data from available population-based studies, including the first taste protocol (11).
Taste functioning can be assessed by measuring the perceived intensity of tastants, sampled with the whole mouth or regionally applied to areas of taste innervation, and the number of fungiform papillae (FP) on the anterior tongue, a proxy for taste receptor density (2,12). Complete or severe loss of taste is rare, as multiple cranial nerves throughout the oral cavity and throat are involved in taste perception (2). Regional loss of taste sensation, particularly from the anterior tongue, is more common, related to damage to the taste fibers of the chorda tympani branch of cranial nerve VII by viral infections, middle-ear surgeries, oral infections, head trauma, and some dental procedures (2). Diminished taste sensations on the tongue tip may be unnoticed due to the release of inhibition from other taste-related cranial nerves for the preservation of whole-mouth taste functioning (2). With chorda tympani taste damage, this disinhibitory feedback may alter oral sensations from foods and beverages and, in the extreme, cause dysgeusia (2). Diminished taste intensity on the tongue tip, whether examined alone or relative to whole-mouth intensity, has been associated with differences in preference for and intake of vegetables (13), alcoholic beverages (14), and sweet/fatty foods (3). Whole-mouth to tongue-tip ratios, in particular, could be a useful measure of taste functioning as they associate with dietary behaviors (13,14) and can diminish individual variability in intensity scale usage.

Studies investigating associations between taste functioning and weight in the literature are few and inconsistent. Some have found that, compared to normal-weight individuals, individuals with obesity have lower taste functioning (15-18), whereas others have observed no such differences (19,20). Taste phenotype and reduced FP density have been linked with excess adiposity and with dietary behaviors that may influence weight and adiposity (1-3,21,22).

Exposure to risk factors of taste alteration, including tonsillectomy and otitis media, have been associated with regional taste losses (3) and separately linked to elevated adiposity (3,7-9). In contrast, weight loss also has been linked to dysgeusia resulting from tonsillectomy or other causes (23,24). There are no reports examining whether taste functioning mediates the relationship between taste-related risk factors and adiposity.

Similar to the NHANES 2013-2014 taste protocol, the present study assessed regional and whole-mouth taste intensities of concentrated quinine (bitter) and NaCl solutions as measures of taste functioning. The rationale for selection of these taste measures in NHANES have been described in detail elsewhere (11). Briefly, the NHANES taste measures were selected on their ability to capture genetic and environmentally mediated variation in taste as well as relevance to diet and health outcomes. Here, we analyzed an existing database of similar taste measures, health history, and anthropometric data to model taste-adiposity associations and provide an analytical framework for future population-based studies. Specifically, we aimed to identify key taste measures that predicted variability in adiposity and were explained by exposures to taste-related risk factors. We also investigated the ability of taste intensity measures to predict adiposity relative to FP density, another presumed marker of variation in oral sensation that has been associated with dietary behaviors and adiposity (1-3,21,22).

Using a latent variable approach under SEM, we examined direct and indirect associations between taste-related risk factors, taste measures, and adiposity in adult females. We hypothesized that taste-related risk factors (multiple ear infections, tonsillectomy, head trauma) will be associated with diminished taste functioning, with both showing direct associations with increased adiposity.

### Methods

#### Participants

A convenience sample of 407 nonsmoking, ostensibly healthy women (mean age 35.5 ± 16.9 years) was recruited via posters in the areas surrounding the university campus. Exclusion criteria included pregnancy, severe food allergies, and dietary restrictions. The study had University of Connecticut-Storrs IRB approval. All participating women gave written consent and received monetary compensation.

#### Risk factors of taste alterations

Women answered questions on history (yes/no) and frequency (once, twice, 3-5 times, 6+ times) of middle ear infections, if ever received treatment with antibiotics (yes/no) for ear infections, and if ever had tympanostomy tubes inserted for treatment (yes/no). History of multiple ear infections was dichotomized into “absent” or “present” (having ear infections ≥3 times or being treated with tympanostomy tubes). History of head trauma was also dichotomized; participants who answered “no” or “yes, not serious” to the question “Have you ever suffered from a head injury?” were classified as “absent” for head trauma, whereas those who answered “yes, had either concussion or loss of consciousness” were classified as having a history of head trauma. Participants who answered affirmatively to the yes/no question of “Did you ever have a tonsillectomy?” were indicated as having a history of tonsillectomy.

#### Taste functioning

**Taste assessment.** Regional and whole-mouth taste intensity was measured using the validated general Labeled Magnitude Scale (gLMS) (25). The gLMS was vertically oriented, labeled from the bottom (“no sensation”) (scale score = 0) to the top (“strongest sensation of any kind”) (100), with intermediate labels “barely detectable” (1.4), “weak” (6), “moderate” (17), “strong” (34), and “very strong” (53). Prior to use, the women received verbal gLMS orientation/training with instructions to treat the top of the scale as generalized across all sensory domains. The participants then practiced rating intensities of recalled sound and light experiences (e.g., loudness of a conversation, brightness of the sun) and five 1,000-Hz tones ranging in 12-dB hearing level steps from 50 to 98 dB.

Participants used the gLMS to report intensities for 1 M NaCl and 1 mM quinine hydrochloride drawn along the tongue tip with a cotton-tipped applicator (12,26). Next, they sampled three solutions with the whole mouth (0.32 M NaCl, 1 mM quinine, 1 M NaCl) using a sip-and-spit procedure. The taste test concentrations were selected to be matched in intensity across quality (12) and were consistent with the NHANES taste protocol (11). After each taste stimulus, the participants rinsed their mouths with water to remove any residual stimulus.
FP assessment. The number of FP, the tissue structures containing taste buds on the anterior tongue, was measured in a 6 mm circular area on the anterior tongue with color videomicroscopy using a procedure described previously (14).

Measures of adiposity
Trained technicians measured the women’s height and weight using a standard balance-beam scale that included a stadiometer for height measurement (Health-o-meter, Bridgeview, Illinois). BMI (kg/m²) was calculated and classified as underweight (<18.5), normal (18.50-24.99), overweight (25.00-29.99), obesity (30.00-34.99), severe obesity (35.00-39.99), and morbid obesity (≥40.00). Waist circumference was measured to the nearest 0.5 inch at the height of the iliac crest using a tape measure.

Statistical analyses
Statistical analyses were accomplished using SPSS 20.0 (Chicago, Illinois) and Mplus 7.0 (Los Angeles, California). Statistical significance was set at $P \leq 0.05$; multiple comparisons were adjusted for using the Bonferroni correction. Missing data (14%) were imputed using the Markov Chain Monte Carlo method. Linear relationships between taste intensities and adiposity measures were evaluated with Pearson’s correlations ($r$); t tests examined the mean differences in adiposity and taste intensities between individuals with and without exposure to taste-related risk factors (multiple ear infections, head trauma, and tonsillectomy).

The theoretical model that taste-related risk factors influence taste functioning, and that both of these associate with adiposity measures, was tested using a latent variable approach under SEM. First, we used confirmatory factor analysis measurement models to determine which of the taste measures could effectively define the latent construct of taste functioning. Taste measures for this model were taste ratios, obtained by dividing the whole-mouth taste intensity by tongue-tip intensity. Intensities of 1 M NaCl and 1 mM quinine on the tongue tip were expressed as ratios relative to the corresponding whole-mouth intensities of these stimuli as well as relative to the whole-mouth intensity of 0.32 M NaCl.

Next, a series of SEM was tested with direct and indirect pathways of associations between taste-related risk factors, latent variable taste functioning, and either BMI or waist circumference. Age, FP count, and race/ethnicity were included as covariates. The models were estimated using the default maximum likelihood estimation method. The model fit was evaluated using four measures: chi-square (non-significance desirable), comparative fit index (CFI), root mean squared error of approximation (RMSEA), and Tucker-Lewis index (TLI). For RMSEA, values ≤ 0.05 were considered a good fit; values between 0.05 and 0.08 were interpreted as an acceptable fit. For CFI and TLI, values > 0.95 were considered a good fit; values between 0.90 and 0.95 were considered an acceptable fit. We used normalizing transformations for variables with skewed or elongated distributions, but analyses with transformed and untransformed data produced similar results; the latter are reported.

Results
Table 1 shows the descriptive and anthropometric measures of the sample. The majority of the women were non-Hispanic white (80.6%). Risk factors for taste alterations were well represented, with frequencies consistent with those observed among women respondents in NHANES 2011-2012. There was variability in adiposity measures—27.3% of the women were classified as overweight, 12% of the women had obesity, and 24% had elevated waist circumference (>88 cm) according to the National Heart, Blood, and Lung Institute criteria (27).

As shown in Supporting Information Table S1, perceived intensities for 1 mM quinine and 1 M NaCl on the tongue tip were significantly lower in women with histories of tonsillectomy and multiple ear infections. In contrast, taste intensities for 1 M NaCl on the tongue tip were greater in women with history of head trauma. Whole-mouth intensities of quinine and 0.32 M NaCl were significantly lower in women with histories of tonsillectomy and multiple ear infections, whereas no whole-mouth intensity differences were observed with history of head trauma.

Table 2 shows the mean differences in constructed taste intensity ratios and adiposity measures between women with and without reported exposures to taste-related risk factors. History of tonsillectomy was associated with higher whole-mouth to tongue-tip ratios, significant for all four constructed taste ratios. Head trauma, conversely, was associated negatively with all taste ratios. History of multiple ear infections only was associated with higher whole-mouth to tongue-tip ratio for quinine. In terms of adiposity measures, history of tonsillectomy was significantly associated with greater waist circumference and greater BMI, whereas history of head trauma was significantly associated with lower waist circumference. Although women with multiple ear infections had greater waist circumference and BMI, the differences failed to reach statistical significance.
TABLE 2 Mean differences in constructed taste intensity ratios and adiposity measures between women with and without reported exposures to taste-related risk factors

| Characteristic                              | Tonsillectomy | Multiple ear infections | Head trauma |
|---------------------------------------------|---------------|-------------------------|-------------|
|                              | Yes  | No  | P value | Yes  | No  | P value | Yes  | No  | P value |
| ** Constructed taste ratios **              |      |      |         |      |      |         |      |      |         |
| 1 mM quinine WM/quinine tongue-tip ratio   | 3.9 ± 0.3 | 2.9 ± 0.1 | 0.001 | 3.4 ± 0.2 | 3.0 ± 0.1 | 0.08 | 2.7 ± 0.2 | 3.3 ± 0.2 | 0.13 |
| 0.32 M NaCl WM/quinine tongue-tip ratio    | 2.7 ± 0.2 | 1.9 ± 0.1 | 0.001 | 2.2 ± 0.2 | 2.1 ± 0.1 | 0.70 | 1.6 ± 0.1 | 2.2 ± 0.1 | 0.02 |
| 1 M NaCl WM/NaCl tongue-tip ratio          | 3.2 ± 0.4 | 2.2 ± 0.1 | 0.001 | 2.4 ± 0.2 | 2.5 ± 0.1 | 0.85 | 2.0 ± 0.2 | 2.5 ± 0.1 | 0.10 |
| 0.32 M NaCl WM/NaCl tongue-tip ratio       | 2.2 ± 0.2 | 1.6 ± 0.1 | 0.002 | 1.7 ± 0.1 | 1.8 ± 0.1 | 0.89 | 1.3 ± 0.1 | 1.9 ± 0.1 | 0.001 |
| ** Adiposity measures **                    |      |      |         |      |      |         |      |      |         |
| Waist circumference (in)                   | 33.9 ± 0.4 | 31.2 ± 0.2 | 0.001 | 32.3 ± 0.3 | 31.4 ± 0.3 | 0.06 | 30.9 ± 0.4 | 32.1 ± 0.2 | 0.03 |
| BMI (kg/m²)                                | 26.0 ± 0.4 | 24.0 ± 0.2 | 0.001 | 24.9 ± 0.3 | 24.0 ± 0.3 | 0.07 | 24.0 ± 0.4 | 24.6 ± 0.2 | 0.34 |

Data are presented as mean ± standard error of the mean. WM = whole mouth.

TABLE 3 Correlationsa among variables used in structural models

| Variable # | Variable                      | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    |
|------------|-------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1          | Age                           | 1     |      |      |      |      |      |      |      |      |       |
| 2          | Quinine tongue-tip            | -0.29 | 1     |      |      |      |      |      |      |      |       |
| 3          | 1 M NaCl tongue-tip           | -0.26 | -0.56 | 1     |      |      |      |      |      |      |       |
| 4          | Quinine WM/quinine tongue-tip | 0.21  | -0.57 | -0.29 | 1     |      |      |      |      |      |       |
| 5          | 0.32 M NaCl WM/quinine tongue-tip | 0.18 | -0.54 | -0.19 | 0.71 | 1     |      |      |      |      |       |
| 6          | 1 M NaCl WM/NaCl tongue-tip   | 0.24  | -0.23 | -0.46 | -0.44 | 0.32 | 1     |      |      |      |       |
| 7          | 0.32 M NaCl WM/NaCl tongue-tip | -0.20 | -0.16 | -0.54 | -0.29 | 0.45 | 0.72 | 1     |      |      |       |
| 8          | FP count                      | -0.10 | -0.85 | -0.05 | -0.05 | -0.01 | -0.09 | 0.10 | 1     |      |       |
| 9          | Waist circumference           | 0.34  | -0.17 | -0.11 | -0.17 | -0.22 | 0.12  | 0.12 | -0.15 | 1     |       |
| 10         | BMI                           | 0.33  | -0.15 | -0.13 | -0.17 | 0.16  | 0.17  | 0.12 | -0.16 | 0.83 | 1     |

WM = whole mouth; FP = fungiform papillae. *Correlations above 0.14 were significant at P < 0.005.

Among the five taste measures, only the quinine tongue-tip intensity was associated significantly with waist circumference and BMI, with lower intensity associating with higher adiposity (Table 3). Among the four constructed taste ratios, whole-mouth to tongue-tip ratio for quinine and the ratio of 0.32 M NaCl whole-mouth intensity to quinine tongue-tip were positively and significantly correlated with waist circumference and BMI.

Confirmatory factor analyses identified a latent construct of taste functioning, defined by three indicators of whole-mouth to tongue-tip taste ratios (Figure 1) with good fit indices (CFI = 0.99; TLI = 0.99; RMSEA = 0.03). The three taste ratio indicators were correlated (Table 3) with a high degree of internal consistency (Cronbach’s alpha = 0.72) and factor loadings > 0.5 (Figure 1). Based on the hypothesized conceptual model and supporting bivariate analyses, an overall SEM examined direct or indirect associations between the three taste-related risk factors, the latent variable taste functioning, and waist circumference, with age and FP count included as covariates; race/ethnicity was removed as a covariate as it did not adequately explain differences in the exposures or outcomes. Nonsignificant paths (P > 0.10) were trimmed and the respecified model fit was tested before being provisionally accepted. The final model shown had all paths significant and good fit indices (X² = 21.9 [df = 13], P = 0.06; CFI = 0.98; TLI = 0.96; RMSEA = 0.04).

Figure 1 shows the final model with standardized parameter estimates. The latent variable taste functioning was independently predicted by tonsillectomy and head trauma after mutually adjusting for each other, as well as age. Age and tonsillectomy history were associated positively with latent variable taste functioning, indicating that women who were older and had tonsillectomy had diminished sensations on the tongue tip compared to the whole mouth; women with head trauma had lower ratios, and, thus, head trauma associated negatively with latent variable taste functioning. FP count was initially included as a covariate in these paths but was removed due to lack of association. The taste functioning latent variable was not associated with history of multiple ear infections after controlling for age and other taste-related risks. Accordingly, this path also was removed.
Age, the latent variable taste functioning, FP count, and all three taste-related risk factors were independent predictors of waist circumference after controlling for other variables in the model. Women with histories of tonsillectomy and multiple ear infections had higher waist circumferences than those without these respective histories. Women with head trauma, in contrast, had significantly lower waist circumferences than those without. Greater FP count was also associated with lower waist circumference. The latent variable of taste functioning was associated positively with waist circumference. Additionally, taste functioning partially mediated (indirect effect, $\beta = -0.03$, $P < 0.05$) the negative association between head trauma and waist circumference. Overall, the model explained 17.7% of the variance in waist circumference.

Additional models were tested, first without FP count, and second with BMI as the primary outcome variable (data not shown). The model excluding FP count and with waist circumference as the adiposity measure showed similar paths of associations with good model fit ($\chi^2 = 21.9$ [df = 13], $P = 0.06$; CFI = 0.98; TLI = 0.96; RMSEA = 0.04). WM, whole mouth; FP, fungiform papillae; CFI, Comparative Fit Index; RMSEA, Root Mean Squared Error of Approximation; TLI, Tucker-Lewis Index.

**Discussion**

The present study examined an existing laboratory database to identify measures of taste functioning that were significantly associated with taste-related risk factors as well as adiposity among adult females. These taste measures, which have been incorporated into the NIH Toolbox (26) and NHANES 2013-2014 (11), included tongue-tip and whole-mouth intensities of concentrated quinine and NaCl solutions. Diminished taste intensity on the tongue tip, measured directly or as a ratio to whole-mouth intensity, was associated with greater adiposity and was explained by reported exposures to taste-related risk factors. Through structural equation modeling, we identified direct associations between risk factors of taste alteration and adiposity, as well as some indirect associations mediated by taste functioning. These associations were significant after excluding or controlling for FP density, an anatomical marker of taste functioning not included in the NIH Toolbox or NHANES protocol.

Direct associations between taste-related risk factors and adiposity have been previously reported. In our study, women with histories of tonsillectomy and multiple ear infections had higher adiposity than women without such histories. These findings are consistent with a recent study (3), which reported that histories of tonsillectomy and otitis media were independently associated with greater adiposity in adolescent girls. Several other studies have linked chronic otitis media with excess adiposity in children (2,8-10). Associations between tonsillectomy and weight also have been mostly studied in children, who show significant weight gain following the surgery (28-30). Case studies of weight loss after tonsillectomy have been reported as well, but only with the presence of dysgeusia (24).
Although there are some studies to the contrary (31,32), the literature suggests that tonsillectomy and chronic otitis media are associated with diminished or altered taste. For tonsillectomy, most studies on postoperative taste changes have been focused on qualitative symptoms like dysgeusia, which are found to be common but transient (33). Data on measured regional taste loss from tonsillectomy are scarce, presumably because such loss is likely to be unnoticed by patients due to disinhibition from undamaged taste nerves (3,33). In our study, women with tonsillectomy and multiple ear infections had diminished taste sensations on the tongue tip for both NaCl and quinine. In contrast, Bartoshuk and colleagues (3) observed significant differences between individuals with and without tonsillectomy for taste intensities on the posterior but not the anterior tongue; for individuals with otitis media, NaCl and sucrose distributions, but not quinine, were significantly displaced toward lower intensities on the tongue tip. Similar to our study, Shin and colleagues (8) reported that children with chronic otitis media had higher adiposity and lower taste perception on the tongue tip.

Otitis media and tonsillectomy are hypothesized to contribute to excess adiposity through changes in taste perception. In this study, tonsillectomy and otitis media were associated with both diminished taste and excess adiposity, but taste failed to show a significant mediating effect. One explanation may be that these chronic infections can alter oral sensations beyond taste, which were not measured in this study. Disruptions in the central inhibitory taste circuits from taste nerve damage, for example, can alter other oral sensations including retronasal olfaction and tactile sensations from fatty foods and are thought to explain the enhanced palatability of energy-dense fat/sweet foods in adults with histories of tonsillectomy and otitis media (3). Alternatively, otitis media and tonsillectomy may contribute to excess adiposity through nondietary mechanisms, such as inflammatory mediators and decreased systemic catecholamines (8,30).

In contrast to tonsillectomy and ear infections, history of head trauma was significantly associated with decreased central adiposity in our study. Head trauma in our sample was defined by either loss of consciousness or concussion due to head injury, and hence is likely to capture the milder spectrum of traumatic brain injury (TBI). In the literature, associations between TBI and weight changes have been mixed, with reports of both weight gain and loss following the injury (34-36). The negative association between head trauma and central adiposity in our study was statistically mediated, in part, by taste functioning. Specifically, women with head trauma reported significantly greater intensities for NaCl on the tongue tip and had lower whole-mouth to tongue-tip ratios. One possible explanation is that mild chorda tympani damage from head trauma may have released inhibition of cranial nerve V, resulting in heightened somatosensory sensations from taste-irritant stimuli like concentrated NaCl (3). Conversely, more severe damage, or damage to more than one nerve such as by tonsillectomy, may result in reductions in overall taste sensations (3). It is unclear why we observed the negative associations between head trauma and adiposity in our sample. However, clinical reports of eating disorders, including anorexia following TBI, have been reported previously (37,38). Head trauma may also cause olfactory dysfunction and subsequently decrease appetite or desire to eat (11).

Our study had several limitations. Causal relationships between taste-related risk factors, taste functioning, and adiposity cannot be established due to our cross-sectional data. We were unable to verify the presence of the self-reported risk factors by physical exams or medical records. Self-reported childhood otitis media by adults, in particular, may be susceptible to recall bias; however, its validity and reliability have been demonstrated previously (39,40). Our sample had lower rates of obesity than is typically seen among adult females in the United States. Additionally, other confounding factors such as physical activity, dietary intake, and early-life risk factors of otitis media (e.g., breastfeeding status/duration, exposure to air pollutants) were not evaluated. The observed taste-adiposity associations may have been mediated by differences in food preference and intake and should be examined in future studies. Because taste perception is modulated by the endocrine system, it is possible that metabolic disorders such as obesity may influence taste perception rather than vice versa (4). Longitudinal studies are needed to evaluate this possibility of reverse causation. Our database consisted of a relatively homogenous sample, which increases the ability to examine the taste-adiposity relationship but decreases the generalizability of the findings.

Despite the limitations, our study supports the utility of regional and whole-mouth taste assessments included in the NIH Toolbox and NHANES 2013-2014 taste protocols, as well as their relevance to nutrition-related health outcomes. In our study, diminished taste function was associated with increased adiposity and was partly explained by common risk factors for taste alterations. The present study provides a framework for analyzing population-based studies employing the NIH Toolbox or the related NHANES 2013-2014 taste protocol. Examination of the NHANES 2013-2014 taste data will provide an opportunity to confirm the present study findings in a national study and also elucidate whether dietary factors mediate the observed taste-adiposity associations. 

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